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From Exoplanets to Distant Galaxies: SPICA'S NEW WINDOW on the Cool Universe

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Conference Photo

In front of Ito International Research Center
June 19, 2013

Photo by Y. Sugiyama
Preface

After the Big Bang, the Universe was quickly enriched by metal and dust through star formation activity in galaxies and transformed into the present heterogeneous Universe with a large variety of phenomena, including the emergence of life. It has been revealed that production of stars and metal elements reached their peak at the “dusty era”, where most photons from stars were converted into and emitted in the infrared, and planet formation occurs in the regions deeply embedded in thick dust clouds, where ultraviolet and optical observations cannot make a significant contribution. As a consequence, infrared observations are indispensable for the characterization of these obscured objects. SPICA (SPace Infrared telescope for Cosmology and Astrophysics) is a space telescope with unprecedented sensitivity in the mid- to far-infrared. With its cryogenically cooled telescope, SPICA will try to reveal how and when the Universe was enriched by metal and dust and prepared habitable regions.

After the symposium, the SPICA project have gone through the major changes of the framework. We here present short project updates of SPICA as of July 2017. SPICA is re-defined as a space infrared telescope covering 12 - 230 µm with a cryogenically cooled (below 8 K) 2.5 m diameter telescope. The international collaboration framework of SPICA has been revisited as an ESA-led mission. SPICA under the new framework passed the Mission Definition Review by JAXA in 2015. A Cosmic Vision M5 proposal to ESA was submitted in Oct. 2016, waiting for its 1st selection of the candidates.

Although the mission has gone through major changes, the new SPICA has a lot in common with the SPICA concept presented in the symposium 2013, and we believe that many science cases are valuable for the discussions on future missions like new SPICA. Hence we publish this volume, hoping this will provide valuable information to disentangle the major science questions mentioned above.

Finally, we sincerely apologize to all the contributors for the delay of publication.

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SESSION 1:

GALAXY FORMATION AND EVOLUTION AS REVEALED IN THE INFRARED
The Mid- and Far-Infrared View on Galaxy Evolution

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ABSTRACT

This review provides a summary of spectroscopic diagnostics in the mid- and far-infrared which are relevant for the study of galaxy evolution with SPICA. It starts with a description of (some of) the contemporary subjects that have to be addressed for a comprehensive study of this topic. Subsequently, relevant tools are introduced and their application demonstrated with previous results. This review does not aim at being complete in any sense, but is meant as an introduction to the galaxy evolution part of these proceedings, and wants to highlight the tremendous potential for future progress in this area with SPICA, in particular with its mid-and far-infrared spectrometers MCS and SAFARI.

1. THE KEY QUESTIONS IN GALAXY EVOLUTION

The baryonic lifecycle of galaxies is determined by a balance between three rates: (1) the inflow rate of baryons through filaments of the cosmic web or galaxy mergers; (2) the rate at which stars form out of cooled gas; and (3) the outflow rate of material, blown out by supernovae, or radiation pressure from young stars or AGNs. Temporary imbalances between these three forces will cause a reduction or increase of its internal gas reservoir. The galaxy and its halo accumulate more mass over time, which leads to structural growth of the AGN and stellar component. Eventually, bulges emerge as galaxies mature, and depart from their star-forming steady state to join the quiescent population.

This is the simplified, qualitative picture of galaxy evolution that has emerged in recent years. A complete and quantitative understanding of the cosmic history of galaxy formation and evolution, however, requires to address a large number of questions and to overcome an almost discouraging amount of problems. Yet, for the purpose of this review it shall suffice to take a very simplistic point of view: if we can answer the following three questions we are pretty much done:

• How many galaxies exist at which redshifts?
• What kind of galaxies are they? E.g. what is the relative importance of star formation and AGN, gas and stellar masses, star formation rates, dust content, black hole masses and accretion rates, etc.
• How did they form their stars and black holes, and how did they evolve into today’s population?

In the following I will address various aspects that are directly related to these questions, such as galaxy counts and luminosity functions, the cosmic star formation history, the main sequence of galaxy evolution, the co-evolution of SMBHs and host galaxies, feedback, the different modes of star formation, metallicity evolution, the role of H2 or the role of clustering and environment.

2. DETERMINING THE COSMIC STAR FORMATION HISTORY

A natural first goal is to get a complete census of the star formation history of galaxies over the entire age (or most of it) of the Universe. While the COB (cosmic optical background) measures the light directly emitted by stars and unobscured AGN, a significant fraction (∼50%) of the integrated light of the Universe would be missed by using only (redshifted) UV light as a tracer of star formation. For a complete picture the dust-obscured star formation has to be measured from the CIB (cosmic infrared background). The necessary infrared studies can be sorted roughly in a sequence of four steps:

• How many galaxies are there at which redshifts? Resolve the far infrared background into discrete sources
• determine redshifts and luminosities
• identify (hidden) AGN contribution to these sources and quantify its role
• identify (hidden) star formation contribution and quantify its role

By the time SPICA will be launched, the deep cosmological surveys undertaken in the past by ISO, AKARI and Spitzer and with Herschel (e.g. Berta et al. 2010; Gruppioni et al. 2010; Eales et al. 2010; Clements et al. 2010, 2011; Lutz et al. 2011; Oliver et al. 2012) will have produced catalogues containing the fluxes of many tens of thousands of faint MIR/FIR/submm sources. It is clear that the statistical census provided by deep look-back surveys has played and will play an important role in establishing the broad scope of the “equilibrium-growth-model” for galaxies described above. See the contributions by Lutz et al., Goto et al., and related posters elsewhere in these proceedings. However, many important elements of such a model require information that only spectroscopy can provide.

Substantial progress in studying galaxy evolution can therefore only be achieved by following up on the photometric surveys with mid- to far-IR spectroscopic surveys, which will identify AGN, provide measured (rather than estimated)
redshifts and also unambiguously characterize the detected sources, by measuring the AGN and starburst contributions to their bolometric luminosities over a wide range of cosmological epochs and by allowing various kinds of modeling. **SPICA** will enable us to do for the first time spectroscopic deep surveys and, hence, to match the deep imaging surveys with such spectroscopic information. In the following I will briefly recap the mid- and far-infrared spectroscopy toolbox for these purposes.

### 3. THE MID-/FAR-INFRARED TOOLBOX

#### 3.1. Identifying AGN, and Quantifying SFR and AGN Contribution

The fine-structure atomic and ionic lines accessible with **SPICA** cover a large range in critical density and ionisation potential and thus trace out a wide range of different physical-excitation conditions (e.g. Spinoglio & Malkan 1992). These transitions constrain a wide range of physical conditions and phases of the ISM, from the neutral molecular and atomic ISM, through the ionized ISM (as seen in photo-dissociation regions and H II regions) to the highly ionized AGN and “coronal” regions. These features do not suffer the heavy extinction that affects the UV, optical and even the near-IR lines, and therefore provide an almost unique insight into highly obscured regions. In the mid-infrared **ISO** demonstrated that emission lines tracing the hard UV field found in the narrow line region of AGN (e.g., [Ne V], [O IV], [Ne VI]) are excellent tools to unambiguously identify the presence of an AGN. Their line strengths relative to lines tracing stellar H II regions (e.g., [S III], [Ne II]) can be used to quantify the relative contributions of AGN and star formation to the combined light of their galaxies (e.g. Genzel et al. 1998). But also the weakness or absence of mid-IR PAH, dust, or ice features as well as a strong warm continuum peak (peaking in the 10–20 µm range) are good tracers of AGN activity. **Spitzer** observations have refined and extended these methods and enabled the calibration of the line and dust feature luminosities relative to the bolometric luminosities of dusty galaxies (Dale et al. 2006; Desai et al. 2007; Armus et al. 2007; Veilleux et al. 2009; Tommasin et al. 2010). Spectral decomposition methods which try to fit the mid- to far-IR SED with a combination of different template SEDs have also been successful in identifying and quantifying the various components (e.g. Marshall et al. 2007; Schweitzer et al. 2008; Veilleux et al. 2009). PAH and ice features have been applied to **Spitzer** and **AKARI** observations to characterize infrared bright galaxies such as ULIRGs and SMGs in the local Universe as well as out to z ~ 3 (e.g. Valiante et al. 2007; Spoon et al. 2007; Pope et al. 2008; Menéndez-Delmestre et al. 2009; Imanishi et al. 2010).

#### 3.2. Further Characterizing the AGN

Hot and young stars as well as black hole accretion discs show strong differences in the shape of their primary ionizing continuum. However the far-UV continuum, dominating the total bolometric output luminosity in both processes, is in general not observable directly, due to absorption by H I and, at longer wavelengths, by dust. In both starbursts and AGN a continuum. However the far-UV continuum, dominating the total bolometric output luminosity in both processes, is in

3.2. Further Characterizing the AGN

Hot and young stars as well as black hole accretion discs show strong differences in the shape of their primary ionizing continuum. However the far-UV continuum, dominating the total bolometric output luminosity in both processes, is in general not observable directly, due to absorption by H I and, at longer wavelengths, by dust. In both starbursts and AGN a fraction of the ionizing continuum is absorbed by gas and then re-radiated as line emission. As described above, emission lines ratios from the photoionized gas are, hence, the best tracers and discriminators of accretion and star formation processes (see, e.g., Osterbrock & Ferland 2006). Photoionization models can be used to reconstruct the ionizing UV continuum and hence to further constrain the properties of the AGN (e.g. Alexander et al. 1999, 2000; Spinoglio et al. 2000; Sturm et al. 2002). Dasyra et al. (2011) presented a calibration of the (luminosity-corrected) line widths of highly ionized mid-IR lines to the masses of the central SMBHs.

In the far-IR high-J rotational transitions of CO, together with ionized molecules like H$_2$O$^+$ and OH$^+$, are a promising new tool to help identifying the X-ray dominated regions (XDRs) around AGNs. XDRs are mostly heated by direct photoionisation of the gas, which produces fast electrons that lose energy through collisions with the gas. In contrast, the dominant heating mechanism at the edge of the typical photodissociation regions (PDRs) in star forming regions is photo-electric heating: FUV photons are absorbed by dust grains, which release electrons that lose their surplus kinetic energy to the gas by Coulomb interactions. The impact of X-rays on the ISM is therefore different from UV photons. In the recent past models have become available (e.g. Meijerink et al. 2007; Schleicher et al. 2010) which can be used to predict the strength of high-J CO lines in the FIR and to distinguish between XDRs and PDRs. With the *Herschel Space Observatory* it has become possible for the first time to observe these CO lines.

However, observationally there is a lot of scatter, and cosmic rays and shocks have to be considered as excitation mechanisms, too. Therefore a good sampling of the CO line SED up to really high-J (e.g. J = 40 at 65 µm) is needed (and expansion of the models). Hailey-Dunsheath et al. (2012) have demonstrated both the power and the caveats of this new tool on the example of the archetypical Seyfert 2 galaxy NGC1068. Full line SEDs will be hard to observe with ground based observatories like ALMA and NOEMA. An alternative solution could be ratio-ratio diagrammes invoking just a few transitions at strategic J levels. For instance diagrams using CO(18–17)/CO(1–0) vs. CO(6–5)/CO(1–0), which trace very warm components (J = 18), the peak of normal star forming galaxies (J ~6) and the cold component (J = 0), must be explored more both observationally and theoretically. First attempts at this (Masian et al. in prep.) are promising. As mentioned above, interpretation of high-z high-J CO lines with, e.g., CCAT, NOEMA, or ALMA will not be straightforward. *Herschel* has allowed first observations, but only **SPICA** can help to calibrate and fine tune this new tool fully in the local universe.

**SPICA** will for the first time enable the kind of mid- and far-IR emission line studies described above — i.e. direct identification of AGN in dusty galaxies, quantifying the role of SF and AGN, and determining the physical properties of
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the ISM and AGN — at redshifts around the peak of the cosmic star and SMBH formation history ($z = 1.3$, and beyond using PAH features).

4. CO-EVOLUTION AND FEEDBACK

A well known correlation between the mass of galaxy spheroidal components and super-massive black holes (SMBH Ferrarese & Merritt 2000) strongly suggests that star-formation in galaxies (several kpc scale) and SMBH mass growth (<pc scale, the so-called AGN activity) are closely linked, and that galaxies and SMBHs have co-evolved. Both star-formation and AGN activity went through an accretion phase in the early universe, show peaks at $z \sim 1−2$, and have been winding down towards $z = 0$. Whether or not this co-evolution is reflecting a direct physical link is a major subject of current astronomy. Possible controlling mechanisms providing positive feedback are common feeding (e.g. in mergers), ‘secular’ disk instabilities and clumps, bars, nuclear spiral structures, or triggered star formation through winds/shocks from AGN and/or stars. On the other hand, negative feedback could come from the quenching of star formation and starvation of BHs via strong (e.g. radiation pressure driven) winds/outflows from AGN and/or stars.

In particular the winding down phase is hard to explain without some kind of negative feedback mechanisms. Something must have stopped the growth of both galaxies and SMBHs around the same time at $z \sim 1$, otherwise there would be much more massive galaxies today than we observe. In order to reproduce this winding down behaviour quantitatively many galaxy evolution models include some kind of negative feedback mechanism that would quench both star formation and AGN growth. Somehow the steady accretion of material or the enhanced inflow during a merger has to be stopped, if not removed entirely. A prime candidate for this is negative feedback from the AGN: once an AGN has grown powerful its winds and/or radiation pressure are supposed to blow away the gas that is feeding the SMBH as well as the star formation around it. Galactic winds have been known for a long time, but mostly in ionized or neutral atomic gas. Stars are formed from cold molecular gas, however. Hence, in order to witness the quenching process in action, we have to observe outflows in molecular gas. Recent observations with Herschel-PACS have allowed exactly this: the detection of strong molecular outflows, as traced by P-Cygni profiles or blue shifted absorption of OH, in ~60 local ULIRGs and QSOs (Fischer et al. 2010; Sturm et al. 2011; Veilleux et al. 2013; Spoon et al. 2013). These observations show a correlation of the outflow velocity with AGN luminosity, with maximum velocities reaching well above 1000 km/s in the most luminous AGN-ULIRGs. Sturm et al. (2011) have modeled the outflows in a handful of objects applying radiative transfer models. They find mass loss rates of up to 1000 $M_\odot$/yr, mass loading factors (mass loss rate/star formation rate) of up to ~10, momentum fluxes ($dM/dt \times v$) reaching ~ 10$L(AGN) / c$, and mechanical luminosities ($dM/dt \times v^2$) of a few per cent of $L(AGN)$. These values strongly suggest that radiation pressure from the AGN is the main driver of these outflows (e.g. Debuhr et al. 2012), in line with the high velocities and correlation of velocities with $L(AGN)$. SPICA will be able to trace molecular outflows, and therefore to probe a key feedback mechanism, at the peak epoch of cosmic evolution (using OH transitions below rest wavelengths of 100 $\mu$m).

The mid-IR range provides a large number of tools to address the issue of co-evolution in various ways. E.g. the star formation in the hosts of QSOs can be studied via PAH features and other star formation tracers like [Ne II] (Schweitzer et al. 2006; Lutz et al. 2008). The construction of luminosity functions from high ionization lines like [O IV] can be used as a means of studying the accretion rate history of the Universe that is an alternative to X-rays, in particular for Compton thick sources. The widths of the same lines depend on the kinematics of the clouds that they probe, determined by either the gravitational potential out to a radius that the AGN luminosity dictates, or by AGN feedback effects. They can be used to weigh the masses of black holes, permitting the creation of black hole mass functions that include obscured AGN with SAFARI out to redshift of ~4 using the [O IV] line.

5. THE MAIN SEQUENCE AND DIFFERENT Modes OF STAR FORMATION

The rate at which galaxies produce new stars is proportional to the amount of stellar mass they already assembled. This relation is known as the main sequence of star formation, on which ~98% of star forming galaxies reside. The tight locus defined by the vast majority of star forming galaxies in this $M_* - SFR$ plane is dominated by disk-like systems while rarer “outliers” above and below this “main sequence” show more compact, cusping morphologies (Wuyts et al. 2011). Resolved measurements of the kinematics and structure of high-$z$ galaxies provided key evidence that smoother accretion and internal dynamical processes play a dominant role in growing galaxies, rather than violent major mergers that had been favored for some time. In other words, most star formation happens near the main sequence, in a rather steady way (and fed from the cosmic web/minor mergers rather than major mergers). This main sequence is observed at all wavelengths, but with some evolution: at a given stellar mass, galaxies on this sequence were forming stars at much higher rates in the distant universe relative to today (e.g. Brinchmann et al. 2004; Noeske et al. 2007; Daddi et al. 2007; Elbaz et al. 2007; Peng et al. 2010; Rodighiero et al. 2010; Whitaker et al. 2012), i.e. the specific star formation rate ($SSFR = SFR/M_*$) decreased from $z = 2$ to $z = 0$. While a galaxy evolves upward on the main sequence, the whole main sequence shifts downwards, i.e. the SFR stays roughly constant over long times. This points towards secular effects: the galaxies have to accrete material steadily over long periods.

Many IR properties of infrared bright galaxies are therefore best described in relation to the evolving main sequence of star forming galaxies, rather than simply by $L_{IR}$ and a (ULIRG nomenclature: locally, the galaxies with IR luminosities exceeding $10^{12} L_\odot$ are predominantly associated with mergers of comparable mass spirals. At high $z$, high IR luminosities
can be achieved via galaxy mergers, but as described above smooth, steady accretion of cold gas in cooling flows turns out to be the more important mode: major mergers manifest themselves in the $M_\star$–SFR as “outliers” in a region above the main sequence.

The trend with redshift is consistent with the larger molecular gas fractions of galaxies at earlier epochs. They produce more stars because they have more material for star formation available. However, the SSFR in galaxies (i.e. the position in the SFR–$M_\star$ plane) is not determined by variations in the molecular gas content alone. Also the efficiency to convert this gas into stars (star formation efficiency, SFE) seems to vary. Independent support for the different star-forming relations in normal disk galaxies and major merger systems has come from recent far-IR spectroscopy with Herschel (Graciá-Carpio et al. 2011). Galaxies with high $L_{FIR}/M_{H_2}$ ratios tend to have weaker fine structure lines relative to their far-infrared continuum than galaxies with “normal” $L_{FIR}/M_{H_2}$. As $H_2$ is the reservoir for star formation, and $L_{FIR}$ is proportional to the amount of star formation that has already appeared (being UV light from young stars that has been absorbed by dust and re-emitted in the infrared), this ratio can be considered a star formation efficiency. The $L_{FIR}/M_{H_2}$ value where these line deficits start to manifest is similar to the limit that separates between the two modes of star formation found in the above mentioned studies of galaxies on the basis of their gas-star formation relations (Genzel et al. 2010; Daddi et al. 2010). In other words, galaxies above the main sequence have a higher SFE, and their ISM, as traced by the line deficiencies, is warmer, denser and more compact (Graciá-Carpio et al. 2011 and in prep.; Díaz-Santos et al. 2013).

The strength of far-IR fine structure lines relative to the $L_{FIR}/M_{H_2}$ ratios of their galaxies can therefore be used as a tool to examine the mode of star formation in high redshift galaxies. This has been applied for the first time with Herschel-PACS. For instance, Sturm et al. (2010) have analyzed IRAS F10214+4724, a well studied lensed $z = 2.29$ HyLIRG (Sy2) with coeval star formation and AGN activity. This object exhibits a strong O III deficit, which points towards a major merger history. A second object in their study, MIPS J142824.0+352619, is, like F10214, a hyperluminous lensed object at $z = 1.32$, but without AGN signatures. Contrary to F10214, J142824 does not show an O III deficit, i.e. this object has the luminosity of a local ULIRG, but the star formation efficiency of a normal starburst, probably forming stars in a more steady accretion mode. These Herschel observations are promising, but were naturally restricted to a handful of the brightest objects. Only SPICA will be able to further develop and apply this tool to large numbers of objects at high redshifts and to determine their mode of star formation without the need to determine their stellar masses (and hence their position in the $M_\star$–SFR plane).

6. METALLICITY EVOLUTION

Another important property to distinguish various galaxy evolutionary scenarios is the metallicity of gas and stars in galaxies, since metals reflect the history of both the star-formation activity and the gas inflow and outflow in galaxies.

In the past mostly rest-frame optical emission lines have been generally used to measure the metallicity. To accurately determine the metallicity of dust-obscured galaxies, and accordingly to understand the chemical evolution of dusty populations, mid- and far-infrared tools are needed, which are less affected by extinction. Usually, the strengths of fine structure lines relative to hydrogen recombination lines are used to derive the metallicity of the gas producing these emission features. In practice, however, the hydrogen lines within the mid- to far-IR wavelength range (e.g. Pfα 7.5 µm and Hα 12.4 µm) are very faint and close to other spectral lines and dust features. In the ISO and Spitzer era such measurements were difficult (Verma et al. 2003; Bernard-Salas et al. 2009 for starburst galaxies) or could only be done for stacked spectra of large samples (Veilleux et al. 2009 for ULIRGs).

However, thanks to the higher sensitivity and spectral resolution, the medium resolution spectrometer (MRS) of SPICA/MCS promises to detect Hα α at least 10 times fainter limits than Spitzer/IRS. Metallicity measurement for star-forming galaxies (including the very dusty populations) can hence be extended out to $z > 1$. Note that SPICA/MCS is more powerful in this metallicity study than JWST/MIRI at $z > 0.6$, where Hα (and the neon emission lines) shift beyond 20 µm.

Nagao et al. (2011) proposed diagnostics of the gas metallicity which does not make use of hydrogen recombination lines but is based on far-infrared fine-structure emission lines, like [O iii]52 µm, [O iii]88 µm, and [N iii]57 µm. These lines are among the brightest fine structure lines and nearly unaffected by dust extinction even in the most obscured systems. Metallicity measurements with these fine-structure lines will be feasible at relatively high redshift ($z\sim1$ or more) with SPICA, even in galaxies with rather modest star formation rate.

7. THE ROLE OF H$_2$ AS MAJOR COOLANT IN THE FIRST GALAXIES

How the first stars (population III stars) formed out of primordial gas is one of the most important questions in modern astrophysics. It has long been realized that the gravitational collapse of the primordial clouds must have been induced by H$_2$ line cooling (e.g. Saslaw & Zipoy 1967). Kamaya & Silk (2002) and Mizusawa et al. (2004) considered the H$_2$ rotational emission from primordial molecular cloud kernels to be associated with the formation of the first stars at the earliest epochs of $z \sim 20$. Millennium simulations predict how the H$_2$ mass function has evolved with redshift (Obruchek & Rawlings 2009). The simulations suggest that a large fraction of galaxies at redshifts 8–10 are expected to have $M(H_2) \sim 10^9 M_\odot$. This would correspond to a flux of $H_2S(0)$ of a few $10^{-18}$ Wm$^{-2}$, which is within the reach of SAFARI.

Few observations of H$_2$ at high redshift exist today: it has been detected in stacked spectra of $z \sim 1$ galaxies (Daslya et al. 2009), in $z \sim 2$ galaxies (Fiolet et al. 2010) and in a highly magnified LIRG behind the Bullet Cluster at $z = 2.79$.
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(Gonzalez et al. 2010). Spitzer observations of z < 0.3 radio galaxies (Egami et al. 2006; Ogle et al. 2007, 2010), also unveiled a class of “H$_2$ luminous galaxies” whose spectra have extremely bright H$_2$ rotational lines, possibly due to the jet-ISM interaction. Similarly, the H$_2$ S(1) transition is by far the brightest emission line in the whole 10–35 µm range in Stefan’s Quintet (Appleton et al. 2006). The lack of PAH and hydrogen recombination line emission rules out UV fluorescence as a possible excitation mechanism, indicating that H$_2$ is produced by shocks which deposit large amounts of kinetic energy into the ISM. These H$_2$ luminous galaxies may represent a population at high redshift where interactions and mergers are more common (see the contribution by P. Appleton to these proceedings).

8. THE ROLE OF CLUSTERING / ENVIRONMENT

Galaxy properties are known to be strong functions of the environment. Hence, the large-scale structure formation in the Universe should play a role in shaping individual galaxies. For instance, high-density environments such as galaxy clusters are dominated by red early-type galaxies with old stellar population, while galaxies in low-density fields are mostly blue late-type galaxies with on-going star formation (e.g. Dressler 1980; Lewis et al. 2002; Gómez et al. 2003). The young “progenitors” of the present-day passive cluster galaxies should therefore be observable as strong dusty starbursts in the distant Universe. An important goal of the SPICA mission is therefore to directly detect such dust-obscured star-formation along the young, forming large-scale structures, and to identify the role of environment at the frontier redshift at z > 1.

A study of the evolution of the Large Scale Structure in the Universe and of the three-dimensional clustering will be a natural “by-product” of large area deep spectroscopic surveys with SPICA, which will deliver precise spectroscopic redshifts of thousands of sources out to high redshifts, together with their physical properties. Galaxies observed by SPICA surveys will either reside in overdense or underdense regions. This will allow to investigate the impact of environment on galaxy formation and evolution as a function of redshift up – and possibly beyond – the epoch which marks the bulk of AGN/stellar activity. This shall provide answers to a number of questions, such as whether there is any large-scale influence between the surrounding environment and AGN/stellar activity and, if so, if seeds for such a phenomenon were already in place by z ~2–3. Beside the redshift measure, the spectroscopic diagnostics will be essential to measure directly the star formation and AGN luminosities in each cluster component.

Significant clustering has been measured in high-redshift (z ~1–3) Spitzer galaxies (Farrah et al. 2006; Magliocchetti & Brüggen 2007; Magliocchetti et al. 2008), with a strength which increases with redshift. Comparisons with theoretical models have provided a direct estimate of the dark matter mass of such sources, and the derived values (M = 10$^{11}$ M$_\odot$) indicate that luminous IR galaxies at z ~ 2 are indeed most likely the progenitors of the giant ellipticals which reside locally in rich clusters, as speculated above. This implies that studies of the IR population at redshifts z >1–1.5 provide a unique tool to investigate the formation and evolution of super-structures such as proto-clusters and clusters, from even before the peak time of cosmic star formation activity. While the results from Spitzer necessarily suffered from limitations due primarily to the lack of measured redshifts, SAFARI will, for the first time, be able to overcome such problems and provide definite answers to many crucial issues.

9. THE BIG STEP FORWARD WITH SPICA

SPICA offers a sensitivity up to two orders of magnitude better than Herschel, covering the mid-to-far-IR (the full 5–210 µm range). This major increase in sensitivity, combined with a wide field of view and simultaneous coverage of large wavelength ranges, will allow us to spectroscopically explore the nature of the tens of thousands of objects that Herschel, JWST (and SPICA itself) will discover in photometric surveys or the regions that are too extended to be mapped with ALMA. SPICA will have for the first time the spectroscopic capabilities necessary to perform deep spectroscopic surveys, wide and deep enough to measure the underlying physical processes driving galaxy evolution out to high redshifts (see the line strength prediction by Spinoglio et al. (2012) and the contribution by L. Spinoglio to these proceedings). This will be a truly unique big step forward for our understanding of the star and galaxy formation history of the universe.

I would like to thank the organizers for such a fruitful and pleasant conference. This summary presentation is based on the works of a large number of colleagues, whom I want to express my respect and gratefulness. Yet this overview can only be a rather incomplete, and I apologize to all those ingenious colleagues whose work could not be mentioned here, solely for the lack of space. In preparing this contribution I have benefitted invaluabley form the SAFARI Yellow Book and the MCS Science Case Document, and I want to particularly thank the authors of these documents.

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Sturm

The Mid- and Far-Infrared View on Galaxy Evolution

SPICA Spectroscopic Cosmological Surveys to Unravel Galaxy Evolution

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ABSTRACT

The main energy-generating mechanisms in galaxies are black hole (BH) accretion and star formation (SF) and the interplay of these processes is driving the evolution of galaxies. MIR/FIR spectroscopy are able to distinguish between BH accretion and SF, as it was shown in the past by infrared spectroscopy from the space by the Infrared Space Observatory and Spitzer. Spitzer and Herschel spectroscopy together can trace the AGN and the SF components in galaxies, with extinction free lines, almost only in the local Universe, except for a few distant objects. One of the major goals of the study of galaxy evolution is to understand the history of the luminosity source of galaxies along cosmic time. This goal can be achieved with far-IR spectroscopic cosmological surveys. SPICA in combination with ground based large single dish submillimeter telescopes, such as CCAT, will offer a unique opportunity to do this. We use galaxy evolution models linked to the observed MIR-FIR counts (including Herschel) to predict the number of sources and their IR lines fluxes, as derived from observations of local galaxies. A shallow survey in an area of 0.5 square degrees, with a typical integration time of 1 hour per pointing, will be able to detect thousands of galaxies in at least three emission lines, using SAFARI, the far-IR spectrometer onboard of SPICA.

1. INTRODUCTION

One of the major goals of the cosmological studies of galaxy evolution is to understand the full cosmic history of energy generation by stars (through the fusion process) and black holes (through accretion of matter). This history cannot only be retrieved by high luminosity objects, i.e. the quasars, but mainly by low to intermediate luminosity galaxies, such as those objects corresponding to the Seyfert galaxies in the local Universe, which dominate at the knee of the Luminosity Function. The importance of measuring these energy production rates lies also in the fact that these provide a measure of the built up of the mass of the central black hole, on one side, and of galactic stars, on the other side and must–ultimately–be consistent. This will lead us to understand the inter-relation of quasar activity and star formation, and ultimately the key processes responsible for shaping the mass and luminosity functions of galaxies.

Optical continuum measurements alone are completely inadequate to obtain these data and even optical spectroscopy on a massive scale cannot yield definitive answers because dust reddening may block our view at short wavelengths. What is needed therefore is spectroscopy at longer rest wavelengths to uncover how much of this emission is partly or heavily extinguished.

2. WHY WE NEED SPICA?

2.1. Comparing Different Techniques and Regimes for Separating AGN and SF

No single criteria can be used to distinguish AGN and SF, but there are limits and potentialities of different observational techniques:
– UV/Optical/NIR observations are able to measure galaxy morphology and spectra, however they seriously suffer from dust obscuration.
– X-ray observations are good tracers of AGN, however only weak X-ray emission can be detected from star formation and, even more importantly, heavily-obscured AGN (Compton-thick) are completely lost.
– Radio observations (with planned facilities like EVLA, SKA) can detect AGN and SF to large \( z \) and can see through gas and dust, they can measure morphology and spectral energy distributions (SED), detect polarization and variability, however not always redshifts can be measured. At its highest frequencies, SKA could be able to measure redshifted molecular lines in the ISM of galaxies.
– mm/submm observations (e.g. ALMA, CCAT) will provide spectra from SF (redshifted CO, \([\text{C} \text{II}]\), etc.), however we need to find AGN tracers at the longest FIR wavelengths. One candidate is CO: spectral line energy distributions (SLED)
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Figure 1. **Left:** a Critical density for collisional de-excitation vs. ionization potential of IR fine-structure lines, showing the diagnostic power of the infrared fine-structure lines to trace different astrophysical conditions: from photodissociation regions, to stellar/H II regions, to AGN environments and high excitation coronal line regions (Spinoglio & Malkan 1992). **Right:** b Mid-IR spectra of Seyfert galaxies in the local Universe normalized at 27 µm, showing a sequence with decreasing level of non-thermal activity, from Seyfert type 1’s through Hidden Broad Line Region (HBLR) galaxies and type 2 AGN to low luminosity AGN (non-Seyfert’s), compared to those of starburst galaxies (Bernard-Salas et al. 2009). The bright emission features and their ratios can be used to measure the AGN and starburst components in galaxies (Tommasin et al. 2010).

are in fact different from PDR (SF) and XDR (AGNs). Another candidate can be OH at 119 µm (that at redshift of z ~ 2 gets into the 350 µm atmospheric window) that can measure high velocity AGN driven outflows (see, e.g., Fischer et al. 2010; Spoon et al. 2013).

– Rest-frame MIR/FIR imaging spectroscopy can provide a complete view of galaxy evolution by measuring the role of BH and SF because it can (provided that large field of view and high sensitivity can be reached) trace simultaneously both SF and AGN, measure redshifts and see through large amounts of dust. It seems therefore to be the most promising technique.

2.2. The Power of Infrared Spectroscopy

Figure 1-a shows how well the IR fine structure lines cover the density-ionization parameter space which characterizes the photoionized and photon dissociated gas (see, e.g., Spinoglio & Malkan 1992). A combination of these lines and line ratios can trace both star formation and black hole accretion. The long wavelengths of these lines, ranging from the far-IR for the photodissociation and H II region lines through the mid-IR for the AGN lines, to the near-IR for the coronal lines, ensure that we can observe these different tracers by minimizing the effect of dust extinction.

The rich rest-frame mid-IR spectra, that have been recently observed in active and starburst galaxies in the local Universe with the mid-IR spectrometer IRS (Houck et al. 2004) onboard the Spitzer satellite (Werner et al. 2004) can be observed in the far-IR in the redshift range of 0.4<z<3.0.

Figure 1-b shows the average Spitzer IRS high-resolution mid-IR spectra (Tommasin et al. 2010) of subclasses of Seyfert galaxies from the the 12 µm Seyfert galaxy sample of Rush et al. (1993). For comparison, we also show the average spectrum of starburst galaxies (Bernard-Salas et al. 2009). The quality of the data is very high and shows the many features that can distinguish between AGN and star formation processes, such as the high-ionization lines from [Ne v] at 14.3 µm and 24.3 µm originated exclusively from AGN or the 11.2 µm PAH feature and the low ionization lines from [Ne II] and [S III], typical of H II and star forming regions. Mid-/far-IR imaging spectroscopy is therefore able to trace galaxy evolution throughout cosmic times in an unbiased way by minimizing dust extinction.

As one can see from the line ratio diagrams in Figure 2, mid-IR and far-IR extragalactic spectroscopy is currently at the same stage as optical spectroscopy more than one decade ago. Due both to the atmospheric absorption, which leaves open only a few sparse windows in the near- and mid-IR, and to the high thermal background at room temperature at IR wavelengths, it has soon been realised that infrared astronomy to be successful had to be done from space telescopes, as it was demonstrated by the success of the IRAS (Neugebauer et al. 1984), ISO (Kessler et al. 1996), Spitzer (Werner et al. 2004), AKARI (Murakami et al. 2007) and finally Herschel (Pilbratt et al. 2010) missions. However, due to the sensitivity limits and the poor multiplexing power of the spectrographs onboard of these spacecrafts, only a few limited samples of distant objects have been successfully observed (e.g. Yan et al. 2007; Menéndez-Delmestre et al. 2009; Sturm et al. 2010), while most of the spectroscopic work has been done in the Local Universe. Substantial progress in studying
galaxy evolution therefore can only be achieved by using direct mid- to far-IR spectroscopic surveys, which will provide measured (rather than estimated) redshifts and also unambiguously characterise the detected sources, by measuring the AGN and starburst contributions to their bolometric luminosities over a wide range of cosmological epochs through the spectroscopic signatures of both AGN and star formation emission.

**SPICA** (Nakagawa et al. 2011) will be the next-generation, space infrared observatory, which, for the first time, will contain a large (3.2-meter) actively cooled telescope (down to 6K), providing an extremely low background environment. With its instrument suite, designed with state-of-the art detectors to fully exploit this low background, **SPICA** will provide not only high spatial resolution and unprecedented sensitivity in mid- and far-infrared imaging, but especially large field medium spectral resolution imaging spectroscopy. These characteristics put **SPICA** among the best planned facilities to perform spectroscopic cosmological surveys in the mid- to far-IR. Using theoretical models for galaxy formation and evolution constrained by the luminosity functions observed with both Spitzer and Herschel and the relations between line and continuum far-IR luminosity, as measured in the local Universe for active and starburst galaxies, Spinoglio et al. (2012) have predicted, as a function of redshift, the intensities of key lines able to trace AGN and star formation activity along cosmic history.

Figure 3 shows graphically the number of galaxies that can be detected by the far-IR FTS spectrometer SAFARI (Roelofsema et al. 2012) planned to be onboard of **SPICA**, in each spectral line for the two different populations of AGN-dominated and starburst-dominated galaxies, comparing the output of two models used. The total numbers of detectable objects agree, taking the different models, to within a factor of 2-3 for most lines and z ranges. At least a thousand galaxies will be simultaneously detected in four lines at 5σ over a half square degree. A survey of the given assumptions will lead to the detection of bright lines (e.g., [O I] and [O III]) and PAH features in thousands of galaxies at $z > 1$. Hundreds of $z > 1$ AGN will be detected in the [O IV] line, and several tens of $z > 1$ sources will be detected in [Ne V] and H$_2$.

On the other hand, the Cerro Chajnantor Atacama Telescope (CCAT) (Sebring 2010) will be highly complementary to **SPICA**, being able to observe the [O III]88 μm line at $z > 1.3$, where this line leaves the SAFARI spectral range. We also find that CCAT will be a most efficient instrument for studies of [C II], an important coolant of the interstellar medium
Figure 3. Number of objects detected as a function of redshift, per spectral line and per object type, (AGN-dominated are shown as continuum lines, and starburst-dominated galaxies as dashed lines) in an hour integration per pointing, 0.5 deg$^2$ survey with the SPICA-SAFARI instrument (Roelfsema et al. 2012) requiring 450 hours of total integration time (Spinoglio et al. 2012), following the two different models of Franceschini et al. (2010) and of Gruppioni et al. (2011).

(ISM), at all $z < 5$. At $3 < z < 4$ alone, it will detect more than 300 galaxies at 5$\sigma$ level in a 0.5 deg$^2$ survey (Spinoglio et al. 2012).

3. CONCLUSIONS

We summarise this work with these points:

- After many decades of efforts, we are close to having reliable measures of star formation rate and AGN accretion power, through MIR/FIR spectroscopic surveys, unaffected by dust.
- Accurately measuring the star formation rate and the AGN accretion power is the first step towards understanding galaxy evolution over the history of the Universe.
- Blind FIR spectroscopic surveys with SAFARI-SPICA will be the way to physically measure galaxy evolution.
- Given the expected sensitivity of SAFARI-SPICA $\sim 2.5 \times 10^{-19}$ W/m$^2$ (5$\sigma$, 1 hr.) thousands of sources will be detected in more than 4 lines in typical 0.5 sq. deg. surveys (total t=450 hours).
- Complementary to SAFARI, CCAT will detect several tens to hundreds of galaxies at $R \sim 1000$ in a 0.5 sq. deg. survey in 4.5 hours in the [O III]88 $\mu$m line and thousands of galaxies in the [C II]158 $\mu$m line.
- These surveys will be essential to clarify the inter-relation between quasar activity and star formation, which of the two processes influence the other and ultimately will test the processes able to shape the mass and luminosity functions of galaxies.

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Figure 3. Number of objects detected as a function of redshift, per spectral line and per object type, (AGN-dominated are shown as continuum lines, and starburst-dominated galaxies as dashed lines) in an hour integration per pointing, 0.5 deg$^2$ survey with the SPICA-SAFARI instrument (Roelfsema et al. 2012) requiring 450 hours of total integration time (Spinoglio et al. 2012), following the two different models of Franceschini et al. (2010) and of Gruppioni et al. (2011).

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- These surveys will be essential to clarify the inter-relation between quasar activity and star formation, which of the two processes influence the other and ultimately will test the processes able to shape the mass and luminosity functions of galaxies.

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SPICA Spectroscopic Cosmological Surveys
Luminous Infrared Galaxies Near and Far: The Promise of SPICA

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ABSTRACT

With ISO, Spitzer and Herschel, we have made great strides toward understanding the heating and cooling in Luminous Infrared Galaxies (LIRGs): those sources with $L_{IR} \geq 10^{11} L_\odot$ whose bolometric energy output is dominated by re-radiated infrared emission from dust, which were first discovered with IRAS. We have quantified the relative importance of Active Galactic Nuclei (AGN) and starbursts to statistically significant samples of low-$z$ LIRGs, and have used the MIR dust and gas diagnostics to measure the power sources in samples of SMGs and QSOs out to $z \sim 4$ with Spitzer/IRS. Recently, we have measured the bright FIR fine-structure cooling lines in large numbers of local LIRGs and starburst galaxies with Herschel, establishing key scaling relationships between the central starbursts, AGN, and the FIR emission lines. In addition, fast, massive outflows of cold molecular gas have been detected which provide a direct window on the interaction of the central source and the molecular gas reservoir. SPICA, with its large, cold primary and suite of sensitive instruments promises to once more revolutionize our picture of the infrared Universe, carrying forward the work we have done with Spitzer and Herschel to fainter and more distant galaxies, building large samples of LIRGs at high-$z$, and reaching the brightest sources at the earliest epochs.

1. INTRODUCTION

The Infrared Astronomical Satellite (IRAS) provided the first unbiased survey of the sky at mid and far-infrared wavelengths, giving us a comprehensive census of the infrared emission properties of galaxies in the local Universe. A major result of this survey was the discovery of a large population of luminous infrared galaxies (LIRGs) which emit a significant fraction of their bolometric luminosity in the far-infrared, and have $L_{IR} \geq 10^{11} L_\odot$. LIRGs are a mixture of single galaxies, disk galaxy pairs, interacting systems and advanced mergers, exhibiting enhanced star formation rates and a higher fraction of Active Galactic Nuclei (AGN) compared to less luminous galaxies. A detailed study of low-redshift LIRGs is critical for our understanding of the cosmic evolution of galaxies and black holes since (1) LIRGs comprise the bulk of the cosmic infrared background and dominate star-formation activity between $0.5 < z < 1$ (Magnelli et al. 2013) and (2) AGN fueling and mass accretion onto a central black hole may preferentially occur during episodes of enhanced nuclear star formation, helping to naturally explain the scaling of black hole and stellar bulge masses seen in the local Universe (e.g., Magorrian et al. 1998).

With the Great Observatories All-sky LIRG Survey — GOALS (Armus et al. 2009), we are measuring the properties of a large, complete sample of low-redshift LIRGs across the electromagnetic spectrum using Spitzer, HST, Chandra, GALEX, Herschel, and a number of ground-based observatories including Keck, the JVLA, and ALMA. The GOALS targets are drawn from the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003), a complete sample of 629 galaxies with $IRAS S_{60} > 5.24 \text{ Jy}$, and Galactic latitudes $b > 5 \text{ deg}$. There are 202 LIRGs, including 22 ULIRGs (those with $L_{IR} \geq 10^{12} L_\odot$) in the RBGS, and these galaxies define the GOALS sample. At the highest luminosities, LIRGs consist of predominantly interacting systems, covering the entire range of the merger sequence from widely separated pairs to late-stage mergers. They provide an ideal sample for studying interaction-induced star formation and AGN fueling at low-redshift. We have observed the entire GOALS sample with Spitzer and Herschel, and we summarize some of our key results here, along with the results of others targeting complementary samples of LIRGs and ULIRGs both locally and at high-redshift. These results lay the groundwork for future surveys and detailed studies of individual galaxies with the Space Infrared telescope for Cosmology and Astrophysics, SPICA, and we discuss some possible avenues for this research in the following sections.

2. PROBING THE HEATING SOURCES WITH SPITZER/IRS

There are a number of reasons that mid-infrared spectroscopy is attractive for studying the central power sources and ISM in LIRGs. First, the extinction is low compared to the optical and even the near-infrared, where traditional diagnostic lines are found. Second, lines from highly ionized atomic gas (e.g., Ne$^+4$ and O$^{+3}$) are present, providing effective diagnostics of the radiation field. In addition the pure rotational H$_2$ lines are direct probes of the warm (100–500 K) molecular gas. This molecular gas can be heated by the central source (young stars and/or an AGN) in addition to large-scale shocks associated with an outflowing wind. The H$_2$ lines, therefore, are sensitive to the feedback of the energy source responsible for the
FIR emission, on the reservoir of cold, molecular gas out of which stars form. Finally, aromatic features from Poly-cyclic Aromatic Hydrocarbons (PAHs) are extremely strong, typically dominating the MIR spectrum of a star-forming galaxy. Their relative strength provides information on the average size and ionization state of the transiently heated small grains.

While the mid-infrared spectra of local LIRGs and ULIRGs span a large range in shape, caused by variations in the strength of the PAH features, and absorption from dust (silicates) and ices and hydrocarbons (Armus et al. 2004, 2007; Spoon et al. 2007; Farrah et al. 2007; Imanishi et al. 2007; Veilleux et al. 2009), the majority of the LIRGs in the GOALS sample (Stierwalt et al. 2013) have high 6.2 μm PAH equivalent width (> 0.4 μm) and moderate silicate absorption (s9.7 > −1). The strong PAH emission and (relatively) weak MIR continuum near 5 μm suggest that most LIRGs are starburst dominated. While ∼ 20% show evidence for a buried AGN (Petric et al. 2011), these AGN contribute < 10–15 % of the bolometric power across the sample. The scatter in the PAH ratios (6.2/7.7 and 7.7/11) among SB-dominated LIRGs (Figure 1) is consistent with other, low-luminosity starburst galaxies, suggesting no overall change in the ionization state or size of the PAHs in LIRGs compared normal galaxies (Stierwalt et al. 2014). Sources with evidence for an AGN show a much larger scatter in the PAH feature flux ratios, but no obvious trend to have more ionized or larger grains overall (see Figure 1).

There is a general trend among the LIRGs for both silicate depth and mid-infrared (MIR) slope to increase with increasing $L_{\text{IR}}$. Also, LIRGs in the late to final stages of a merger also have, on average, steeper MIR slopes and higher levels of dust obscuration, consistent with dust being funneled towards the nuclei, leading to a compact starburst and high obscuration. As a result, the dust temperature increases leading to a steeper MIR slope. LIRGs with extremely low PAH equivalent widths, which may harbor buried AGN, separate into two distinct spectral types: relatively unobscured sources with a very hot dust component (and thus very shallow MIR slopes) and heavily dust obscured nuclei with a steep temperature gradient.

The most heavily obscured LIRGs are also the most compact in their MIR emission, suggesting that the obscuring (cool) dust is associated with the (outer regions of the) starburst, and not simply a measure of the dust along the line of sight through a large, edge-on, disk. A marked decline is seen for the fraction of high PAH EQW sources as the merger progresses, accompanied by an increase in the fraction of composite sources. Across the merger sequence, the fraction of sources dominated by an AGN remains low.

Most GOALS LIRGs have elevated $L_{\text{H}_2}/L_{\text{PAH}}$ ratios well above those observed for normal star-forming galaxies, and exhibit a trend for increasing $L_{\text{H}_2}/L_{\text{PAH}}$ ratio with increasing $L_{\text{H}_2}$ (see Figure 1). While LIRGs can exhibit both increased H$_2$ emission and decreased PAH emission, it is natural to explain the LIRGs with extremely strong H$_2$ emission as those where the molecular gas has an additional heating component from slow shocks which would not cause enhanced PAH emission — see Stierwalt et al. (2014).

When compared to the MIR spectra of $z \sim 2$ SMGs, LIRGs, and especially ULIRGs, show deeper silicate absorption and stronger PAH emission. However, when the AGN contributions to both the local GOALS LIRGs and the high-$z$ SMGs are removed, the average local SB-dominated LIRG closely resembles the starburst-dominated SMGs (Stierwalt et al. 2013). Local LIRGs have a constant (high) average 6.2 μm PAH EQW over nearly two orders of magnitudes in $\nu L_{\nu}$ at 24 μm.
similar to high redshift SMGs and star forming galaxies at higher $\nu L_\nu$, but unlike local ULIRGs which show a trend for decreasing EQW with increasing 24 $\mu$m luminosity.

For the starburst dominated LIRGs, there is a rough inverse correlation between the ratio of $L_{IR}$ and emission at 8 $\mu$m (IR8) — a measure of the distance of a galaxy from the star-forming main sequence (Elbaz et al. 2011), and the MIR PAH fraction. However the fractional drop in PAH emission within the IRAC 8 $\mu$m band is much less than the rise in IR8 (see Figure 2). No obvious link is seen between IR8 and the 7.7/11.3 PAH ratio, suggesting that grain processing is not responsible for the lower PAH fraction among sources with high IR8 (Stierwalt et al. 2014). It is more likely a decrease in the PDR emission relative to $L_{IR}$ as the starbursts become more compact, and the warm dust and overall LIR rise (see also Diaz-Santos et al. 2013).

In Inami et al. (2013, and this volume) we compare the IRS high-res spectra to models of starbursts (Levesque et al. 2010) and shocks (Allen et al. 2008), in order to constrain ages, ionization parameters, and metallicities in the (starbursting) LIRG nuclei. Starbursting LIRGs have ages of 1–4.5 Myr, metallicities of 1–2 Z$_\odot$, and ionization parameters of 2–8x10$^2$ cm$^{-3}$ s$^{-1}$.

A large number (80) of the GOALS sources have resolved neon emission line profiles (FWHM $\geq$ 600 km s$^{-1}$), and a small number (six SB and five AGN) show a clear trend of increasing line width with ionization potential, suggesting a compact energy source and stratified ISM in their nuclei.

Given the limited resolution of the IRS spectra, it is difficult to measure detailed line profiles or subtle features in the gas dynamics — something that will be much easier with SPICA (see below). As expected, there is a strong correlation between the sum of the [Ne II] and [Ne III] emission lines, as well as [S II] line, with infrared luminosity and the $L_{24}$, consistent with all three lines tracing ongoing star formation. As outlined in Inami et al. (2013) there is no correlation between the hardness of the radiation field or the emission line width and IR8. This may be a function of the fact that the infrared luminosity and the mid-infrared fine-structure lines are sensitive to different timescales over the starburst, or that IR8 is more sensitive to the geometry of the region emitting the warm dust than the radiation field producing the H II region emission.

3. COOLING LINES AND OUTFLOWS WITH HERSCHEL

The far-infrared includes several of the most important cooling lines in the neutral and ionized atomic ISM, notably the [C II] 157.7 $\mu$m, [O I] 63.2 $\mu$m, [O III] 88.4 $\mu$m, [N II] 122 $\mu$m and [N II] 205 $\mu$m far-infrared, fine structure emission lines. The [C II] and [O I] lines dominate the cooling of the warm neutral medium, whereas [O III] and [N II] originate from ionized regions and directly trace young, hot stars. The lines cover an extremely large range in critical density, from $\sim 100$ cm$^{-3}$ to almost $10^6$ cm$^{-3}$, and the ([O I]+[C II])/LIR ratio provides a measure of the gas heating efficiency.

Observations of the FIR cooling lines in representative samples of local star-forming galaxies and AGN were pioneered with ISO (e.g., Malhotra et al. 1997, 2001; Luhman et al. 1997; Helou et al. 2001; Brauer et al. 2008), but the relationships discovered between the FIR cooling lines, $L_{IR}$ and the dust temperature were based on relatively small numbers of bright galaxies (AGN, LIRGs, mergers, etc.) and they showed a great deal of scatter. Recent work with Herschel/PACS (Gracia-Carpio et al. 2011) suggests that there may be a bi-modal relationship between the [C II]/FIR ratio and the star formation...
efficiency, as defined by the ratio of the FIR emission to the cold molecular gas mass, with the most powerful starbursts having the largest line deficits.

In the first study of the [C II] emission from a large sample of LIRGs with *Herschel*, Diaz-Santos et al. (2013) find a tight inverse correlation of [C II]/FIR with far-infrared color (warmer sources have larger [C II] "deficits"), and between [C II]/FIR and the strength of the 9.7 µm silicate absorption feature (denser, more absorbed starbursts have deeper silicate absorption and large [C II] deficits). A correlation exists as well between the [C II]/FIR ratio and the luminosity surface density of the starburst (see Figure 2). Warmer, more compact starbursts have substantially smaller [C II]/FIR ratios. This is confirmed by the correlation of [C II]/FIR with the normalized specific star-formation rate.

While LIRGs with AGN can have extremely low [C II]/FIR ratios (well below $10^{-3}$), the [C II]/FIR ratio among pure SB sources drops by an order of magnitude with FIR flux density ratio, silicate absorption and luminosity surface density, suggesting that the [C II] deficit is a real function of the starburst, and furthermore, that the [C II] luminosity is not a good quantitative indicator of the star-formation rate in powerful starburst galaxies (Figure 3).

Because of the large number of LIRGs in the complete GOALS sample, Diaz-Santos et al. (2013) are also able to estimate the fractional AGN contamination among future [C II]-derived samples, such as those that might be assembled with ALMA or CCAT. As discussed in Diaz-Santos et al. (2013), at least 1/3 of LIRGs with extremely low [C II]/FIR < $5 \times 10^{-4}$ should be compact SB and not AGN. Furthermore, a measure of the [C II] and FIR emission in high-redshift starbursts should yield a prediction of the size of these starburst (see Stacey et al. 2010), which could be compared directly with measurements of the molecular gas and/or cold dust with ALMA on scales similar to that achieved with PACS on the GOALS sources.

Arguably one of the most spectacular early results from *Herschel* was the discovery of blueshifted absorption in the far-infrared OH lines in Mrk 231 and other nearby ULIRGs (Fischer et al. 2010; Sturm et al. 2011). These features arise from fast (1000 km s$^{-1}$ or more), massive outflowing winds of molecular gas. Although model dependent, the derived mass outflow rates in these molecular winds can be comparable to the star-formation rates (hundreds of solar masses per year), and therefore a significant factor in the depletion of the molecular ISM. Recently the ubiquity of these winds in ULIRGs has been confirmed (Veilleux et al. 2013; Spoon et al. 2013) along with the correlation of the fastest winds with the presence, and power of a central AGN. Although winds from starburst galaxies and ULIRGs have been known and studied for decades (e.g. Heckman et al. 1990), these blue shifted molecular outflows seen with *Herschel* are a unique way to directly probe the feedback of the central source on the reservoir of cold molecular gas.

4. THE PROMISE OF SPICA

The high spatial resolution, spectral resolution, and sensitivity of *SPICA* will allow us to study local LIRGs and ULIRGs in much greater details than has been possible with *Spitzer/IRS*, and build up large samples of LIRGs at high-redshift with high SNR MIR spectra for the first time. In particular, the high-spectral resolution of the MCS/MRS instrument ($\sim 100$ km s$^{-1}$ — about a factor of five higher than the IRS), will allow us to explore outflows and large-scale gas motions via the MIR fine-structure lines in the most dusty galaxies, even when extremely high-velocity, AGN-driven motions are not present. Even in the GOALS sample, obtaining high SNR, high-res spectra for the more distant sources was difficult, and only the most powerful galaxies at $z > 0.1$–0.2 were within reach of the SH and LH modules of the IRS. Since the fine-structure lines are often narrow, the increased spectral resolution or MCS/MRS facilitates greater sensitivity (a gain of nearly an order of magnitude over the IRS), allowing us to measure the flux and line profiles of the key diagnostic
emission lines in LIRGs and ULIRGs out to \( z = 1–2 \) in an hour of integration (see Inami et al. in this volume). In the local Universe, the 3–4× higher spatial resolution of SPICA compared to Spitzer will also enable sub-kpc studies of the gas in and around galaxy nuclei, further enhancing our ability to look for direct connections between ongoing starbursts and AGN in even the most obscured sources.

By targeting the FIR molecular lines, such as OH with SPICA, we will not only be able to build a complete census of molecular driven outflows in ULIRGs out to \( z \sim 1 \), we will be able to carefully disentangle the multiple velocity components in the multi-phase outflows and link these to the physical conditions in the gas and the central source by directly comparing the FIR absorption features to the MIR emission lines.

While the [C II] line itself will not be visible in high-\( z \) galaxies with SPICA, other fine structure cooling lines (e.g., [O I], and [O III]) will be readily detected. These could be effective probes of the sizes and physical properties of the starbursts, even in unresolved, distant galaxies. High-redshift, high-luminosity galaxies with strong [O I] emission, compared to FIR, should have cool dust temperatures, and extended star formation. Sources with weak [O I] emission, and warm dust temperatures, should be extremely compact, and/or have a buried AGN (if the deficit is extremely large).

SPICA/SAFARI will deliver unbiased surveys of ULIRGs out to \( z \sim 4 \) and beyond, with large samples of LIRGs to \( z \sim 1–2 \). With more than an order of magnitude leap in sensitivity compared to Herschel, SAFARI will reach FIR line flux levels of \( 10^{-19} \) W m\(^{-2} \) in about an hour of integration, and be able to measure the key cooling lines in hundreds of starburst galaxies and AGN out to the peak in the star formation rate density at \( z \sim 2–3 \) (Spinoglio et al. 2012). Of course, the real diagnostic power of SPICA will be in it’s broad wavelength coverage and far-infrared sensitivity, enabling a direct comparison of the heating and cooling of the atomic and molecular ISM in actively star-forming galaxies over a huge range of cosmic time. The synergy of SPICA and JWST to image and study the physical conditions in dusty starbursts and AGN across the complete infrared spectrum will be truly astounding.

From IRAS to ISO, Spitzer and Herschel, and with ongoing ground-based studies with CARMA, CSO, PdBI, the JVLA and most recently, ALMA, we have unmasked the power sources and probed the physical conditions in the most heavily obscured, and powerful galaxies in the local Universe, reaching out to \( z \sim 6 \) (Pope et al. 2008; Rigby et al. 2008; Menendez-Delmestre et al. 2009; Farrah et al. 2008; Maiolino et al. 2009; Walter et al. 2009; Stacey et al. 2010; Sturm et al. 2010; Diaz-Santos et al. 2013; Carilli et al. 2013; Wagg et al. 2014; Vieira et al. 2013; Wang et al. 2013; Riechers et al. 2013). However, our knowledge of the general properties of high-redshift IR luminous galaxies is still quite limited, due to small sample sizes and/or natural selection biases. We are now ready to take the next big step in our understanding of the far-infrared Universe of star formation and black hole growth with SPICA.

I would like to personally thank the organizers for an exciting and productive conference, and for the opportunity to once more visit the University of Tokyo, to see the spectacular Hotaru at the Hotel Chinzanso and, most importantly, to participate in the discussions about, and planning for, SPICA.

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IR Cooling Lines in Violently Turbulent Environments: From Spitzer/Herschel to the High-z World

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ABSTRACT

Observations with Spitzer of Stephan’s Quintet, the Taffy galaxies and several other Hickson Compact Groups showed evidence for enhanced warm molecular rotational lines of hydrogen which suggest strong heating in shocks and turbulence. We present new Herschel, CARMA and Chandra data of several systems which support the idea that shock/turbulent heating is present in these systems, through a study of the far-IR cooling lines, X-ray luminosity and peculiar CO dynamics. We show that SPICA/SAFARI is capable of detecting rotational molecular hydrogen from the brightest known H2 emitting galaxies (Zw 3146 and the “Spiderweb”) to 0.5 < z < 6 if they exist there, or if less luminous systems are significantly lensed. Turbulent systems may be common at high-z where the most extreme objects are likely to lie in the largest massive dark-matter halos.

1. POWERFUL MOLECULAR HYDROGEN EMITTING GALAXIES (MOHEGS)

During the Spitzer mission, it was discovered that there exists a population of galaxy systems with extremely large values of $L(H_2)/L(\text{PAH}_{1,7})$ ratio. One of the most striking examples was found in the giant intergalactic filament in Stephan’s Quintet (Appleton et al. 2006; Cluver et al. 2010), where the mid-IR molecular hydrogen lines 0–0 S(0),(1)..(5) were found to be the most dominant line coolant. This giant cosmic shock-wave is believed to be caused by the collision of a high-speed intruder galaxy with a suspected tidal filament in this compact group (see Figure 1). Guillard et al. (2009) explained the coexistence of weak X-ray emission and strong molecular hydrogen emission as an effect caused by high speed shocks driven into a multi-phase medium. Another system which showed some similarities with Stephan’s Quintet is the Taffy galaxies (UGC12914/5). These galaxies are thought to have recently interpenetrated at high-speed, and have now moved through each other, drawing out a “splash” bridge (Struck 1997; Vollmer et al. 2012) which was first detected in the radio continuum (Condon et al. 1993) as the possible merging and stretching of magnetic fields between them. Like Stephan’s Quintet’s shock, which is also strongly detected in the radio continuum, Taffy is over-luminous at 20cm compared with its far-IR emission, suggesting that the system is boosted by shocks (Lisenfeld & Völk 2010). Peterson et al. (2012) showed that the bridge between the two galaxies also contains a significant amount of warm molecular hydrogen which cannot be explained by the low-levels of star formation detected in the bridge, but is more likely heated by shocks and turbulence.

Ogle et al. (2010) showed that 20% of nearby 3CR radio galaxies also showed excessively high warm H2/PAH ratios, and coined the term MOHEG (Molecular Hydrogen Emission Galaxies) to describe those galaxies with mid-IR spectra dominated by warm emission from molecular hydrogen — most likely from shocks caused by the passage of the radio jets through the host galaxy (see Nesvadba et al. 2010; Nesvadba et al. 2011). Guillard et al. (2012) showed that radio galaxies exhibiting strong HI outflows also were MOHEGs, although in most cases the H2, although very turbulent, was not outflowing.

Cluver et al. (2013) have studied 78 galaxies in 23 Hickson Compact Groups (HCGs), and discovered that more than 10% of the galaxies show unusually large $H_2/PAH$ ratios. Moreover, these same galaxies were found to exhibit lower-than-normal specific star formation rates and mid-IR colors, placing many of them in the uv-optical “Green Valley”. In this paper, we suggested that one explanation for the “transitional” colors of the galaxies is that shocks are suppressing star formation, causing a drift in color as star formation shuts down. To test this further we proposed to study some of the same objects with Herschel and CARMA.

2. FAR-IR COOLING LINES AND CO EMISSION

In order to investigate whether other lines, especially the diffuse ISM cooling lines of [C II] and [O I] were important in the same systems, we recently used Herschel to make observations with the PACS IFU spectrometer. Figure 2 and 3 show the results for both the Stephan’s Quintet system and the Taffy galaxies. Figure 2 shows initial results from the Herschel
Figure 1. The giant shocked filament in Stephan’s Quintet: Center: An HI tidal tail (Williams et al. 2002) contains a gap (red oval) where it is believe the high-speed intruder NGC 7318b has struck the tail, causing it to emit both faint soft-Xray emission left panel; (Trinchieri et al. 2003), and strong rotational line-emission ($\lambda 17 \mu m$) from warm molecular hydrogen right panel: Blue = H$_2$ emission superimposed on optical HST image: Cluver et al. (2010). The surprising transformation of HI into highly turbulent H$_2$ in high-speed collisions is one of the discoveries of Spitzer.

Figure 2. PACS observation footprints and spectra of the [C II]157.7 $\mu$m and [O I]63 $\mu$m line show the detection of extremely broad emission along and across the giant shock structure in Stephan’s Quintet (Appleton et al. 2013). IRAM 30-m spectra taken close to the same positions are also plotted and show similar profiles in CO, suggesting that the molecular and atomic gas phases are well mixed.

A 40 ks observation was made of the Taffy galaxies in X-rays with Chandra (Wang et al. in preparation), as well as deep photometry and spectroscopy with Herschel — see Figure 3. Again strong [C II] emission is detected in the northern bridge in the same region as weak soft X-ray emission is detected. Like Stephan’s Quintet, the [C II]/PAH and [C II]/FIR ratios are elevated compared with normal galaxies, and the X-ray emission is faint enough that it cannot be responsible for heating the molecular gas and exciting the [C II] transition. We believe that cosmic-rays, which are obviously present in the bridge (since we detect radio synchrotron), are also insufficient to explain the heating. Turbulent energy dissipation is the most likely cause of the heating of the warm gas seen between the galaxies. Such turbulence is expected to decay on a timescale of 10–20 million years, and can provide plenty of energy to heat the medium — causing a boost to the mid- and far-IR line emission over that expected from UV heating from stars alone.
The main faces of the Taffy galaxies (from Wang et al. and Peterson et al. in preparation) from our Chandra and Herschel programs.

Our team has recently begun to follow-up the Cluver et al. (2013) sample of HCG MOHEGs with Herschel to study the far-IR lines and dust continuum properties, but also to investigate the distribution and dynamical state of the colder molecular gas through CARMA CO imaging. The first example of such a study (Alatalo et al. in preparation) is shown in Figure 4. The results show interesting differences in the [C II]/CO ratio in the two galaxies, HCG57d, the smaller northern galaxy has usually large [C II]/CO and [C II]/FIR ratios compared with the southern galaxy. Although such effects could be due to low metallicity, optical spectra do not support this. Although the raised [C II] emission could be due to a large ionized component to the galaxy (this is under examination by IFU optical imaging), the similarities with the Taffy are striking. The MOHEG galaxy (HCG57a — the edge-on galaxy) has less extreme integrated properties, but shows very peculiar CO dynamics, exhibiting a possible nuclear CO outflow, as well as double-line profiles in the north-western disk. Like the Taffy, these galaxies may be examples of a near-head-on collision which has created highly turbulent conditions in the disks of both galaxies.

3. **SPICA AND THE HIGH-REDSHIFT UNIVERSE**

Before Spitzer ran out of cryogen, it detected a number of very powerful H$_2$-emitting galaxies, including several central cluster galaxies (e.g. Zw 3146 at $z = 0.3$; Egami et al. 2006), where the H$_2$ line luminosity is an order of magnitude brighter than those seen in individual galaxy collisions. Shocks and cosmic ray heating may be responsible for some of these large luminosities, but by far the most powerful warm H$_2$ emitting system was detected by Ogle et al. (2012) in the $z = 2.15$ radio galaxy proto-cluster PKS1138-26 (known as the Spiderweb). The luminosity is a single H$_2$ rotational line (the 0–0 S(3) line at $\lambda_{\text{rest}} = 9.66 \mu m$), was a phenomenal $1.44 \times 10^{44}$ ergs s$^{-1}$, with a strong likelihood that this is a low-limit to the total H$_2$ power, and over 100x brighter than Stephan’s Quintet. Although this system is clearly not in the same category as the nearby MOHEGs (the star formation rate in the central galaxy is in the range 500–1200 M$\odot$ yr$^{-1}$), nevertheless the extended structure of the Spiderweb, and its large associated proto-cluster dark matter halo, suggests the possibility that some fraction of the H$_2$ luminosity might be mechanical heated via shocks and turbulence.
Figure 5. Estimates of the 0–0 S(0) 28 \mu m and 0–0 S(1) 17 \mu m ground-state pure-rotational H$_2$ line fluxes (W m$^{-2}$) for the Spiderweb (PKS1138-26) and the central cluster galaxy in Zw 3146 shifted in increments of $\Delta z = 0.5$ as a function of observed wavelength. For the Spiderweb it is assumed that these lines are equally as bright as the observed 0–0S(3) line ($0.41 \times 10^{-17}$ W m$^{-2}$ of Ogle et al. 2012), and the S(3) line ($2.3 \times 10^{-17}$ W m$^{-2}$) for Zw 3146 (Egami et al. 2006) and a standard $\Lambda$CDM cosmology assumed. The horizontal lines represent the effective limit of detection with SPICA/SAFARI. To detect fainter object we must await future far-IR missions with instruments like BLISS (Bradford et al. 2010) that would be capable of going deeper.

The existence of such extreme H$_2$ emitters begs the question of whether H$_2$ could be used to probe turbulence in the early universe (see Appleton et al. 2009). Up to a redshift of $\sim 15$, the rotational H$_2$ lines are within the far-IR domain, and can barely be reached by ALMA. Figure 5 shows a plot of the sensitivity limits of SPICA/SAFARI (Roelfsema et al. 2012) for H$_2$ line luminosities in the 0–0 S(0) and 0–0 S(1) rotational molecular hydrogen lines assuming similar luminosities for the most extreme known H$_2$ emitters. If Spiderweb-like sources exist up to $z = 6$, the S(0) and S(1) lines could be detected with SAFARI, and to $z = 1.5$ for sources like Zw 3146. Most sensitive studies will have to exploit high-$z$ lensing amplification, or employ more sensitive low-resolution spectrometers on future telescope, like the BLISS instrument proposed by Bradford et al. (2010). Higher-order rotational transitions could also be probed by JWST in the mid-IR, but if most of the power was concentrated in the lowest-order rotational states (cool gas), the far-IR may be the only way to directly detect rotational H$_2$ emission from turbulent primordial clouds.

REFERENCES

Infrared Diagnostics of Quasar Mode Feedback

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ABSTRACT

Quasar mode AGN feedback is a popular concept in cosmological models to explain the observed galaxy mass function, but observational evidence for this idea remains controversial. We review recent results from Herschel and Spitzer that provide strong evidence that quasar mode feedback can have a profound impact on AGN host galaxies, and that much of this impact happens while the AGN is still obscured. Holistic studies of quasar mode feedback thus require observations that span a wide wavelength range; in the far-infrared early on in the feedback phase, through to the optical/UV near the end of the feedback phase. We review how SPICA can contribute to this effort, by tracking quasar mode feedback across a wide range in obscuration levels.

1. INTRODUCTION

‘Quasar’ mode AGN feedback is the idea that a central SMBH exerts influence on short (∼10\textsuperscript{7}–8 yr) timescales and large (~kpc) spatial scales to quench star formation in its host galaxy. It is thought to occur when radiation from the accretion disk drives a wind of partially ionized gas into the host, which then empties the galaxy of fuel for star formation by kinetically driving the ISM gas out of the galaxy, and/or heating the ISM so it cannot collapse to form stars.

There is strong theoretical motivation for quasar mode feedback from models that trace the assembly of galaxies with redshift. Models without quasar mode feedback have difficulty in reproducing the observed redshift evolution of the galaxy mass function (e.g. Benson et al. 2003) whereas models with it show dramatic improvements in their consistency with observations (e.g. Somerville et al. 2008). Moreover, simulations of individual galaxies suggest that quasar mode feedback has a profound influence (e.g. Di Matteo et al. 2005; Debuhr et al. 2012; Choi et al. 2012). Observationally, quasar mode feedback has been inferred indirectly from e.g. the properties of molecular outflows in IR-luminous galaxies (Chung et al. 2011), and from the presence of winds with high kinetic fluxes in BAL QSOs (Moe et al. 2009), though some recent claims for quasar driven suppression of star formation (Page et al. 2012) are controversial (Harrison et al. 2012).

Overall however, the observational evidence for quasar mode feedback is weaker than theoretical evidence. We do not yet have a holistic observational picture for how quasar mode feedback impacts its host galaxy as a function of time. Primarily this is for three reasons. First, quantifying the impact of an AGN wind on its host galaxy, via e.g. the momentum injected into the galaxy ISM, is extremely difficult. Second, much of the most active periods of AGN growth, particularly in mergers, occur while the system is at least moderately obscured, making observations in the infrared essential. Third, uncertainties in our understanding of the evolution of IR-luminous systems mean it is not yet clear whether obscured mergers are invariably the antecedents of classical QSOs.

2. OBSERVATIONAL EVIDENCE FOR AGN FEEDBACK

Recently, there have been several important observational advances in our understanding of possible AGN feedback mechanisms. We briefly highlight two of these advances here.

First is the work of Spoon et al. (2013), who used Herschel PACS spectroscopy to study the properties of the hydroxyl (OH) feature at 119 \textmu m in 24 low-redshift ULIRGs. The OH profiles were found to display a range in shapes; some were seen purely in absorption, some purely in emission, but at least two-thirds of the sample displayed prominent P-Cygni profiles, consistent with outflowing molecular gas. In some cases the maximum outflow velocities exceeded 1000 km\textsuperscript{s}\textsuperscript{−1}. A crude negative correlation was observed between the equivalent width of the OH 119 feature, and the strength of the Silicate feature at 9.8 \textmu m (Figure 1), consistent with the most powerful outflows occurring in moderately to deeply embedded ULIRGs, rather than lightly obscured systems. Furthermore, the maximum outflow OH 119 speed was found, in general, to correlate with AGN luminosity, but not with starburst luminosity (Figure 2). This is consistent with the AGN rather than star formation powering the outflow, presumably via radiation pressure on dust grains (e.g. Martin 2005). Finally, a small number of sources also showed asymmetries in their [C II] 158 \textmu m profiles, consistent with disruption of the neutral gas reservoir by the outflow.

These results are consistent with powerful AGN driven molecular outflows being common among ULIRGs, particularly in deeply obscured systems. This suggests that quasar mode feedback is a key phase among ULIRGs, well before the AGN is visible as a classical QSO. This is consistent with expectations from models (Di Matteo et al. 2005), and implies that the large number of obscured AGN in high redshift systems (e.g. Martínez-Sansigre et al. 2005) could in some circumstances have a profound impact on their host galaxies, even though they are not bolometrically dominant.
Second is the work of Farrah et al. (2012), which studied the “FeLoBAL” class of QSOs. FeLoBAL QSOs (Hazard et al. 1987; Hall et al. 2002; Gibson et al. 2009) have recently emerged as excellent candidates for being closely linked to both powerful AGN-driven winds, and to a brief ($\sim 10^7 - 10^8$ yr) transition stage in which a starburst is nearing its end, and a young QSO is emerging. The evidence for the former is twofold. First, FeLoBAL QSOs, like all BAL QSOs, exhibit broad, deep UV absorption troughs that are clear signatures of radiatively driven, AGN powered winds. Second, FeLoBAL QSOs are the only class of object for which the winds have been shown to extend several kiloparsecs into the host galaxies (Moe et al. 2009), implying that the winds can directly affect star formation. The evidence for the latter is that the FeLoBAL QSOs are always extremely IR-luminous (Farrah et al. 2007), and sometimes harbour intense starbursts (Farrah et al. 2010) that are factors of several more intense than those seen in classical QSOs (e.g. Floyd et al. 2013). This contrasts with LoBAL QSOs, for which less than half are IR-luminous, and do not show high levels of star formation (compare e.g. Farrah et al. (2012) with Lazarova et al. (2012)).

Farrah et al. (2012) investigated the relationship between wind strength and star formation rate in FeLoBAL QSOs using data from the Spitzer space telescope. Wind strengths were estimated from the Balnicity Index of the Mg II 2799Å line; the low ionization state and (relatively) long wavelength of this line mean it is a reasonable proxy for the kinetic flux in the BAL wind. Star formation rates and AGN luminosities were estimated by fitting radiative transfer models to the IR SED across 4–160 µm. It was found that the strength of the winds anti-correlates with the contribution from star formation to the total IR luminosity, with a much higher chance of seeing a high starburst contribution in systems with weak outflows than in systems with strong outflows (Figure 3 left). Several possible explanations were tested to explain this result. The most plausible explanation was found to be that the wind is acting to quench star formation in the host galaxy. An alternative explanation, that the effect could be explained simply by a generally more luminous AGN, with no relation to the starburst, was rejected at significant confidence (Figure 3 right). This paper thus demonstrates that quasar mode feedback is in the act of happening in FeLoBAL QSOs. Not only are they going through the $\sim 10^7 - 10^8$ year phase between a ULIRG and a QSO, but are also going through a phase during which quasar driven winds are actively suppressing star formation.

3. FUTURE PROSPECTS

The work of Farrah et al. (2012) and Spoon et al. (2013) provides some refinement to our observational understanding of quasar mode feedback in galaxy mergers (though with the caveat that FeLoBAL QSOs have not been directly linked to galaxy mergers). These papers suggest that quasar mode feedback can be significant from approximately partway through the initial encounter, while obscuration levels are still very high and the AGN may be invisible in the optical, until at least the reddened QSO stage, when obscuration is still significant but the AGN can be seen in the optical. Adopting canonical time-scales for a merger ($10^8 - 9$ years), a classical QSO ($\sim 10^8$ years) and a feedback phase ($10^7 - 8$ years), then this is consistent with quasar mode feedback having a significant impact on the host galaxy ISM only until at most shortly after the reddened QSO phase has ended.

SPICA will provide fundamental advances in our understanding of the obscured phases of quasar mode feedback. A key diagnostic will be high resolution measurements of multiple hydroxyl profiles, since this can provide a quantitative estimate of the mass flux in the molecular gas (e.g. González-Alfonso et al. 2012). It is also plausible that outflow activity may be seen in denser gas tracers, such as HCN. Assembling a dataset for of several tens of ULIRGs, with molecular...
This contrasts with LoBAL QSOs, for which less than half are IR-luminous, and do not show high levels of star formation that are factors of several more intense than those seen in classical QSOs (e.g. Floyd et al. 2013). Data from the Spitzer space telescope feature is in emission. Assembling a dataset for several tens of ULIRGs, with molecular data from the Spitzer space telescope, may be seen in denser gas tracers, such as HCN. It is also plausible that outflow activity is in significant but the AGN can be seen in the optical. Adopting canonical estimates of the mass flux in the molecular gas (e.g. González-Alfonso et al. 2012). The evidence for the latter is twofold. First, FeLoBAL QSOs, like all BAL QSOs, exhibit broad, deep UV absorption troughs that are clear signatures of radiatively driven, AGN powered winds. Second, and a young QSO is emerging. The evidence for the former is that the strength of the winds anti-correlates with the contribution from star formation to the total IR luminosity, with a much higher chance of seeing a high starburst contribution in systems with weak outflows than systems with strong outflows (Figure 3 left). Several possible explanations were tested to explain this result. The most popular explanation, that the effect could be explained simply by a generally more luminous AGN, with no relation to the starburst, will provide fundamental advances in our understanding of the obscured phases of quasar mode feedback. A key diagnostic will be high resolution measurements of multiple hydroxyl profiles, since this can provide a quantitative estimate of the mass flux of less powerful AGN-driven winds, and to a brief (5–75 yr) transition stage in which a starburst is nearing its end, the reddened QSO stage, when obscuration is still significant but the AGN can be seen in the optical. Adopting canonical values of obscuration for the initial encounter, while obscuration levels are still very high and the AGN may be invisible in the optical, until at least 10^7−10^8 years, then this is a classical QSO (α>10^3 yr), a classical QSO (α>10^3 yr), then this is a FeLoBAL phase, but are also going through a phase during which quasar driven winds are actively suppressing star formation. The work of Farrah et al. (2012) and Spoon et al. (2013) provides some refinement to our observational understanding of quasar mode feedback in galaxy mergers (though with the caveat that FeLoBAL QSOs have not been directly linked to PDRs and HII regions. Comparison with mid-IR line profiles, particularly the [Ne V] 14.32 µm line, will give a a better understanding of how outflows relate to obscured AGN luminosity, and to outflow activity seen in the mid-IR line emitting gas. Perhaps most importantly; the relative brevity of the feedback phase means that SPICAs ability to assemble much larger samples than Herschel or Spitzer will be invaluable for picking apart degeneracies in the feedback process, and for assessing potentially differing levels of impact as a function of redshift.

**Figure 2.** Upper panel: Maximum OH 119 outflow velocity as a function of AGN luminosity. The circle size is proportional to the silicate depth of the target. Triangles indicate upper limits. The dotted line is a power law fit to all but two sources: IRAS 03521 and 20414. The power law has the form log(v_{max}/km s^{-1}) = -2.64(±1.80) + 0.47(±0.15) × log(L_{AGN}/L_⊙). Lower panel: Maximum OH 119 outflow velocity as a function of star formation rate (SFR). In both panels starburst-dominated sources (α < 0.25) are shown in blue, AGN-dominated sources (α > 0.75) in green, and intermediate sources in purple.
Figure 3. Left: Probability Distribution Function for starburst contribution divided according to their absorption strengths. The solid line is the PDF for the whole sample, the dashed line for objects with weak outflows (Balnicity Indices of $<3500$ km s$^{-1}$), and the dotted line for objects with strong outflows (Balnicity Indices of $>3500$ km s$^{-1}$). Error regions have been omitted for clarity, see Farrah et al. (2012) for the full versions. Objects with weak outflows show a significantly elevated chance of obtaining a starburst fractional luminosity in excess of 25% compared to objects with strong outflows. Right: Probability Distribution Function for starburst contribution, this time divided according to their AGN luminosities; the dashed line is for objects with $L_{\text{AGN}} < 10^{12.5}$ $L_{\odot}$ while the dotted line is for objects with $L_{\text{AGN}} > 10^{12.5}$ $L_{\odot}$. The difference between the two PDFs is significantly smaller than in the left hand figure, suggesting that the IR luminosity of the AGN is not driving the different starburst fractional luminosities seen in the samples divided by outflow strength.

Finally, there is the exciting potential of a mid-IR coronagraphic instrument. With resolution on kpc scales or finer, coupled with narrow-band filters that target both a star formation tracer and an AGN wind diagnostic (e.g. a PAH feature and the [Ne V] 14.32 $\mu$m line respectively), it may be possible to directly image the impact of an AGN-driven wind on star formation in the host galaxy, providing the most direct evidence possible that feedback is taking place.

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Cosmic Star Formation History and AGN Evolution Near and Far: from AKARI to SPICA

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ABSTRACT

Infrared (IR) luminosity is fundamental to understanding the cosmic star formation history and AGN evolution, since their most intense stages are often obscured by dust. Japanese infrared satellite, AKARI, provided unique data sets to probe these both at low and high redshifts. The AKARI performed an all sky survey in 6 IR bands (9, 18, 65, 90, 140, and 160 μm) with 3–10 times better sensitivity than IRAS, covering the crucial far-IR wavelengths across the peak of the dust emission. Combined with a better spatial resolution, AKARI can measure the total infrared luminosity (L_{TIR}) of individual galaxies much more precisely, and thus, the total infrared luminosity density of the local Universe. In the AKARI NEP deep field, we construct restframe 8 μm, 12 μm, and total infrared (TIR) luminosity functions (LFs) at 0.15 < z < 2.2 using 4128 infrared sources. A continuous filter coverage in the mid-IR wavelength (2.4, 3.2, 4.1, 7, 9, 11, 15, 18, and 24 μm) by the AKARI satellite allows us to estimate restframe 8 μm and 12 μm luminosities without using a large extrapolation based on a SED fit, which was the largest uncertainty in previous work. By combining these two results, we reveal dust-hidden cosmic star formation history and AGN evolution from z=0 to z=2.2, all probed by the AKARI satellite. The next generation space infrared telescope, SPICA, will revolutionize our view of the infrared Universe with superb sensitivity of the cooled 3m space telescope. We conclude with our survey proposal and future prospects with SPICA.

1. LESSONS FROM AKARI

1.1. Background

Revealing the cosmic star formation history is one of the major goals of observational astronomy. However, UV/optical estimation only provides us with a lower limit of the star formation rate (SFR) due to obscuration by dust. A straightforward way to overcome this problem is to observe in the infrared, which can capture star formation activity invisible in the UV. The superb sensitivities of Spitzer and AKARI satellites have revolutionized the field.

In the local Universe, often used IR LFs are from the IRAS (e.g., Sanders et al. 2003; Goto et al. 2011a) from 1980s, with only several hundred galaxies. In addition, bolometric infrared luminosities (L_{IR,500μm}) of local galaxies were estimated using equation in Péault (1987), which was a simple polynomial, obtained assuming a simple blackbody and dust emissivity. Furthermore, the reddest filter of IRAS was 100 μm, which did not span the peak of the dust emission for most galaxies, leaving a great deal of uncertainty. Using deeper AKARI all sky survey data that cover up to 160 μm, we aim to measure local L_{IR}, and thereby the IR LF more accurately.

At higher redshifts, most of the Spitzer work relied on a large extrapolation from 24 μm flux to estimate the 8, 12 μm or total infrared (TIR) luminosity, due to the limited number of mid-IR filters. AKARI has continuous filter coverage across the mid-IR wavelengths, thus, allowing us to estimate mid-IR luminosity without using a large k-correction based on the SED models, eliminating the largest uncertainty in previous work. By taking advantage of this, we present the restframe 8, 12 μm, and TIR LFs, and thereby the cosmic star formation history derived from these using the AKARI NEP-Deep data.

1.2. AKARI All Sky Survey: Low-z Universe

AKARI performed an all-sky survey in two mid-infrared bands (centered on 9 and 18 μm) and in four far-infrared bands (65, 90, 140, and 160 μm). In addition to the much improved sensitivity and spatial resolution over its precursor (the IRAS all-sky survey), the presence of the 140 and 160 μm bands is crucial to measure the peak of the dust emission in the FIR wavelength, and thus the L_{IR} of galaxies. We have cross-correlated the AKARI FIS bright source catalog with the SDSS DR7 galaxy catalog, obtaining 2357 cross-matched spectroscopic redshifts.

It is fundamental to separate IR contribution from two different physical processes; the star-formation and AGN activity. In Figure 1 Left, we use [N II]/Hα vs [O III]/Hβ line ratios to classify galaxies into AGN or SFG (star-forming galaxies). It is interesting that the majority of (U)LIRGs are aligned along the AGN branch of the diagram, implying the AGN fraction is high among (U)LIRGs. This is more clearly seen in Figure 1 Right, where we plot fractions of AGN as a function of L_{IR}. These results agree with previous AGN fraction estimates (Goto 2005). Improvement in this work is that due to much
Figure 1. **Left:** Emission line ratios used to select AGNs from the AKARI all sky sample. The contour shows distribution of all galaxies in the SDSS with $r < 17.77$ (regardless of IR detection). The dotted line is the criterion between starbursts and AGNs described in (Kewley et al. 2001). The dashed line is the criterion by (Kauffmann et al. 2003). Galaxies with line ratios higher than the dotted line are regarded as AGNs. Galaxies below the dashed line are regarded as star-forming. Galaxies between the dashed and dotted lines are regarded as composites. The blue and red dots are for ULIRGs, and LIRGs, respectively. The green squares are Seyfert 1 galaxies identified by visual inspection of optical spectra.

**Right:** Fractions of AGN and composite galaxies as a function of $L_{\text{IR}}$. AGN are classified using (Kewley et al. 2001) among galaxies with all 4 lines measured. Composite galaxies include those classified as AGN using Kauffmann et al. (2003).

Figure 2. Infrared luminosity function of AKARI-SDSS galaxies. The $L_{\text{IR}}$ is measured using the AKARI 9, 18, 65, 90, 140 and 160 $\mu$m fluxes through an SED fit. Errors are computed using 150 Monte Carlo simulations, added to a Poisson error. The dotted lines show the best-fit double-power law. The green dotted lines show IR LF at $z=0.0082$ by Goto et al. (2011a). The dashed-dotted lines are higher redshift results from the AKARI NEP deep field (Goto et al. 2010a,b).

Larger statistics, we were able to show fractions of AGN in much finer luminosity bins, more accurately quantifying the increase. Especially, a sudden increase of $f_{\text{AGN}}$ at $\log L_{\text{IR}} > 11.3$ is notable due to the improved statistics in this work.

For these galaxies, we estimated total IR luminosities ($L_{\text{IR}}$) by fitting the AKARI photometry with SED templates. We used the LePhare code\(^1\) to fit the infrared part ($>7 \mu$m) of the SED. We fit our AKARI FIR photometry with the SED templates from Chary & Elbaz (2001, hereafter CHEL), which showed most promising results among SED models tested by (Goto et al. 2011a).

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\(^1\) [http://www.cfht.hawaii.edu/˜arnouts/lephare.html](http://www.cfht.hawaii.edu/˜arnouts/lephare.html)
AKARI redshift results from the best-fit double-power law. The green dotted lines show IR LF at fluxes through an SED fit. Errors are computed using 150 Monte Carlo simulations, added to a Poisson error. The dotted lines show the increase. Especially, a sudden increase of Left: LePhare used the templates from Chary & Elbaz (2001, hereafter CHEL), which showed most promising results among SED models tested. Right: TIR LFs. The redshift bins used are 0.2 < z < 0.5, 0.5 < z < 0.8, 0.8 < z < 1.2, and 1.2 < z < 1.6.

Figure 3. Left: Restframe 8 μm LFs. The blue diamonds, purple triangles, red squares, and orange crosses show the 8 μm LFs at 0.38 < z < 0.58, 0.65 < z < 0.90, 1.1 < z < 1.4, and 1.8 < z < 2.2, respectively. The dotted lines show analytical fits with a double-power law. Vertical arrows show the 8 μm luminosity corresponding to the flux limit at the central redshift in each redshift bin. Middle: Restframe 12 μm LFs. The blue diamonds, purple triangles, and red squares show the 12 μm LFs at 0.15 < z < 0.35, 0.38 < z < 0.62, and 0.84 < z < 1.16, respectively. Right: TIR LFs. The redshift bins used are 0.2 < z < 0.5, 0.5 < z < 0.8, 0.8 < z < 1.2, and 1.2 < z < 1.6.

With accurately measured $L_{IR}$, we are ready to construct IR LFs. Since our sample is flux-limited at $r = 17.7$ and $S_0$ μμ= 0.7 Jy, we need to correct for a volume effect to compute LFs. We used the $1/V_{max}$ method. We estimated errors on the LFs with 150 Monte Carlo simulations, added to a Poisson error.

In Figure 2, we show infrared LF of the AKARI-SDSS galaxies. The median redshift of our galaxies is $z = 0.031$.

Once we measured the LF, we estimate the total infrared luminosity density by integrating the LF, weighted by the luminosity. We used the best-fit double-power law to integrate outside the luminosity range in which we have data, to obtain estimates of the total infrared luminosity density, $\Omega_{IR}$. Note that outside of the luminosity range we have data ($L_{IR} > 10^{11.5} L_\odot$ or $L_{IR} < 10^{7} L_\odot$), the LFs are merely an extrapolation and thus uncertain.

The resulting total luminosity density is $\Omega_{IR} \approx (3.8^{+1.2}_{-1.0}) \times 10^{-2} L_\odot \text{ Mpc}^{-3}$. Errors are estimated by varying the fit within 1σ of uncertainty in LFs. Out of $\Omega_{IR}$, 1.1±0.1% is produced by LIRG ($L_{IR} > 10^{11} L_\odot$), and only 0.03±0.01% is by ULIRG ($L_{IR} > 10^{12} L_\odot$). Although these fractions are larger than at $z = 0.0081$ (Goto et al. 2011a), still a small fraction of $\Omega_{IR}$ is produced by luminous infrared galaxies at $z = 0.031$, in contrast to the high-redshift Universe.

1.3. AKARI NEP Deep Field: High-z Universe

The AKARI has observed the NEP deep field (0.4 deg$^2$) in 9 filters ($N2$, $N3$, $N4$, $S7$, $S9W$, $S11$, $L15$, $L18W$ and $L24$) to the depths of 14.2, 11.0, 8.0, 48, 58, 71, 117, 121 and 275 μJy ($5\sigma$, Wada et al. 2008). This region is also observed in $BVR'z'$ (Subaru), $u'$ (CFHT), $FUV,NUV$ (GALEX), and $J, Ks$ (KPNO2m), with which we computed photo-z with $\Delta z/\sigma_z = 0.043$. Objects which are better fit with a QSO template are removed from the analysis. We used a total of 4128...
IR sources down to 100 µm in the L18 filter. We compute LFs using the 1/V_{max} method. Data are used to 5σ with completeness correction. Errors of the LFs are from 1000 realization of Monte Carlo simulation.

1.3.1. Restframe 8 µm Luminosity Functions

Monochromatic 8 µm luminosity (L_{8µm}) is known to correlate well with the TIR luminosity (Goto et al. 2011b), especially for star-forming galaxies, because the rest-frame 8 µm flux is dominated by prominent PAH features such as at 6.2, 7.7 and 8.6 µm. The left panel of Figure 3 shows a strong evolution of 8 µm LF. Overplotted previous work had to rely on SED models to estimate L_{8µm} from the Spitzer S24µm in the MIR wavelengths where SED modeling is difficult due to the complicated PAH emissions. Here, AKARI’s mid-IR bands are advantageous in directly observing redshifted restframe 8 µm flux in one of the AKARI’s filters, leading to more reliable measurement of 8-µm LFs without uncertainty from the SED modeling.

1.3.2. Restframe 12 µm Luminosity Functions

12 µm luminosity (L_{12µm}) represents mid-IR continuum, and known to correlate closely with TIR luminosity (Pérez-González et al. 2005). The middle panel of Figure 3 shows a strong evolution of 12 µm LFs. Here the agreement with previous work is better because (i) 12 µm continuum is easier to be modeled, and (ii) the Spitzer also captures restframe 12 µm in S24µm at z=1.

1.3.3. Total Infrared Luminosity Functions

Lastly, we show the TIR LFs in the right panel of Figure 3. We used Lagache et al. (2003)’s SED templates to fit the photometry using the AKARI bands at >6 µm (S7, S9W, S11, L15, L18W and L24). The TIR LFs show a strong evolution compared to local LFs. At 0.25 < z < 1.3, L_{TIR} evolves as ∝ (1+z)^{3.1±0.4}.

1.3.4. Cosmic Star Formation History

We fit LFs in Figure 3 with a double-power-law, then integrate to estimate total infrared luminosity density at various z. The restframes 8 and 12 µm LFs are converted to L_{TIR} using Pérez-González et al. (2005) and Caputi et al. (2007) before integration. The resulting evolution of the TIR density is shown in Figure 4 Left. The right axis shows the star formation density assuming Kennicutt (1998). We obtain S^{SF}_{AGN}(z) ∝ (1+z)^{3.1±0.4}. Comparison to Ω_{TIR} by Schiminovich et al. (2005) suggests that Ω_{TIR} explains 70% of Ω_{total} at z=0.25, and that by z=1.3, 90% of the cosmic SFD is explained by the infrared. This implies that Ω_{TIR} provides good approximation of the Ω_{total} at z > 1.

In Figure 4 Left, we also show the contributions to Ω_{TIR} from LIRGs and ULIRGs. From z=0.35 to z=1.4, Ω_{IR} by LIRGs increases by a factor of ~1.6, and Ω_{IR} by ULIRGs increases by a factor of ~10. More details are in Goto et al. (2010a).

1.3.5. Cosmic AGN Accretion History

We have separated the Ω_{IR}^{AGN} from Ω_{IR}^{AGN}. Therefore, we can also investigate Ω_{IR}^{AGN}. By integrating IR LF_{AGN}, we show the evolution of Ω_{IR}^{AGN} in Figure 4 Right, which shows a strong evolution with increasing redshift. At a first glance, both Ω_{IR}^{AGN} and Ω_{IR}^{AGN} show rapid evolution, suggesting that the correlation between star formation and black hole accretion rate continues to hold at higher redshifts, i.e., galaxies and black holes seem to be evolving hand in hand. When we fit the evolution with (1+z)^γ, we find Ω_{IR}^{AGN} ∝ (1+z)^{4.1±0.5}. A caveat, however, is that Ω_{IR}^{AGN} estimated in this work is likely to include IR emission from host galaxies of AGN, although in optical the AGN component dominates. Therefore, the final conclusion must be drawn from a multi-component fit based on better sampling in FIR by Herschel or SPICA, to separate AGN/SFG contribution to L_{IR}. The contribution by ULIRGs quickly increases toward higher redshift; By z=1.5, it exceeds that from LIRGs. Indeed, we found Ω_{IR}^{AGN}(ULIRG) ∝ (1+z)^{8.7±0.6} and Ω_{IR}^{AGN}(LIRG) ∝ (1+z)^{3.4±0.5}.

2. WIDE AREA SURVEY WITH SPICA’S MID-INFRARED CAMERA AND SPECTROGRAPH (MCS)

SPICA (Nakagawa et al. 2011) is the next-generation, space infrared (5–210 µm) telescope (target launch in 2022). With its 3.2-meter telescope cryogenically cooled to 6 Kelvin, SPICA is 100 times more sensitive than its precursors. Its Mid-infrared Camera and Spectrograph (MCS; Kataza et al. 2012; Wada et al. 2012) has a large field of view of 5×5 arcmin², and is sensitive in 5–38 µm. In Figure 5, we compare SPICA/MCS’s survey speed (in 5×5 arcmin² area) with that of James Webb Space Telescope (JWST). The figure shows that SPICA’s survey speed is comparable to JWST at < 15 µm, and superior at > 18 µm. Note however at > 20 µm, SPICA reaches galaxy confusion limit (the blue filled circles) in less than one hour. Taking advantage of the wide-field of view, and superb sensitivity of the MCS, we propose a wide area confusion-limited imaging survey using all the broad filters of MCS.

2.1. Survey Design

2.1.1. Deep Survey

It has been known that infrared (IR) properties of galaxies depend on galaxy environment. For example, Goto (2005) showed that galaxy density distribution depends on IR luminosity, in a sense that more IR luminous galaxies are in less dense environment in the local Universe. Goto et al. (2010a) showed that the shape of the restframe 8 µm LFs depends
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Figure 5. Comparison of survey speed for 5x5 arcmin$^2$ area (1 hour, S/N=5, R=5). SPICA’s confusion limit is shown in the blue filled-circles.

on the local galaxy density. Koyama et al. (2008) found the excess of 15-µm-detected galaxies in the medium-density environments. These examples show that we need to investigate various environments from dense cluster cores to rarefied field, to fully understand infrared properties of galaxies and their evolution. As a minimum of such study field, we propose one deg$^2$ survey area. Such a field covers 30×30 Mpc$^2$ at $z=3$, including one massive cluster in the survey area, allowing us to investigate from dense cluster core to the rarefied field continuously.

This survey is also where the MCS is technically advantageous; the MCS’s field of view (5′×5′) is much larger than that of the JWST/MIRI (1.7′×1.3′). Therefore, in terms of the survey speed of 5′×5′ area or larger, the MCS is comparably sensitive to the JWST/MIRI even at <20 µm (Figure 5). At longer wavelength of >20 µm, the MCS is more sensitive than the JWST/MIRI.

We need the depth of ~1 µJy at 10 µm to investigate ULIRGs up to $z=3$. In order to fully sample mid-IR SED, we aim to image the area in all 8 broad filters of WFC-S channel and all 7 broad filters of WFC-L channel. Since in the WFC-L wavelength range, we reach the galaxy confusion limit in a short exposure time (~15 min), and because the WFC-S and WFC-L channel can observe simultaneously, the imaging in the 7 filters of the WFC-L channel can be obtained during the longer exposure of the WFC-S channel. In total, we need 9.67 hours per FoV (net exposure time of 1 hour per filter). We cover 0.9 deg$^2$ by 12×12 tiling. This will take 1392 hours, or 60 days. This is 6% of 2.5 years of SPICA mission lifetime.

The survey needs to be coordinated to be in the same region as the far-infrared SAFARI survey. The SAFARI survey needs ~1000 hours to observe 1 deg$^2$ region, to the depth of $z=3$ ULIRGs. Therefore, in total, we need ~2600 hours, or 3.6 months of SPICA time to observe the field. This is a large amount (12 %) of the SPICA mission lifetime, and therefore, the field needs to be of a good visibility. Ancillary data from other wavelengths are desirable. We propose the north ecliptic pole or south ecliptic pole regions as candidates. IR cirrus confusion needs to be smaller than galaxy confusion. We need to avoid regions with >3 MJy/sr.

The near-infrared FPC camera (5′×5′ field of view, 5 broad filters in 0.7–5 µm) can observe while the MCS is taking image (one of the HRS or MRS cameras need to be off). Therefore, in this region, near-IR image in 5 broad filters of FPC can be obtained simultaneously. The depth in one hour FPC exposure is expected to detect ULIRGs at $z=3$. These near-IR photometry will be useful to compute photometric redshift of MCS sources combined with the ground-based optical imaging.

The WFC-L will expose for one hour in each filter, while it reaches confusion limit in 15 min. Therefore, >4 times redundant data will be obtained in each filter of WFC-L. The survey needs to be carefully sampled to plan variability of the sources in various time scales.

The survey volume at $z=3$ is $1.5 \times 10^5$ Mpc$^3$ (with $\Delta z$ of 0.2). The number density of ULIRGs at $z=3$ is $10^{-3}$ Mpc$^{-3}$ dex$^{-1}$. Therefore, we expect to detect 150 ULIRGs at $z=3$ in a slice of $\Delta z$ of 0.2.

At $z=1$, the survey volume is $4.0 \times 10^5$ Mpc$^3$ (with $\Delta z$ of 0.2). The number density of ULIRGs measured by AKARI at $z=1$ is $10^{-4}$ Mpc$^{-3}$ dex$^{-1}$ (Figure 4 Left; Goto et al. 2010b). Therefore, we expect to detect 40 ULIRGs at $z=1$ in a slice of $\Delta z$ of 0.2.

2.1.2. Wide Survey

Complementary to the deep survey, the wide survey aims to detect rare objects that could not be found in numbers in the deep survey. For example, the number density of hyper luminous infrared galaxies at $z=3$ is $10^{-4}$ Mpc$^{-3}$ dex$^{-1}$. In the volume of deep survey ($1.5 \times 10^5$ Mpc$^3$, $\Delta z$ of 0.2 at $z=3$), there will be only 15 hyper LIRGs, and thus, not enough
for statistical study. In the wide survey, we aim to survey 10 deg$^2$ to the limit of 3–30 $\mu$Jy. This will give us a 10 times larger volume, and thus, we will create a large enough sample for statistical study with 150 hyper-LIRGs.

To reach $3 \mu$Jy, the total time required is 0.975 hrs per FoV. 38 by 38 tiling can cover 9.05 deg$^2$. Total telescope time required is then 1407 hours, or 6% of 2.5 years of mission lifetime.

It is ideal that central part of the wide field to be covered by the deep survey, so that we understand the location of the deep field in terms of larger scale. However, both surveys require significant fraction (6% each) of mission lifetime, and both require SAFARI counterpart surveys and various follow-up spectroscopic observation. Considering these factors, the deep and wide surveys are likely to be separated one at NEP and another near SEP.

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Observeing Mid-Infrared Atomic Fine-Structure Emission Lines of U/LIRGs with SPICA

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ABSTRACT

One of the most powerful ways to diagnose the central energy source and the physical conditions in the gas within and around the dust enshrouded nuclei of U/LIRGs, is to use the dust-penetrating power of mid-infrared spectroscopy. SPICA will have high resolution and high sensitivity spectroscopy which will provide access to a suite of fine-structure emission lines and hydrogen molecular lines that can be used to distinguish starburst- and AGN-dominated sources and reveal properties such as the hardness of the radiation field, the gas density, shocks, and the temperature and mass of the warm molecular gas. Based on the sample from the GOALS project, we have derived properties of local U/LIRGs using atomic fine-structure emission lines detected with Spitzer IRS high-resolution spectroscopy. While Spitzer/IRS has been successfully used to study nearby objects, it has been difficult to investigate higher-z U/LIRGs. SPICA with its sensitive spectrographs will revolutionize our understanding of the physical and chemical conditions of the gas in dusty galaxies in both the nearby and distant Universe.

1. INTRODUCTION

The dust-penetrating power of mid-infrared observations allow us to reveal gas/dust properties (e.g., ionization, metallicity, kinematics, density) in and around the dust enshrouded nuclei of dusty objects. Traditional optical spectroscopic observations are hampered by the large amounts of dust around the nuclei of luminous infrared galaxies (LIRG; \( L_{IR} > 10^{11} L_{\odot} \)). SPICA with its unprecedented sensitivity and high spatial and spectral resolution will let us carry out detailed studies of dusty galaxies at both low and high redshifts. In this proceedings, we will discuss gas properties that can be derived from mid-infrared atomic fine-structure emission lines and the advantages of SPICA.

In Section 2, we show some results from Inami et al. (2013) who report the gas properties in local LIRGs investigated using the Spitzer Space Telescope. Then in Section 3 we discuss new insights that we expect with SPICA, followed by the summary in Section 4.

2. GAS PROPERTIES OF LOCAL STARBURST LIRGS REVEALED WITH MID-INFRARED EMISSION LINES

In Inami et al. (2013) we present IRS (the Infrared Spectrograph; Houck et al. 2004) high-resolution spectra of a large, flux limited sample of LIRGs drawn from the Great Observatories All-Sky LIRG Survey — GOALS (Armus et al. 2009). By comparing these data to models of starbursts and shocks, we are able to understand the physical and chemical conditions in the ionized gas. The Spitzer IRS high-res data consist of Short-High (SH) and Long-High (LH) observations of 244 and 246 galactic nuclei, respectively. The following emission lines were readily detected: [S IV], [Ne III], [Ne V], [Ne II], [S II] 18.7 \( \mu \)m, [O IV], [Fe II], [S III] 33.5 \( \mu \)m, and [Si II]. The line flux ratios of these emission lines have been used to estimate gas densities and to compare with those predicted from stellar photo-ionization (Levesque et al. 2010) and shock-ionization (Allen et al. 2008) models to constrain star formation ages, ionization parameters, and metallicities in the starburst LIRG nuclei. The starburst- and AGN-dominated sources are classified using 6.2 \( \mu \)m polycyclic aromatic hydrocarbon (PAH) equivalent widths (EQWs) and [Ne V]/[Ne II] line ratios. Sources are considered to be AGN-dominated in the mid-infrared if they have 6.2 \( \mu \)m PAH EQW \( \leq 0.3 \) \( \mu \)m or [Ne V]/[Ne II] \( \geq 0.1 \). There are 57 GOALS nuclei in this category, and the remainder are considered to be starburst-dominated sources. This is consistent with the majority of GOALS sources being powered by starbursts (Petric et al. 2011).
The [S III] 33.5 μm/[S III] 18.7 μm ratio is a good tracer of the gas density. The density in GOALS starburst nuclei is typically one to a few hundred cm$^{-3}$, with a median electron density of ~300 cm$^{-3}$, for those sources above the low density limit for these lines.

A diagram of [S IV]/[Ne II] vs. [Ne III]/[Ne II] as a function of starburst age shows that the majority of the GOALS sources have line flux ratios in agreement with the starburst models with ages between 1–4.5 Myr (Inami et al. 2013). These starburst models assume an electron density of 100 cm$^{-3}$. The other model parameters shown in the figure are metallicity (dark blue: $Z = 0.4Z_⊙$, light blue: $Z = Z_⊙$, green: $Z = 2Z_⊙$) and ionization parameter (orange: $q = 2 \times 10^7$ cm s$^{-1}$, magenta: $q = 8 \times 10^7$ cm s$^{-1}$, red: $q = 4 \times 10^8$ cm s$^{-1}$). The red circles represent the AGN dominated sources with 6.2 μm PAH EQW $\leq 0.3$ μm or [Ne V]/[Ne II] $\geq 0.1$.

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A diagram of [S IV]/[Ne II] vs. [Ne III]/[Ne II] as a function of starburst age shows that the majority of the GOALS sources have line flux ratios in agreement with the starburst models with ages between 1–4.5 Myr (Inami et al. 2013). These starburst models assume an electron density of 100 cm$^{-3}$, the instantaneous star formation history, the Pauldrach/Hillier& Miller atmospheres, the standard Geneva stellar evolution track, and the Salpeter IMF (see also Levesque et al. 2010). In Figure 1, we display this [S IV]/[Ne II] vs. [Ne III]/[Ne II] diagram at a starburst age of 3.5 Myr. The GOALS starburst-dominated sources typically agree with the models with ionization parameters between $q = 2–8 \times 10^7$ cm s$^{-1}$ and metallicities between 1–2 $Z_⊙$.

In the left panel of Figure 2, the same [S IV]/[Ne II] vs. [Ne III]/[Ne II] diagram is presented but with the shock-ionization models (Allen et al. 2008). The emission line flux ratios of 10 starburst dominated sources can be reproduced by the shock models with shock speeds of 100–200 km s$^{-1}$ and magnetic field strengths of 1–100 μG. Five of them also show resolved neon emission line profiles (FWHM $\geq 600$ km s$^{-1}$). Another shock indicator [Fe II] is also employed to identify shock ionization in the targets (Figure 2 Right). There are about 10 starbursts that show an excess in [Fe II] emission with a 10–30% level of shock contribution to their line fluxes.

3. SPICA FOR EXPLORING MID-INFRARED EMISSION LINES

Mid-infrared atomic fine-structure lines are one of the most powerful tools for exploring the physical and chemical conditions in the gas of dusty galaxies (e.g., Groves et al. 2008; Bernard-Salas et al. 2009). While ISO, AKARI, and Spitzer have provided a glimpse of the gas properties in local galaxies, SPICA will significantly improve our current understanding of dusty galaxies at high redshift that were unaccessible. With its high sensitivity and high spatial resolution, observations made with SPICA will let us resolve the active regions (star formation or active galactic nucleus) at a scale of 1″7 at 20 μm. Its high spectral resolution spectroscopy ($R = 2000–3000$ for MCS/MRS-S and $R = 1100–1400$ for MRS-L) will provide detailed measurements of line profiles to study gas kinematics at a scale of $\gtrsim 100$ km s$^{-1}$. One of its high sensitivity detectors, MCS, will facilitate detections of [Ne II] in ULIRGs ($log(L_{12}/L_⊙) > 12$) at $z \lesssim 1.5$ in an hour of integration time.

3.1. In the Local Universe

A factor of ~3.5 better spatial resolution of SPICA than Spitzer will be particularly valuable for observing galaxies in the local Universe. The resolution of Spitzer is 5″/8 and SPICA is 1″/7 at 20 μm. At the median distance of the entire GOALS sample (100 Mpc), these correspond to the physical scales of 2.8 kpc and 0.8 kpc, respectively. SPICA will enable
us to investigate the innermost region of nuclei and measure the extent of each line emission and continuum emission (from dust heating). Thus it will be possible to study structures of H II regions, photo-dissociation regions, and the distribution of warm dust in dusty galaxies.

The spectral resolutions of SPICA/MCS MRS will allow us to detect line velocity shifts and widths down to a ~ 100 km s\(^{-1}\) scale, a factor of five better than what was achievable with Spitzer/IRS. The IRS spectral resolution has been valuable for determining gas kinematics with high speed outflows or large-scale gas motions (Spoon et al. 2009; Spoon & Holt 2009; Dasyra et al. 2011; Inami et al. 2013). With SPICA/MRS, we will be able to probe gas motions in more typical star-forming galaxies and explore the dynamics of the ionized gas on much larger scales (Sturm et al. 2011; Farrah et al. 2013). Unveiling feedback processes through outflows, particularly in star-forming galaxies will undoubtedly lead to a more complete understanding of star formation driven feedback on a wide variety of galactic scales.

In AGN dominated galaxies, a correlation is found among line widths, line luminosities, and black hole masses using Spitzer/IRS (Dasyra et al. 2011). With SPICA / MCS MRS we can expand this study to galaxies with lower black hole masses (6 \(\lesssim \log(M_{\text{BH}}/M_\odot) \lesssim 7\)), which are expected to have lower line luminosities and line widths that have been difficult to detect with IRS. In addition, a correlation between line widths and ionization potentials indicates the presence of a compact energy source (more ionized species arise closer to the central compact energy source). Beside AGN dominated sources, a handful of GOALS starbursts also show this correlation, implying that they may harbor a very compact star-forming region. When we cannot resolve star-forming regions (especially for high-z galaxies), finding this correlation may be useful for investigating the compactness of star-forming regions (Elbaz et al. 2011).

3.2. In the High-z Universe

The SPICA/MCS spectroscopy is estimated to have a factor of ~ 10 improvement in sensitivity compared with the Spitzer/IRS high-resolution spectroscopy. It will make detections of [Ne II] possible in galaxies with \(\log(L_{\text{IR}}/L_\odot) = 11\) (\(\log(L_{\text{IR}}/L_\odot) = 12\)) up to \(z \sim 0.8\) (\(z \sim 1.5\)) in an hour of integration time, based on the median [Ne II]/FIR value of the entire GOALS starburst sample. With the same integration time, [S IV], [Ne V] 14.3 \(\mu\)m, [Ne III], [Ne II], and [S III] 18.7 \(\mu\)m can be detected up to \(z \sim 0.4\) (\(z \sim 0.5\), or \(z \sim 1.0\) without taking [Ne V] 14.3 \(\mu\)m into account). SPICA will open a new window on the star formation and evolution by providing the first measurements of these emission lines in the distant Universe.

Two different modes of star formation, “main sequence” normal star-forming and “starburst” galaxies, can be distinguished using specific star formation rates (SSFR = SFR/\(M_\odot\)) of galaxies (Noeske et al. 2007; Daddi et al. 2010; Genzel et al. 2010). SPICA will shed new light on understanding gas properties in high-z dusty galaxies as a function of SSFRs. In the local Universe, Inami et al. (2013) find no correlation between the hardness of the radiation field or the emission line width and the ratio of the total infrared to 8 \(\mu\)m emission (IR8), a measure of the strength of the starburst and the distance of the LIRGs from the star-forming main-sequence. However, at higher redshifts, where galaxies are more gas rich (e.g., Tacconi et al. 2013), we may expect correlations between the physical conditions in the gas and the SSFR or the distance from the star-forming main-sequence. The emission lines that SPICA can detect will provide estimates of gas

Figure 2. Left: The same line ratio diagram as Figure 1, but with the shock model grids (Allen et al. 2008) superposed. The AGN dominated sources are indicated with the red circles. The black crosses (\(\times\)) denote the sources with at least one of the neon lines having a line width (FWHM) of \(> 600 \text{km s}^{-1}\). The parameters of shock velocities \(V\) and the magnetic fields \(B\) increase with the directions of the arrows, in steps of 100, 200, 400, 500, 100 \(\mu\)G (from the light blue to the dark blue lines), respectively. Right: A [Fe II]/[O IV] vs. [O IV]/[Ne II] diagram for the GOALS sources. The symbols are the same as the left panel, but here we also indicate the sources which lie on the shock model grids in the left panel as the blue stars. The two large diamonds at the top right are supernovae IC 443 and RCW 103 (Oliva et al. 1999a,b) for comparisons. The grids are simple mixing lines from Lutz et al. (2003) which indicate the contribution of shocks from supernova remnants or AGN (0\%, 10\%, 20\%, ...).
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ionization, metallicity abundance, and gas kinematics (see Sections 2 and 3.1). Comparisons of gas properties in a large range of SSFRs can quantify physical and chemical states of the gas and give important clues to the origin and fate of the interstellar medium. In addition, searching for the correlation between line widths and ionization potentials may play an important role in studying star formation compactness which also correlates well with SSFRs (Elbaz et al. 2011).

4. SUMMARY

The high spatial resolution, spectral resolution, and sensitivity of SPICA will advance our understanding of galaxy formation and evolution to new levels. Based on the mid-infrared atomic fine-structure emission lines that SPICA can detect, we will be able to exploit its high spatial resolution to study the distribution of the gas in galaxies in the local Universe. With the high-spectral resolution of the MCS/MRS on SPICA, we will be able to probe gas outflows and large-scale gas motions down to a velocity of \( \sim 100 \text{ km s}^{-1} \). This will allow us to address feedback processes which regulate star formation and black hole accretion. We can also extend these studies to high redshifts thanks to its high sensitivity spectroscopy. SPICA is expected to provide a breakthrough in our knowledge of the physical and chemical states in star formation and the growth of massive black holes over the history of the Universe.

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Far-infrared Galaxy Evolution Surveys with *Herschel*

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**ABSTRACT**

The 2009-2013 mission of the *Herschel Space Observatory* has dramatically enhanced our ability to use dust-reradiated far-infrared emission in the context of multiwavelength studies of galaxy evolution. Near its peak, three quarters of the cosmic infrared background are now resolved into individually detected sources. The use of far-infrared diagnostics of dust-obscured star formation and of interstellar medium conditions has expanded from rare extreme high-redshift galaxies to more typical main sequence galaxies and hosts of active galactic nuclei, out to $z \gtrsim 2$. These studies shed light on the evolving role of steady equilibrium processes and of brief starbursts, at and since the peak of cosmic star formation and black hole accretion.

1. A RESOLVED VIEW OF THE COSMIC FAR-INFRARED BACKGROUND

Since the first indications for an evolving population of infrared galaxies found in *IRAS* data, a suite of space infrared observatories has made ever better use of this window on galaxy evolution. *ISO* obtained the first deep surveys at both mid- and far-infrared wavelengths and pioneered the use of mid-infrared spectra as diagnostics of dusty galaxies. *Spitzer* revolutionized mid-infrared surveys and obtained direct mid-infrared spectroscopy of high-$z$ galaxies. *AKARI* provided uniquely detailed mid-infrared photometric coverage. All these small fully cryogenic telescopes were severely limited by source confusion when aiming for deep surveys in the far-infrared, needed to measure the dominant SED range without uncertain extrapolations. The *Herschel* 3.5 m large mirror has opened the full 70–500 $\mu$m range for photometric surveys of unpreceend depth, used by key projects such as HerMES (Oliver et al. 2012), PEP (Lutz et al. 2011), GOODS-Herschel (Elbaz et al. 2011), H-ATLAS (Eales et al. 2010) and the Herschel lensing survey (Egami et al. 2010).

Figure 1 visualizes the current state of deepest far-infrared surveys. Surveys with small 5″ to 30″ beams are now available over the full 24–870 $\mu$m range. In the deepest fields, they are confusion limited for all wavelengths except at ~70 $\mu$m. Unique future opportunities exist for a 3 m class cryogenic observatory such as SPICA in (i) making a large step in wide and deep mid-infrared surveys (ii) making use of the diagnostic power of the 30–100 $\mu$m range in particular for studying the coexistence of AGN and star formation (iii) lifting the limitations that are set by the small areas over which *Herschel* could obtain its deepest 100–160 $\mu$m surveys, and most importantly (iv) providing for the first time far-infrared spectroscopy of the typical detected sources, a capability that was out of reach of the *Herschel* passively cooled telescope.

![Image](image_url)

**Figure 1.** Current status of deepest 24–870 $\mu$m infrared surveys, visualized by 4′ × 4′ cutouts in the HUDF region. Data are from the GOODS project (24 $\mu$m), PEP and the combined PEP and GOODS-Herschel data (70–160 $\mu$m), HerMES (250–500 $\mu$m), and the groundbased LESS survey (870 $\mu$m, Weiß et al. 2009).
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Figure 2. The cosmic far-infrared background as seen by direct measurements and as resolved by Herschel. Direct measurements (grey) include the γ-ray based limits of Mazin & Raue (2007), COBE-DIRBE results as presented in Dole et al. (2006) (asterisks), the COBE-FIRAS λ > 200µm spectrum of Lagache et al. (1999) and the modified blackbody fit of Fixsen et al. (1998). CIB contributions by resolved sources are from Berta et al. (2011) and Magnelli et al. (2013b) (70–160 µm), Béthermin et al. (2012) (200–500 µm) and Zemcov et al. (2010) (850 µm). Stacking results are from Béthermin et al. (2010) (70 µm) Berta et al. (2011) (100, 160 µm) and Béthermin et al. (2012) (250–500 µm), power law count extrapolations from the same works and Zemcov et al. (2010) (850 µm). The lower panel shows the contributions of different redshift slices to the part of the CIB that is contained in resolved sources (PACS) and covered by stacking (SPIRE) (Berta et al. 2011; Magnelli et al. 2013b; Béthermin et al. 2012).

Around three quarters of the cosmic infrared background (CIB) near its peak are now resolved into individually detected sources (Figure 2). The extrapolation of the directly measured counts is consistent with direct CIB measurements, and provides smaller uncertainties at some wavelengths. At longer wavelengths where confusion is more severe, statistical methods can still be applied. In total, Herschel provides a quantification of the contribution of different redshift slices to the 70–500 µm CIB.

Using the direct Herschel measurements near the rest frame far-infrared SED peak which minimize the uncertainty in deriving the total infrared luminosity of a galaxy, infrared luminosity functions and the contribution of dust-obscured star formation to the cosmic star formation density are now measured out to z ∼ 3 (Gruppioni et al. 2013; Magnelli et al. 2013b).

2. INFRARED SEDS IN RELATION TO THE MAIN SEQUENCE OF STAR FORMING GALAXIES

Traditionally, studies in the local universe make use of a terminology of “luminous infrared galaxies (LIRGs)” defined by their total 8–1000 µm infrared luminosity $L_{\text{IR}} > 10^{11} L_\odot$, and their “ultra-” and “hyper-” luminous ULIRG and HYLIRG
Galaxy evolution surveys with Herschel

equivalents above $10^{12}$ and $10^{13}\, L_\odot$, respectively. These are handy acronyms, but for the purpose of galaxy evolution studies it is important to recall that connotations of these classifications that were carefully calibrated in the local universe may not apply at high redshift. For example, local ULIRGs are found to be major mergers with unusually dense and warm interstellar medium. The same cannot necessarily be assumed for their higher redshift equivalents at same infrared luminosity.

An incarnation of this problem emerged when the rich Spitzer mid-infrared surveys were extrapolated to total infrared emission, typically using locally calibrated luminosity dependent spectral templates (e.g. Chary & Elbaz 2001). These libraries encode the physical properties of local infrared galaxies, specifically the lower ratio of 8 $\mu$m PAH emission to total infrared for local ULIRGs, which relates to the compact star forming regions and intense radiation fields of these galaxy mergers. Already during the Spitzer era, observations suggested that at $z \sim 2$ application of these templates leads to overpredicted IR luminosities (Papovich et al. 2007; Daddi et al. 2007). This ‘mid-IR excess’ was ascribed to either relatively stronger PAH emission in $z \sim 2$ galaxies, or to a strong AGN mid-IR continuum.

Herschel observations clearly determine this mismatch for large samples and for individual detections. There is a factor ~5 overprediction of $z \sim 2$ SFRs if using 24 $\mu$m photometry and typical locally calibrated template families (Nordon et al. 2010, 2012; Elbaz et al. 2010, 2011). The effect conspicuously sets in close to $z \sim 2$ when the strongest PAH feature enters the MIPS 24 $\mu$m band (Elbaz et al. 2010, 2011), suggesting it is due to enhanced PAH emission rather than to AGN continuum. This is unambiguously confirmed (Nordon et al. 2012) by fully reproducing the photometric trends by trends in the PAH emission in the ultradep low resolution Spitzer spectra of $z \sim 1$ and $z \sim 2$ galaxies by Fadda et al. (2010).

Over the last years, it has been established that most star forming galaxies follow a rather tight (dispersion ~ 0.3 dex) relation between star formation rate and stellar mass, dubbed the main sequence of star forming galaxies. This relation is defined to at least $z \sim 2$ and its normalisation rises steeply with redshift, in line with the increased molecular gas content of high redshift galaxies (e.g. Tacconi et al. 2013). Using a combination of Herschel star formation rates for highly star forming systems and optical/UV SFRs at lower star formation rate, Rodighiero et al. (2011) establish that at $z \sim 2$ most cosmic star formation happens on this main sequence. Only ~2% of galaxies representing ~10% of the total SFR are in ‘starbursts’ well above the sequence, which may reflect short merger-induced bursts rather than the steady star formation fed from the cosmic web that must be typical for the main sequence.

For a variety of infrared properties characterising galaxies and their interstellar medium, a picture emerges in which the specific star formation rate offset from the main sequence provides a more consistent and less redshift-dependent description than the traditional way of describing properties of (U)LIRGs by simple IR luminosity (see also Figure 3). The ‘mid-IR excess’ discussed above relates to the fact that high redshift main sequence galaxies have a similar ratio of mid-infrared PAH to total infrared emission as local main sequence galaxies, despite much higher SFR (Elbaz et al. 2011; Nordon et al. 2012). This ratio can be specified as a function of SFR offset from the main sequence in a redshift independent way. A similar situation occurs for the dust temperature characterising the far-infrared SED peak. At high-z, $T_{\text{dust}}$ is lower than in local galaxies of same IR luminosity (e.g. Symeonidis et al. 2013) but can be consistently expressed as a function of main sequence offset (Magnelli et al. 2013a). The differences between low and high redshift seen in the amount of deficit for the [CI] far-infrared line compared to infrared luminosity ($L_{\text{IR}}/L_{\text{IR}}$) largely disappears when plotting against $L_{\text{IR}}/M_{\text{HI}}$ (a proxy to main sequence offset) rather than $L_{\text{IR}}$ (Graciá-Carpio et al. 2011).

Using Herschel and other data to place large numbers of galaxies on the stellar mass — SFR plane out to $z \sim 2$ and then studying their HST morphologies, Wuyts et al. (2011) find main sequence galaxies characterised by large sizes and disk-like Sersic indices. These findings as well as kinematic evidence for high-$z$ (clumpy) disks (e.g. Förster Schreiber et al. 2009) all fit a simple pattern: While a local ULIRG with SFR ~200 M$_\odot$yr$^{-1}$ inevitably is an interacting or merging system with a very compact region of intense star formation, a $z \sim 2$ galaxy of same SFR may be a large clumpy disk supporting this same SFR out of its large gas content.

3. STAR FORMATION IN AGN HOSTS

Given the local relations between black hole mass and host properties as well as the similar cosmic evolution of star formation and accretion, studying the relation of SFR and AGN luminosity in individual high redshift objects is of interest. However, many popular star formation indicators are easily overwhelmed by the AGN emission, in particular for type 1 AGN. The rest frame far-infrared offers the best contrast between host emission and AGN induced emission, and several empirical approaches indicate it to be host dominated for typical high-$z$ AGN, with the exception of systems with particularly large ratios of AGN luminosity and SFR. Given area and depth of Herschel surveys, it has been possible to map out average star formation rates for X-ray selected (and other) AGN as a function of redshift, AGN luminosity, and in comparison to stellar mass matched references of non-AGN galaxies (e.g. Shao et al. 2010; Santini et al. 2012; Rosario et al. 2012, 2013b; Mullaney et al. 2012).

Over most of the parameter range studied, there is little correlation between host SFR and AGN luminosity, as might have been expected if major merger triggering of both enhanced star formation and AGN activity would play a dominant role (Figure 4). Such a correlation may be indicated only for luminous AGN at low redshift. The typical SFRs however rise with redshift similar to the rise of the ‘main sequence’. Comparison with stellar mass matched samples of star forming and passive galaxies suggests that AGN hosts have star formation rates similar to main sequence galaxies of same redshift and stellar mass, but are less likely to be passive/quenched. The similarity between AGN hosts and star forming galaxies...
Figure 3. Changes in infrared SEDs of galaxies and their relation to the evolving star forming sequence. **Top left**: Total infrared vs. $8 \mu m$ luminosity for a local sample (blue dots) and a $z \lesssim 2.5$ *Herschel* sample (orange dots, diagonal lines visualize median ratio and dispersion for this sample). The blue line shows the locus traced by the Chary & Elbaz (2001) local SED library. Figure adapted from Elbaz et al. (2011). **Top right**: Relation between the offset in specific SFR from the evolving main sequence (‘starburstiness’) and the ratio of total infrared and $8 \mu m$ luminosity. The high-$z$ sample of Elbaz et al. (2011) is shown in orange. Average values from Nordon et al. (2012) are plotted for $z \sim 1$ (green) and $z \sim 2$ (black), along with their proposed redshift-independent relation (black, their Equation 3). **Bottom left**: Median Sersic indices for galaxies in the $z \sim 1$ star formation rate — stellar mass plane. Low values indicating preference for disk morphologies are found near the main sequence which is qualitatively located by the white line (adapted from Wuyts et al. (2011)). **Bottom right**: Mean temperature of dust in the $z \sim 1$ SFR — stellar mass plane (adapted from Magnelli et al. (2013a)).

A picture emerges in which black hole feeding and star formation seem to be connected by the common gas reservoir and gas supply on a long galaxy evolution timescale, and major mergers seem to play a less important role. The shorter
timescales of variations in AGN luminosity compared to variations in SFR are however important in shaping the observed relations, and detailed AGN feeding mechanisms are little constrained.

This contribution reflects the work of many individuals, in particular from the PEP consortium. Special thanks go to Stefano Berta for Figure 2.

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Figure 4. Growth of galaxies and their black holes. Average rest frame far infrared emission of AGN hosts expressing the star formation rate is plotted as a function of AGN luminosity, in different redshift bins. Data for local BAT AGN and for $z < 2.5$ X-ray selected AGN are reproduced from Rosario et al. (2012). Data for optically selected high redshift QSOs are from Serjeant et al. (2010, and priv. comm.) and the $z\sim4.8$ sample of Mor et al. (2012, square). Far-infrared luminosities are mean values that include direct detections as well a stacked nondetections. They include all AGN in a bin, and are plotted at the median AGN luminosity with horizontal error bars showing the range including 80% of the bin’s sources. The dotted line indicates the proportionality for a continuous host and black hole growth that would produce the local universe relation between black hole mass and bulge mass (from Häring & Rix 2004, assuming black hole accretion efficiency of 0.1). The diagonal dashed line is the correlation for local AGN-dominated sources as proposed by Netzer (2009), and the diagonal grey band the approximate 1σ range exhibited by empirical pure AGN ‘intrinsic’ SEDs (see Rosario et al. (2012) for details).
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Far-Infrared Properties of UV Selected Galaxies from $z=4$ to $z=1.5$: Unveiling Obscured Star Formation

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ABSTRACT

We report on our recent results about the IR properties of FUV selected samples from the COSMOS field at $z= 4$, 3 and 1.5. The measurements are obtained by stacking at 250, 250 and 500 microns in the Herschel/SPIRE images. Almost no galaxy is detected individually and the stacking is performed as a function of FUV luminosity and stellar mass. We are able to reconstruct the average relation between dust attenuation and stellar mass and the so-called main sequence (star formation rate-stellar mass relation) of galaxies. Implications on star formation histories of galaxies are discussed. We investigate the future impact of SAFARI/SPICA in the study of distant FUV selected galaxies.

1. GENERAL CONTEXT

Star formation rates (SFR) and stellar masses ($M_\star$) are the main parameters measured on large samples of galaxies and at different redshifts to constrain their star formation history and the evolution of their baryonic content. Various calibrators are used to measure the SFR, in particular the far-ultraviolet (FUV- 1500 Å) and the infrared (IR-5-1000 µm) emissions: the direct un-attenuated light from young stars is preferentially observed in the ultraviolet whereas the energy of photons is efficiently captured by dust. This energy is re-emitted in IR between 5-8 and 1000 µm with in general more energy is locked in IR and in FUV (Burgarella et al. (2013)). The IR emission is most of the time a reliable indicator of the SFR, the derivation from FUV data is more difficult since it relies on estimations of the amount of dust attenuation that are very uncertain when IR data are not available. The best situation is of course reached when both IR and FUV data are available. In this contribution we will focus on the measure of the SFR of FUV selected galaxies in the COSMOS field from $z = 1.5$ to $z = 4$ by using deep Herschel data combined to optical ones, corresponding to the FUV rest-frame (Heinis et al. (2013) and Heinis et al. (2013, MNRAS submitted)). The FUV-selection is useful for comparison with high redshift surveys performed in the visible or near-IR. The results of this study will help us to predict the huge improvement SPICA will provide for the study of these galaxies.

Figure 1. Left: $L_{IR}/L_{FUV}$ ratio versus $L_{FUV}$, the IR fluxes are measured using stacking in bins of log($L_{FUV}$). Right: $L_{IR}/L_{FUV}$ ratio versus the stellar mass $M_\star$, the IR fluxes are measured per bins of log($M_\star$). The different lines represent other related studies in the literature. The top histograms in both figures represent the number of galaxies included in the stacking measurements, the arrows show the mass completeness limit.
Figure 2. SFR measured as the sum of IR and FUV contributions versus log$(M_\star)$, the various lines reproduce relations found in the literature and corresponding to redshifts close to those of our current study.

Figure 3. sSFR plotted as a function of z for 3 different bins of stellar mass. Other measures from the literature as well as model predictions are over-plotted.

2. DUST ATTENUATION AND STAR FORMATION FROM $z = 1.5$ TO $z = 4$ IN THE COSMOS FIELD

The COSMOS field was observed by Herschel/SPIRE in the framework of the HerMES key programme (Oliver et al. 2012). Three rest frame FUV-selected samples are built at $z \sim 1.5$, 3, and 4 using the optical images in u*, r+, and i+ and the photometric redshifts of Ilbert et al. (2013). ~42000, ~24000, and ~7700 galaxies are thus selected. Less than 1% of these sources are detected in the SPIRE images so we rely on a stacking analysis on the position of the selected sources. We first show the results of the stacking procedure as a function of the FUV luminosity $L_{\text{FUV}}$ and then as a function of $M_\star$ in Figure 1. The $L_{\text{IR}}/L_{\text{FUV}}$ ratio can be translated in a measure of dust attenuation $A_{\text{FUV}}$ (Buat et al. 2005). The average IR emission of the FUV selected galaxies put them in the LIRG and sub-LIRG range (corresponding to $L_{\text{IR}} < 10^{11} L_\odot$). Dust attenuation is mostly independent of $L_{\text{FUV}}$ at $z = 1.5$. Its decrease observed at $z = 3$ and 4 when $L_{\text{FUV}}$ increases as well as the average increase of dust attenuation with redshift is found to be linked to the stellar mass of the galaxies. Indeed, dust attenuation as traced with the $L_{\text{IR}}/L_{\text{FUV}}$ ratio correlates with $M_\star$ and we do not find any clear evolution with redshift of the correlation. The SFR traced by the FUV and IR emissions (Figure 2) correlates with $M_\star$ defining a main sequence at each redshift considered well described by a power law (SFR $\propto M_\star^{-0.7}$) with a similar amplitude at $z = 3$ and 4, which is found lower by a factor of 4 at $z = 1.5$. In Figure 3 the specific SFR (sSFR = SFR/$M_\star$) is plotted as a function of $z$ for different bins of $M_\star$ and compared to other measurements and various model predictions. The measured value is
The discrepancy with models is found stronger for the lower bin of mass.

3. WHAT CAN WE EXPECT FROM SPICA OBSERVATIONS?

The detection of FUV selected objects in the IR is a challenge. As we have seen in section 2, Herschel was almost unable to detect individual galaxies from our samples. The studies based on stacking analyses bring only general trends and the specific properties of the galaxies are not accessible. The situation with SPICA will evolve dramatically. With a deep cosmological survey at 70 $\mu$m a large number of individual UV selected galaxies will be directly detected. Let us assume a detection limit of 50 $\mu$Jy at 70$\mu$m, such a value can be reached using a detection technics based on priors. Using the Dale & Helou (2002) templates with $\alpha = 2$ (representative of FUV selected galaxies up to $z=2$ (Buat et al. 2012)). Based on the average fluxes found with the stacking analysis, we expect to detect more than 9000 galaxies per sq.deg. at $z=1.5$, more than 3000 at $z=3$ and around 900 objects at $z=4$. With such a large sample of individual detections we will be able to measure the dispersion of the SFR-M$_{\odot}$ relation and to characterize normal versus starbursting galaxies by measuring their specific star formation rate and to compare their properties to those from models of high redshift galaxies.

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**Herschel Observations: Constraints on Dust Attenuation and Star Formation Histories at High Redshift**

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**ABSTRACT**

*SPICA* is one of the key projects for the future. Not only its instrument suite will open up a discovery window but they will also allow to physically understand some of the phenomena that we still do not understand in the high-redshift universe. Using new homogeneous luminosity functions (LFs) in the Far-Ultraviolet (FUV) from VVDS and in the Far-Infrared (FIR) from *Herschel*/PEP and *Herschel*/HerMES, we studied the evolution of the dust attenuation with redshift. With this information, we are able to estimate the redshift evolution of the total (FUV + FIR) star formation rate density (*SFRD*TOT). Our main conclusions are that: 1) the dust attenuation *AFUV* is found to increase from *z* = 0 to *z* ~ 1.2 and then starts to decrease until our last data point at *z* = 3.6; 2) the estimated SFRD confirms published results to *z* ~ 2. At *z* > 2, we observe either a plateau or a small increase up to *z* ~ 3 and then a likely decrease up to *z* = 3.6; 3) the peak of *AFUV* is delayed with respect to the plateau of SFRD*TOT* but the origin of this delay is not understood yet, and *SPICA* instruments will provide clues to move further in the physical understanding of this delay but also on the detection and redshift measurements of galaxies at higher redshifts. This work is further detailed in Burgarella et al. (2013).

**1. INTRODUCTION**

Over the past 15 years or so, astronomers have tried to measure the evolution of the cosmic star formation rate density (SFRD) moving higher and higher in redshift. However, we quickly understood that one of the main issues was to account for the total SFRD and not only for the far-ultraviolet (FUV) one. This means either a dust correction of the FUV SFRD or, better, a measure of the total i.e., FUV plus far-infrared (FIR = bolometric IR) SFRD. Knowing how the dust attenuation evolves in redshift is therefore mandatory if one wishes to study the redshift evolution of the SFRD.

Takeuchi et al. (2005) estimated the cosmic evolution of the SFRD from the FUV and FIR. An increase of the fraction of hidden SFR is found to *z* = 1 where it reaches ≈84%. The dust attenuation increases from *AFUV* ≈ 1.3 mag locally to *AFUV* ∼ 2.3 mag at *z* = 1. From the FUV only Cucciati et al. (2012) show that the mean dust attenuation *A_FUV* agrees with Takeuchi et al. (2005) over the range 0 < *z* < 1, remains at the same level to *z* ~ 2, and declines to ~1 mag at *z* ~ 4.

Using FUV luminosity functions (LFs) published in Cucciati et al. (2012) and FIR LFs from *Herschel* (Gruppioni et al. 2013), we are able to constrain the redshift evolution of log10(*L_FIR*/*L_FUV*) (aka *IRX*) to *z* ~ 4 for the first time directly from FIR data. With this information, we can estimate the redshift evolution of ρ_FIR/ρ_FUV as well as ρ_TOT = ρ_FIR + ρ_FUV. The information gathered in this work poses a number of questions that would be addressed by *SPICA*. The physical study with *SPICA* of the high redshift galaxies detected by *Herschel* is crucial to better understand the formation and evolution of galaxies.

Throughout this paper we adopt a ΛCDM cosmology with (H₀, Ω_m, Ω_A) = (70, 0.3, 0.7), where H₀ is in km s⁻¹ Mpc⁻¹. All SFR and stellar masses presented assume, or have been converted to, a Salpeter IMF.

**2. ABOUT LUMINOSITY FUNCTIONS**

Figure 1 shows the redshift variation of the LFs in FIR. The known difference in the FUV and FIR LFs (e.g. Takeuchi et al. 2005) is clearly illustrated here: bright FIR galaxies are more numerous than bright FUV galaxies at *z* ~ 5. In the FUV, except in the highest redshift bins, L* and Φ* remain approximately constant while the faint-end slope evolves. The FIR faint end slope is not observationally constrained at high *z*, and Gruppioni et al. (2013) fixed it to α = 1.2. However, L* and Φ* were allowed to change with redshift. These different evolutions of the FUV and FIR LFs are reflected in Figure 1 and explain the evolution of the cosmic SFRD and dust attenuation.

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1 From two Herschel Large Programmes: PACS Evolutionary Probe (PEP, Latz et al. 2011) and the Herschel Multi-tiered Extragalactic Survey (HerMES, Oliver et al. 2012)
3. ABOUT THE EVOLUTION OF THE COSMIC DUSTINESS

Figure 2 presents the dust attenuation in the FUV vs. \( z \) and the ratio of the FIR-to-FUV LDs integrated in the range \( \log_{10}(L/L_⊙) = [7, 14] \) in the FUV (i.e. \( L_{\text{FIR}}^{\text{min}} = 1.65 \times 10^{-4} L_⊙^{−3} \), Bouwens et al. 2009) and [8, 14] in the FIR. The FUV dust attenuation is estimated from the IRX and converted to \( A_{\text{FUV}} \) using Burgarella et al. (2005)\(^2\). The redshift evolution of \( A_{\text{FUV}} \) agrees with Cucciati et al. (2012). Note that Cucciati et al. (2012) estimated \( A_{\text{FUV}} \) through an analysis of individual SEDs up to \( \lambda_{\text{obs}} = 2.2 \mu m (K\text{-band}) \). Figure 2 suggests a local minimum at \( z \sim 2 \) that might be caused by UV-faint galaxies (see Figure 7 in Cucciati et al. 2012) that are responsible for a peak observed in the FUV LD that is not observed in the FIR. Since the fields observed in FUV and in FIR are not the same, another origin might be found in cosmic variance. The bottom line is that the existence of this trough in \( A_{\text{FUV}} \) must be explored with SPICA. Finally, higher redshift \( A_{\text{FUV}} \) from the UV slope, \( \beta \), suggests a continuous decline at least to \( z = 6 \) (Bouwens et al. 2009).

We conclude that the cosmic dust attenuation \( A_{\text{FUV}} \) reaches an absolute maximum at \( z \sim 1.2 \) followed by a global decline to \( z = 3.6 \), where it reaches about the same level as measured at \( z = 0 \). Beyond \( z = 4 \), we do not expect any increase (e.g. Burgarella et al. 2005).

4. ABOUT THE TOTAL FUV+FIR STAR FORMATION DENSITY

Figure 3 suggests a flattening of the total SFRD up to \( z \sim 3 \) (as in Chary & Elbaz 2001; Le Floc’h et al. 2005; Franceschini et al. 2010; Goto et al. 2010; Magnelli et al. 2012), where the UV data favor a peak followed by a decrease. Note that we cannot rule out a small increase or decrease within the uncertainties. All in all, our total SFRD agrees fairly well with that of Hopkins & Beacom (2006) in the same redshift range. However, discrepancies exist: our total SFRD is lower at \( z < 1 \) and is only marginally consistent, but lower, at \( z > 3 \). Moreover, PACS data are less sensitive at higher than

\[ A_{\text{FUV}} = -0.028 \left( \log_{10} \frac{L_{\text{FIR}}}{L_{\text{FUV}}} \right) + 0.392 \left( \log_{10} \frac{L_{\text{FIR}}}{L_{\text{FUV}}} \right)^2 + 1.094 \left( \log_{10} \frac{L_{\text{FIR}}}{L_{\text{FUV}}} \right) + 0.546 \]

\(^2\) The conversion from IRX to \( A_{\text{FUV}} \) from Burgarella et al. (2005) is valid at \( \log_{10}(L_{\text{FIR}}/L_{\text{FUV}}) > -1.2 \): \( A_{\text{FUV}} = -0.028 \left( \log_{10} \frac{L_{\text{FIR}}}{L_{\text{FUV}}} \right) + 0.392 \left( \log_{10} \frac{L_{\text{FIR}}}{L_{\text{FUV}}} \right)^2 + 1.094 \left( \log_{10} \frac{L_{\text{FIR}}}{L_{\text{FUV}}} \right) + 0.546 \)
at lower redshift because the rest-frame wavelength moves into the mid-IR. The preliminary FIR SFRD from Vaccari et al. (2013, in prep.) (Herschel/SPIRE selection) agrees excellently over the $0 < z \leq 2$ range, but is slightly higher than that derived from PACS at $z > 3$. However, this is only a $\sim 2\sigma$ difference. Barger et al. (2012) published a FIR SFRD based on SCUBA-2 data that also agrees with ours at $2 < z < 4$. We first tried to fit SFRD$_{TOT}$ with a one-peak analytical function (e.g. Hopkins & Beacom 2006; Behroozi et al. 2012), but the results are not satisfactory. So, we combined two Gaussians,

$$A_FUV = a_1 e^{-\frac{(z-z_1)^2}{2\sigma_1^2}} + a_2 e^{-\frac{(z-z_2)^2}{2\sigma_2^2}},$$

with $a_1 = 0.1261 \pm 0.0222$, $\sigma_1 = 0.5135 \pm 0.0704$, $z_1 = 1.1390 \pm 0.0959$ and $a_2 = 0.2294 \pm 0.0222$, $\sigma_2 = 0.8160 \pm 0.0964$, $z_2 = 2.7151 \pm 0.0839$. At higher redshifts, we made assumptions that are explained below.

The cosmic SFRD presents a (weak) maximum at $z \sim 2.5$–3.0 (i.e., between 2.6–2.1 Gyr) while the dust attenuation presents a maximum at $z \sim 1.2$ (i.e., 5 Gyr). We tried to lock the faint-end slope of the UV LF $-1.2$, to see how far out in redshift the obscuration peak could potentially move, but we detected no change, suggesting this effect is solid. We have no definite explanation for this delay of $\sim$2.7 Gyr. Type II supernovae start producing dust earlier than AGB stars (e.g. Figure 3 in Valiante et al. 2009) but the difference in timescales is too small and only on the order of a few 10 Myr for the onset of dust formation. Dust grain destruction in the ISM might play a role (e.g. Dwek & Cherchneff 2011) but the efficiency of destruction is only poorly known and depends on the star formation history. These dust-related origins for the delayed maximum are unlikely. The best explanation might be that this delay is related to a global move of galaxies in the $[\log (L_{FIR}/L_{FUV})]$ vs. $[\log (L_{FIR} + L_{FUV})]$ diagram. Buat et al. (2009) showed that galaxies evolve in redshift from $z = 0$ to $z = 2$ in this diagram, with high-redshift sources having lower IRX at given total luminosities.
5. CONCLUSIONS

On the one hand, the variation of the cosmic dust attenuation with redshift suggests a peak in the dust attenuation at $z \sim 1.2$ followed by a decline to $z \sim 3.6$. On the other hand, the total (FUV+FIR) cosmic SFRD increases from $z = 0$ to $z = 1.2$, remains flat to $z = 2.5-3.0$ followed by a decrease at higher redshifts and reaches the same level at $z \sim 5-6$ as is measured locally if we assume no variations in this trend.

So, the SFRD and $A_{\text{FUV}}$ do not exactly follow the same trends as seen in Figure 2 and Figure 3. The peak of the dust attenuation is delayed with respect to the plateau of the total SFRD by about 3 Gyrs. To better understand the delay, it is necessary to perform an analysis via models that are fed with data of the gas content and the metallicity evolution. Also, a deeper analysis of the dust and metallicity characteristics of these galaxies would provide some insight on the origin of this delay. SPICA/SAFARI spectroscopy is probably the best instrument that could be used to carry out this work.

Figures 2 and 3 taken together at face value would suggest that the universe’s dusty era (meaning dust attenuation higher than in the local universe) started at $z = 3-4$ simultaneously with the rise of a universe-wide star-formation event.

Figure 3 allowed us to follow the SFRD over most of the Hubble time in a consistent way. However, large uncertainties prevented us from closing the case. To go further in redshift, we need to detect and characterize galaxies at higher redshifts. This means better sensitivities and redshift measurements. SPICA spectroscopy and SPICA/Mid-IR instrument are best suited to extend the present work to much higher redshift.

This work is further detailed in Burgarella et al. (2013).

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**Figure 3.** SFRD densities in the FUV (blue), in the FIR (red), and in total (i.e., FUV + FIR) in green (other colors are due to overlaps of the previous colors). The lines are the mean values, while the lighter colors show the uncertainties evaluated from the 2000 runs as in Figure 2. After the initial increase of the total SFRD from $z = 0$ to $z \sim 1.2$, it remains flat or slightly increases/decreases up to $z = 2.5-3.0$ followed by a decrease. Globally and over $0 < z \lesssim 3.6$, the total average SFRD is slightly below that reported in Hopkins & Beacom (2006) and agrees with that of Behroozi et al. (2012) up to $z \sim 2$. The SFRD from Barger et al. (2012) and preliminary results from Herschel/SPIRE estimated by Vaccari et al. (2013, in prep.) agree with these trends. Symbols and lines are explained in the plot.
Figure 3. SFRD densities in the FUV (blue), in the FIR (red), and in total (i.e., FUV + FIR) in green (other colors are due to overlaps of the previous colors). The lines are the mean values, while the lighter colors show the uncertainties evaluated from the 2000 runs as in Figure 2. After the initial increase of the total SFRD from $z = 0$ to $z \sim 1.2$, it remains flat or slightly increases/decreases up to $z \sim 2.5–3.0$ followed by a decrease. Globally and over $0 < z \leq 3.6$, the total average SFRD is slightly below that reported in Hopkins & Beacom (2006) and agrees with that of Behroozi et al. (2012) up to $z \sim 2$. The SFRD from Barger et al. (2012) and preliminary results from Herschel/SPICA estimated by Vaccari et al. (2013, in prep.) agree with these trends. Symbols and lines are explained in the plot.

5. CONCLUSIONS

On the one hand, the variation of the cosmic dust attenuation with redshift suggests a peak in the dust attenuation at $z \sim 1.2$ followed by a decline to $z = 3.6$. On the other hand, the total (FUV+FIR) cosmic SFRD increases from $z = 0$ to $z \sim 1.2$, remains flat to $z \sim 2.5–3.0$ followed by a decrease at higher redshifts and reaches the same level at $z \sim 5–6$ as is measured locally if we assume no variations in this trend. So, the SFRD and $A_{\text{FUV}}$ do not exactly follow the same trends as seen in Figure 2 and Figure 3. The peak of the dust attenuation is delayed with respect to the plateau of the total SFRD by about 3 Gyrs. To better understand the delay, it is necessary to perform an analysis via models that are fed with data of the gas content and the metallicity evolution. Also, a deeper analysis of the dust and metallicity characteristics of these galaxies would provide some insight on the origin of this delay. SPICA/SAFARI spectroscopy is probably the best instrument that could be used to carry out this work. Figures 2 and 3 taken together at face value would suggest that the universe’s dusty era (meaning dust attenuation higher than in the local universe) started at $z = 3–4$ simultaneously with the rise of a universe-wide star-formation event. Figure 3 allowed us to follow the SFRD over most of the Hubble time in a consistent way. However, large uncertainties prevented us from closing the case. To go further in redshift, we need to detect and characterize galaxies at higher redshifts. This means better sensitivities and redshift measurements. SPICA spectroscopy and SPICA/Mid-IR instrument are best suited to extend the present work to much higher redshift. This work is further detailed in Burgarella et al. (2013).

REFERENCES

Starforming Galaxies Detected in Blind Spectroscopic Surveys with 
SPICA/SAFARI: Model Predictions

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ABSTRACT

By exploiting the galaxy evolutionary model of Cai et al. (2013), which reproduces the most recent estimates of the luminosity function of infrared-selected galaxies, Bonato et al. (2013) have predicted the number and redshift distribution of star forming galaxies detected in blind spectroscopic surveys with the SpicA FAR infrared Instrument (SAFARI) onboard of the Space Infra-Red Telescope for Cosmology and Astrophysics (SPICA). Here we summarize their results in relation to different survey strategies and for galaxies that are detected in two or more lines, a condition needed to ensure a robust redshift measurement. We conclude that in a reference survey of 450 hours the number of detections is maximized by keeping the integration time to 1 hour per field of view rather than going deeper over a smaller area. Only the statistics of \( z > 3 \) galaxies would benefit from a longer integration time per field of view, although their number would remain quite low (a few tens of objects for an investment of hundreds of hours). We envisage that follow-up observations of lensed galaxies discovered at sub-millimeter/millimeter wavelengths is a more efficient way to explore the mid- to far-infrared spectral properties of high redshift galaxies with SPICA/SAFARI.

1. INTRODUCTION

The star formation history in galaxies is one of the key processes we have to understand in order to reconstruct how the Universe evolved from small matter perturbations at the recombination epoch to the present richness of structures. While on large scales the evolution is driven by gravity, and numerical simulations in the framework of the current consensus cosmology have been remarkably successful in reproducing the galaxy distribution, on galaxy scales the complex baryon-physics comes into play and current theories are still not up to the challenge of accurately modeling it. The only way to probe the physical processes at work in galaxies is by means of spectroscopy. While spectroscopic observations are routinely carried out at optical and near-IR wavelengths, the same observations are limited to small (and sometimes biased) samples of galaxies at longer wavelengths, where several key probes of the atomic, ionized and molecular phase of the interstellar medium are present (Spinoglio 1992). In the (sub-)millimeter the situation is rapidly improving thanks to the advent of instruments like the Atacama Large (sub-)Millimeter Array (ALMA), but at mid-/far-infrared wavelengths the spectral properties of galaxies remain almost un-explored, particularly in the distant Universe. In order to fill this gap, the Japan Aerospace Exploration Agency (JAXA) and its European collaborators are proposing the Space Infra-Red Telescope for Cosmology and Astrophysics (SPICA), that will host SAFARI (Roelfsema et al. 2012), an imaging spectrometer operating in the 34–210 \( \mu \)m wavelength range, with a 2' \( \times \) 2' field of view (FoV).

Recently Bonato et al. (2013) have worked out the number and redshift distribution of star forming galaxies detected in spectroscopic surveys with SPICA/SAFARI using the hybrid evolutionary model of Cai et al. (2013) for IR-galaxies and the latest values of the SAFARI line sensitivities. Here we summarize their results by focusing on galaxies detected in at least two lines, a condition necessary to ensure a robust redshift determination.

2. MODEL LUMINOSITY FUNCTION

The model by Cai et al. (2013) combines a physical forward approach for the evolution of high-redshift proto-spheroidal galaxies (Lapi et al. 2011), with a phenomenological backward approach for late-type galaxies and AGNs. The model builds on the observational evidence that relatively old (age \( \geq 8–9 \) Gyr) stellar populations are found in early-type galaxies and in massive bulges of Sa galaxies while irregular galaxies and the disc component of spirals contain younger stellar populations (age \( \leq 7 \) Gyr). Therefore, early-type (proto-spheroidal) galaxies are the dominant star-forming population at \( z \geq 1.5 \), while IR galaxies at \( z < 1.5 \) are mostly late-type “cold” (normal) and “warm” (starburst) galaxies. The former are modelled within the standard bottom-up scenario of dark matter structure formation, following the cooling of baryons within dark matter haloes and accounting for the effect of feedback from supernovae explosions and from the activity associated with a growing super-massive black hole in the central region of the galaxy (Granato et al. 2004; Lapi et al. 2006, 2011). The evolution of late-type (warm starburst and cold normal) galaxies and of \( z < 1.5 \) type-1 and type-2 AGNs is described using a parametric phenomenological evolution approach, based on a power-law density
and luminosity evolution. The model reproduces a wide range of multiwavelength data (see Cai et al. 2013), including the recent determination of the IR luminosity function of star forming galaxies (Gruppioni et al. 2013); in particular it accounts for the transition from Euclidean to extremely steep counts at (sub-)mm wavelengths (Clements et al. 2010) and for the (sub-)mm counts of strongly lensed galaxies (Negrello et al. 2010; Viera et al. 2010).

In working out their predictions, Bonato et al. (2013) have focused on star forming galaxies (i.e. late-type galaxies and proto-spheroids) alone, as they provide the dominant contribution to the IR luminosity function (the contribution of AGNs to the line luminosity function will be discussed in a forthcoming paper). The IR continuum (8–1000 µm) luminosity is converted into a line luminosity assuming a constant line-to-IR luminosity ratio that is calibrated on data available in the literature and is also tested against simulations based on the public library of line luminosities compiled by Panuzzo et al. (2003). Predictions for the number and redshift distribution of galaxies detected in two or more lines are worked out using Monte Carlo simulations in which infrared galaxies are drawn from the model IR luminosity function and the line luminosities are randomly assigned to each source by accounting for the effect of dispersion in the line-to-IR luminosity ratios. The final number of detections is obtained by averaging over the results of 300 simulated catalogues.

### Table 1. Number of late-type galaxies and of proto-spheroids detected in two or more lines (i.e. the line considered plus at least another one) by a SPICA/SAFARI survey covering 0.5 deg² in 1 hr integration per FoV (2nd and 3rd columns), in 4 hr integration per FoV (4th and 5th columns) and in 9 hr integration per FoV (6th and 7th columns). The total number of objects detected in at least two lines (regardless of which lines are actually detected) is shown in the last line, while the value in parentheses represents the subsample of proto-spheroids with redshift \( z > 3 \).

<table>
<thead>
<tr>
<th>Spectral line</th>
<th>1 hour per FoV</th>
<th>4 hours per FoV</th>
<th>9 hours per FoV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µm</td>
<td>late-type</td>
<td>proto-sph.</td>
</tr>
<tr>
<td>PAH 11.25</td>
<td></td>
<td>1</td>
<td>508</td>
</tr>
<tr>
<td>[Ne II] 12.81</td>
<td></td>
<td>12</td>
<td>242</td>
</tr>
<tr>
<td>[Ne III] 15.55</td>
<td></td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>(H₂) 17.03</td>
<td></td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>[S III] 18.71</td>
<td></td>
<td>220</td>
<td>125</td>
</tr>
<tr>
<td>[S III] 33.48</td>
<td></td>
<td>1591</td>
<td>334</td>
</tr>
<tr>
<td>[Si II] 34.82</td>
<td></td>
<td>2187</td>
<td>479</td>
</tr>
<tr>
<td>[O III] 51.81</td>
<td></td>
<td>2638</td>
<td>610</td>
</tr>
<tr>
<td>[N III] 57.32</td>
<td></td>
<td>728</td>
<td>139</td>
</tr>
<tr>
<td>[O I] 63.18</td>
<td></td>
<td>2010</td>
<td>307</td>
</tr>
<tr>
<td>[O III] 88.36</td>
<td></td>
<td>2545</td>
<td>27</td>
</tr>
<tr>
<td>[N II] 121.9</td>
<td></td>
<td>410</td>
<td>0</td>
</tr>
<tr>
<td>[O I] 145.5</td>
<td></td>
<td>137</td>
<td>0</td>
</tr>
<tr>
<td>[C II] 157.7</td>
<td></td>
<td>625</td>
<td>0</td>
</tr>
<tr>
<td>≥2 lines</td>
<td>3649</td>
<td>899 (66)</td>
<td>6932</td>
</tr>
</tbody>
</table>

and luminosity evolution. The model reproduces a wide range of multiwavelength data (see Cai et al. 2013), including the recent determination of the IR luminosity function of star forming galaxies (Gruppioni et al. 2013); in particular it accounts for the transition from Euclidean to extremely steep counts at (sub-)mm wavelengths (Clements et al. 2010) and for the (sub-)mm counts of strongly lensed galaxies (Negrello et al. 2010; Viera et al. 2010).

In working out their predictions, Bonato et al. (2013) have focused on star forming galaxies (i.e. late-type galaxies and proto-spheroids) alone, as they provide the dominant contribution to the IR luminosity function (the contribution of AGNs to the line luminosity function will be discussed in a forthcoming paper). The IR continuum (8–1000 µm) luminosity is converted into a line luminosity assuming a constant line-to-IR luminosity ratio that is calibrated on data available in the literature and is also tested against simulations based on the public library of line luminosities compiled by Panuzzo et al. (2003). Predictions for the number and redshift distribution of galaxies detected in two or more lines are worked out using Monte Carlo simulations in which infrared galaxies are drawn from the model IR luminosity function and the line luminosities are randomly assigned to each source by accounting for the effect of dispersion in the line-to-IR luminosity ratios. The final number of detections is obtained by averaging over the results of 300 simulated catalogues.

### 3. SPECTROSCOPIC SURVEYS WITH SPICA/SAFARI: PREDICTIONS

The expected SAFARI 5σ line detection limits for an integration of 1 hour per field of view (FoV) are \( 3.7 \times 10^{-19} \) W/m² for the first band (34–60 µm), \( 3.4 \times 10^{-19} \) W/m² for the second band (60–110 µm) and \( 2.9 \times 10^{-19} \) W/m² for the third band (110–210 µm) (B. Sibthorpe, private communication).

Following Spinoglio et al. (2012), Bonato et al. (2013) consider a reference spectroscopic survey of 450 hours and 1 hour of integration time per FoV (t_{\text{FoV}}). This corresponds to a total areal coverage of 0.5 deg² (excluding overheads). The number of galaxies detected in two or more lines by such a survey is reported at the bottom of Table 1 for late-type galaxies (second column) and proto-spheroids (third column; with the number of \( z > 3 \) detections indicated in parentheses). Also shown in the table is the number of detections in each spectral line for objects detected in at least two lines (i.e. each of the thousands of galaxies seen in e.g. [O III] 51.81 µm is also detected in one or more of the lines listed in the same table). The brightest lines, which provide the highest number of detections, are [S III] 33.48 µm, [Si ii] 34.82 µm, [O III] 51.81 µm, [O I] 63.18 µm, [O III] 88.36 µm and [N II] 121.9 µm. These lines will represent the most useful redshift indicators and the most easily available probes of the physical conditions in star forming galaxies detected by SAFARI.

The redshift distribution of galaxies detected in at least two lines in the reference spectroscopic survey is shown by the blue histogram in Figure 1. The majority of galaxies have \( z \lesssim 2 \) with only ~70 detections above \( z = 3 \). The way to
One of the thousands of galaxies seen in e.g. [O III] 51.81 detected by such a survey is reported at the bottom of Table 1 for late-type galaxies (second column) and proto-spheroids (third column; with the number of detections indicated in parentheses). The redshift distribution of galaxies detected in at least two lines in the reference spectroscopic survey is shown by the grey line in Figure 1. The majority of galaxies have a blue histogram in Figure 1. The contribution of proto-spheroids is shown as a function of redshift. The way to increase the statistics of high redshift galaxies is to improve the line sensitivity by means of longer integration time per FoV. The effect is illustrated by the black dashed line in Figure 2, where the number of galaxies detected in two or more lines is shown as a function of $t_{\text{FoV}}$. As the integration time per FoV increases, the line sensitivity decreases by a factor $\sqrt{t_{\text{FoV}}}$ while the area is scaled down by a factor $1/t_{\text{FoV}}$. The net effect is the loss of statistics as the decreasing number of detections due to the smaller areal coverage is not overcame by the increasing number density of galaxies. In fact, around
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the faintest line fluxes probed by SAFARI, the line integral number counts have slope $\gamma \sim 1$ (with $N(> F_\ell) \propto F_\ell^{-\gamma}$, where $F_\ell$ is the line flux).

Alternatively, one can keep the area to 0.5 deg$^2$ and just increase the amount of time invested in the survey. The result of this approach is shown by the solid lines in Figure 2, and also reported in Table 1 for an $t_{\text{FoV}} = 4$ hours and $t_{\text{FoV}} = 9$ hours per FoV. The corresponding redshift distributions are shown in Figure 1. We find that improving the line sensitivity by a factor of 3 (i.e. $t_{\text{FoV}} = 9$ hours) will gain about $\times 6$ more galaxies detected in at least two lines at $z > 3$ compared to what expected for the reference survey. However this would require an investment of 4050 hours for the entire survey. A wiser approach to the study of star formation activity in the distant Universe would be to follow-up the hundreds of high redshift lensed galaxies discovered meanwhile at sub-millimeter and millimeter wavelengths (Negrello et al. 2010; Bussmann et al. 2013; Vieira et al. 2013). With an apparent infrared luminosity exceeding $10^{13} \, L_\odot$, those galaxies will be detected at 5$\sigma$ in several mid-/far-IR lines in about 15 minutes, or less, with SPICA/SAFARI.

4. CONCLUSIONS

In light of the predictions made by Bonato et al. (2013) for galaxies detectable in at least two lines with SPICA/SAFARI, we conclude that a spectroscopic survey of 450 hours would maximize the number of detections if the integration time is kept to 1 hour per FoV, for a total observed area of 0.5 deg$^2$, rather than going deeper over smaller areas. On the other hand, to compensate for the relatively small statistics of $z > 3$ detections we suggest to integrate the spectroscopic survey with a follow-up program focusing on high redshift lensed galaxies discovered meanwhile at sub-mm/millimeter wavelengths.

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Extra-Galactic Studies with the SCI: AGNs and Nuclear Starburst Galaxies

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ABSTRACT

To reveal triggers of active galactic nucleus (AGN) and nuclear starburst generations and effects of the central activities to the circumnuclear environments, we propose the mid-infrared spectroscopic observations not only in central nuclei but also in the environments very close to central nuclei. The environments provide important information on supplying fuel to galactic nuclei, evidence for presence of materials processed by central activities and a connection between a nucleus and a host galaxy. To perform this kind of observations, we need a high contrast capability to reduce halo components of a point spread function of a bright central core. Reducing the halo components will be effective in not only obtaining the information of the faint environments around the core but also reducing the observing time. The SPICA Coronagraph Instrument (SCI) will provide such a high contrast capability in the mid-infrared. Using the SCI, we will obtain the circumnuclear structures and the compositions of dust, especially silicate and polycyclic aromatic carbons, in the environments very close to the bright central core in AGNs and nuclear starburst galaxies.

1. INTRODUCTION

The centers of galaxies are the sites of the two most wide-studied phenomena: active galactic nuclei (AGNs) and starburst galaxies. The AGN harbors in the center of a host galaxy. The radiation of the AGN is as luminous as or more than that of the host galaxy. The reason of the strong radiation is because mass accretion toward a super massive blackhole (SMBH) in the center releases the gravitational energy. The accretion is also important to the growth of the SMBH. A dusty torus is surrounding the SMBH and the accretion disk. The torus is an important component for infrared radiation as well as for a mass reservoir. However, for $10^{11} \ L_\odot$ AGNs, we need a mass accretion rate of $0.1 \ M_\odot \ yr^{-1}$ at least. If the mass of torus is $10^7 \ M_\odot$, the life time is only $10^8 \ yr$. Thus, we need fueling to the dusty torus from the host galaxy to maintain the torus.

Starburst galaxies are also important to understand the evolution of star formation history of the Universe. Especially, dusty starburst galaxies with infrared luminosity of $10^{12} \ L_\odot$, which are identified as ultra-luminous infrared galaxies (ULIRGs), play important roles in the history. However, because the galaxies are very dusty, current observations only revealed the central part in the infrared. It is important to know the environment close to the central part, which will provide the triggers and the effects of nuclear starburst galaxies.

The SPICA Coronagraph Instrument (SCI) can reveal the phenomena and the environments of central regions of galaxies to obtain evidence for the fueling mechanism, the processing of materials, and co-evolutions of AGNs and the host galaxy. In this paper, we focus on science case for AGNs and nuclear starburst galaxies with the SPICA/SCI and discuss the merits of the SCI.

2. SCIENTIFIC MOTIVATIONS

2.1. Fueling mechanism of AGNs

The fueling mechanism to a dusty torus from a host galaxy is important to maintain the torus. However, there is an angular momentum problem. We have to remove large angular momentum to fuel gas to the dusty torus. Several ideas are proposed to remove angular momentum. One is galaxy mergers. The gravitational torque can be used due to galaxy-galaxy interaction to remove the angular momentum of the gas (e.g. Barnes & Hernquist 1991). The stellar bar structure is also one of the ideas. The gas in the bar structure induces shocks which inflows toward the center are formed (e.g. Athanassoula 1992). The star formation activity in the central 100 pc region have also been considered as reasonable means of removing angular momentum of the rotating gas (e.g. Wada 2001). However, systematic observations have not shown any clear excess of bars or companions in galaxies with AGNs (Schmitt 2001). Moreover observations of the circumnuclear regions suggest no significant differences in the spatial distribution of the nuclear dust between active and inactive galaxies (Martini et al. 2003).
Figure 1. Spectral energy distributions of the galaxies with dusty AGNs found by the AKARI All-Sky Survey. (a) LEDA 84274 and (b) IRAS 01250+2832. The lines (blue) shows the AKARI near-infrared spectra. Squares, triangles, and crosses represent the AKARI All-Sky Survey, IRAS, and 2MASS photometry. Black solid and dotted lines represent galaxy templates and blackbody components of dust.

The observations of the circumnuclear region, especially the region where gas and dust in a host galaxy flow into a dust torus, will provide clues to the mechanism to remove the angular momentum. In particular, silicate features will have information not only at present but also in the past, e.g. the crystallization reflects the thermal history. The distributions of silicate, especially silicate heated or crystallized by galaxy-scale shocks, will be distorted and spread widely over the galaxy scale if the galaxy-galaxy interactions are a major cause. If the bar mechanism works, silicate will be heated or crystallized by the shocks induced by the flow in the bar structures. If the nuclear star formation activities are a main mechanism, the features will show variations of crystalline silicate features from inside to outside.

2.2. Processing of solid materials

Using the Spitzer Space Telescope, Spoon et al. (2006) reported the discovery of narrow absorption features in the mid-infrared, which is characteristic of crystalline silicates, in ULIRGs. The fact that the absorption features are seen in ULIRGs implies that the crystalline silicates are located in the cooler and outer regions of the galaxies. This would require a crystallization process for the large area of a galaxy such as shocks by a galaxy-galaxy merging process or a large-scale mechanism to transport the crystalline silicates outward and distribute it over the surrounding medium after central activities crystallize silicate.

Polycyclic aromatic carbons (PAHs) are also processed in galaxies. Using AKARI near-infrared spectroscopy, Yamada et al. (2013) found the decline of the ratio of PAH 3.3 μm luminosity to total infrared luminosity in the high luminosity end of star-forming galaxies after excluding galaxies with AGN signatures. The interpretation of this decline is a scarcity of PAHs relative to large grains. The merger process may cause this scarcity, because PAHs are more easily destroyed by shocks than large grains.

One of important themes for the study of AGNs is to understand the role of relativistic jets. The interaction between the radio-emitting outflows and gas/dust occurs in regions from near-nuclear to intergalactic environments. Rouan et al. (2004) observed the diffraction-limited images around the core of NGC 1068 in the K-, L-, and M- bands with the VLT. The observations indicated that the dust is delineating the cocoon of the radio jet and the temperature of a part of the dust components estimated from the near-infrared color reaches about 600 K which is higher than the expectation of classical large grain. It is most probably the signature of transiently heated very small dust grains, possibly nano-diamond particles. Very small grains form very efficiently in shocks induced by jets.

Processed materials provide very important information of the central activities. We need to know where the processed materials are and how they are processed.

2.3. Co-evolution of an AGN and the host galaxy

The tight correlation between a supermassive black hole (SMBH) mass and a mass of the stellar spheroid is well-known and important in the cosmological context of black hole growth and galaxy evolution (e.g. Gültekin et al. 2009). It is generally accepted that the relation $M_{BH}/M_{bulge} \sim 10^{-3}$ should be valid for all spheroids irrespective of the mass scale and the environment. It does not matter whether a black hole is active or not.

The tightness of the correlation suggests that some kind of feedback acts to maintain the connection between SMBH mass and the spheroid mass. Various models (Silk & Rees 1998; King 2003) are proposed to explain the mechanism to
maintain the correlation by using outflows from the central engine. In the mechanism, no consensus has been reached. One of the difficulties of the observations is that targets in the evolutionary stage are probably obscured by dust.

As shown in Figure 1, Oyabu et al. (2011) found galaxies with dusty AGNs in the low-redshift Universe using the AKARI mid-infrared all-sky survey catalog (Ishihara et al. 2010). The galaxies show the AGN signatures only in the near- and mid-infrared, not in other wavelengths. The dusty AGNs also followed the correlation between the SMBH mass and the spheroid mass even though dusty AGNs are expected to be young systems which are growing up at present. It makes sense if black holes grow at the same rate as the stellar spheroid in which they reside. It is unclear how to connect the growth of the black hole and the stellar spheroid, but we can imagine a close link between black hole growth and galaxy evolution.

To reveal how they interact, we need to obtain not only spectra of a central engine of a dusty AGN but also spectra of a host galaxy. If outflows maintain the correlation, we will find clues in both spectra. If there are AGNs which do not follow the correlation, they are probably populations before outflows occur.

### 3. MERITS OF THE SCI OBSERVATIONS

We are motivated to investigate the environments close to the central part of AGNs and starburst galaxies by the science cases as mentioned above. However, a very bright nucleus such as an AGN and a nuclear starburst prevents us from observing the regions close to a galaxy nucleus. Coronagraph systems can benefit the research for the regions on galaxy nuclei because they reduce halo components of a point spread function (PSF) of a bright central core. Using the capabilities of the SCI, we propose spectroscopic observations of regions near bright central cores in AGNs and nuclear starburst galaxies.

High contrast capability of the SCI can reduce the confusion of the central nuclei to the environments close to the nuclei. Without the coronagraph, a surface brightness of the PSF halo can be comparable to that of the environments and the spectra of the environment are contaminated by the halo of the central PSF. Therefore, the SCI can obtain the pure spectrum of the faint environments in the host galaxies.

In addition to the reduction of the confusion, the high contrast capability of the SCI can also dramatically reduce the noise caused by the halo of bright central core. It is very powerful to reduce observing time. When we look at 10 Jy sources at the mid-infrared with the coronagraph, the exposure time will be one hundredth of the exposure time without the coronagraph. For the 0.1 Jy sources, it is still a few times faster than the observations without the coronagraph.

Our targets are central 10–1000 pc regions of galaxies with AGNs and nuclear starbursts. If they are located at the distance of 4 Mpc, we can resolve 20 pc at 10 μm. In galaxies at 20 Mpc and 40 Mpc, 100 pc and 200 pc region can be resolved at 10 μm, respectively. Using the AKARI Mid-infrared All-Sky Survey catalog, we selected target candidates with a bright central core at 9 μm. We have 94 galaxies with 9 μm flux of $F_{9\mu m} > 1$ Jy in 20 Mpc as targets. If we extend our sample to more distant or fainter targets, the number of targets increases dramatically. The observation efficiency of
the SCI will be able to increase the number of observed targets and to help understanding the environments very close to galactic nuclei.

4. SUMMARY

Fueling mechanisms, processing of materials and connections between a nucleus and a host galaxy are important science topics for the study of AGNs and nuclear starburst galaxies. In order to tackle such science topics, we need to observe the environments very close to bright central cores of AGNs and nuclear starburst galaxies. However, the halo components of a PSF of a bright central core prevent us from observing the regions.

The coronagraph capabilities of the SCI overcome the obstacle. The reduction of the halo components of the PSF will distinguish the environment components from the bright central core and reduce the observation time. Therefore, we propose the spectroscopic observations of AGNs and nuclear starburst galaxies with the SCI. The SCI will be able to take mid-infrared spectra of the environment very close to bright central cores. These spectra will reveal the circumnuclear structures and the compositions of dust, especially silicate and PAHs, in the environments.

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Luminosity and Dust Mass Functions of Galaxy Clusters

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ABSTRACT

We have been using Herschel data at 100–500 μm to study the far-infrared luminosity functions of Virgo, Coma and Fornax cluster galaxies and to compare them to those of field galaxies. We show that the Virgo cluster lacks the very bright and the numerous faint sources detected in other surveys of the general field carried out by both Herschel and Planck (typically a luminosity function faint end slope of −1.0 compared to −1.5). We fit the far-infrared spectral energy distributions using a fixed (β = 2) emissivity index to obtain dust masses and temperatures. The dust mass function has a similar shape to that of the field, so the disparity in cluster and field galaxy luminosity functions must be due to different dust temperatures not different quantities of dust. The Virgo cluster is over dense in dust by about a factor of 100 compared to the field.

1. INTRODUCTION

We use as our starting point the Herschel data presented and described in Auld et al. (2013). This consists of observations of a total area of 84 sq deg made using Herschel in parallel scan map mode to obtain data in five bands (100, 160, 250, 350 and 500 μm). A full discussion of this data and its reduction and calibration are given in Davies et al. (2012) and Auld et al. (2013) and will not be repeated here. The result is the detection at 250 μm of 251 galaxies selected in the optical from the Virgo Cluster Catalogue (VCC, Binggeli et al. 1985). Although it is not ideal to have an optical rather than a far-infrared selected sample we have no other way of ensuring that we have a pure cluster sample rather than one contaminated by background sources. We will show below that there is no evidence for additional cluster far-infrared sources missed by our selection method.

The 251 galaxies listed by Auld et al. (2013) extend in distance (as given in the GOLDMINE database, Gavazzi et al. 2003) from 17 to 32 Mpc with galaxy groupings at 17, 23 and 32 Mpc. This range of 15 Mpc in depth is large for a cluster and much larger than the linear size we survey on the plane of the sky (about 4 Mpc at a distance of 23 Mpc). For this reason in this paper we restrict our analysis to galaxies with distances of 17 and 23 Mpc so that line-of-sight and plane of sky distances are comparable. These distances correspond with those of sub-cluster A containing M87 and sub-cluster B containing M49 (Gavazzi et al. 1999). Restricting distances to between 17 and 23 Mpc leads to a sample of 208 galaxies and a surveyed volume of about 62.4 Mpc³.

2. DATA

The 251 galaxies listed by Auld et al. (2013) extend in distance (as given in the GOLDMINE database, Gavazzi et al. 2003) from 17 to 32 Mpc with galaxy groupings at 17, 23 and 32 Mpc. This range of 15 Mpc in depth is large for a cluster and much larger than the linear size we survey on the plane of the sky (about 4 Mpc at a distance of 23 Mpc). For this reason in this paper we restrict our analysis to galaxies with distances of 17 and 23 Mpc so that line-of-sight and plane of sky distances are comparable. These distances correspond with those of sub-cluster A containing M87 and sub-cluster B containing M49 (Gavazzi et al. 1999). Restricting distances to between 17 and 23 Mpc leads to a sample of 208 galaxies and a surveyed volume of about 62.4 Mpc³.

3. LUMINOSITY FUNCTIONS

Figure 1. Top left: The Virgo field 250 μm faint galaxy number counts (dark grey line) compared to the faint galaxy number counts in the H-ATLAS NGP field (black line). The light grey line shows the number counts using the 207 galaxies from the Auld et al. (2013) data. The diagonal dashed line has a slope of 1.5 and indicates the expected counts for a non-evolving Euclidean universe. The dotted line indicates the minimum flux density detectable given the minimum detection area and 1σ noise level in the NGP data. Top right: as for Virgo, but now this is Coma. Bottom: as for Virgo, but now this is Fornax.
Figure 2. Virgo cluster galaxy luminosity functions for the 5 Herschel far-infrared bands. The data has been arbitrarily off-set from each other to avoid confusion.

Figure 3. A comparison of luminosity functions at different wavelengths and over different environments. In each case the solid line is taken from Figure 2 (Virgo cluster). Top left: IRAS data with fit. Top right: Herschel field data with fit. Bottom left - Herschel (lower) and Planck data (upper) with fits. Bottom right: Herschel (lower) and Planck data (upper) with fits.

The Auld et al. (2013) data is obtained from the positions of optically selected galaxies in the VCC. This is not ideal as we would prefer to select galaxies via their far-infrared flux density when constructing far-infrared luminosity functions. To address this issue we have carried out a faint galaxy number count analysis of the Virgo field and compared it to the faint galaxy number counts derived from the North Galactic Pole (NGP) field observed by the H-ATLAS consortium (Eales et al. 2010), both at 250 µm. Our motivation for doing this is to compare the number counts from the general field (NGP) with that obtained by ‘looking through’ the Virgo cluster into the Universe beyond.

The NGP data is fully described in (Valiante et al., in preparation). We have used the source detection programme SExtractor to extract faint sources from both the Virgo and NGP data, taking great care to apply identical methods to both fields. The derived number counts for both the NGP and Virgo fields are shown in Figure 1. The solid black line shows the NGP number counts. The counts are consistent with other counts and detection methods used on previous H-ATLAS data (Clements et al. 2010). The important question is whether there is a faint galaxy excess in the Virgo field that might be associated with a far-infrared population not detected using our optical source list. Looking at Figure 1 we can see that below about 1 Jy the black line traces the dark grey line very well and there is no evidence for an excess population over and above that detected by our optical selection.

In Figure 1 (middle and bottom) we also show our preliminary results from carrying out a similar analysis on Coma and Fornax (Fuller et al., in preparation). From these three figures our initial assessment is that the luminosity functions of all three clusters are flatter at the faint end than that of field galaxies. We conclude that there is no good evidence for an additional population of faint far-infrared sources that is not associated with the previously identified optical sources. In Figure 2 we show the derived luminosity functions with the best fitting Schechter functions — fitting parameters are given in Table 1. To illustrate the disparity between the cluster and field, we also show in Table 1 the Schechter fitting parameters for luminosity functions derived by others — see also Figure 3. The IRAS ‘field’ 100 µm data comes the compilation of 629 galaxies in the Bright Galaxy sample of Sanders et al. (2003). The Herschel data comes from the H-ATLAS survey (Eales, private communication) using data from the three SPIRE bands at 250, 350 and 500 µm. The Planck data is taken directly from Negrello et al. (2013).

The most disparate wavelength between cluster and field is 100 µm, where the IRAS luminosity function of nearby bright galaxies is considerably steeper at the faint end than that in the cluster (Sanders et al. 2003). With a slope of $\alpha = -1.0$ our
LUMINOSITY AND DUST MASS FUNCTIONS OF GALAXY CLUSTERS

Table 1. Schechter function fitting parameters.

<table>
<thead>
<tr>
<th>Band (µm)</th>
<th>Instrument</th>
<th>Region</th>
<th>α</th>
<th>L* (10^24 W Hz⁻¹)</th>
<th>ϕ (Mpc⁻³ dex⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Herschel</td>
<td>Virgo</td>
<td>−1.0 ± 0.1</td>
<td>2.1 ± 0.6</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>160</td>
<td>Herschel</td>
<td>Virgo</td>
<td>−1.0 ± 0.1</td>
<td>2.8 ± 1.0</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>250</td>
<td>Herschel</td>
<td>Virgo</td>
<td>−0.9 ± 0.1</td>
<td>0.8 ± 0.2</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>350</td>
<td>Herschel</td>
<td>Virgo</td>
<td>−1.0 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>500</td>
<td>Herschel</td>
<td>Virgo</td>
<td>−1.0 ± 0.1</td>
<td>0.2 ± 0.01</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>100</td>
<td>IRAS</td>
<td>Field</td>
<td>−2.1 ± 0.1</td>
<td>46 ± 15</td>
<td>0.000012 ± 0.000007</td>
</tr>
<tr>
<td>250</td>
<td>Herschel</td>
<td>Field</td>
<td>−1.19 ± 0.04</td>
<td>1.6 ± 0.1</td>
<td>0.0017 ± 0.0002</td>
</tr>
<tr>
<td>350</td>
<td>Herschel</td>
<td>Field</td>
<td>−1.22 ± 0.05</td>
<td>0.7 ± 0.1</td>
<td>0.0014 ± 0.0002</td>
</tr>
<tr>
<td>500</td>
<td>Herschel</td>
<td>Field</td>
<td>−1.58 ± 0.12</td>
<td>0.4 ± 0.1</td>
<td>0.0067 ± 0.0003</td>
</tr>
<tr>
<td>350</td>
<td>Planck</td>
<td>Field</td>
<td>−1.65 ± 0.08</td>
<td>0.9 ± 0.1</td>
<td>0.0013 ± 0.0003</td>
</tr>
<tr>
<td>550</td>
<td>Planck</td>
<td>Field</td>
<td>−1.78 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.0010 ± 0.0003</td>
</tr>
</tbody>
</table>

cluster luminosity function either lacks faint dusty galaxies and/or the star formation required to heat the dust. Another noticeable difference between the cluster and the field is the lack of very luminous infrared sources in the cluster — the derived $L'_{100}$ for the field is about a factor of 20 higher than in the cluster. With a faint-end slope of $α > −2.0$ the IRAS luminosity function is unbound and we cannot calculate a luminosity density ($ρ_{IR} = ϕ L' (2.0 + α)$).

Comparing our Virgo longer wavelength luminosity functions with others, we find that a steeper faint-end slope and a larger value of $L'$ are a common feature of the field. Eales et al. (private communication) have derived the 250, 350 and 500 µm luminosity functions using H-ATLAS data for galaxies with $z ≤ 0.1$ ($D ≤ 411$ Mpc). Negrello et al. (2013) have done a similar thing using Planck 350 and 550µm data for galaxies with $D ≤ 100$ Mpc, see Table 1, and Figure 3. When comparing the two the Planck data gives a steeper faint-end slope, about the same $L'$ and a luminosity density a factor of about 2 higher than the Herschel data. Generally the cluster has a far-infrared luminosity density about two orders of magnitude higher than that of the field. It is clear that at all far-infrared wavelengths there is a lack of fainter sources in the cluster compared to what is generally found in the local field. There is either a relative lack of emitting dust, it is cold or if far-infrared emission is closely connected to star formation then there is a lack of star formation in low luminosity cluster systems.

4. DUST MASS, TEMPERATURE

We have used the 100–500 µm data to fit modified blackbody curves to the far-infrared spectral energy distributions of the 207 Virgo galaxies. We use a power law dust emissivity $κ_λ = κ_0 (λ_0/λ)^β$ with $κ_0 = 0.192$ m² kg⁻¹ at $λ_0 = 350$ µm and a fixed $β (= 2)$. As discussed in Davies et al. (2012) (see their Figure 6) many galaxy far-infrared spectral energy distributions fit modified blackbodies with $β = 2$ very well. Having dust masses for our galaxies we can construct the dust mass function in a similar way to the luminosity functions described earlier (Figure 4). The fitted mass function parameters are given in Table 2. Note that the dust mass function value of $M'_{Dust}$ is very close to the value recently measured for M31 (5.4 × 10⁷ M⊙) by Draine et al. (2013).

We have also compared our dust mass function parameters with those obtained for the general field by Dunne et al. (2011). The dust mass density is about a factor of 100 higher in the cluster than it is in the field. All three mass functions shown in Figure 4 are essentially flat at the low mass end with no evidence for them being different in this respect between field and cluster. This is in contrast to the luminosity functions which were all steeper in the field than in the cluster. This can only come about if we have generally hotter dust in the lower luminosity field galaxies and so the steepness of the field galaxy luminosity functions must be due to enhanced star formation. We might have expected that if dust stripping processes are important in the cluster environment that the relative numbers of low and high dust mass galaxies may have changed between cluster and field i.e. lower mass galaxies more readily losing their dust, but this does not appear to be so.

5. CONCLUSIONS

• Faint galaxy number counts both on and off the cluster field indicate that the optical selection of galaxies does not miss a population of previously undetected cluster far infrared sources.

• Cluster luminosity functions are generally flatter at the faint end than those derived for field galaxies — the cluster lacks faint far-infrared sources.
Davies

Figure 4. The dust mass function. The black line is for all 207 galaxies which have either measured or predicted flux densities in all five Herschel bands and have then been fitted with a $\beta = 2$ model. The blue line is the field galaxy dust mass function taken from Dunne et al. (2011).

Table 2. Schechter function fitting parameters to the Virgo cluster dust mass function. For comparisons we also give the values for the field taken from Dunne et al. (2011).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\alpha$</th>
<th>$M_{Dust}^*$ ($10^7 M_\odot$)</th>
<th>$\phi$</th>
<th>$\rho_{Dust}$ ($10^7 M_\odot$ Mpc$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta = 2$</td>
<td>$-0.9 \pm 0.1$</td>
<td>$5.7 \pm 1.3$</td>
<td>$0.7 \pm 0.1$</td>
<td>$1.8$</td>
</tr>
<tr>
<td>Field</td>
<td>$-1.0$</td>
<td>$3.6$</td>
<td>$0.006$</td>
<td>$0.02$</td>
</tr>
</tbody>
</table>

- The cluster dust mass function has a similar shape to that of field galaxies so the differences in the luminosity functions must be due to temperature — more low dust mass star forming galaxies in the field.
- The cluster is over dense in dust by about a factor of 100 compared to the field.
- Individual galaxies have a range in global dust temperatures similar to that found in different regions of a typical galaxy like M31 (15–25 K).

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From *AKARI* to *SPICA*: a New Window to Understand Links between Cosmology and Galaxy Evolution

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**ABSTRACT**

Understanding the complex relation between the evolution of large scale structure of the Universe and of galaxies themselves is one of the key problems of modern cosmology. It is well known that galaxy clustering depends on galaxy types and properties, and that this relation evolved with cosmic time in a way which is not yet well understood. In the same time, optical surveys cannot be sufficient to solve the emerging questions: one of the key problems is the evolving dust extinction in galaxies. Hence the necessity of deep multiwavelength infrared observations to understand the link between galaxies and the underlying large scale structure. However, the present-day infrared observations usually suffer from relatively low resolution which makes it impossible for example to trace the relation between the evolution of galaxies and the history of intergalactic interactions. Also, the spectroscopic data in the infrared are limited. In this paper, we summarize some of the results of our measurements of clustering of dusty galaxies from on the AKARI data, both deep surveys and all-sky survey. We mention the key problems which could not be successfully solved yet: the relation between galaxy clustering and interactions inside one dark matter halo; the evolution of the position in the large scale structure of the extreme types of infrared galaxies, like (U)LIRGs. We discuss the perspectives to answer these questions thanks to SPICA unique sensitivity, resolution, and spectroscopic capabilities.

1. **INTRODUCTION**

According to the widely accepted paradigm in modern cosmology, the formation and evolution of the large scale structure of the Universe, was driven by gravitational instability. So-called hierarchical scenario of the structure formation assumes that galaxies formed and evolved inside (cold) dark matter halos, growing under the effect of gravity. It implies that the density field of dark matter at all cosmic epochs can be, in general, traced by the distribution of galaxies. However, galaxies are *biased* tracers of the dark matter field; moreover, the corresponding bias depends both on cosmic time and on galaxy properties: morphological types, colors, masses, luminosities. Since galaxies evolve with time, in the evolving large scale net of dark matter, the interplay between evolution of their properties and position in the dark matter large scale structures, is not-trivial and not yet well understood.

It is well known that in the present cosmic epoch different types of galaxies cluster differently. Large, luminous, red, non-star forming elliptical galaxies are typically strongly clustered; they are usually found in highly overdense environments, e.g. in the central parts of galaxy clusters. Inversely, small, spiral or irregular, blue star-forming galaxies are usually characterized by low clustering amplitude, since they are located in low-density areas (e.g. Zehavi et al. 2011). However, it is clear that at some moment in the past the situation must have been different: today’s passive red galaxies in the clusters’ centers must have once produced their star populations; thus, once upon a time they much have been blue and active. This shift of star formation activity to smaller galaxies and towards low density areas with cosmic time is (in many varieties of the precise definition) known as downsizing.

However, it is still unclear when this process of moving star formation outside of dense environments took place, what was its timescale and what were the key mechanism behind it. In the largest existing deep galaxy surveys (e.g. VIPERS: Guzzo et al. 2013) we find structure very similar to today’s one at least up to z ~ 1.2; already then massive red galaxies were strongly clustered while blue star forming galaxies were located in the less dense environments. Only much more detailed studies show some possible hints for reversal of this tendency, but strongly dependent on galaxy properties (Cucciati et al. 2006). Also, the mechanism of formation of different morphological types of galaxies are still debatable: both initial conditions in the place where galaxy has been formed and interactions between galaxies might have played the role. The question about the level of importance of both these factors is nicknamed sometimes as cosmological "nurture or nature" problem.

To make a census of all possible types of galaxies at different cosmic epochs, deep surveys at all possible wavelength ranges, with spectroscopic information available, are crucial. In particular, information gathered at infrared (IR) wave-
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Figure 1. Left: Angular correlation function $\omega(\theta)$ of galaxies in the northern Galactic hemisphere in the AKARI All-Sky Survey for four flux-limited samples. Right: Spatial clustering lengths $r_0$ of the same four flux limited galaxy samples as in the left panel, reconstructed from the angular correlation function using the Limber inversion.

lengths plays an important role. First of all, observations in the IR significantly increase the sample of detected galaxies. One reason is that at near IR (NIR) dust is nearly transparent; it allows for galaxy surveys at NIR to cover much larger part of the sky than for optical surveys, which are limited by dust extinction from the disk in our own galaxy. At longer IR wavelengths emission from dust reveals the presence of dust obscured galaxies, often barely visible or undetectable by optical observations. Additionally, IR observations are crucial for proper estimation of key galaxy properties, in particular of their star formation rates (e.g., Takeuchi et al. 2010).

The large-scale structure of dusty galaxies can be then seen as the star-formation density field in galaxies. It may thus allow us to trace the relation between the dark matter density and star formation activity at different epochs (e.g., Malek et al. 2010; Solarz et al. 2013).

The breakthrough in the studies of dusty galaxies came with the launch of the IRAS satellite in 1983 (Neugebauer et al. 1984). More than 20 years later a Japanese satellite AKARI opened new possibilities to explore the whole sky in the mid- and far-infrared (Murakami et al. 2007). The primary purpose of the AKARI mission was to provide second-generation infrared (IR) catalogs characterized by a better spatial resolution and a wider spectral coverage than the IRAS catalogs. In addition to the all-sky surveys, some pointed deep observations were made by AKARI, in particular deep extragalactic surveys at the northern and southern ecliptic poles. These two deep surveys are now referred to as AKARI North Ecliptic Pole (NEP) and AKARI Deep Field-South (ADF-S) fields.

2. CLUSTERING OF AKARI GALAXIES

There was a number of attempts so far to investigate clustering of galaxies bright in IR both in AKARI All-Sky Survey and in the deep fields at NEP and ADF-S. Among others, Malek et al. (2010) have performed an attempt to identify the FIR-bright extragalactic sources in the ADF-S and then used their correlation function to estimate the limitations of the completeness of the sample due to source confusion. Matsuura et al. (2011) measured the power spectrum of the cosmic infrared background (CIB) in the ADF-S, providing a new upper limit for the clustering properties of distant infrared galaxies and any diffuse emission from the early universe which might have contributed to the CIB.

2.1. Local galaxies in the AKARI All-Sky Survey

Two all sky surveys, performed at FIR (90 $\mu$m) and mid-IR (MIR) can be counted among the main achievements of AKARI. Its Far-Infrared Surveyor (FIS; Kawada et al. 2007) scanned 96% of the entire sky, and the resulting AKARI/FIS Bright Source Catalogue v.1.0 (Yamamura et al. 2010) contains 427,071 point sources measured at 65, 90, 140 and 160 $\mu$m. Among them, 18,087 were identified as extragalactic sources located at low extinction areas of the sky, which are not affected by the dust neither from Milky Way nor Magellanic Clouds (Pollo et al. 2010, 2013a). After the cross-identification with the public catalogs it was found that a majority (over 60%) of these sources are very nearby galaxies at $z < 0.1$, and the remaining galaxies are mostly also local, at not much higher redshifts.

A positive clustering signal of galaxies from this sample in both Galactic hemispheres extends up to 40° (Pollo et al. 2013a). As shown in the left panel of Figure 1, angular correlation function $\omega(\theta)$ for flux-limited subsamples displays a clear tendency: bright galaxies have a higher angular clustering amplitude. However, as presented in the right panel of Figure 1, a spatial clustering amplitude $r_0$ of these galaxies, reconstructed from their $\omega(\theta)$ using the Limber inversion, depends only weakly on the limiting FIR flux $S_{90}$; the observed differences in the angular clustering are rather related to different redshift distributions of different flux limited samples - brighter galaxies are typically more nearby.
The spatial correlation length for local AKARI FIR-bright galaxies is \( r_0 \sim 4.5 \, h^{-1} \) Mpc. This value is – with respect to the measurement uncertainties – consistent with \( r_0 \sim 5 \, h^{-1} \) Mpc typical for local optically bright galaxies. A weak dependence of \( r_0 \) of the limiting FIR flux may suggest that the luminosity of a galaxy in FIR is not related simply to the mass of the host dark halo of a galaxy but is affected also by other factors, like star formation rate in the galaxy. In the same time, the measured \( r_0 \) of this local population of FIR-selected star forming galaxies is significantly higher than the correlation lengths measured for local star forming galaxies selected w.g. according to their UV observed flux. It might imply that different tracers of star formation favor different populations of star-forming galaxies (Pollo et al. 2013b).

### 2.2. Star forming galaxies in the AKARI NEP-Deep field

The NEP-Deep survey covers an area of 0.4 square degree, and it was observed by nine NIR and MIR filters of the AKARI Infra-Red Camera (IRC, Onaka et al. 2007). Solarz et al. (2013) measured clustering of 1339 24 \( \mu \)m-selected sources, classified as galaxies using the Support Vector Machines (SVM, Solarz et al. 2012). Photometric redshifts of these galaxies, estimated with the aid of the CIGALE code (Noll et al. 2009; Malek et al. 2013), and calibrated using the spectroscopic follow-up data, cover a wide redshift range from \( z \sim 0 \) to 3.

As shown in the left panel of Figure 2, the redshift distribution of 24 \( \mu \)m-selected NEP galaxies displays three clear peaks. The broad peak centered at \( z \sim 0.6 \) most probably consists of star forming galaxies, including (Ultra)Luminous IR Galaxies (ULIRGs). A second peak at \( z \sim 1.2 \) might be due to 12.7 \( \mu \)m polycyclic aromatic hydrocarbons (PAH) feature and 12.8 \( \mu \)m Ne II emission line entering the selection wavelength. Finally, the most tentative peak at \( z \sim 2.4 \) might consist of Active Galactic Nuclei (AGNs) and/or sources with a strong 8 \( \mu \)m PAH line. As shown in the plot, similar two or three different populations of galaxies at comparable redshifts were also detected by other surveys of 24 \( \mu \)m-selected galaxies.

All these populations seem to be strongly clustered. In the right panel of Figure 2 the spatial clustering length \( r_0 \) of these galaxies is presented as a function of redshift \( z \). Its high values are consistent with other measurements of similar populations found in the literature and suggest that all these three populations, although not directly related, represent strongly clustered galaxies residing in the massive dark matter haloes. In the same time, their IR features imply ongoing active star formation in them. The precise link between these galaxy populations, their star formation histories, and properties of underlying dark matter field, remains to be revealed by future studies.

### 3. SPICA: WHAT WE WANT AND WHAT WE EXPECT

The planned SPICA mission (Nakagawa et al. 2011) should become a next major milestone in the investigations of all types of IR-bright galaxies and their relations to the underlying dark matter field. Thanks to the resolution and sensitivity much superior to any of the previous missions it should allow to go down to the very small scales and solve the question of small scale environment of IR-bright galaxies. As shown e.g. by Malek et al. (2010), among galaxies very bright at FIR we find a much higher percentage of interacting galaxies, or galaxies with disturbed morphologies, bearing traces of interactions, than in the optical catalogs. Malek et al. (2010) have also shown that the reconstruction of a shape of correlation function at small scales allows to expect a significant amount of "invisible" galactic companions, not detected.
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by optical observations and in IR hidden by the source confusion. Careful analysis of small scale environment of dusty star forming galaxies should allow to solve the question about the role of environmental effects in triggering star formation at different cosmic epochs and in different galaxy types and environments.

Another, and probably most important feature of SPICA will be the presence of spectroscopic instruments. All the IR space missions until now have had only limited spectroscopic capabilities. In the same time, spectroscopy is the key to the galaxy studies: on one hand, it allows for much wider and more precise estimation of galaxy properties than any estimators based only on photometric data. On the other hand, IR spectroscopy allows for precise redshift measurement independently on the optical spectroscopy. This becomes particularly important for galaxies for which optical redshift measurement is not possible or very difficult. Among such galaxies we have very dusty galaxies like Dust Obscured Galaxies (DOGs) or (U)LIRGs.

A well known limitation of optical redshift surveys is related to the existence of so-called redshift desert: at $1.4 \leq z \leq 2.5$ typical galaxies do not have strong emission lines falling into optical regime; this property makes the measurement of their redshifts very difficult. Redshift histograms $N(z)$ of deep optical surveys usually show a depletion in this redshift range, which results only from this technical limitation (see, e.g., Le Fèvre et al. 2005, 2013). The successful redshift measurements require spectroscopic observations at wavelengths other than optical. On the other hand, redshift desert may be the cosmic epoch when and where we can find clues to the origin of well developed large scale structure formed by different types of galaxies which we observe at lower redshifts.

IR spectroscopic measurements by SPICA should lead to new cosmological surveys which create a new view of different epochs, and link the star formation history of galaxies to the local properties of dark matter field in which they formed and evolved.

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Studying Galaxy Formation with *SPICA* and Future Extremely Large Telescopes

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**ABSTRACT**

2020’s will be the era of 30–40 m telescope for the ground-based optical and infrared astronomy. These Extremely Large Telescopes (ELTs) have synergy with *SPICA* in studying galaxy formation in the history of the universe. In this presentation, we introduce the planned capabilities of ELTs, focusing on Thirty Meter Telescope (TMT) which Japanese astronomers promote with the international collaboration. We then discuss science cases where TMT and *SPICA* will have complementarity and synergy in the field of galaxy formation and evolution.

1. 2020’S: ERA OF 30–40 M EXTREMELY LARGE TELESCOPES

Following the great success of the 8–10 m class telescopes including Subaru, VLT, Keck, and Gemini, now ground-based astronomy is moving forward to develop the telescopes with significantly larger aperture, 30–40 m. At this moment, three such projects of Extremely Large Telescopes (ELTs) are being proceeded; Thirty Meter Telescope (TMT1), Giant Magellan Telescope (GMT2), and European Extremely Large Telescope (E-ELT3). These facilities are very powerful tools and will produce the results that bring new insights in many fields of astronomy from extrasolar planets to cosmology. In the past several years, National Astronomical Observatory of Japan (NAOJ) and Japanese astronomers have made the efforts, with the international partners including UC, Caltech, Canada, India, and China, to develop the TMT project. In 2013 June, it was announced that the Japanese government fiscal year budget was allotted to fund a portion of the expenses for the preparation and construction of TMT. The science goals of TMT shall be (i) characterizing extrasolar planets, (ii) studying the earliest galaxy formation beyond Cosmic Reionization, (iii) studying Dark Energy and dark matter, and (iv) providing opportunities of the deepest and the highest-resolution optical and NIR observations. Especially in studying galaxy formation, *SPICA* has complementarity and synergy with the ELTs. In Table 1, we briefly summarize the basic properties of TMT early light phase with those of *SPICA*.

<table>
<thead>
<tr>
<th><strong>Table 1.</strong> A brief comparison of TMT and <em>SPICA</em></th>
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<tbody>
<tr>
<td><strong>TMT (early light)</strong></td>
</tr>
<tr>
<td>Wavelength coverage</td>
</tr>
<tr>
<td>Spatial resolution</td>
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<td>Instruments</td>
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<td>Field of View</td>
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<td>spectral resolution</td>
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</tbody>
</table>

1 http://www.tmt.org/
2 http://www.gmto.org/
3 http://www.eso.org/public/teles-instr/e-elt/
YAMADA

Table 2. TMT early light instruments

<table>
<thead>
<tr>
<th>TMT instruments</th>
<th>description</th>
<th>E-ELT</th>
<th>GMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIRAOS</td>
<td>Narrow-field IR AO System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRIS</td>
<td>IR imager and integral field spectrograph</td>
<td>HARMONI</td>
<td>HRCAM</td>
</tr>
<tr>
<td>WFOS-MOBIE</td>
<td>Wide-field multi-object optical spectrograph</td>
<td>OPTIMOS</td>
<td>GMACS</td>
</tr>
<tr>
<td>IRMS</td>
<td>IR multi-slit spectrograph and imager</td>
<td></td>
<td>NIRMOS</td>
</tr>
</tbody>
</table>

Table 3. Line up of the second stage instrument proposals

<table>
<thead>
<tr>
<th>TMT instruments</th>
<th>description</th>
<th>E-ELT</th>
<th>GMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICHI</td>
<td>MIR Camera, High-disperser, and IFU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRMOS/AGE</td>
<td>Multi-IFU, near-DL, near-IR Spectrometer</td>
<td>EAGLE</td>
<td></td>
</tr>
<tr>
<td>HROS</td>
<td>High Resolution Optical Spectrograph</td>
<td>CODECS</td>
<td></td>
</tr>
<tr>
<td>NIRES</td>
<td>NIR High Dispersion Spectrograph</td>
<td>SIMPLE</td>
<td></td>
</tr>
<tr>
<td>SEIT</td>
<td>Second-Earth Imager for TMT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFI</td>
<td>Planet Formation Instrument</td>
<td>EPICS</td>
<td></td>
</tr>
<tr>
<td>MIRRES</td>
<td>Mid-IR Echelle Spectrometer and Imager</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are many fields that SPICA has strong synergy with the TMT and its early light instrument. For example, SPICA can characterize the star-formation properties of the distant galaxies by their dust emission as well as the redshifted fine structure lines, which can be combined with the internal structure of the galaxies resolved with TMT/IRIS. The field of view of SAFARI matches with that of IRMS. It must be useful to obtain NIR spectra of the SAFARI sources very efficiently. We will discuss some interesting cases in the next section.

Table 2 and 3 summarize the planned early-light (i.e., for a few years from the first light) and future instruments for TMT together with the ‘rival’ instruments proposed for E-ELT and GMT. At the early light phase, TMT will be equipped with the three instruments, namely, IRIS (AO assisted integral field unit spectrograph and imager), IRMS (AO assisted multi-objects NIR spectrograph), and MOBIE (optical seeing-limited multi-object spectrograph). While TMT as well as its instruments are built for general purposes, the primary science cases with IRIS are; spectroscopy of the galaxies at high redshift beyond the cosmic reionization, studying the internal physical and kinematical properties of forming galaxies, studying the relativistic phenomena near the Black Hole at the Galactic Center, and characterization of extrasolar planets. The MOBIE science cases include mapping of intergalactic medium by using the background galaxy light, detailed spectroscopy of the ultraviolet emission of the high-redshift star-forming galaxies. IRMS is also a very powerful tool to study the redshifted rest-frame optical and ultraviolet spectra of faint galaxies.

More than a few concepts of the instruments which have the capabilities complementary to the early light instruments have been discussed (Table 3). Of these, MICHI, MIR Camera, High-disperser, and IFU, proposed by the international consortium (see Packham, C., this conference) has the great synergy and complementarity with SPICA as they observe the common range of wavelength (8–20 µm). It is obvious that the advantage of MICHI is the higher spatial resolution thanks to the 30 m TMT aperture, which provides the diffraction limited image of FWHM~1” at 20 µm.

2. TMT AND SPICA: COMPLEMENTARITY AND SYNERGY

We here discuss some relevant science cases for which TMT and SPICA have complementarity and/or strong synergy.

2.1. Galaxies Beyond the Epoch of Cosmic Reionization

Redshift beyond z = 8 is the frontier left for unveiling the earliest galaxy formation in the universe (e.g., Robertson et al. 2010; Ellis et al. 2013). It is one of the primary questions in the modern astronomy to understand when, where, and how the first-generation of stars and galaxies were formed in the early history of the universe, and to reveal how the cosmic reionization occurred. Obviously, the most direct way to answer these questions is to observe the objects in the era and to constrain their physical properties. So far the ultra-violet (UV) emission from the galaxies is observed to z ~ 8 and

...
SPICA and ELTs

Table 4. Expected surface number density per 1 deg$^2$ of high-redshift galaxies brighter than 28AB mag

<table>
<thead>
<tr>
<th>redshift</th>
<th>Luminosity Evolution</th>
<th>Semi-Analytic Model</th>
<th>DMH proportional</th>
</tr>
</thead>
<tbody>
<tr>
<td>8–9</td>
<td>1690.</td>
<td>630.</td>
<td>850.</td>
</tr>
<tr>
<td>11–12</td>
<td>100.</td>
<td>50.</td>
<td>4.</td>
</tr>
<tr>
<td>14–17</td>
<td>0.7</td>
<td>1.</td>
<td>0.003</td>
</tr>
</tbody>
</table>

the Ly$\alpha$ emission from the galaxies at $z = 7.2$ was firmly detected (Shibuya et al. 2012). While it is very likely that the neutral fraction of the universe increases toward $z \sim 6$ and beyond, cosmic reionization may have started before $z \sim 10$ as inferred from the observation of the polarization of Cosmic Microwave Background (CMB) radiation (Komatsu et al. 2009). It is then essential to expand the observations of galaxies beyond $z \sim 8$, toward the redshift well beyond $z = 10$.

TMT will have the great sensitivity compared to the current facilities in spectroscopic observation for a very compact object. In the several hours integration with the spectral resolution of $R = 4000$, the expected signal to noise ratio $> 10$ per resolution element will be achieved for the galaxies $H \sim 27$ mag at the spectral region between the strong OH atmospheric lines (e.g., Wright et al. 2010). We have estimated the expected number density as a function of the apparent magnitude by extrapolating the UV luminosity function at $z = 6–8$ observed with HST toward $z = 15$, and found that the significant number of the objects which are brighter than the TMT sensitivity can be detected by the wide-field deep NIR observations from space; the expected surface number densities of the objects per 1 deg$^2$ area brighter than 28AB magnitude (at the detection wavelength) is summarized in Table 4 (from WISH Mission Proposal Draft, 2012).

If the diffraction limited image at 5 $\mu$m is assumed, SPICA FPC-S direct imaging mode will have the sensitivity limit of $\sim$28 AB magnitude with $\sim$ 10 h integration at 2–4 $\mu$m. While the field of view of SPICA FPC-S, $5' \times 5'$ is not ideal for the purpose, if there is enough amount of time such as in the Parallel Operation or in the Warm Mission Phase, sky coverage of $\sim 0.1$ deg$^2$ (that needs 700 hours, assuming 50 hours per field with four filters) yields O(100) of the galaxies at $z = 8–9$, and O(10) galaxies at $z = 11–12$. In this sense, SPICA can provide the spectroscopic targets to ELTs. Dedicated survey missions such as WISH, however, will produce significantly larger sample for such a purpose.

SPICA, on the other hand, can address the issue by somewhat different approach. First, study of the spectrum of Cosmic Near InfraRed Background (NIR) and its spatial variation is the primary science case for FPC-S. The unidentified spectral shape, especially the broad peak near 1 $\mu$m can be a signature of the earliest star formation in the universe that is not resolved to the individual sources. Spatial variation of the spectra will provide the key information to distinguish such possibilities. Another interesting approach is to observe the H$\alpha$ emission of the objects at $z > 6.5$ by MCS to constrain their Ly$\alpha$/H$\alpha$ ratio. While the 1h sensitivity of MCS is 1–a few $\times 10^{-20}$ W/m$^2$, the H$\alpha$ line flux from a $z = 7$ object of $2 \times 10^{-20}$ W/m$^2$ corresponds to the Star Formation Rate (SFR) of $\sim 100 M_\odot$/yr. While the volume density of such luminous object is likely to be as small as $10^{-7}$ Mpc$^{-3}$, preselection by other facilities such as Subaru HSC, WISH, or sub-mm survey telescope is possible. By observing the Ly$\alpha$/H$\alpha$ ratio of more than a few objects will constrain the neutral fraction of the hydrogen at such high redshift. Indeed, an object with SFR of 2900 $M_\odot$/yr at $z = 6.34$ was discovered by the HerMES survey with the Herschel telescope and the follow-up observations so far.

2.2. Physical Process in Hierarchical Galaxy Formation

SPICA and ELTs should have a great synergy in studying the physical properties of the galaxies in their formation phase. SPICA can characterize the star-formation and AGN activity by their dust emission, and against the dust obscuration. Fine structure lines from the H II regions and PDR, PAH emission, and dust thermal continuum emissions are powerful tools to make diagnostics of the high-redshift galaxies, especially the massive galaxies in their early stages of formation with dusty environment. By observing the ratio of the appropriate set of the fine structure lines, one can constrain the hardness of the ionizing radiation (presence of AGN, starburst age, upper mass limit of IMF, metallicity), ionization parameters, electron density. This even allows observing the properties of episodic star formation with relatively short time scale, which enables to draw the whole demography of the galaxy formation phenomena. The expected observed flux of the most ubiquitous [Ne II] and [Ne III] lines from a ULIRG with $L(\text{IR}) \sim 10^{12} L_\odot$ is $f([\text{Ne II}] + [\text{Ne III}]) \sim 8 \times 10^{-19}$ W/m$^2$, $1 \times 10^{-19}$ W/m$^2$, $5 \times 10^{-20}$ W/m$^2$ for the object at $z = 1$, $z = 2$, and $z = 3$, respectively. The expected sensitivity of SPICA SAFARI is $\sim 1 \times 10^{-19}$ W/m$^2$ (1h, 5$\sigma$), we may obtain the ratio of the lines from such a ULIRG at $z \sim 1$, and at higher redshift for more luminous objects.

On the other hand, TMT reveals the internal kinematics, structures, resolved properties of the ionized gas (traced by the lines at shorter wavelength), and the stellar population of the high-redshift galaxies. In this sense, TMT and SPICA are very much complementary and have strong synergy. By having both the capabilities, we can study the wide range of the phenomena during galaxy formation to understand their physical processes.

As for an example, we introduce the multiple merging galaxies at high redshift as an ideal target for the combined observations with SPICA and TMTs. Figure 1 shows the Subaru MOIRCS $K$-band image of a sub-mm source at $z = 3.1$. Within the error circle, there are six very red objects, which satisfy the color criteria of Distant Red Galaxies ($J - K > 1.4$) or Hyper Extremely Red Galaxies ($J - K > 2.1$). The number density of the DRGs and HEROs is extremely high,
Figure 1. Examples of multiple merging galaxies from Uchimoto et al. (2012). A sub-mm source SSA22-AZTEC-14 is shown in the $K$-band image. More than a few very red $K$-band detected galaxies (DRGs and HEROs) are detected in the error circle for the sub-mm source. The number density of the DRGs and HEROs is extremely high, suggesting that they are physically associated with each other at the same redshift. Some of them are spectroscopically confirmed to be at $z = 3.1$. They are likely to be the mixture of dusty star-forming galaxies and post-starburst quiescent galaxies. SPICA SAFARI’s extremely deep spectroscopy may simultaneously obtain the spectra of active star-forming galaxies and the diagnostics from the fine structure lines enable us to reveal the presence of AGN or their starburst ages. On the other hand, TMT IRIS or IRMS spectroscopy provides the resolved kinematic information as well as the stellar population. Combining the data obtained by SPICA and TMT, we may unveil the whole nature of the very massive galaxies in their early formation phase.

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A Search for the Light of First Stars with SPICA

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4Seoul National University, Korea

ABSTRACT

FPC-S is a back up of the fine guidance camera, but is usable for the scientific observation. FPC-S is optimized to observe the spectrum and fluctuation of near-infrared background. One of main scientific targets is to search for the light of first stars of the universe and to delineate the star formation history and structure evolution during the dark age of the universe. The expected performance and its scientific significance is presented.

1. INTRODUCTION

First star of the universe is crucially important to understand the evolution of the universe after the recombination era. It has been believed UV radiation of first stars re-ionized the universe. Detection of individual first star is extremely difficult, however, light of first star could be detected as a part of near-infrared extragalactic background light. Recent observations indicate there exists significant excess sky brightness over the known background that has a blue stellar spectrum (Matsumoto et al. 2005). Large excess fluctuation of sky brightness was also detected at large angular scale (Matsumoto et al. 2011; Kashlinsky et al. 2005, 2012). Origin of excess brightness and fluctuation could be attributed to the first stars, however, observed level is too high to be explained by the standard theory based on high-z galaxies (Cooray et al. 2012). To solve the controversial situation, more observational evidences are needed, and FPC-S on SPICA is an ultimate instrument for the observation of near-infrared background. Compared to JWST, FPC has much higher sensitivity owing to a large throughput and a capability of efficient low resolution spectroscopy. FPC-S will provide firm observational evidences on the near-infrared extragalactic background light and delineate the formation and evolution of first stars.

2. FPC-S

FPC-S is a camera with refractive optics which covers wavelength region from 0.7 μm to 5.2 μm. Filter wheel is provided in front of the detector array. One characteristic feature of FPC-S is the observation with linear variable filters (LVF). LVF is a square shaped and transmitting wavelength linearly changes along one direction. Spectroscopic observation with LVF needs scanning mode for SPICA telescope but makes low resolution spectroscopy for extended source very efficient. Specification of FPC-S is summarized in Table 1. 5σ detection limit for R<5 with 100sec integration is ~25.5 AB magnitude. Details of the FPC is presented in this proceedings by D-H Lee.

3. PERFORMANCE OF FPC-S

3.1. Observation of the spectrum of the sky

Figure 1 shows the summary of observations of extra-galactic background light (EBL). Recent observations at optical region show fairly low level EBL (Matsuoka et al. 2011; Mattila et al. 2011) comparable to integrated light of galaxies (solid line), while COBE and IRTS results indicate fairly high EBL (Matsumoto et al. 2005).

Spectrum of the sky can be observed with LVF by pointed observation. In this observation mode, each pixel observes different field on the sky with a different wavelength. Since fluctuation of the sky is fairly low, co-adding of the pixels

<table>
<thead>
<tr>
<th>Detector</th>
<th>InSb 1k×1k array</th>
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</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>5 arcmin</td>
</tr>
<tr>
<td>Pixel scale</td>
<td>0.3 arcsec</td>
</tr>
<tr>
<td>Wide band filter: R = 5</td>
<td>J, H, K, L and M (tentative)</td>
</tr>
<tr>
<td>LVF: R = 20</td>
<td>(0.7–1.4 μm) (1.4–2.8 μm) (2.6–5.2 μm)</td>
</tr>
</tbody>
</table>
with same wavelength band after removing point sources makes significant improvement of signal to noise ration possible. Dotted line in Figure 1 indicates the detection limit for 100 sec integration with LVF.

One of the key issue to observe EBL is how to subtract foreground emission components, which are zodiacal light (ZL), integrated star light (ISL) and diffuse galactic light (DGL).

As for the ZL, we propose to perform LVF observations at different ecliptic latitudes and at different epoch of the year. By making use of annual time variation of ZL, we will be able to construct the much more reliable model of the zodiacal light than that of COBE/DIRBE (Kelsall et al. 1998), since ISL is negligible for FPC-S owing to high sensitivity of FPC-S.

Another foreground emission source, DGL can also be detected by taking systematic correlation study with far infrared emission. Coordinated observation with SAFARI is crucially important for the study of DGL.

Owing to precise measurement of the foreground emission, accurate and reliable spectrum of EBL will be obtained. Furthermore, it could be possible to detect features of redshifted Lyα and other lines/bands.

3.2. Observation of the fluctuation of the sky

Fluctuation of the sky provides another important observational evidence which is independent from foreground emission, since ZL is fairly isotropic (Pyo et al. 2012). Figure 2 shows the result of AKARI observation towards NEP at 2.4 μm (Matsumoto et al. 2011) and the preliminary result of AKARI NEP wide field. Excess fluctuation is clearly detected at the angle larger than 100 arcsec which extends to degree scale. Spitzer detected a similar fluctuation at 3.6 and 4.1 μm (Kashlinsky et al. 2005, 2012).
with same wavelength band after removing point sources makes significant improvement of signal to noise ratio possible. Thin solid line indicate the integrated light of galaxies. By making use of annual time variation of ZL, we will be able to construct the much more reliable model of the zodiacal integrated star light (ISL) and diffuse galactic light (DGL). Furthermore, it could be possible to detect features of redshifted Ly\textsubscript{3.2}. Detection, since ZL is fairly isotropic (Pyo et al. 2012). Figure 2 shows the result of As for the ZL, we propose to perform LVF observations at different ecliptic latitudes and at different epoch of the year. Owing to precise measurement of the foreground emission, accurate and reliable spectrum of EBL will be obtained. Another foreground emission source, DGL can also be detected by taking systematic correlation study with far infrared symbols/DIRBE (Kelsall et al. 1998), since ISL is negligible for FPC-S owing to high sensitivity of FPC-S. Figure 2 shows excess fluctuation can be detected at the angular scale depending on the redshift, correlation study between wavelength bands could delineate the evolution of the large scale structure. Observation for 5 arcmin square with 26 mag detection limit requires 3.3 hours plus maneuvering time.

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**SPICA as a Probe of Cosmic Reionization**

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**ABSTRACT**

Current data indicate that the reionization of the Universe was complete by redshift \(z \approx 6\)–7, and while the sources responsible for this process have yet to be identified, star-forming galaxies are often considered the most likely candidates. However, the contribution from \(z \gtrsim 6\) galaxies to cosmic reionization critically depends on the fraction of ionizing (Lyman continuum, LyC) photons escaping from these objects and into the intergalactic medium. At \(z \lesssim 4\), the escaping LyC flux can be measured directly, but the opacity of the neutral intergalactic medium precludes such measurements at higher redshifts. In a recent paper, we argue that since the LyC escape fraction regulates the contribution of nebular emission to the rest-frame optical/UV spectra of galaxies, the *James Webb Space Telescope* should be able to indirectly assess the LyC escape fraction for galaxies at \(z \approx 6\)–9. *JWST* can, on the other hand, not constrain the fraction of LyC photons directly absorbed by dust, and this is where *SPICA* comes in. The dust continuum emission from gravitationally lensed LyC-leakers at \(z \approx 6\) may in principle be detectable with *SPICA*, thereby constraining the level of LyC extinction in these objects.

1. **INTRODUCTION**

Several independent lines of evidence indicate that cosmic reionization was complete by \(z \approx 6\)–7 (e.g. Fan et al. 2006; Zahn et al. 2012), and while star-forming galaxies at \(z \gtrsim 6\) may well be numerous enough to produce the required LyC photons (e.g. Finkelstein et al. 2012; Alvarez et al. 2012; Mitra et al. 2013; Robertson et al. 2013), this scenario requires that LyC photons can escape from these galaxies and into the intergalactic medium (IGM). LyC leakage from galaxies can be measured directly at \(z \lesssim 4\), but the opacity of the increasingly neutral IGM prevents such measurements at higher redshifts (Inoue & Iwata 2008). In a recent paper (Zackrisson et al. 2013), we argue that since the LyC escape fraction \(f_{\text{esc}}\) regulates the impact of nebular emission on the spectra of galaxies, it will nonetheless be possible to indirectly probe LyC leakage well into the reionization epoch. Spectroscopy with the James Webb Space Telescope (*JWST*, scheduled for launch in 2018) should be able to provide a rough handle on \(f_{\text{esc}}\) for galaxies at \(z \approx 6\)–9, but since *JWST* cannot probe dust emission from such objects, there will be lingering uncertainties regarding the fraction of LyC flux lost due to dust absorption. Here, we explain how *SPICA* can contribute to this field by measuring the dust continuum emission from gravitationally lensed galaxies at \(z \approx 6\).

2. **DUST EMISSION AND THE ROLE OF SPICA**

Comparisons between ultraviolet, optical and far-infrared (FIR) star-formation indicators suggest that a substantial fraction of the LyC photons produced in local star-forming galaxies are directly absorbed by dust (Inoue et al. 2001; Hirashita et al. 2003). If this effect could be quantified also for reionization-epoch galaxies, this would greatly simplify the task of pinning down the LyC escape fractions of such objects (Zackrisson et al. 2013). Since the dust heated by LyC photons re-emits the absorbed energy at rest-frame FIR wavelengths, this requires some handle on the FIR luminosities of galaxies at \(z \gtrsim 6\).

The dust emission of \(z \approx 6\)–9 galaxies is predicted to peak at a few hundred \(\mu\)m (Takeuchi et al. 2005), and can in principle be probed with the Atacama Large Millimeter/sub-millimeter Array (ALMA), or upcoming telescopes like the *Space Infrared Telescope for Cosmology and Astrophysics (SPICA)* and the Cerro Chajnantor Atacama Telescope (CCAT). However, the low intrinsic luminosities of these galaxies make this an extremely challenging task. Gravitational lensing by foreground galaxy clusters can boost the fluxes of galaxies in the reionization epoch by a factor of up to \(\mu \approx 100\) (e.g. Zackrisson et al. 2012; Bradley et al. 2013), and the best targets for this endeavour are therefore likely to lie in strongly lensed fields.

In Figure 1, we plot the predicted dust continuum bump for a SFR = 10 M\(_{\odot}\) yr\(^{-1}\) dwarf galaxy (Takeuchi et al. 2005), superposed on an *Yggdrasil* (Zackrisson et al. 2011) model for the stellar and nebular (line and continuum) components of the spectrum. The object is assumed to be at \(z = 6\) and to be gravitationally magnified by a factor of \(\mu = 100\). At this redshift, i.e. at the end of the reionization epoch, the peak of the dust continuum bump falls right between the *SPICA*/SAFARI and ALMA detection windows, which makes estimates of the total luminosity in the bump very tricky. ALMA can in principle detect the low-energy (high-wavelength) part of the bump, but this requires integration times of more than 10 hours. *SPICA*/SAFARI is better suited to measure the high-energy (low-wavelength) part of the bump, but is
Figure 1. The dust emission peak of a gravitationally lensed galaxy at $z = 6$ (magnification $\mu = 100$). The dust bump predicted by Takeuchi et al. (2005) for a $z = 6$ dwarf galaxy with star formation rate SFR = 10 M$_\odot$ yr$^{-1}$ has here been superposed on a matching Yggdrasil stellar + nebular galaxy spectrum (Zackrisson et al. 2011). The SPICA confusion limit and the ALMA 1 h and 10 h detection limits are marked by dashed lines. In this case, detection of the high-energy part of dust emission bump requires photometry with SPICA at flux levels a factor of several below the confusion limit (the lower, thick dashed SPICA line marks the threshold reached a factor of 7 below the formal confusion limit). This may be possible by taking advantage of the deep, high-resolution observations at both shorter (JWST) and longer (ALMA) wavelengths. ALMA may in principle detect the low-energy part of the dust bump, but this would require integration times of more than 10 h.

confusion limited at these wavelengths. SAFARI is able to reach its $\approx$50–160 $\mu$m confusion limits in two minutes or less, but to reach the dust continuum, one needs to push the detection limit a factor of several below this limit. We suggest that this may be accomplished through the use of auxiliary, high-resolution data from other wavelength bands (e.g. obtained with JWST or ALMA) to subtract off the estimated flux contribution from nearby objects in the SPICA bands. However, detailed simulations are required to determine the exact limits of this technique. While CCAT may be able to observe at wavelengths down to 200 $\mu$m, its sensitivity is insufficient to reach the peak of the dust continuum bump for $z = 6$ galaxies of this type, as this would require integration times of much more than 100 hours.

3. SUMMARY

An important step in the quest to identify the sources responsible for the reionization of the Universe is to determine the typical LyC escape fractions of galaxies at $z \gtrsim 6$. Since the LyC escape fraction regulates the ratio of nebular emission to direct star light in the rest-frame ultraviolet/optical part of the spectrum, spectroscopy with JWST should allow LyC escape fractions of individual galaxies at $z \approx 6–9$ to be constrained. However, JWST by itself cannot assess the fraction of LyC photons directly absorbed by dust. At $z \approx 6$, this effect may instead be investigated through SPICA observations of the brightest, gravitationally lensed galaxies. Observations of this type are, however, extremely challenging, and require photometry at fluxes a factor of several below the formal SPICA confusion limits at 50–160 $\mu$m. However, this can possibly be accomplished through the use of auxiliary, high-resolution observations from other wavelength bands.

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Reionization with SPICA

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Probing the Stellar Contents of Star-Forming Galaxies at Re-Ionisation Era

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ABSTRACT

We propose a narrowband imaging survey of star-forming galaxies at re-ionisation era. The survey will exploit the wide-field imaging capability of SPICA/MCS by using narrowband filter to detect Hα emission from the redshift 7 ≤ z ≤ 10. We estimated the feasibility of this survey, showing that the number of detectable sources highly depends on the IMF of the stellar population. Since the age constraints are fairly strong at such high redshifts, and extremely young star-forming galaxies are presumably less dusty, the survey should give the first direct and meaningful constraints on the IMF of population III (popIII) star formation.

1. BACKGROUND: DIFFICULTIES IN DERIVING THE STAR-FORMATION HISTORY WITH UV

Recent surveys in optical/NIR wavelengths have revealed star-formation history at high redshifts, now approaching to reionisation era (up to z ∼ 10; e.g., Bouwens et al. 2011, 2013; Ellis et al. 2013; Oesch et al. 2013). The star-formation history of the universe revealed with these studies provides us with general understanding of galaxy-formation history up to z ∼ 10, and thus reionisation history of the universe. Also, studies of Lyα emission from high-z galaxies are reaching to redshifts up to z ∼ 7.5 (Schenker et al. 2012; Ono et al. 2012; Shibuya et al. 2012; Finkelstein et al. 2013). Combined with the UV continuum, the information from the Lyα provides with the neutral fraction of IGM in the high-z universe, leading to detailed measurements of the reionisation history, and search for the photon suppliers for the reionisation. Such studies should be further expanded to higher redshifts in the JWST era.

However, these studies are based on the rest-frame UV observations, and the star-formation rates (SFRs) are derived from their UV luminosities. Especially for the survey observations, JWST can only probe the rest-UV regime. The future large ground-based telescopes such as TMT or E-ELT cannot probe the rest-frame optical to NIR wavelengths either. In order to probe the correct star-formation history at such a high redshifts up to z ∼ 10, we definitely need information of MIR. For instance, the UV continuum is the most commonly used to derive the SFRs. However, the conversion from the UV luminosity to the SFR usually assumes Salpeter’s IMF, solar metallicity, and constant star formation over > 107 yrs (Madau et al. 1998; Kennicutt 1998). These kinds of assumption should not be valid for reionisation era, in which the age of the universe is only several 106 yrs.

Even in the low redshifts up to z ∼ 2, the SFRs derived from the UV luminosities seem to be different from those derived from the Hα luminosities. Figure 1 shows the difference of the SFRs derived from the UV and Hα luminosities in term of the luminosity functions (LFs). The axes on the top and the bottom in this plot are scaled so as to match the SFRs derived from the both quantities (local calibrations; see Figure 2). The difference between the UV- and Hα-based SFRs increases with increasing redshift. Although the dust attenuation is not corrected for these LFs, this tendency should hold at least qualitatively. Observing UV-selected galaxies may thus lead to a significant underestimate of the galaxy number density at high redshifts.

2. THE SPICA Hα SURVEY

2.1. Basic Ideas

SPICA/MCS has a wide-field imaging capability, 5′ × 5′, and the survey speed exceeds that of JWST in almost the whole wavelength coverage. Here we propose the narrow-band imaging survey of Hα emitters at z ≥ 7 to fully exploit the high survey efficiency. This will construct a unique sample of Hα-selected star-formation galaxies, which cannot be surveyed with NIR imaging. Assuming the resolving power of the narrowband R ∼ 100, we estimated the line sensitivity (5σ, 1 hr) to be ∼ 1 × 10−17 erg s−1. We here show the estimates for the z = 7.0 and z = 10.5 cases for example. Considering the limitation of the available observing time, we assumed the survey coverage to be an order of ∼deg2 observed with ∼102 pointings.
Since the $H\alpha$ line strength depends on the age, the metallicity, and the IMF, the detectability of the $H\alpha$ emission strongly reflects these fundamental properties related to the star-formation history. First we show the simplest estimate of the detectability based on observational constraints from the UV LFs available in the literatures. Figure 2 shows the expected number of $H\alpha$ emitters as a function of the detection limit. The simplest estimates from currently available observations suggests that the number of sources above the detection limit is almost zero: $\sim 10^{-10}$–$10^{-8}$ sources per FoV for $z = 10.5$, and $\sim 10^{-5}$–$10^{-4}$ sources per FoV for $z = 7.0$ if we use the UV LFs from the literatures.

2.2. Dependence of the Number Density of $H\alpha$ Emitters

The calibration of the SFRs based on the UV continuum, however, may not be a good probe to predict the $H\alpha$ luminosities (i.e., the detectability) of star-forming galaxies at very high redshifts. If we use the $z \sim 2$ $H\alpha$ LFs scaled with the cosmic SFRD, the expected number raises to order of $10^{-2}$ per FoV for $z = 10.5$, and $10^{-1}$ for $z = 7.0$. Although the detectability

Figure 1. Comparison of the two SFR indicators at four redshift bins, $z = 0.4, 0.8, 1.5, \text{ and } 2.2$. For each panel, the grey curve shows the $H\alpha$ luminosity function (LF), and the vertical grey dotted line shows the $L^*$ at the redshift noted on the upper-right corner (Sobral et al. 2013). The black curve and vertical dotted line show the UV LF and $M^*$ at the corresponding redshift (Arnouts et al. 2005). The top and bottom axes are scaled so as to match the SFRs derived from the both quantities.

Figure 2. Expected number of $H\alpha$ emitters at $z = 7.0$ and $z = 10.5$ as a function of the $H\alpha$ luminosity (bottom axes) and UV luminosity (top axes). The $H\alpha$ fluxes at $z = 7.0$ and 10.5 are shown on the two axes near the bottom of each panel. The $SPICA/MCS$ detection limit at each redshift is shown with the vertical dotted line. (Left) Based on $z \sim 2$ observations. The grey curves are based on the $H\alpha$ LF at $z \approx 2$ from Sobral et al. (2013), and the black curves are based on the UV LF at $z \approx 2$ from Arnouts et al. (2005). The $L^*_{H\alpha}$ and the $M^*_{UV}$ are shown with the vertical dashed lines. The curves marked “scaled” show the LFs scaled with the cosmic star-formation rate density (SFRD) at $z \sim 10$, assuming that the SFRD is lower than $z \sim 2$ by a factor of $\sim 10$ as suggested by Hopkins & Beacom (2006). (Right) Based on $z \sim 2$ and $z \sim 8$ observations. The symbols are same as the left panel. The $H\alpha$ LF is taken from Hayes et al. (2010), showing almost the same results as the left panel, and the UV LF is taken from the $z \sim 8$ result of Bouwens et al. (2011).
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might be highly overestimated in the case of using H\(\alpha\) LF at \(z \sim 2\), there are some factors causing the significant underestimate of the number of H\(\alpha\) emitters when we use the UV LFs.

Inoue et al. (2011) suggest that low metallicity conditions give larger number of ionising photons, leading to larger H\(\alpha\) luminosities at the given SFRs. The zero-metallicity case gives a factor of \(\sim 3\) larger H\(\alpha\) luminosity, and the LFs shifts rightward on the Figure 2. This gives the number of H\(\alpha\) sources detected here to be \(\sim 10^{-4}\) for \(z = 10.5\), and \(\sim 10^{-2}\) for \(z = 7.0\), if galaxies at these epochs are predominantly metal free. Although the number is still very small, the change is quite significant since we are looking at the very bright end of the LF.

Further significant boost of H\(\alpha\) luminosity comes from the stellar IMF. For example, Schaerer (2003) suggests that some cases of IMF with large stellar masses (50–500 \(M_\odot\)) give an H\(\alpha\) luminosity higher by a factor of \(\sim 10\). This corresponds to \(\sim 10^{-1}(10^9)\) sources per FoV for \(z = 10.5(7.0)\). If the galaxies at these epochs are dominated by those with IMF that prefer such large stellar masses, \(\sim 10^1\) of H\(\alpha\) emitters should be detected in total even at \(z \sim 10\), and \(\sim 10^2\) or more at \(z \sim 7\). The LF of the H\(\alpha\) emitters at such high redshifts should thus put meaningful constraint on the stellar IMFs of very early-phase star formation like popIII.

3. IMPORTANCE OF THE H\(\alpha\) SURVEY AT \(Z > 7\)

The number density (i.e., the LF) of H\(\alpha\) emitters thus strongly reflects the properties of star-forming galaxies that determines the correct star-formation history of the universe, especially the IMF. The popIII IMF is totally unknown, and the uncertainties to determine the SFRs or other properties should be much severer at higher redshifts.

Since the UV continuum may not trace correctly the star-formation activities especially at higher redshifts (e.g., Wilkins et al. 2012), studies of alternative SFR indicators should be quite essential. The H\(\alpha\) emission has been extensively used, and is the most well-calibrated SFR indicator. The SFR of galaxies in reionisation era has been studied almost only with the rest-frame UV lights, so that using H\(\alpha\) is quite essential.

Another advantage is that the age constraints are quite strong at such high redshifts. The age of the universe is \(\sim 0.7\) (0.4) Gyr at \(z = 7\) (10.5). Considering that the major epoch of popIII star formation is \(\sim 20\), the typical duration of star formation activity is up to \(\sim 200–500\) Myr. The short duration also implies that the amount of dust is presumably small. These facts help us to break the degeneracy between the IMF and the stellar age, and also dust contents. The H\(\alpha\) survey at \(z \sim 7–10\) should give the first meaningful constraints on the popIII IMF from direct observations.

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Studies of (Ultra) Infra-Red Galaxies in the Far-Infrared Surveys: from
AKARI to SPICA

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ABSTRACT

We present the results of the analysis of multiwavelength Spectral Energy Distributions (SEDs) of Far-Infrared (FIR) galaxies detected in the AKARI Deep Field-South (ADF-S) Survey. FIR data in connection with optical and UV measurements enable us to fit SED models and investigate physical properties of detected sources. We focus on 186 ADF-S galaxies with the best SED fits. More than 25% of sources we identified as (Ultra) Luminous Infra-Red Galaxies. We present the average properties of ULIRGs and other galaxies found in the ADF-S. We discuss how the future SPICA data will help to understand the history of formation and evolution of (U)LIRGs.

1. INTRODUCTION

Nowadays the multiwavelength sky surveys play a fundamental role in astronomy. The resources of collected data are constantly expanding, providing discoveries of new types of objects or more detailed studies of previously known types of sources. Recent advances in satellite observations extended the studies of galaxies evolution by measuring their radiation at long wavelengths. Infrared (IR) observations allow for observations of dust heated by newly born stars, and therefore, measurements of warm dust component — an indicator of star formation (SF) activity. Observations in the ultraviolet (UV) and optical ranges alone cannot provide a detailed description of the SF processes in galaxies — the dust component should also be taken into account. Only combined UV, optical, and IR data can give the full information about the SF history and rate — a key observable for understanding the physical processes in galaxy formation and evolution. Additionally, the ratio between the UV and far-IR (FIR) emission sheds light on evolution of Ultra Luminous Infrared Galaxies (ULIRGs).

Satellite IR observations in wide fields allow us to analyze the SF history from a global, statistical point of view, and to test existing physical models of galaxy evolution. AKARI (Murakami et al. 2007), the Japanese satellite dedicated to IR observations, provided the second-generation, after IRAS (Neugebauer et al. 1984), all sky IR catalog. This catalogue, as well as two deep surveys centered at the North (NEP) and South (ADF-S) Ecliptic Poles (e.g., Wada et al. 2008; Takagi et al. 2012; Matsuura et al. 2011), vastly improved our knowledge of IR astronomical sources. Future observations provided by SPICA (Nakagawa et al. 2009), ranging from mid- to far-IR, will give us even a more precise insight into the basic question of how galaxies were formed and evolved.

2. DATA

The sample used in our analysis is drawn from AKARI ADF-S presented by Malek et al. (2010). For the catalog based on 90 µm band 545 optical counterparts were found in public catalogues (NED, SIMBAD, IRSA). The sample in total consists of the 545 ADF-S sources from the so-called 6σ catalog (S60µm > 0.0301 Jy, which corresponds to the 6σ detection level). Additional measurements, mostly from WISE (Wright et al. 2010) and GALEX (Martin et al. 2005), and further data from public databases were used in the present analysis (see also Malek et al. 2013b).

Combining data from Malek et al. (2010) and Sedgwick et al. (2011) we found spectroscopic redshifts zspec for 173 galaxies from our sample in the range 0 < zspec < 0.25 (the range used by Sedgwick et al. 2011). Median redshift of this sub-sample is 0.058.

Our main aim was to build a galaxy sample with high quality fluxes from the UV to the FIR to be used for Spectral Energy Distribution (SED) fitting and studying of physical parameters of the ADF-S sample. Consequently, we selected galaxies with the highest quality photometry and at least six measurements covering all the galaxy spectra from FIR to UV. Each galaxy from the sample used for the SED fitting has at least one measurement in FIR, 95% of them have WISE MIR measurements, 85% are detected in all 2MASS bands, all of them have the APM (Maddox et al. 1990) measurement, and a half of our sample was detected by GALEX in the UV. For galaxies without known zspec we estimated photometric redshifts zphot. We used two codes: Le PHARE (Arnouts et al. 1999; Ilbert et al. 2006), widely used for zphot estimation, and CIGALE (Noll et al. 2009) — SED-fitting program, originally not developed as a tool for estimation of zphot but, as
we have shown, providing correct photometric redshifts especially in case of FIR-bright galaxies (Małek et al. 2013a). We performed a series of tests using both codes for a sample of ADF-S galaxies with known $z_{\text{spec}}$. Both codes gave similar results, but CIGALE allowed to obtain $z_{\text{phot}}$ more often, especially for galaxies with more FIR and MIR data, and lack of UV and few optical measurements.

3. SED FITTING AND AVERAGE SEDS

We used CIGALE to estimate physical properties of ADF-S galaxies. We checked the reliability of obtained parameters using mock catalogs (Małek et al. 2013b). CIGALE computes model spectra, based on a set of input parameters, and calculates fluxes in the observed filters. It determines the best-fit model for each galaxy using $\chi^2$ minimization. Based on the $\chi^2$ distribution and visual inspection of obtained fitted spectra, we restrict the final sample to the SEDs with $\chi^2$ value lower than four. As a result, our final sample consists 73 galaxies with known $z_{\text{spec}}$ and 113 galaxies with estimated $z_{\text{phot}}$, in total 186 sources.

As one of the main points of our analysis, we created average SEDs separately for (U)LIRGs, and for normal, star-forming galaxies in our ADF-S sample. We have normalized obtained models at 90 $\mu$m, and divided them in three groups: ULIRGs, LIRGs, and the remaining galaxies. These groups consist of 17, 31, and 138 sources, respectively. To select (U)LIRGs we applied a Sanders & Mirabel (1996) criterion on the total IR luminosity. In the next step we calculated an average SED for each of these three sub-samples. The result is shown in Figure 1. We have found that (U)LIRGs contain cooler dust than the remaining galaxies of our sample, and that their maximum of dust emission is shifted towards longer wavelengths (it is located at 1.49$\pm$0.6, 1.25$\pm$0.63, and 0.93$\pm$0.35$\times$10$^6$ Å for ULIRGs, LIRGs, and the remaining ADF-S galaxies, respectively). The difference in $z_{\lambda_{\text{max}}}$ is not very strong given the uncertainties of the measurement, however, according to Symeonidis et al. (2011) and other previous studies, measured dust temperature of ULIRGs is rather related to the sample selection function, than to their general physical properties. Our results confirm this claim.

We suggest that more detailed studies of ULIRGs, with more numerous samples and wider spectral coverage in the MIR and FIR, are needed to solve the problem of their dust temperatures and properties. SPICA can provide an important break in these studies.

4. SUMMARY: AKARI VS SPICA

The presented analysis of ADF-S (U)LIRG sample allows us to expect that SPICA mission will provide data crucial to explain the physical properties of this rare class of galaxies. The SPICA mission (Sturm 2009) will provide a much better coverage in the FIR part of ULIRGs spectra with a much better resolution, as well as direct spectroscopic measurements in the FIR. It will allow for excellent SED fitting, thanks to continuous observations from NIR to FIR, and for much more precise measurement of the dust temperatures and other properties of (U)LIRGs in different cosmic epochs. The SPICA coherent data and unprecedented sensitivity of SPICA instruments should allow us to minimize error bars on the fitted spectra, and to improve significantly the models used in all the fitting procedures, thanks to precise spectroscopic measurements. In the future, we plan to perform tests of SED fitting using different models of the dust spectra (e.g. Dale & Helou 2002; Siebenmorgen & Krügel 2007; Chary & Elbaz 2001; Casey 2012), and, if needed, to develop new models.
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better describing properties of ULIRGs. These new results will help to study properties and evolution of IR-bright galaxies of different types.

This work is based on observations with AKARI, a JAXA project with the participation of ESA. This research made use of the SIMBAD database, operated at CDS, Strasbourg, France, the NASA/IPAC Extragalactic Database (NED) and the NASA/IPAC Infrared Science Archive, both operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. KM and AP were financed by the research grants of the Polish National Science Center N N203 512938 and N. 2012/07/B/ST9/04425. KM has been supported from the Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellowship for Foreign Researchers, P11802. MM acknowledges support from NASA grants NNX08AU59G and NNX09AM45G for analysis of GALEX data in the AKARI Deep Fields. TTT has been supported by the Grant-in-Aid for the Scientific Research Fund (23340046, and 24111707) and for the Global COE Program Request for Fundamental Principles in the Universe: from Particles to the Solar System and the Cosmos, Strategic Young Researches Overseas Visits Program for Accelerating Brain Circulation commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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Distribution of IR and Submillimeter Line Emitting Galaxies in Cosmological Simulations

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ABSTRACT

We present a forecast for detection of high-redshift star-forming galaxies using SPICA-SAFARI and ALMA Band 10–11. We use the outputs of large cosmological simulations of galaxy formation to calculate the fluxes of infrared and far-infrared emission lines ([O III]88.3 µm, [O III] 51.8 µm, [N III]57.2 µm and [C II]158 µm). To this end, we assume empirical relations between the line fluxes and the star formation rate or far-infrared luminosities. We consider a large survey programme with a 2' × 2' field-of-view and the limiting flux densities of > 21 and > 32 µJy (5α). Our models predicts that there are 604±59 galaxies to be detected by such a survey. The number of [C II] emitters with \( L_{\text{[C II]}} < 10^8 L_\odot \) is expected to be 543 ±52.

1. INTRODUCTION

The chemical evolution and star-formation activities of high-redshift galaxies will be studied by high-resolution mm/submm/IR observations by SPICA and ALMA. Infrared fine structure lines such as [O III]51.8 µm, [N III]57.21 µm and [O III]88.3 µm can be used as metallicity diagnostics (Nagao et al. 2011), whereas [C II]158 µm line is thought to be an ideal tracer of star-formation activity. The particular emission line can also constrain the metallicity of a high redshift galaxy in combination with [N II] 205 µm (Nagao et al. 2012).

In order to address the feasibility of observations of high-redshift galaxies, we use the results of a large cosmological hydrodynamics simulation of galaxy formation. Throughout this paper we adopt the Λ-CDM cosmology with the matter density \( \Omega_M = 0.27 \), the cosmological constant \( \Omega_\Lambda = 0.73 \), the Hubble constant \( h = 0.7 \) in units of \( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \), the baryon density \( \Omega_B s = 0.046 \).

2. METHOD

We use one of the cosmological simulations in Shimizu et al. (2012). Briefly, the simulation employs \( 2 \times 640^3 \) particles in a comoving volume of \( 100 \text{ h}^{-1} \text{ Mpc} \) on a side. The mass of a dark matter particle is \( 2.41 \times 10^7 \text{ h}^{-1} M_\odot \), and of a gas particle \( 4.95 \times 10^4 \text{ h}^{-1} M_\odot \). They implement relevant physical processes such as star formation, supernovae and galactic wind feedback and chemical enrichment. We calculate the SEDs of individual galaxies using the population synthesis code PEGASE2. Then, wavelength-dependent dust absorption is calculated such that the resulting UV luminosity function at high redshifts matches to the result of recent observations. In order to calculate FIR luminosity \( L_{\text{FIR}} \), we assume that the UV photons absorbed by thermal dust grains are re-emitted in FIR. Namely, we set \( L_{\text{FIR}} \) to be equal to the total energy of UV photons absorbed:

\[
L_{\text{FIR}} = \int \left[ L^{\text{int}}(\nu) - L^{\text{real}}(\nu) \right] d\nu
\]

where \( L^{\text{int}}(\nu) \) is the intrinsic luminosity (per frequency) of the galaxy and \( L^{\text{real}} \) is the luminosity after absorption. The above integration is evaluated from UV to optical wavelengths. The model reproduces UV luminosity function at \( z = 2.5 \). Furthermore, the source number counts of SMGs for observed frame of 850 µm and 1.1 mm are consistent with observation (Shimizu et al. 2012).

In order to calculate the [C II], [N III] and [O III] luminosities, we adopt empirical relations by mostly observations of local star-forming galaxies. We calculate [C II] luminosity \( L_{\text{[C II]}} \) using the following three empirical laws:

\[
L_{\text{[C II]}}/L_\odot = (L_{\text{FIR}}/L_\odot)^{-0.157} \times 10^{-1.12},
\]

\[
\text{SFR}/(M_\odot/\text{yr}) = (L_{\text{[C II]}}/L_\odot)^{0.987} \times 10^{-7.0},
\]

\[
\text{SFR}/(M_\odot/\text{yr}) = (L_{\text{[C II]}}/L_\odot) \times 10^{-7.08}.
\]

The first is derived from Swinbank et al. (2012) (hereafter \( L_{\text{[C II]}}^{\text{SW}} \)). The last two equations are derived from De Looze et al. (2012) and Sargsyan et al. (2012) (hereafter \( L_{\text{[C II]}}^{\text{DL}}, L_{\text{[C II]}}^{\text{SA}} \)). We compare the resulting luminosity functions based on the three relations in Figure 1. Clearly, there is little model dependence.
Figure 1. [C II] luminosity function at $0.6 < z < 3.05$.

Figure 2. SMGs with submm line fluxes greater than 20 $\mu$Jy at $z < 3.05$. The field of view is $2' \times 2'$. The colour indicates the flux density $F$ of [O III] $51.8 \mu$m (cyan), $50 \mu$Jy < $F$ < $100 \mu$Jy (green), $100 \mu$Jy < $F$ < $1$ mJy (orange), $1$ mJy < $F$ (magenta).

We also use simple relations between $L_{\text{FIR}}$ and other fine structure lines (Nagao et al. 2011):

\[
\frac{L_{\text{[O III]}88.33}}{L_{\text{FIR}}} = 1.8 \times 10^{-3},
\]

\[
\frac{L_{\text{[O III]}51.80}}{L_{\text{FIR}}} = 1.8 \times 10^{-3},
\]

\[
\frac{L_{\text{[N III]}57.21}}{L_{\text{FIR}}} = 6.0 \times 10^{-4}.
\]

3. LINE DETECTION BY SPICA-SAFARI AND ALMA

The SPICA-SAFARI with band-pass 34–210 $\mu$m can detect [O III]$51.80 \mu$m emission from galaxies at $z < 3.05$. If we also detect [O III]$88.33$ and [N III]$57.21$, we can utilize the metallicity diagnostics of SMGs by measuring $(L_{\text{[O III]}51.80} + 88.33) / L_{\text{[N III]}57.21}$ (Nagao et al. 2011). In order to detect these two lines, we consider another observation of ALMA Band 10 and 11, or CCAT. Let us consider combination of SPICA-SAFARI and ALMA. With the high sensitivity of SPICA, faint ($< 10^9 L_{\odot}$) [C II] emitters can be detected.

The field of views of SPICA-SAFARI is $2' \times 2'$, and the limiting source flux densities within 1 hour are estimated to be 21, 32 $\mu$Jy (5$\sigma$) for the 2 channels, respectively. We adopt this condition and repeat 10 times to calculate scatter. The flux density $F$ is given by

\[
F = 0.96 \times 10^3 \frac{(L/L_{\odot})(1+z)}{d_L^2 \Delta \nu \nu_{\text{rest}}} \ [\text{Jy}],
\]

where $L$ is luminosity in erg/s, $d_L$ is luminosity distance in Mpc, $\nu_{\text{rest}}$ is rest frequency of the line in GHz, and $z$ is redshift. We assume line width of $\Delta \nu = 120$ km/s for simplicity.

4. RESULT

We plot the spatial distribution of our simulated SMGs on the past light cone of an observer in Figure 2.
also detect \([\text{O III}]\) 88.33 and \([\text{N III}]\) 57.21, we can utilize the metallicity diagnostics of SMGs by measuring \((\text{[O III]} 51.80 + 
\text{density F of [O III]} 20
\text{density F is given by} \mu 21, 32
\text{line width of} 88.33) / \text{[N III]} 57.21 \) (Nagao et al. 2011). In order to detect these two lines, we consider another observation of ALMA SPICA Band 10 and 11, or CCAT. Let us consider combination of

\[L = L_{\text{FIR}} \text{ luminosity in erg/s,} \]

\[\nu^0 = 120 \text{km/s for simplicity.}\]

We also use simple relations between \(L_{\text{FIR}}\) and other fine structure lines (Nagao et al. 2011): \(L_{\text{FIR}} / \nu^0 = 10^9 L_\odot\) for the 2 channels, respectively. We adopt this condition and repeat 10 times to calculate scatter. The flux of \([\text{C II]}\) luminosity function at \(\nu < 10^3\) is \(< 10^3 L_\odot\) \([\text{C II]}\] emitters can be detected.

We also detect \([\text{O III]}\) 51.80 \([\text{O III]}\) 88.33) / \([\text{N III}]\) 57.21 \(\) (Nagao et al. 2011). In order to detect these two lines, we consider another observation of ALMA SPICA Band 10 and 11, or CCAT. Let us consider combination of

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We also consider effect of the gravitational lensing (Takahashi et al. 2011). Several sources can be strongly lensed, but lensing does not affect considerably to the expected number counts (Figure 3).

For our proposed survey, the number of SMGs to be detected is 604±59 (Max: 727, min: 534). The corresponding value of \([\text{C II]}\] emitters whose luminosity \(L_{\text{C II}} \text{Sw} < 10^9 L_\odot\) is 543 ± 52 (Max: 655, min: 482). We also consider effect of the gravitational lensing (Takahashi et al. 2011). Several sources can be strongly lensed, but lensing does not affect considerably to the expected number counts (Figure 3).

Our calculations adopting empirical laws provide an educated estimate of the number counts. However, we cannot examine the metallicity diagnostics in this way, because the calculated line ratios do not depend on the metallicity. We plan to develop a physical model of line emissions that utilize the output of cosmological simulations.

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The First Broad-Range CO Ladders from the M83 and 30 Doradus

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ABSTRACT

We present the spectral observation results from M83 and 30 Doradus, using the Spectral and Photometric Imaging REceiver (SPIRE) of the Herschel Space Observatory. The warm CO lines covered in this wavelength include \( J = 4–3 \) to \( J = 13–12 \) transitions, which allow us to determine the peak CO ladder intensities and beyond. We model the physical conditions in the objects \((N (\text{CO}), T_{\text{kin}}, n (\text{H}_2))\) using a large velocity gradient (LVG) code. We also investigate the \([\text{N} \, \text{II}] \) 205 \( \mu \)m map from M83 and compare our result with the CO \( J = 1–0 \) and H\alpha maps.

1. INTRODUCTION

M83 is a nearby starburst spiral galaxy at 5 Mpc away. Structure-wise, it is very similar to the Milky-way, and its face-on orientation makes it ideal to study the star-forming regions inside. 30 Doradus is a giant H II region in the Large Magellanic Cloud 50 kpc away from the Milky-Way. It is the brightest star-forming region in the LMC. We compare the CO lines observed by the Herschel SPIRE FTS from these two objects in this poster. The wavelength covered by the SPIRE FTS provides an unprecedented detection of the molecular features at the peak of the CO energy distribution.

2. DATA

We obtain the spectral data with both short-wavelength (SSW; 960 < \( \nu < 1545 \) GHz) and long-wavelength (SLW; 450 < \( \nu < 990 \) GHz) modules. The observation is part of the Herschel Guaranteed Time Key Programs, Very Nearby Galaxies Survey (VNGS, P.I. Chris Wilson) for M83 and Survey with Herschel of the ISM in Nearby Infrared Galaxies (SHINING, P.I. Eckhard Sturm) for 30 Doradus. We compare the CO spectral line energy distribution from the center of M83 (13\( ^h 37^m 0^s \), 9, −29 deg 51′56″78) and at (5\( ^h 38^m 49^s \), 61, −69 deg 4′29″64) from 30 Doradus. At these two chosen pointings, the central bolometers, SLWC3 and SSWD4, of the SLW and SSW modules are concentric. Before comparison, the two spectra are corrected for the objects’ spatial light distribution, taking into account that the beam full-width-half-maximum (FWHM) varies from ∼20″ to ∼40″, using the method discussed in Wu et al. (2013). After correction, since the spatial distribution of the emission from both M83 and 30 Doradus is quite extended relative to the largest beam FWHM (41″) of the SPIRE FTS, the effective beam FWHM of the corrected spectrum can be approximated as 41″. The corrected spectrum of M83 is presented in Figure 1.

The M83 is observed in the full-sampling mode. The complete Nyquist sampled map of the SPIRE FTS has a bolometer spacing of ∼12″. We also compare the \([\text{N} \, \text{II}] \) 205 \( \mu \)m map of M83 with star-formation rate (SFR), calculated with the far-UV (FUV) and the 24 \( \mu \)m maps of M83 using the calibration given in Hao et al. (2011). The details of the map-making procedure is described in Wu et al. (2014, in preparation).

3. RESULTS

3.1. Comparison of the Star-forming Regions in M83 and 30 Doradus

Figure 2 compares the SLEDs from M83 and 30 Doradus from the pointings described in the previous section where the two central bolometers of SLW and SSW are concentric. Based on the SPIRE FTS observation, the distribution of the CO lines from M83 nucleus follows a similar trend as the observed result from M82 (Kamenetzky et al. 2012). However, the CO lines from 30 Doradus imply a rather high kinetic temperature with prominently excited high-\( J \), e.g. \( J = 12–11 \), CO lines and its SLED peaking beyond the bandwidth of the SPIRE FTS. We analyze the temperature compositions from the two SLEDs with a radiative transfer model which assumes local statistical equilibrium (RADEX; van der Tak et al. 2007). The interpretation from the model indicates that the fraction of warm-to-cold CO component is approximately 0.01 from the observed region in M83 and is nearly 1 from the observed region in 30 Doradus. At the distance to M83, the observed region is approximately 1 kpc. For 30 Doradus, the observed region is approximately 10 pc. The difference observed in Figure 2 can possibly be explained by the relative distance to the observed star-forming region. This result clearly reveals the interaction of the molecular cloud and star-formation and can help determine the cooling efficiency contributed by CO molecules in photo-dissociation regions (PDRs).

3.2. Using \([\text{N} \, \text{II}]\) to Trace Star Formation?

To investigate how the \([\text{N} \, \text{II}]\) 205 \( \mu \)m and \( \Sigma_{\text{SFR}} \) relate to each other and how this relationship compares with the existing one between \( \Sigma_{\text{SFR}} \) and CO \( J = 1–0 \) transition from M51 (Kennicutt et al. 2007), we compare the pixel-by-pixel values of...
Figure 1. The spatial light distribution corrected spectrum from the M83 nucleus.

Figure 2. A comparison of the CO SLEDs from M83 and 30 Doradus.
The First Broad-Range CO Ladders from the M83 and 30 Doradus

Figure 3. Comparison of the [N II] 205 µm, $S_{\text{CO}(1-0)}$, and, $\Sigma_{\text{SFR}}$. The embedded figure shows the integrated properties of M83 on the relationship calibrated with a sample of ULIRGs and star-forming galaxies (Wu et al. 2014, in preparation).

the [N II] 205 µm surface brightness with the $\Sigma_{\text{SFR}}$, and of the $S_{\text{CO}(1-0)}$ with $\Sigma_{\text{SFR}}$, which is calculated from the FUV and 24 µm photometry maps of M83 following the calibration given in Hao et al. (2011). Figure 3 shows that the values of [N II] 205 µm follow a close relationship with the $\Sigma_{\text{SFR}}$, and when compared with the $S_{\text{CO}(1-0)}$, the surface brightness of [N II] 205 µm is generally around two orders of magnitude higher. A recent work by Zhao et al. (2013) has shown that the [N II] 205 µm luminosity holds the following relationship with the total SFR (calibrated with the total infrared luminosity, $L_{\text{IR}}$), among a sample of 70 luminous infrared galaxies (LIRGs) and 30 star-forming galaxies. Figure 3 also compares the $S_{\text{CO}(1-0)}$ with $\Sigma_{\text{SFR}}$. The calibration of $\Sigma_{\text{SFR}}$, estimated by the $H\alpha$ surface brightness, as a function of $\Sigma_{H_2}$, estimated by the CO J = 1−0 intensity ($I_{\text{CO}}$; Kennicutt et al. 2007), is indicated by the blue dashed line.

4. CONCLUSION

We show the Herschel SPIRE FTS observations from the regions inside the M83 spiral arms and 30 Doradus. We successfully corrected the spectra from the concentric central bolometers of SPIRE FTS by taking into account the source distribution-beam coupling effect. Comparison of the M83 nucleus and 30 Doradus CO SLED shows that a higher portion of warm molecular gas is present in 30 Doradus. A good correlation is found between the [N II] 205 µm and SFR surface density. However, we observe a disagreement from the fainter [N II] 205 µm regions with the trend demonstrated by bright [N II] 205 µm regions. Caution should be exercised before one applies this line as a general SFR tracer.

REFERENCES

Near-Infrared High-Resolution Spectroscopy of the Obscured AGN
IRAS 01250+2832

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ABSTRACT

We provide a new physical insight on the hot molecular clouds near the nucleus of the heavily obscured AGN
IRAS 01250+2832, based on the results of near-infrared high-resolution spectroscopy of gaseous CO ro-vibrational
absorption lines with Subaru/IRCS+AO188. The detected CO absorption lines up to highly excited rotational levels reveal
that hot dense molecular clouds exist around the AGN under the extreme physical conditions.

1. INTRODUCTION

Recent observations at many wavelengths, for example the X-ray background observations, infrared deep cosmological
surveys, and (sub)millimeter deep galaxy surveys, surely show the importance of heavily obscured active galactic nuclei
(AGNs) in the galaxy evolution history. However, the physical conditions of obscuring molecular clouds near the nuclei
have never been measured directly, and the exact nature of the obscured AGNs is still controversial. IRAS 01250+2832 is a new notable object which is identified as an obscured AGN using the catalogue of AKARI
Mid-infrared All-Sky Survey (Oyabu et al. 2011). AKARI detected the excess of mid-infrared emission that implied the
existence of hot dust associated with an AGN. Though the optical spectrum of this galaxy is that of a typical elliptical
galaxy, the AKARI near-infrared spectrum shows a steep red continuum with deep CO absorption feature (see Figure 1).
AKARI/IRC has superb sensitivity with no influence of atmosphere. However, its spectral resolution is moderate (R~100)
and is not enough to resolve the CO absorption into each CO ro-vibrational absorption line.

2. OBSERVATION

First, we performed near-infrared imaging observations using the IRCS+AO188 on the Subaru Telescope, to check the
compactness of the emission region. Figure 2 shows the reduced multi-band (J, H, K, L’, M’) images with the pixel scale
of 20 mas. Thanks to the high spatial resolution (∼0”.1) of IRC+AO188, which corresponds to the physical scale of
~90 pc on IRAS 01250+2832 at z = 0.0428, we can resolve the extended stellar emission in the host galaxy at JHK-bands.

![IRAS 01250+2832](image)

Figure 1. AKARI/IRC NIR grism spectrum of IRAS 01250+2832 (black circles; Oyabu et al. 2011), which shows a steep red continuum with strong CO absorption feature. Gray lines are the Subaru/IRCS L-grism spectrum taken with the 0”.23-wide slit (this work). The good agreement of these spectra indicates that the infrared dust emission of IRAS 01250+2832 is dominated by a compact (∼kpc) nuclear source with a very small contribution from extended starburst activity in the host galaxy. The black thick lines show the wavelength coverage of the Subaru/IRCS M-echelle spectrum shown in Figure 3.
Figure 2. Subaru/IRCS+AO188 images of IRAS 01250+2832 obtained at J-band (1.25 \( \mu \)m; top left panel), H-band (1.63 \( \mu \)m; top center panel), K-band (2.20 \( \mu \)m; top right panel), L’-band (3.77 \( \mu \)m; bottom left panel), and M’-band (4.68 \( \mu \)m; bottom right panel). North is up and East is left. The color scale in each panel is linear.

While, L’M’-band images suggest that the infrared dust emission of this galaxy is quite compact (\( \lesssim \) kpc) to be composed of the hot dust associated with an AGN.

In order to investigate the physical conditions of molecular clouds near the AGN directly, we have made high-resolution (\( R \approx 10,000 \)) spectroscopic observations at M-band toward this heavily obscured AGN IRAS 01250+2832 with the IRCS+AO188 on the Subaru Telescope. We observed fundamental (\( v = 1 \leftarrow 0 \)) ro-vibrational absorption lines of gaseous CO centered around 4.7 \( \mu \)m. Continuum emission associated with the bright, compact central engine of the AGN is used as a background continuum source, and the foreground molecular clouds are to be observed in absorption. This technique is unique and very powerful, because the detection of many lines at different excitation levels enables us to make the direct estimates of temperatures and column densities of the molecular clouds very accurately (Shirahata et al. 2013).

3. RESULTS

Figure 3 shows the observed spectrum toward IRAS 01250+2832, which clearly shows many absorption lines up to highly excited levels (\( J > 30 \)). These lines are very deep (\( \tau_{\text{max}} \approx 4 \)) and extremely broad (FWHM \( \approx 200 \) km s\(^{-1} \)), and also have the complicated line profile consisting of some velocity components. The characteristics of the detected CO lines are very similar to that of the CO absorption in other obscured AGNs, IRAS 08572+3915 and UGC 05101 (Shirahata 2006). This result is remarkable in the sense that IRAS 01250+2832 shows very strong CO absorption but no dust absorption features, though the other obscured AGNs having CO absorption always show the strong dust absorption features.

4. DISCUSSION

On the assumption of local thermodynamic equilibrium, the detected CO absorption lines of IRAS 01250+2832 reveal two distinct components; a hot gas with a temperature of 700 K, and a warm gas with a temperature of 150 K. The CO column density of the hot molecular gas is estimated to be \( N_{\text{CO}} \approx 1.3 \times 10^{19} \) cm\(^{-2} \), which corresponds to a H\(_2\) column density of \( N_{\text{H}_2} \approx 7.2 \times 10^{22} \) cm\(^{-2} \), for a covering factor of 0.5. The CO column density of the warm molecular gas is estimated to be \( N_{\text{CO}} \approx 8.0 \times 10^{18} \) cm\(^{-2} \), which corresponds to a H\(_2\) column density of \( N_{\text{H}_2} \approx 4.4 \times 10^{22} \) cm\(^{-2} \), for a covering factor of unity. The high temperatures combined with the large column density of both components imply that the CO absorption originates in molecular clouds near the nucleus of the AGN. The thermal excitation of CO up to the
The direct estimates of temperatures and column densities of the molecular clouds very accurately (Shirahata et al. 2013). A background continuum source is used, and the foreground molecular clouds are to be observed in absorption. This absorption originates in molecular clouds near the nucleus of the AGN. The thermal excitation of CO up to the high temperatures combined with the large column density of both components imply that the detected CO lines are highly excited levels ($N_{\text{CO}} > 10^{18}$ cm$^{-2}$). These lines are very deep ($\Delta \lambda / \lambda \sim 20$ km s$^{-1}$). These lines are very deep ($\Delta \lambda / \lambda \sim 20$ km s$^{-1}$).

5. SUMMARY

We have observed and analyzed a high-resolution $M$-band spectrum of the obscured AGN, IRAS 01250+2832, which contains strong absorption lines of the fundamental ($\nu = 1 \leftarrow 0$) band of CO. The detected CO ro-vibrational absorption lines reveal that hot dense molecular clouds exist around the AGN. The derived extreme physical conditions of molecular clouds with insinuated complex geometry indicate that the environment around the AGN is not as simple as that proposed in the unified scheme of AGNs.

We acknowledge all the staff and crew of the Subaru Telescope for their professional help in our observations. We would also like to thank the IRCS and AO188 team members for their continuous support.

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Monitoring Observations of Buried AGNs in the NEP Field with \textit{SPICA} \\

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ABSTRACT \\
We propose \textit{SPICA}/MCS monitoring observation at North Ecliptic Pole region to search MIR-variable faint obscured AGNs to study faint end early phase AGN properties. We have carried out deep near to mid infrared survey with \textit{AKARI}/IRC (2–24 $\mu$m) and follow-up multi-wavelength observations (X-ray–radio), and found many AGN candidates. However there is possibility to miss identify obscured AGNs which can be just-activated early phase ones. \textit{SPICA}/MCS monitoring survey will give us a great help to investigate these early phase AGNs. When we carry out 1 hour observation, once per half a month, then we can survey 12 MCS-field-of-views ($12 \times 5' \times 5'$), and $\sim$50 type-1 AGN and $\sim$50–200 type-2 AGN detection is expected. This survey can monitor long time scale (3–5 years) variability of these AGNs.

1. ACTIVE GALACTIC NUCLEI \\
Studies in the last two decades indicate that there exists a strong correlation between properties of the galactic bulge (e.g., mass, luminosity, and velocity dispersion) and the mass of its central Super Massive Black Hole (SMBH) (Magorrian et al. 1998). The correlation links the notion that SMBHs may play an intrinsic role in galaxy formation and evolution. Active Galactic Nucleus (AGN) emits vast amounts of energy from the center region of galaxies by releasing gravitational potential energy of materials accreting onto a SMBH into radiative energy, indicating that the SMBH is in a phase of rapid growth. Therefore, an understanding the AGN properties is one of the most essential aspects in the study of AGN–galaxy co-evolution.

1.1. AGN identification \\
As AGNs are broadband emitters, they can be identified via a variety of multi-wavelength techniques. X-ray emission in AGN is thought to form in a hot corona around the accretion disk. Electrons in the corona inverse-Compton scatter optical and UV accretion disk photons to higher (i.e., X-ray) energies. These X-ray can easily come though the obscuring medium, provided that the column density of the torus is not Compton-thick (i.e., $N_{\text{H}}>10^{24}$ cm$^{-2}$). In the optical, prominent emission lines are usually visible in spectra of AGNs, resulting from accretion disk photons ionizing the surrounding gas. AGN can be identified with emission lines with broad line width (type-1 AGN) or emission line ratios (i.e., [O III]5007Å/H$\beta$ and [N II]6583Å/H$\alpha$) known as BPT diagrams (Baldwin et al. 1981). Obscuring medium enshrouding an AGN absorbs optical and UV accretion disk photons and re-radiates the emission in the infrared. AGNs can thus be identified based on their MIR spectral energy distribution (SED) of power-law shape, or ratios of flux densities, providing a useful tool for selection those sources where the optical and UV emission are affected by strong extinction. Thus, in order to identify AGNs, multi-band data sets are needed.

1.2. \textit{AKARI} NEP-Deep field \\
Japanese infrared satellite \textit{AKARI} carried out wide and deep surveys with all nine bands (2–24 $\mu$m) of IRC in the North Ecliptic Pole (NEP) survey program (Figure 1). In addition, we carried out many follow-up observations at the NEP field in multi-wavelength (Table 1). These multi-band data sets are very powerful for studying AGN properties. From \textit{Chandra} data (left panel of Figure 2), we can identify $\sim$420 X-ray sources as AGN candidates. Several dozen of optical spectra show broad emission lines, and a few hundred \textit{AKARI} sources have MIR power-law SED (right panel of Figure 2).

These different selection methods have various biases. X-ray emission will be extinct in Compton-thick sources due to both photo-electric absorption of X-ray photons and Compton scattering of photons out of the line of sight. Since optical emission lines used to identify AGN are attenuated in dusty galaxies, causing some AGN be missed. AGN samples selected by IR methods can be contaminated by star-forming galaxies, while some faint AGNs which do not dominate their MIR SED can be missed.

2. MONITORING SURVEY AT NEP FIELD WITH \textit{SPICA} \\
2.1. Variability survey for AGNs \\
At the beginning of AGN phase, just-triggered AGN activities should be weak and AGN could be varied by a large amount of gas and dust. Although these objects are thought to exist as faint end obscured AGNs, they are hardly identified as AGN with those methods above. For identification of faint end dust obscured AGNs, variability observation can be
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Table 1. Multi-wavelength data at NEP-Deep area

<table>
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<tr>
<th>Observatory</th>
<th>Imaging Data</th>
<th>Spectroscopic Data</th>
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<td>g', r', i', z'</td>
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Figure 1. The coverage of multi-band surveys in the NEP field. Dark green circle and image regions represent AKARI NEP-Wide and Deep survey areas. The light green, dark purple, light purple, light blue, pink, orange, and dark red show the regions of Chandra, GALEX, Subaru/S-Cam, CFHT/MegaCam, CFHT/WIRCam, and Herschel/PACS, and Herschel/SPIRE observation areas, respectively.

powerful. In the past, many studies of AGN variability have carried in optical wavelength (e.g., Vanden Berk et al. 2004; Morokuma et al. 2008), and found that variability amplitude is higher for lower luminosity AGN — meaning that variability study could be a great method for identification of faint AGNs. In fact, ~50% of variability sources are not identified by X-ray nor MIR, suggesting the possibility that the AGNs identified by variability are early phase AGNs. However, it is still possible that heavily obscured AGNs can be missed in optical observation.

Kozłowski et al. (2010) carried out the monitoring survey with Spitzer (<18 mag in 3.6 and 4.5 µm) and found that variability amplitude of AGN is still higher for lower luminosity in infrared wavelength — meaning the IR variability...
study is also powerful for faint AGNs. The monitoring survey carried out for ~ 2 years and objects brighter than 18 mag are detected. However, from optical variability surveys, there should exist sources fainter than 18 mag in infrared band.

2.2. Survey Design

We aim to investigate properties of faint end dusty AGNs, we propose monitoring survey at NEP field with SPICA/MCS. This survey utilizes the great sensitivity of SPICA/MCS and good location of NEP where is observable in and out of season from space. Moreover, since we already have multi-band data sets, we can scrutinize the properties of discovered faint end obscured AGN from every angle.

From the previous optical and infrared variability AGN studies, the scale of variability amplitude is more than 0.1 mag on timescales of 1–2 years. In order to detect the amplitude of 0.1 mag with S/N = 3, S/N ~ 30 detection on each epoch is needed. The sensitivity of MCS/WFC-S (5–25 μm) is 0.13–3.5 μJy (1 hour, 5σ). When we run 1 hour observation, sources with up to 0.78–21 μJy (24.16–20.59 mag) can be detected with >30σ. 20.5 mag at 25 μm consists with i ~ 24.5 mag with SED templates of Bruzual & Charlot (2003) and Dale & Helou (2002). According to Morokuma et al. (2008), surface density of type-1 AGN is ~500 type-1 AGN/deg² (i<24.5 mag). Since the field-of-view (FoV) of MCS is 5′ × 5′, 4 type-1 AGN could be detected in the FoV with >30σ. The number of type-2 AGN would be 1 to 4 times larger than those of type-1 AGN, 4 to 16 type-2 AGN/FoV(5′×5′) detection can be expected. If we carry out 1 hour observation, once per half a month, then we can survey 12 MCS FoV in a half year, and then ~50 type-1 AGN and ~50–200 type-2 AGN detection is expected. When we continue this monitoring observation for 3–5 years (SPICA’s life) as a half month is 1 cycle, we can monitor variability of these AGNs with long time scale.

We would like to thank AKARI/IRC team members for their support on this work. The AKARI NEP Deep survey project activities are supported by JSPS grant 23244040.

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Search for Dust-free Quasars at $z > 6$ Using $SPICA$ MCS Photometry

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ABSTRACT

I propose to search for dust-free quasars without hot-dust emission at $z > 6$. I plan to perform the deep mid-infrared photometry with Mid-infrared Camera and Spectrometer (MCS). Its high sensitive and continuous-band (5–38 $\mu$m) imaging enables us to investigate the contribution not only of the hot dust component (rest frame: 1–3 $\mu$m) but also of the warm dust component (rest frame: $> 3 \mu$m) of quasars at $z > 6$. When the $SPICA$ begins the observation, several hundreds of quasars at $z > 6$ are expected to be discovered by Hyper Suprime-Cam (HSC) which is a gigantic digital still camera for 8.2 m Subaru telescope. For these $z > 6$ quasars, we examine the hot-dust abundance by utilizing the spectral energy distributions of rest-frame near-infrared regime. This study is expected to provide us the clue about the origin of the dust torus.

1. INTRODUCTION

Active galactic nuclei (AGNs) are among the most energetic objects in the universe. The nuclear activity is powered by a supermassive black hole (SMBH) and its accretion disk, and this central engine is surrounded by a dusty toroidal structure, so-called “dust torus”. The radiation from hot dust (~1,500 K) is one of the characteristics of AGNs (e.g. Kobayashi et al. 1993; Suganuma et al. 2006). It is also widely accepted that the hot dust contributions can be observed as an infrared (IR) bump which starts $\sim 1 \mu m$ and extends to longer wavelength in the near-IR (NIR) region of their spectral energy distributions (SEDs). The hot dust is considered to the inner region of dust torus, based on the unified model of AGNs (Antonucci 1993; Urry & Padovani 1995). Recently, however, two quasars without hot-dust emission were discovered at $z \sim 6$ (Jiang et al. 2010). While these hot-dust-free quasars are suggested to be the first generation ones that do not have enough time to form a dusty torus, the origin of these dust-free quasars is still unclear because the sample was limited to only the two sources.

Figure 1. MCS 5$\sigma$ sensitivity in one hour exposure. The SEDs of quasars at various redshift ($z = 0.1–8$) are also plotted. The SED template was used by Assef et al. (2010). See Takeuchi et al. (this volume) for the confusion limit.
Figure 2. Same as in Figure 1, but localized in the MIR region. MCS provides us the opportunity to discuss not only the hot dust component but also the warm dust component of quasars at $z > 6$, 7, and 8.

2. SURVEY STRATEGY

In order to examine the properties of the hot dust around the AGNs at high redshift statistically, we plan to perform the deep mid-IR (MIR) photometry with Mid-infrared Camera and Spectrometer (MCS: Kataza et al. 2012) on board SPICA (Nakagawa et al. 2012). Its high sensitive and continuous-band (5–38 $\mu$m) imaging enables us to investigate the contribution not only of the hot dust component (rest frame: 1–3 $\mu$m) but also of the warm dust component (rest frame: > 3 $\mu$m) of quasars at $z > 6$. When the SPICA begins the observation, several hundreds of quasars at $z > 6$ are expected to be discovered by Hyper Suprime-Cam (HSC: Miyazaki et al. 2012) which is a gigantic digital still camera for 8.2 m Subaru telescope. For these $z > 6$ quasars, we examine the hot-dust abundance by utilizing the SEDs of rest-frame NIR regime. In addition, we will compare its physical properties (black hole masses and Eddington ratios etc.) to other “normal” quasars.

3. ADVANTAGE OF SPICA

To check the capability of SPICA to discover a lot of dust free quasars, I demonstrate the expected SEDs of high-$z$ quasars. Figures 1 and 2 show the SEDs of quasar which has $M_{1450}(AB) = 26.5$ ($\sim 10^{12.5} L_{\odot}$) at various redshift ($z = 0.1, 1, 2, 3, 4, 5, 6, 7, 8$), based from the quasar SED template (Assef et al. 2010). It should be noted that any extinction was not considered, but when we focus on the MIR regime, the influence of extinction on the SED is expected to be neglected. The $5\sigma$ sensitivity of MCS in one hour exposure is also plotted. For comparison, we also show the capability of other instrument of SPICA (SAFARI, FPC) and notable current (SDSS, Spitzer, AKARI, and WISE) and future missions (HSC-WIDE and JWST/MIRI) in Figures 1 and 2. As shown in these figures, SPICA/MCS has a strong potential to search for not only dust free quasars but also various types of quasars with a high level of confidence. This study is expected to provide us the clue about the origin of the dust torus.

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Far-Infrared Line Deficits in Ultraluminous Infrared Galaxies

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ABSTRACT

We study the origin of the [O I] 63, [N II] 122, [O I] 145, and [C II] 158 line deficits in z < 0.3 Ultraluminous Infrared Galaxies, using data from Herschel. The line deficits are consistent with arising from increased quantities of dust in H II regions, but part of the [C II] deficit may arise from an additional mechanism, plausibly increased grain charging. We briefly discuss some implications from these results for SPICA.

1. INTRODUCTION

Ultraluminous Infrared Galaxies (ULIRGs, LIR > 1012 L⊙, e.g. Lonsdale et al. 2006) at z ≤ 0.3 are invariably observed to exhibit emission from the following four far-infrared fine-structure lines: [O I] at 63 μm, [N II] at 122 μm, [O I] at 145 μm, and [C II] at 158 μm. All four of these lines however show a deficit in their luminosities (as parameterized by the L_{line}/L_{IR} ratio) compared to the ratios expected from systems with lower values of L_{IR} (e.g. Luhman et al. 2003). In contrast, ULIRGs at z > 1 do not show such pronounced deficits (e.g. Stacey et al. 2010), at least for [O I]63 and [C II]. The origin of the line deficits among low-redshift ULIRGs is controversial. Determining their cause may give insight into how different atomic and molecular features trace emission from H II regions, PDRs and the ISM, and into how different far-IR lines trace star formation as a function of redshift. We here explore the origin of these far-IR line deficits via observations of the [O I], [N II] and [C II] lines in 25 ULIRGs at z < 0.27, using data from the Herschel observatory. This study is part of the HERUS program (Efstathiou et al. 2013; Farrah et al. 2013; Spoon et al. 2013).

2. RESULTS & DISCUSSION

We find a deficit in all four lines (Figure 1), with average ratios (compared to lower luminosity systems) of 2.75, 4.46, 1.50, and 4.95 for [O I]63, [N II], [O I]145, and [C II], respectively. The deficits show no dependence on the presence of an AGN, as diagnosed via either optical spectral type or the detection of the [Ne v] line at 14.32 μm.

To investigate the far-IR line deficits further, we employ three comparison variables; the silicate dust feature at 9.7 μm (S_{sil}), merger stage, and PAH luminosity (see Farrah et al. 2013 for definitions). For S_{sil} we see the following. There is no trend of the [O I] deficits with S_{sil}. For the [C II] and [N II] deficits however there is a trend; if S_{sil} ≥ 1.4 then the [C II] and [N II] deficits increase as S_{sil} increases (e.g. lower middle panel of Figure 1). There is however no trend of the [C II] and [N II] deficits with S_{sil} if S_{sil} ≤ 1.4. Turning to merger stage; we find no evidence that the [N II] and [O I] deficits depend on merger stage, but the [C II] deficit is stronger in advanced mergers than in early-stage mergers (lower right panel of Figure 1). We checked for degeneracies between S_{sil} and merger stage by examining the [C II] deficit as a function of merger stage using only those sources with S_{sil} < 1.4. We found that the [C II] deficit still strengthens with advancing merger stage. Finally, for PAH luminosity; ULIRGs in advanced mergers and with S_{sil} ≥ 2 have comparably low L_{PAH}/L_{IR} and L_{CII}/L_{IR} ratios, compared to ULIRGs in early-stage stage mergers and with S_{sil} ≤ 1.4–2 (Figure 2).

If we assume that S_{sil} is a proxy for the dust column in H II regions, then the stronger [C II] and [N II] deficits in sources with higher S_{sil} (at S_{sil} ≥ 1.4) are consistent with an origin connected to dust column and gas ionization in H II regions. In this scenario (e.g. Luhman et al. 2003; González-Alfonso et al. 2008; Abel et al. 2009; Graciá-Carpio et al. 2011), a higher fraction of the UV photons are absorbed by dust rather than gas, either because there is more dust and/or because the gas is so highly ionized that it cannot absorb more UV photons. Thus, the UV photons contribute more to L_{IR} but less to gas heating in the H II regions, thus decreasing line emission relative to L_{IR}. Another possible contributing mechanism is that the dust in compact H II regions is likely warmer than the dust in diffuse H II regions, hence the IR emission from the dust in the compact regions will be higher for the same mass of gas. These mechanisms would also produce a deficit in [C II] and the ‘deficit’ in the PAH emission, even if the bulk of the [C II] and PAHs are in the PDRs, since there would be fewer UV photons for photoelectric heating of the PDRs. Furthermore, this mechanism is consistent with the [O I] deficits. From Figure 3 of Graciá-Carpio et al. (2011) the conditions consistent with the deficits of all four lines are n ≤ 300 cm^{-3} and 0.01 ≤ ⟨U⟩ ≤ 0.1.
Figure 1. The [O I] 63, [N II], [O I] 145, and [C II] ratios vs. \( L_{\text{IR}} \). In each panel, the colored points are our sample, while the black points are from Brauher et al. (2008). The top row shows the line deficits in [O I] and [N II], coded by optical class. Objects with an [Ne V] detection are marked. The bottom row shows the deficit in [C II] coded by optical class, merger stage, and 9.7 \( \mu \)m silicate strength.

Figure 2. The [C II] deficit vs. the \( L_{\text{PAH}}/L_{\text{IR}} \) ratio, coded by merger stage and \( X_{\text{Sil}} \).
FAR-IR LINE DEFICITS IN ULIRGS

There are however two observations that are inconsistent with dustier/more ionized H II regions being the sole origin of the line deficits. First, none of the deficits depend on $S_{\text{sil}}$ when $S_{\text{sil}} \lesssim 1.4$; if the deficit arises entirely in H II regions then we should see a dependence. The assumption that $S_{\text{sil}}$ is a proxy for dust column in H II regions is however not proven. In particular, if $S_{\text{sil}}$ does not act as such a proxy at $S_{\text{sil}} \lesssim 1.4$ then no dependence would be seen. Second, while the [C II] deficit is stronger in advanced mergers, no other line shows a dependence on merger stage. If we assume that advanced mergers host dustier H II regions to explain the rising [C II] deficit, then the [N II] deficit should also depend on merger stage. Thus, part of at least the [C II] deficit likely does not arise due to dustier and/or more highly ionized H II regions.

We consider three possible additional contributors to the [C II] deficit. First is increased dust grain charging (e.g. Malhotra et al. 2001), leading to a lower gas heating efficiency. Second is a softer UV field in the ISM (e.g. Spaans et al. 1994), leading to reduced relative [C II] emission. Third is increased gas density and/or UV field intensity in the PDRs, making [O I] rather than [C II] the primary coolant.

The third possibility is feasible, but we do not have the data to investigate it. The second possibility is unlikely, from the arguments in Luhman et al. (2003). For the first possibility; if the origin of the additional deficit in [C II] is grain charging, then we would see a higher $G_0$ in advanced mergers compared to early stage mergers. From Figure 18 of Farrah et al. (2013) the advanced mergers have an order of magnitude higher $G_0$ for about the same $n$. We therefore cautiously infer, with the caveat that we cannot rule out [O I] providing cooling, that part of the [C II] deficit may arise due to increased grain charging. We further propose that this effect is not driven by AGN activity, since the [C II] deficit does not depend on either optical spectral type or the presence of [Ne V] 14.32.

3. PROSPECTS FOR SPICA

Our results suggest that determining the origin of each line deficit is key to using infrared spectroscopy to trace star formation across the history of the Universe. By combining Spitzer and Herschel data, we have shown that there may be multiple origins for these line deficits, but we lack key diagnostic features that are often not detected in low-ζ ULIRGs, even with Spitzer and Herschel. SPICA, by assembling high S/N spectra covering the key diagnostic features at 5–35 μm and 60–180 μm for hundreds of low-ζ ULIRGs, can conclusively determine the origin of the far-IR line deficits. Example diagnostics include:

- A wider census of line deficits, by observing, across large samples spanning $10^{10} < L_{\text{IR}} < 10^{13}$, a greater number of lines than was possible with Herschel. Key additional diagnostics are the [N II] 205 & [O III] 88 lines.
- The contribution from [O I] in PDRs. SPICA will determine how self-absorption in the [O I] 63 line affects the observed line flux, and to see if the degree of self absorption correlates with the observed deficit. This will quantify the importance of [O I] as a coolant in PDRs.
- The importance of heating from molecular Hydrogen, via measurements of multiple mid-IR H2 lines. Current constraints from Spitzer are relatively poor (Higdon et al. 2006).
- The role of ionization conditions in H II regions: Determine excitation conditions in the H II regions simultaneously from Neon, Sulfur and Silicon line ratios, to see how these conditions correlate with far-IR line deficit strength.

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Probing Star Formation in Ultraluminous Infrared Galaxies Using AKARI Near-Infrared Spectroscopy

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ABSTRACT

We carried out systematic observations of the H\textsc{i} recombination line Br\textalpha\ (4.05 $\mu$m) in nearby ($z < 0.3$) ultraluminous infrared galaxies (ULIRGs), using AKARI near-infrared 2.5–5.0 $\mu$m spectroscopy. We derived star formation rates (SFRs) from the Br\textalpha\ line, whose observed flux is predicted to be the highest among H\textsc{i} recombination lines in conditions with large dust extinction (visual extinction $A_V > 15$ mag) expected in ULIRGs. Using the 3.3 $\mu$m polycyclic aromatic hydrocarbon emission in addition to the Br\textalpha\ line as an indicator of the SFR, we estimated the contribution of the star formation to the total infrared luminosity in 51 ULIRGs. The contribution was on average 28±4% in ULIRGs optically classified as H\textsc{ii}, while 14±2% in ULIRGs optically classified as LINER or Seyfert. This result indicates that the star formation is significantly active in H\textsc{ii} ULIRGs and other energy source, i.e. active galactic nuclei, is needed in LINER ULIRGs.

1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs) radiate most (≥ 90%) of their extremely large luminosities ($> 10^{12}$ $L_{\odot}$) as infrared (IR) dust emission (Sanders et al. 1988). The possible energy source of their enormous IR luminosity is starburst activities and/or active galactic nuclei (AGN). Distinguishing their energy sources has been an important topic, but the large dust extinction makes it difficult to investigate this question.

To avoid the strong dust obscuration and investigate the energy sources of ULIRGs quantitatively, we focused on IR H\textsc{i} recombination line Br\textalpha\ (n : 5 → 4, 4.05 $\mu$m). As shown in Figure 1, the observed flux of the Br\textalpha\ line is predicted to be the highest among H\textsc{i} recombination lines (i.e. H\textalpha\ or Pa\textalpha\ lines) in conditions with large dust extinction (visual extinction $A_V > 15$ mag) expected in ULIRGs (e.g. Genzel et al. 1998). Thus the Br\textalpha\ line is the most suitable for probing star formation (SF) in ULIRGs. We systematically observed the Br\textalpha\ line in ULIRGs using AKARI and derived star formation rates (SFRs) so that the contribution of the SF to the IR luminosity was estimated.

2. OBSERVATION AND RESULTS

The observations were performed with the NG grism mode of the IRC spectrograph (Onaka et al. 2007) onboard the AKARI satellite (Murakami et al. 2007). Our targets were selected from the sources in the AKARI mission program “AGNUL” (P.T. Nakagawa). From AGNUL, we selected all 51 ULIRGs observed during the liquid-He cool holding period (2006 May 8 – 2007 Aug. 26). All targets were nearby ($z < 0.3$) objects. The data were processed through “IRC Spectroscopy Toolkit Version 20110114”, the standard IRC-dedicated IDL toolkit. An example of obtained 2.5–5.0 $\mu$m spectra is shown in Figure 2 (Left). The Br\textalpha\ line flux was estimated from integrating the best fit Gaussian. We succeeded in estimating the Br\textalpha\ line luminosity ($L_{\text{Br}\alpha}$) in 35 ULIRGs.

<table>
<thead>
<tr>
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<th>$\lambda$ (m)</th>
<th>$A_{\text{line}}/A_V$</th>
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<td>H\textalpha\</td>
<td>3→2</td>
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<td>0.776</td>
</tr>
<tr>
<td>Pa\textalpha\</td>
<td>4→3</td>
<td>1.88</td>
<td>0.149</td>
</tr>
<tr>
<td>Br\textalpha\</td>
<td>5→4</td>
<td>4.05</td>
<td>0.0356</td>
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<tr>
<td>Pa\textalpha\</td>
<td>6→5</td>
<td>7.46</td>
<td>0.0020</td>
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Figure 1. Predicted fluxes of H\textsc{i} recombination lines versus visual extinction. The ordinate is normalized by the flux of Br\textalpha\ with no extinction. The theoretical line ratios in case B, $T = 10000$ K with low-density limit of Osterbrock & Ferland (2006) are assumed. The line extinction ratio $A_{\text{line}}/A_V$ is taken from Draine (2003).
Yano et al.

Figure 2. Left panel—example of AKARI 2.5–5.0 μm spectra. The best fit Gaussian profile used for calculating the Brα flux is shown by a blue solid line. Right panel—Comparison of Brα and 3.3 μm PAH luminosities. The solid line shows the regression line $L_{\text{Br}\alpha} = (0.174 \pm 0.003)L_{3.3}$.

Figure 3. Left panel—comparison of SFRs derived from Brα and Hα. The solid line shows the one-to-one relation. Right panel—infrared luminosity derived from SFR versus actual infrared luminosity of the galaxy. The linear black lines indicate the SF contribution to the IR luminosity.

In the remaining objects, the Brα line was too faint to be detected, while the 3.3 μm polycyclic aromatic hydrocarbon (PAH) emission was observed. The 3.3 μm PAH emission also traces UV photons from OB stars and is stronger than the Brα line. However, complex emission mechanisms make it difficult to derive SFRs quantitatively from the luminosity of the 3.3 μm PAH emission ($L_{3.3}$). Therefore, we calibrated $L_{3.3}$ with $L_{\text{Br}\alpha}$ to derive SFRs in the objects with no Brα line detection. Figure 2 (Right) shows a comparison of $L_{3.3}$ with $L_{\text{Br}\alpha}$. The $L_{3.3}$ were taken from Imanishi et al. (2008, 2010). Both $L_{\text{Br}\alpha}$ and $L_{3.3}$ were extinction corrected with Balmer decrement taken from the literature. They were well correlated with each other regardless of the optical classifications of the galaxies. From this result, we derived a relationship of $L_{\text{Br}\alpha} = (0.174 \pm 0.003)L_{3.3}$.

To calculate the SFRs from $L_{\text{Br}\alpha}$ (or $L_{3.3}$), we adopted the calibration provided by Murphy et al. (2011): SFR ($M_\odot \text{yr}^{-1}$) = $1.85 \times 10^{-49} L_{\text{Br}\alpha}$ (erg s$^{-1}$). Using this relation, we estimated SFRs in all our 51 targets.

3. DISCUSSION

3.1. Underestimation of SFRs in ULIRGs with Optical Observation

One of our motives of using the IR H I recombination line Brα was to reduce the effect of dust extinction and estimate the SFRs accurately. To verify this, we compared the SFRs obtained from the Brα line (SFR$_{\text{Br}\alpha}$) with those obtained from the optical Hα line (SFR$_{\text{H}\alpha}$). The Hα line fluxes were taken from the literature and extinction corrected with the Balmer decrement.

As shown in Figure 3 (Left), SFR$_{\text{Br}\alpha}$ was systematically higher than SFR$_{\text{H}\alpha}$ (typically by a factor of 3), although the fluxes of the both lines were dust extinction corrected. This means the optical observation missed some fluxes originates from the heavily dust obscured regions and underestimated the SFRs. Using the Brα line, we now succeeded to reduce the effect of dust extinction.
3.2. Contribution of Star Formation to the Infrared Luminosity

To estimate the contribution of SF to the IR luminosity, we converted SFRs to corresponding IR luminosities $L_{\text{IR}}^{\text{SF}}$ with the calibration provided by Murphy et al. (2011): $\text{SFR}/(150 M_\odot \text{ yr}^{-1}) \approx L_{\text{IR}}^{\text{SF}}/(10^{12} L_\odot)$. Figure 3 (Right) shows the comparison of $L_{\text{IR}}^{\text{SF}}$ with the total IR luminosity $L_{\text{IR}}^{\text{tot}}$. In all targets, $L_{\text{IR}}^{\text{tot}}$ was higher than $L_{\text{IR}}^{\text{SF}}$. This is consistent with the idea that $L_{\text{IR}}^{\text{SF}}$ represents the energy generated by SF, while $L_{\text{IR}}^{\text{tot}}$ corresponds to the total energy of the galaxy. We defined $L_{\text{IR}}^{\text{SF}}/L_{\text{IR}}^{\text{tot}}$ as the SF contribution.

We investigated the difference of the SF contribution among the optical classifications of galaxies. We found the SF contribution of the H II galaxies was systematically higher than that of LINERs or Seyferts (Figure 4 Left). The averaged value of the SF contribution was $28\pm4\%$ in H II galaxies and $14\pm2\%$ in LINERs and Seyferts. We performed the statistical $t$ test and confirmed the difference between H II galaxies and LINERs/Seyferts is significant at the 99.7% level. This result indicates that SF is significantly active in H II galaxies and AGN is needed as the energy source in LINERs.

Using the IR H I recombination line Br$\alpha$, we succeeded in estimating the energy sources of the nearby ULIRGs quantitatively regardless of the strong dust extinction.

4. PROSPECTS FOR SPICA

The high sensitivity of SPICA/MCS will enable us to apply our method to ULIRGs at higher redshift (Figure 4 Right). The higher-order H I recombination lines Pf$\alpha$ and H$\alpha$ are observable at $z < 0.5$. If we calibrate the 7.7 $\mu$m PAH emission with the H I recombination lines, SFRs in ULIRGs at $z > 2.0$, where both SF and AGN activities are at their peak, could be studied.

This research is based on observations with AKARI, a JAXA project with the participation of ESA.

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A Spatially-resolved Study on the Processing and Destruction of Dust Grains in Local ULIRGs

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ABSTRACT

A merging process in infrared (IR) galaxies plays an important role in accelerating the processing of dust grains, which may alter the properties of dust grains, e.g. the relative abundance of polycyclic aromatic hydrocarbons (PAHs) to classical grains. In fact, with AKARI, we find that the ratio of the PAH 3.3 μm to IR luminosity, \( L_{\text{PAH3.3}} / L_{\text{IR}} \), considerably decreases toward the luminous end of \( L_{\text{IR}} > 10^{11.5} \, L_\odot \), using the near-IR (2.5–5 μm) spectra of 100 IR galaxies without AGN signatures. We conclude that local ULIRGs intrinsically possess a smaller amount of PAHs relative to classical grains than less-luminous IR galaxies. Some fraction of PAHs may have been destroyed once by a shock during a merging process, whereas large dust grains survive, which may explain the systematically low abundance ratios of PAHs to classical grains observed for the ULIRGs. To prove this scenario, we should observe a systematic change of the ratio from an interacted region to others, or from outer to inner areas, within a galaxy. With SPICA, especially coronagraphic spectroscopy with the SCI, we can perform a spatially-resolved study of local ULIRGs in both PAH and dust emission, which will reveal the scene of the processing and destruction of dust grains with shocks during merging processes of galaxies.

1. INTRODUCTION

It is well known that a merging process of galaxies plays an important role in the infrared (IR) galaxies which are dominated by star formation activity. From morphological studies, many local ultra-luminous IR galaxies (ULIRGs) seem to have experienced recent mergers. Such merger events are likely to accelerate the processing and destruction of dust grains initially present in galaxies, as well as to trigger star-burst activity. Then the properties of dust grains, e.g. the relative abundance of polycyclic aromatic hydrocarbons (PAHs) to classical grains or dust size distributions, may systematically change with the IR luminosity if their activities originate from mergers. In order to reveal the effect of merging processes on dust grains and relationship with star-forming activity, we study the relative abundance of PAHs to classical grains in galaxies with a wide range of infrared luminosity (Yamada et al. 2013).

2. EVIDENCE FOR THE DESTRUCTION OF THE PAHS IN LOCAL ULIRGS

2.1. Sample Selection and Data Analysis

We selected our targets from the two AKARI mission programs, Mid-infrared Search for Active Galactic Nuclei (MSAGN; Oyabu et al. 2011) and Evolution of ULIRGs and AGNs (AGNUL). We obtained the AKARI near-IR spectra of the 184 galaxies which satisfy the criterion \( F(9 \, \mu m) / F(Ks) > 2 \), and classified into three populations of galaxies according to their \( L_{\text{IR}} \), where \( F(9 \, \mu m) \) and \( F(Ks) \) are the flux densities at 9 μm and the Ks-band taken with AKARI and 2MASS, respectively, and \( L_{\text{IR}} \) is the IR (8–1000 μm) luminosity derived from IRAS (Sanders & Mirabel 1996). Eighteen galaxies are defined as IR galaxies (IRGs: \( L_{\text{IR}} < 10^{11} \, L_\odot \)), 89 luminous IR galaxies (LIRGs), and 55 ULIRGs. The other 22 galaxies have no information on \( L_{\text{IR}} \), because they were not detected with IRAS.

2.2. Result

We detect the PAH 3.3 μm feature from 134 out of 184 galaxies. Most of them show the Brγ emission line. The other galaxies show a red continuum typical of Active Galactic Nucleus (AGNs). We excluded sources which are likely contaminated by AGN activity, based on the rest-frame equivalent width of the PAH 3.3 μm feature (< 40 nm; Moorwood 1986) and the power-law index representing the slope of continuum emission (> 1; Imanishi et al. 2010). As a result, 100 objects are defined as star-forming galaxies (SFG). Figure 1 shows the relationship between the ratio of the PAH 3.3 μm luminosity, \( L_{\text{PAH3.3}} \), to \( L_{\text{IR}} \) and \( L_{\text{IR}} \). At low \( L_{\text{IR}} \left( 10^8–10^{11.5} \, L_\odot \right) \), \( L_{\text{PAH3.3}} / L_{\text{IR}} \) is \( \sim 10^{-3} \), which is a typical value for starburst galaxies (Mouri et al. 1990; Imanishi 2002). At higher \( L_{\text{IR}} \left( \gtrsim 10^{11.5} \, L_\odot \right) \), however, \( L_{\text{PAH3.3}} / L_{\text{IR}} \) shows a significant decline with \( L_{\text{IR}} \).

2.3. Discussion

The decline of \( L_{\text{PAH3.3}} \) with \( L_{\text{IR}} \) (Figure 1) can be caused by (1) effects of hidden AGNs (Kim et al. 2012), (2) photo-dissociation of PAHs under intense ultraviolet (UV) radiation due to star-formation activity, (3) effects by heavily obscured star-forming region (Kim et al. 2012), and (4) intrinsically low abundance ratios of PAHs to classical grains. We compared
Figure 1. $L_{PAH3.3}/L_{IR}$ plotted against $L_{IR}$ for the galaxies with no AGN signatures: IRGs (circles), LIRGs (triangles), and ULIRGs (diamonds). The solid line shows $L_{PAH3.3}/L_{IR}$ of $10^{-3}$ (Mouri et al. 1990; Imanishi 2002).

Figure 2. $L_{PAH3.3}/L_{IR}$ plotted against $T_{dust}$ (Left) and $M_{dust}$ (Right) for the galaxies with no AGN signatures: IRGs (circles), LIRGs (triangles), and ULIRGs (diamonds).

$L_{PAH3.3}/L_{IR}$ of the SFGs with that of the galaxies with AGN signatures. As a result, we confirm that IRGs and LIRGs with AGN signatures show systematically lower $L_{PAH3.3}/L_{IR}$ ratios than those with no AGN signatures. However, for the ULIRGs, there is no systematic difference between galaxies with and without AGN signatures. This suggests that the hidden AGNs, if any, may not appreciably decrease $L_{PAH3.3}/L_{IR}$ for our sample ULIRGs.

Figure 2 displays $L_{PAH3.3}/L_{IR}$ against the dust temperature, $T_{dust}$, and dust mass, $M_{dust}$, which are obtained by the ratio of the IRAS 60 to 100 µm flux densities with the emissivity power-law index $\beta = 1$. The ratio $L_{PAH3.3}/L_{IR}$ systematically changes from population to population. LIRGs and ULIRGs span a wide range of $T_{dust}$ and do not show correlation within each population, which implies that the photo-dissociation by UV radiation is not a major cause because $T_{dust}$ is determined from the intensity of UV radiation.

In Figure 2 Right, ULIRGs, which show small $L_{PAH3.3}/L_{IR}$, have a copious amount of dust grains. If star-forming regions are heavily obscured by the dust, $L_{PAH3.3}/L_{IR}$ decreases due to dust extinction. This is also the case with the ratio of the Br$\alpha$ emission line to IR luminosity, $L_{Br\alpha}/L_{IR}$, because both Br$\alpha$ and PAH 3.3 µm emission appear at similar wavelengths in the near-IR. Besides, soft radiation from heavily-embedded YSOs may contribute to increasing $L_{IR}$, but not much to increasing $L_{PAH3.3}$ because it is too soft to excite PAHs. In this case, it is likely that the Br$\alpha$ emission is relatively weak, similarly to the PAH 3.3 µm emission. Figure 3 Left shows $L_{Br\alpha}/L_{IR}$ plotted against $L_{IR}$, from which we find that $L_{Br\alpha}/L_{IR}$ does not significantly decrease with $L_{IR}$, unlike $L_{PAH3.3}/L_{IR}$. This implies that neither dust extinction nor contribution of soft radiation field on $L_{IR}$ is important.

Figure 3 Right displays $L_{PAH3.3}/L_{IR}$ plotted against $L_{PAH3.3}$, revealing that each galaxy population has a different relationship between $L_{PAH3.3}/L_{IR}$ and $L_{PAH3.3}$. The abundance ratios are systematically different between the populations. Consequently, we conclude that the intrinsically low abundance ratios of PAHs to classical grains are likely to cause the
regions are heavily obscured by the dust, each population, which implies that the photo-dissociation by UV radiation is not a major cause because T changes from population to population. LIRGs and ULIRGs span a wide range of from the intensity of UV radiation.

PAH3.3/IR displays. Figure 2. DISPLA3.3/IR plotted against LIR, ULIRGs, which show small PAH3/IR, because both Br α and PAH 3.3 µ emission. Figure 3. The abundance ratios are systematically different between the populations. (Mouri et al. 1990; Imanishi 2002). This implies that neither dust extinction

small LPAH3.3/IR in the population of the ULIRGs. A plausible scenario is that PAHs may have been destroyed once by a shock during a merging process, whereas large dust grains survive.

3. STUDY WITH THE SPICA/SCI

We aim to observe a systematic change of the ratio from an interacted region to others, or from outer to inner areas, within a galaxy. The spatial resolution of AKARI was too poor to discuss the distribution of PAHs and classical grains. Coronagraphic spectroscopy with the SCI can reveal them near bright central nuclei of local ULIRGs. More specifically, spatial variations in the mid-IR continuum shape would provide us with information on those in the dust size distribution decoupled from those in temperature. Utilizing the silicate features as tracers of classical grains, we investigate spatial variations in the relative abundance of PAHs to classical grains within a galaxy. Thermal annealing during merging processes might even crystallize silicate grains, which is probed by changes in the profiles of the silicate features. They will reveal the scene of the processing and destruction of dust grains with shocks during merging processes.

We would like to thank all the AKARI team members for their continuous efforts. This research is based on observations with AKARI, a JAXA project with the participation of ESA.

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Studying Merger Processes of GOALS Luminous Infrared Galaxies with **SPICA**

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**ABSTRACT**

We present the results of an on-going survey of $^{12}$CO($J=1-0$) with the Nobeyama 45 m telescope of an unbiased sample of 44 Luminous Infrared Galaxies selected from the Great Observatories All-sky LIRG Survey (GOALS). The Nobeyama CO survey is being conducted to investigate molecular gas properties and star-formation efficiencies as a function of merger stage and active galactic nuclei (AGN) fraction in LIRGs. The results show that the $L_{IR}/M_{H2}$ ratio, which is proportional to the star formation efficiency (SFE), is higher at the last stage of merger than at the early and middle stages. **SPICA** will provide highly spatially resolved mid-/far-IR imaging and spectroscopic data, and will enable us to obtain information on individual star-forming associated with merger for local LIRGs. We will present the importance of the IR continuum and mid/far-IR lines local LIRGs at high spatial resolution to investigate variations of structures and activity of the star-forming regions in the process of merging.

1. **INTRODUCTION**

LIRGs, which have the infrared luminosity with $L_{IR} > 10^{11} L_\odot$ (Sanders & Mirabel 1996), are an important class of galaxies for understanding SB and the generation and fueling of AGN. They also dominate the far-IR background for $z > 0.5$. In the local universe LIRGs are in various stages of galaxy-galaxy interaction and have been shown to host powerful SBs and AGN. From detailed studies of the mid-infrared and X-ray spectra of LIRGs (Petric et al. 2011; Díaz-Santos et al. 2010; Iwasawa et al. 2011; Stierwalt et al. 2013) it has been shown that most local LIRGs are SB-dominated. Only about 15–20% of the energy in LIRGs as a class comes from buried AGN. These diverse environments in which local LIRGs are involved are inferred to affect their star formation activities or their evolutions. In studying the star formation of local LIRGs, molecular gas content is basic information. Moreover the molecular gas mass supplies the star formation efficiency (SFE) together with star formation rate. $^{12}$CO ($J=1-0$) emission line ($\nu_{\text{rest}} = 115.27 \text{ GHz}$) is a good tracer to estimate molecular gas mass (Solomon et al. 1987). Therefore a large data set of $^{12}$CO ($J=1-0$) of local LIRGs is required to investigate the star formation statistically. However some previous CO surveys for local LIRGs were biased into more luminous LIRGs on infrared and/or CO line (e.g. Gao & Solomon 2004a,b). Therefore we need to obtain a large unbiased data set of CO for local LIRGs. We conducted a CO survey for local LIRGs of the Great Observatories All-sky LIRG Survey (GOALS). GOALS is a comprehensive project investigating a complete sample of local LIRGs utilizing multi-wavelength observational data (Armus et al. 2009).

2. **$^{12}$CO ($J=1-0$) SURVEY FOR GOALS LIRGS**

We conducted the $^{12}$CO ($J=1-0$) of 74 LIRGs using the 45 m Telescope at the Nobeyama Radio Observatory (NRO) over four observing runs from January 2010 to February 2013. The target sample is uniform and consisting of 67 LIRGs and 7 ULIRGs ($z = 0.014-0.036$) from the GOALS LIRG sample, which includes all LIRGs catalogued in the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003). The target sources include all stages of galactic interaction/merger, has various activities of AGN, and has the IR luminosities of $1.12 \times 10^{11} - 3.72 \times 10^{12} L_\odot$, which are calculated from the IRAS four bands from 12 $\mu$m through to 100 $\mu$m using the equation in Sanders & Mirabel (1996).

CO emissions from the sources were measured by single-point observations whose coordinates are the brightest points in their 24 $\mu$m images of MIPS/Spitzer. We applied the mapping observation with half-beam spacing to some extended sources. The main beam size (i.e. the full width to half maximum of the main beam pattern) of the telescope at 115 GHz is $15''$, corresponding to $\sim 7.3$ kpc at the typical distance of the sample, 100 Mpc. For almost all sources except for those observed in the first run, we utilized a new broad bandwidth spectrometer. This newly introduced spectrometer, SAM45,
enable us to obtain lines with even much wider velocity-width. SAM45, a FX-type correlator, was employed in the mode of a frequency coverage of 2 GHz (=5217 km/s).

3. RESULT AND DISCUSSION

3.1. Large CO Data of GOALS LIRGs

We present the CO emissions from 44 GOALS LIRGs (55 galaxies) observed with the single-point observations in the first to third run. This provides a large CO data set for local LIRGs without any selection bias. Our observational result shows that $M_{\text{H}_2}$ of the sample ranges from $7 \times 10^8 M_\odot$ to $2.6 \times 10^{10} M_\odot$ (CO-H$_2$ conversion factor $\alpha_{\text{CO}} = 2.45 M_\odot (\text{K} \text{ km s}^{-1} \text{ pc}^2)^{-1}$, ref. Bryant & Scoville 1999). Some sources have more than 600 km s$^{-1}$ of the velocity width of the emission line. Some sources have a line with a double-peak.

Some CO fluxes with NRO 45 m (HPBW=15$''$) are about 15–70 % lower than those by a previous study with NRAO 12 m (HPBW=55$''$, Sanders et al. 1991) because of a difference of the beam sizes of the both telescopes. Some galaxies apparently have CO distributions extended over the beam size of NRO 45 m. We therefore flag the extended sources that have a larger spatial profile of the 70 $\mu$m image than the NRO 45 m beam. We hereafter discuss the 55 sources measured by the single point observation in the first three years.

3.2. Merger Process in GOALS LIRGs

Galaxy-galaxy interaction can trigger violent star-forming activity and the fueling of central black holes. Since the SFR is not expected to be uniform during the merger process (e.g., Mihos & Hernquist 1996), exploring the ratio of the infrared luminosity and the molecular gas mass can tell us about the star-formation efficiency during the merger. We compare $L_{\text{IR}}/M_{\text{H}_2}$ ratio, which is proportional to SFE, with the merger stages. The sources are morphologically classified according to the classification in Stierwalt et al. (2013) into three groups. Stage 0 contains the non-interacting galaxies. Stage 1 correspond to the three stages of the pre-mergers, the early-stage mergers and the mid-stage mergers in Stierwalt et al. (2013). The last-stage mergers are assigned to Stage 2. Figure 1 shows a significant increase in $L_{\text{IR}}/M_{\text{H}_2}$ ratio between the Stage 1 and the Stage 2 for a LIRG sample except both AGN-dominated galaxies (Petric et al. 2011; Stierwalt et al. 2013) and the extended galaxies in far-IR. Although this is a preliminary result, it shows higher efficiency of the star formation at the last stage of merger.
STUDY OF MERGER PROCESSES IN GOALS LIRGs WITH SPICA

4. PLAN FOR SPICA

The spatially resolved mid-/far-IR images by SPICA enable us to trace the spatial transition of violent star-forming regions at each merger stage. The resolution of MCS/WFC-L (2″4) compares with giant molecular complexes (a few sub kpc) on local LIRGs. The detailed view on merger processes requires the physical conditions: temperature, density, ionization condition. Fine structure lines observed with SAFARI will provide the physical conditions without effects by heavy dust. While CO(J=1–0) observations trace the cold molecular gas, \( \text{H}_2 \) pure rotation transitional lines in mid-IR trace the warmer molecular gas, which is associated with PDR, X-ray or shock. Therefore \( \text{H}_2 \) lines observation with SPICA provide full amount of molecular gas throughout cold to hot one together with the CO observations. The warm gas fraction at each stage of merger might probe the star-formation in galaxies (Dale et al. 2005). The knowledge of warm molecular gas in local LIRGs can be applied to LIRGs at high redshift. We plan to investigate the evolution of the properties of molecular gas from high redshift to local LIRGs.

5. SUMMARY

We conducted the survey of \(^{12}\text{CO}(J=1–0)\) with the Nobeyama 45 m telescope from the unbiased selected 44 GOALS LIRGs. We find that the \( L_{\text{IR}}/M_{\text{H}} \) ratio increases between the last stage of merger and at the early/middle stages. The high spatial resolution and the high sensitivity of SPICA will enable us to investigate where is the burst induce in local interacting LIRGs and how do the physical conditions or the properties of molecular gas progress as the interacting phase.

We thank the staffs at Nobeyama Radio Observatory, which is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences, for many technical supports on our observations. Takuji Yamashita acknowledges the financial support from the Center of Excellence Program by MEXT, Japan through the “Nanoscience and Quantum Physics” Project of the Tokyo Institute of Technology.

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Perspective on Extra-Galactic Studies with MCS WFC Slit-less Spectroscopy Survey

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2Institute of Space and Astronautical Science, JAXA, Japan
3Department of Earth Sciences, National Taiwan Normal University, Taiwan
4Department of Astronomy, the University of Tokyo, Japan

ABSTRACT

The wide field camera of MCS onboard SPICA will have an unique capability of slit-less grism spectroscopy survey. It utilizes wide (5′ × 5′) field of view (FOV), and spectra of all sources within the FOV would be acquired at once with grisms mounted on filter wheels, covering 5–38 µm in total. We simulate the slit-less spectroscopy images of a realistic deep universe with galaxies populated according to their luminosity function in order to examine detectability of galaxies as a function of their luminosity and redshift while quantitatively assessing source overlapping problem.

1. INTRODUCTION

MCS (Mid-infrared Camera and Spectrograph Kataza et al. 2011) onboard SPICA (Nakagawa et al. 2011) is an imaging and spectroscopy instrument to cover 5–38 µm. For imaging, two wide-field cameras (WFC) cover 5′ × 5′ field of view (FOV) for each -S and -L channel. For spectroscopy, WFC utilizes low-resolution grisms (R ≃ 50) mounted on its filter wheels. Four grisms, SG1, SG2 (both in WFC-S channel), LG3, and LG4 (both in WFC-L channel) cover 5–9, 8–15, 14–26, and 24–39 µm, respectively. In addition to (short-)slit spectroscopy, slit-less mode is available to utilize full WFC FOVs. Since its capability/limitation has not been fully explored yet, this paper addresses its scientific capability for extra-galactic survey science cases by conducting realistic simulations of the sky in slit-less survey mode.

The slit-less mode is unique in many aspects, and here we summarize its pros and cons. Pros in general are: (a) Multi-object spectroscopy is made. (b) Little selection effect is introduced since no a-priori target selection information is needed when compared with targeted slit spectroscopy. Pros specific to extra-galactic science cases are: (c) Spectral typing to identify their activity (normal/star-forming/AGN/stellar) is readily made. (d) Spectroscopic redshift measurement (at R ∼ 50) is made, and luminosity is readily measured. Cons are: (1) Source overlapping/contamination will damage the information. (2) Sensitivity is shallower than the slit spectroscopy due to higher sky background. We believe it important to quantitatively examine those pros and cons to help designing scientifically attractive and technically feasible survey parameters (e.g., sensitivity, redshift range, area coverage, and required hours). Therefore we performed the slit-less observation simulation, and report the results here.

2. SIMULATION DETAILS

The simulation is made of two parts: observation part and source extraction part. For observation simulation, we adopt the latest specifications of MCS and SPICA, including aperture size (3 m), MCS optics (FOV, pixel scale, system throughput, grism wavelength coverage and resolution Kataza et al. 2011) and detector performance (quantum efficiency, readout noise Wada et al. 2011). Galaxies are assumed to follow AKARI rest frame 8 µm luminosity function by Goto et al. (2010) with some extrapolation toward higher redshift, and are randomly distributed on sky. For each galaxy, a representative star-forming galaxy spectral energy distribution (SED), a M82 SWIRE template in which only PAH features around rest 5–15 µm are replaced by M82 ISO/SWS high resolution spectrum. Assuming deep extra-galactic survey toward ecliptic pole, the low zodiacal light conditions (T = 273 K, 15 MJy/str at 25 µm) are used. For comparison, we simulated for two exposure times: 3600 sec and 600 sec. Source detections are made at redshifted PAH 7.7 µm peak (3 sigma), and spectra are extracted over boxes with wavelength- (point spread function (PSF)-) depending width. Once a source is detected in one grism image, extraction is made over all four grism images. When a part of the wavelength region is overlapped by neighbors, only that part is masked in the extracted spectra while it is counted as overlapped source for overlap statistics.

3. RESULTS

Simulated slit-less spectroscopy images are shown in Figure 1. Redshifted galaxies are very red within MCS wavelength coverage, and they become more evident in longer LG3 and LG4 bands. Overlap fraction increases for redder bands and longer exposure case (Table 1), and the extracted one-dimensional spectra show missing wavelength regions due to the overlap masks (Figure 2). Figure 3 highlights luminosity-redshift parameter space where larger number of sources and
Figure 1. Simulated images over $5' \times 5'$ with 3600 sec exposure. Four vertical panels show the same field in broad-band (left columns), slit-less spectroscopy (center columns), and overlap images (right columns) taken with four grisms (SG1, SG2, LG3, and LG4 from top to bottom). In the central columns, wavelength increases upward.

brighter sources are preferentially detected. Note that results with 600 sec exposure are not shown in figures, but overlap statistics is shown in Table 1 together with the case of 3600 sec exposure.

Table 1. Source overlap fraction

<table>
<thead>
<tr>
<th>Exposure time</th>
<th># of detected sources</th>
<th>SG1</th>
<th>SG2</th>
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</tr>
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<tr>
<td>3600 sec</td>
<td>154</td>
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<td>54%</td>
</tr>
<tr>
<td>600 sec</td>
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<td>0%</td>
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4. DISCUSSIONS

With 3600 sec exposure, $> 100$ galaxies are detected per FOV up to $z = 2$ and beyond. For the redshift range, the most prominent PAH $7.7 \mu m$ feature comes at LG3 for $z \lesssim 2$ and SG2 for $z \lesssim 1$, and it can be easily recognized. In such a situation, together with rather low spectral resolution ($R \approx 50$) and limited S/N quality for most distant/faintest sources, detailed spectral feature fitting analysis would not be possible for most sources. Rather, simple Gaussian/Lorenzian PAH fitting seems to work fine for measuring redshift, PAH flux, and, hence, PAH luminosity. Combined analysis with broad-band photometry may also be helpful (see Wada et al. in this proceedings). Overlapping fraction is as high as 50% in the worst case, LG4 in 3600 sec exposure, due to larger PSF in pixel unit. However, we note that even a part of the spectrum is damaged by overlapping, it is flagged to be “overlapped” in this statistics, which may be too stringent. In fact half of the overlapped sources still show detectable PAH $7.7 \mu m$ feature for redshift measurement, and most of them are in SG2 or LG3 where overlapping is less severe.

We are successful in demonstrating that the slit-less extra-galactic survey with MCS/WFC is feasible though with some overlapping problem, and is still powerful for detecting PAH and, hence, spectral typing. We expect the mode provides an
Figure 1. Simulated images over 5′ × 5′ with 3600 sec exposure. Four vertical panels show the same field in broad-band (left columns), slit-less spectroscopy (center columns), and overlap images (right columns) taken with four grisms (SG1, SG2, LG3, and LG4 from top to bottom). In the central columns, wavelength increases upward. Brighter sources are preferentially detected. Note that results with 600 sec exposure are not shown in figures, but overlap statistics is shown in Table 1 together with the case of 3600 sec exposure.

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We are successful in demonstrating that the slit-less extra-galactic survey with MCS/WFC is feasible though with some overlapping problem, and is still powerful for detecting PAH and, hence, spectral typing. We expect the mode provides an efficient way to explore galaxy evolution with PAH-related quantities (cosmic evolution of star formation rate (density), AGN fraction, etc.) up to $z \gtrsim 2$. Optimally designing the survey parameters will be our next step.

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Intensity Mapping of Fine Structure Line Emission as a Probe of Large Scale Structure and the Evolving ISM in Dusty, Star-Forming Galaxies at Moderate Redshift

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ABSTRACT

We explore the possibility of studying redshifted far-IR fine-structure transitions through cosmic time using 3-dimensional power spectra obtained with an imaging spectrometer. The intensity mapping approach measures the spatio-spectral fluctuations due to line emission from all galaxies, including those well below the individual detection threshold. With assumptions about large-scale structure, the large-scale fluctuations measure the total volume emissivity in a given transition, with redshift information naturally encoded. We consider as specific examples the possibility of studying redshifted [O I] 63 μm and [Si II] 35 μm with the SAFARI instrument aboard SPICA. While envisioned SAFARI surveys will only detect the brightest galaxies individually, the fluctuation signal from the aggregate population is detected with high significance: cumulative SNR of order ~100 for both the total and shot noise power spectra, and order ~10 for the clustering power spectrum from surveys sketched in this proceedings article.

1. ABOUT INTENSITY MAPPING

Intensity mapping is a statistical observation of emission line intensity fluctuations in a volume of the Universe, yielding a data cube in which galaxies need not be either spatially or spectrally resolved. Atomic (Visbal & Loeb 2010; Gong et al. 2012) and molecular (Lidz et al. 2011) transitions—such as the 21 cm spin flip transition from H I, CO (2–1), and [C II] 158 μm—have been investigated as candidates for line intensity mapping experiments during the Epoch of Reionization. Of these, the neutral hydrogen case is undoubtedly the most developed in terms of its standing in the literature and in the experimental arena (e.g., PAPER, MWA, and LOFAR), and so interest in measuring other line power spectra has primarily erupted as a means to complement the 21 cm studies at high redshift via the cross-correlation.

Here we examine, however, the feasibility and value of measuring the 3-dimensional (3D) auto-power spectra of infrared fine structure (FS) emission lines at low to moderate redshifts, specifically between 0.5 < z < 3. Two intrinsic qualities of the intensity mapping technique—namely, the ability to map large areas of sky while encoding redshift information in the spectral dimension, and the sensitivity to galaxies which are below the threshold for individual detections of current and future instruments—guide our discussion in what follows.

2. PREDICTIONS FOR FS LINE POWER SPECTRA: AN EMPIRICAL APPROACH

The complete 3D auto-power spectrum of a given FS line (denoted by the subscript i) as a function of wavenumber k and redshift, P_i(k, z), can be separated into power from the clustering of galaxies, P^{clus}_{i,k} and a Poisson term, P^{shot}_{i,k}(z). We compute the full nonlinear dark matter power spectrum, P_{δ,δ}(k, z), with the widely used, publicly available code HALOFIT+ (Smith et al. 2003). The clustering component of the line power spectrum is then written as

\[ P^{clus}_{i,k}(k, z) = \tilde{S}_i^2(z) \tilde{B}_i(z) P_{δ,δ}(k, z). \]  

This expression implicitly assumes that the fluctuations in line emission trace the matter power spectrum with some average bias, \( b_i(z) \).

The mean intensity \( \tilde{S}_i \) and shot noise power \( P^{shot}_{i,k}(z) \) are, in turn, calculated using the IR luminosity function, \( Φ(L_{IR}, z) = \frac{dN(L_{IR}, z)}{dL_{IR}} \):

\[ \tilde{S}_i(z) = \int_{L_{IR, min}}^{L_{IR, max}} dL_{IR} Φ(L_{IR}, z) \frac{f_i L_{IR}}{4πD_L^2} y_i L_A^2 \]  

\[ P^{shot}_{i,k}(z) = \int_{L_{IR, min}}^{L_{IR, max}} dL_{IR} Φ(L_{IR}, z) \left( \frac{f_i L_{IR}}{4πD_L^2} y_i L_A^2 \right)^2, \]
UZGIL, AGUIRRE, AND BRADFORD

Figure 1. Left: Predicted mean intensity of FS line emission plotted versus redshift, and Right: observed wavelength (and frequency).

Figure 2. Left: Predicted [O I] 63 $\mu$m power spectrum. Power from clustering and shot noise are shown as the dotted and dashed curves, respectively (see text for survey parameters). Right: SNR vs $k$ for the total, clustering, and shot noise power.

where $f_i$ is the fraction of IR luminosity emitted in line $i$, $y_i$ is the derivative of the comoving radial distance with respect to the observed frequency, i.e. $y_i = \frac{d\chi}{d\nu} = \frac{\lambda_i}{(1+z)^2/H(z)}$, $D_L$ is the luminosity distance, and $D_A$ is the comoving angular distance. To make explicit predictions, we use the IR luminosity function of Béthermin et al. (2011) and line ratios of Spinoglio et al. (2012). We note that other choices are possible, but the former accurately reproduces the known continuum number counts of galaxies, and the latter summarizes the current state of knowledge of FIR lines from local surveys. The resulting $\bar{S}_i$ for a variety of FS lines are plotted in Figure 1 as functions of redshift and observed frequency. $\bar{S}_i$ vs $\lambda_{obs}$ can be interpreted as identifying the dominant source of fluctuations, according to our model, at a given wavelength. It will be necessary to distinguish between the target line and contaminants from different redshifts which nonetheless contribute power at the observed frequency. Visbal & Loeb (2010) showed how the cross spectra can be used to differentiate between a target line and a so-called “bad line”, since emission at different redshifts will be spatially uncorrelated.

An example power spectrum for the bright line [O I] 63 $\mu$m, observed at $z = 1.5$, is shown in Figure 2 (left panel). For this calculation, total observing time is fixed at 450 hours, and survey size is varied from 5.3 deg$^2$ to 130 deg$^2$, corresponding to a time per pixel of 0.09 to 0.003 hr, respectively. We calculate error bar estimates and Signal-to-Noise Ratio (SNR) for the power spectrum by assuming a spectrally flat noise power spectrum, so that the noise power in each pixel, $P_N$, is $\sigma_N^2 V_{pix} t_{pix}$, where $\sigma_N^2$ is the instrument sensitivity (noise equivalent intensity, or NEI, in units of Jy sr$^{-1}$ Hz$^{-1/2}$), $V_{pix}$ is the pixel volume, and $t_{pix}$ is the time spent observing on a single pixel. The variance of a measured $k$, $\sigma^2(k)$, is $\left(\frac{P_i(k,z) + P_N}{N_{mode}}\right)^2$, where $N_{mode}$ is the number of wavemodes that are sampled for a given $k$ bin of some finite width. In calculating the power spectrum sensitivity, modes with line-of-sight component equal to zero are discarded, since these will likely be compromised by the necessity of continuum foreground subtraction. To demonstrate the feasibility of measuring galaxy clustering modes on the linear scale, the nonlinear scale, and the transition between the two regimes, we also present in Figure 2 (right panel) SNR on the power spectrum as a function of $k$. (Note that we use $\Delta_i^2 = k^3 P_{\delta\delta}(k)/(2\pi^2)$ when plotting the power spectrum throughout this proceedings. In this notation, the factor $k^3$ cancels out the volumetric units in $P_{\delta\delta}(k,z)$, and the integral of $\Delta_i^2$ over dln$k$ equals the variance in real space.)
LINE INTENSITY MAPPING OF FINE STRUCTURE EMISSION

Figure 3. Left: Fraction of total \([\text{O} \text{I}] 63 \mu \text{m}\) intensity as a function of lower limit in the luminosity function. The vertical green dotted line denotes the \(5\sigma - 1\) hr SAFARI sensitivity. Right: \([\text{O} \text{I}] 63 \mu \text{m}\) power spectrum at \(z = 1.5\) before (blue curve) and after (green curve) removal of SAFARI-detected sources.

3. UNIQUELY PROBING THE MAJORITY OF LINE EMISSION

Figure 3 (left panel) shows the fraction of total line intensity recovered by integrating Equation 2 with different \(L_{\text{IR,min}}\), calculated up to \(z = 3\). (\(L_{\text{IR,max}}\) is fixed at \(10^{13} L_\odot\).) Beginning at \(z \approx 1.5\) for \([\text{O} \text{I}] 63 \mu \text{m}\) and most other lines, it becomes apparent that \(\gtrsim 50\%\) of the line intensity from all extragalactic emitters at the same \(z\) will be unresolved by SAFARI. The problem is particularly dramatic at the upper end of the redshift range accessible to SAFARI. For example, \(\lesssim 20\%\) of the \([\text{Si} \text{II}] 35 \mu \text{m}\) emission at \(z = 3\) is recoverable at the \(5\sigma - 1\) hr level, whereas the total SNR on the \([\text{Si} \text{II}]\) power spectrum is \(\sim 40\) in a mere 45 hours of integration time on a 0.5 deg\(^2\) field (figure not shown). However, it is important to note that the shot noise term is weighted more heavily toward high luminosity systems (cf. Equation 3).

On the other hand, the clustering power spectrum is sensitive to intensity fluctuations from the full range of normal to ULIRG-class systems because it is proportional to the first moment of the luminosity function (cf. Equation 2). In order to successfully extract \(\tilde{S}_1\) from the power spectrum, it is necessary to divide out \(P_{\sigma,\delta}(k, z)\) and \(\bar{b}_1\). The confidence with which these are \(a \text{ priori}\) known quantities becomes lower as \(k\) increases. For example, bias appears to be truly independent of luminosity only at large physical scales (Viero et al. 2013), indicating the need to map wide areas in order to derive \(\tilde{S}_1\). Returning, as an example, to the \([\text{O} \text{I}] 63 \mu \text{m}\) power spectrum plotted in Figure 2, Figure 3 (right panel) now compares the predicted power from one such wide, 15 deg\(^2\) survey (blue curve) with the predicted power that remains after galaxies above SAFARI’s detection threshold have been excised from the survey (green curve); the total SNR on the clustering-only power spectrum remains high, decreasing from 15 to 10 as a result of the cut. This kind of wide area survey is prohibitively time-consuming for SAFARI if striving for individual detections, and at 0.09 hr per pixel for the 450 hr integration, SAFARI would not detect \(\sim 80\%\) of \([\text{O} \text{I}] 63 \mu \text{m}-\) bright sources, according to our model. Thus, intensity mapping remains a viable means of measuring aggregate line emission as a function of redshift, and characterizing clustering of the low luminosity population.

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**SPICA Distant Cluster Survey: Unveiling the Dust-Obscured Star Formation Triggered by Young Cluster Environments**

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1National Astronomical Observatory of Japan, Japan
2Institute for Cosmic Ray Research, University of Tokyo, Japan
3Subaru Telescope, National Astronomical Observatory of Japan, U.S.A.
4The Graduate University for Advanced Studies, Japan
5Institute of Space and Astronautical Science, JAXA, Japan

**ABSTRACT**

We present the results of our star-forming galaxy survey of distant clusters of galaxies using Subaru (Hα) and AKARI (MIR). By comparing the Hα and MIR data, we revealed that dust-obscured star-forming galaxies are most preferentially located in the cluster outskirts at \( z \sim 1 \). We propose to extend this Hα- and IR-based environmental study to higher redshifts, but a problem so far is that the existing MIR–FIR surveys always suffer from their limited depths. We can overcome this problem with the wide-field mid-infrared (MIR) camera on-board **SPICA** (5″FoV), which will allow us an efficient, and extremely deep MIR survey of distant clusters. In particular, the expected high sensitivity of **SPICA** at 20–40 μm regime promotes us to extend IR galaxy survey out to \( z = 2–4 \) (i.e. the “peak epoch” of galaxy evolution) based on their rest-frame 8 μm feature. We provide a quick overview of our recent progress with the MAHALO-Subaru collaboration, and then discuss how significantly **SPICA** can improve our understanding of the environmental effects on galaxy evolution in the early universe.

1. **INTRODUCTION**

Galaxy clusters in the distant universe are ideal laboratories for studying environmental effects on galaxy formation and evolution in the early universe. In the local universe, galaxy clusters are dominated by red early-type galaxies (e.g. Dressler 1980; Goto et al. 2003). These red cluster population form a tight colour–magnitude sequence, indicating that the majority of their stellar components are formed in the very early universe at \( z \gg 1 \) with relatively short time scales (e.g. Bower et al. 1992; Kodama et al. 1998). It is therefore crucial to study young (star-bursting) cluster galaxies in order to fully understand the physical drivers of the evolution of cluster galaxies.

Recent observations have shown that star formation (SF) activity in galaxies (as traced through cosmic star formation rate density) has its peak at \( z \sim 1–3 \) (e.g. Hopkins & Beacom 2006). In this peak epoch of galaxy formation, it is suggested that the contribution of LIRG or ULIRG-class population is much higher than in the local universe. In such luminous systems, a large fraction of SF activity are obscured by dust (e.g. Le Floc’h et al. 2005; Goto et al. 2010). This is of course true for distant cluster galaxies as well. Deep MIR–FIR studies of distant clusters are thus essential to unveil the real (dust-obscured) SF activity taking place within young cluster galaxies.

With an advent of **AKARI**, **Spitzer** and **Herschel** space telescopes, recent IR studies of distant clusters have unveiled dust-obscured SF activity (down to LIRG-class population) in distant cluster environments out to \( z \sim 1 \) (e.g. Geach et al. 2006; Koyama et al. 2008). These IR studies of distant galaxy clusters showed that SF activity is enhanced in the cluster in-fall regions (see Section 2). The number of known (proto-)clusters \((z > 1.5)\) have been increased, and Hα or [O II] emission-line surveys of these high-\( z \) clusters have unveiled highly star-forming cluster members in the high-\( z \) cluster core regions, suggesting a dramatic change of the nature of cluster galaxies at the peak epoch of galaxy formation (Hayashi et al. 2010; Tadaki et al. 2012; Koyama et al. 2013a). One of the important goals of the **SPICA** mission is to completely unveil the dust-obscured SF activity within these young forming galaxy clusters with extremely deep MIR–FIR observations (see Section 3).

2. **DUST-ENSHROUDED STAR FORMING GALAXIES AROUND DISTANT CLUSTERS AT \( z \sim 1 \)**

We here present a highlight of our Hα and MIR study of a distant galaxy cluster at \( z = 0.81 \) (RXJ1716+6708) with Subaru and **AKARI**. In the left-hand panel of Figure 1, we show the spatial distribution of narrow-band-selected Hα emitters and MIR galaxies (Koyama et al. 2010). It can be seen that both of these population avoid the cluster central part, suggesting that SF activity of galaxies in the core of this cluster was completely terminated before \( z \sim 0.8 \). On the other hand, a large fraction of galaxies are still actively forming stars in the cluster outskirts regions. We measured their star formation rates independently from Hα and MIR (rest-frame 8 μm) luminosities, and find that the extinction at Hα is
Figure 1. Left: A 2-D map of galaxies around the RXJ1716 cluster at $z = 0.81$. The meanings of the symbols are indicated in the plot. The dashed-line boxes show our MOIRCS FoVs (the survey area of Hα emitters). Note that the Hα survey area is fully covered by our AKARI 15 µm observation. Right: The SFR(IR)/SFR(Hα) ratio plotted against SFR(IR). This plot demonstrates that the Hα emission lines are heavily obscured by dust for very luminous sources, and these dusty sources are most prevalent in the medium-density groups/filaments.

Figure 2. Left: The spatial distribution of Hα emitters at $z = 2.16$ around the PKS 1138 proto-cluster field. The filled circles, triangles, and squares show red ($J - K_s > 1.4$, green ($0.8 < J - K_s < 1.4$), and blue ($J - K_s < 0.8$) emitters, respectively. The open circles and triangles denote DRGs and $K_s$-undetected emitters, respectively. Right: A color–magnitude diagram ($J - K_s$ versus $K_s$) for Hα emitters at $z \sim 2$ in cluster (top) and field environments (bottom). The filled circles show the 24 µm-detected galaxies. It is clear that there is a strong excess of massive/red SF galaxies ($M_\star > 10^{11} M_\odot$) in the cluster environment, while these massive population are very rare in general field environments at the same redshift.

$A_{H\alpha} \sim 1$ mag for moderately star forming galaxies, which is consistent with local spirals. However, in some extremely dusty galaxies, this value exceeds $\sim 3$ mag. Such very dusty galaxies show “red” rest-frame optical colors (as red as passively evolving galaxies). Importantly, we find that these dusty galaxies (probably in the transitional phase under the influence of some environmental effects) are most commonly seen in the cluster surrounding groups or filaments (see right-hand panel of Figure 1), which coincide with the environment where galaxy color transition also takes place (e.g. Kodama et al. 2001; Koyama et al. 2008). This result strongly supports an idea that the cluster surrounding environments hold the key for understanding the physics of environment-driven galaxy evolution. In these ways, with a combination of wide-field Hα and MIR study, we find an evidence that the dust-obscured, enhanced SF activities of galaxies are indeed triggered in the cluster in-fall regions, suggesting a strong link between these hidden activity and environmental effects.
SPICA DISTANT CLUSTER SURVEY

3. MASSIVE STARTBURST GALAXIES DISCOVERED IN PROTO-CLUSTERS AT Z > 2

To extend our SF galaxy survey to higher-redshift clusters, we have been conducting the “MAHALO-Subaru” project (MAppling H-Alpha and Lines of Oxygen with Subaru). The aim of this project is to construct a large, uniformly selected sample of SF galaxies in the distant universe (0.4 < z < 2.6), using a lot of narrow-band filters on Subaru. An important advantage of this project is that we observe wide range in environments from general fields (Tadaki et al. 2011) to rich (proto-)clusters (Kodama et al. 2004; Hayashi et al. 2011, 2012; Tanaka et al. 2011; Koyama et al. 2011), allowing us to study environmental effects in the very early universe.

In the left-hand panel of Figure 2, we show the spatial distribution of Hα emitting galaxies in the PKS 1138 proto-cluster at z = 2.16. By examining the properties of Hα emitters along the filamentary structure, we find that galaxies in the proto-cluster environments tend to have redder colours, higher stellar masses, and higher SFRs compared to galaxies in more underdense regions (see the right-hand panel of Figure 2). We note that these “red” SF galaxies have $M_*>10^{11}$ $M_\odot$, suggesting that they already formed a large part of stellar mass contents before z ∼ 2. Furthermore, we find that many of these red emitters are detected in the 24 µm data taken with Spitzer, indicating that they are still vigorously star-forming objects (SFR > 100 $M_\odot$/yr). However, the current IR instruments can detect only extremely luminous sources at z > 1 (ULIRG or HyLIRG class population).

The important role of SPICA is therefore to fully unveil the dust-obscured SF activity taking place in the forming proto-clusters. In particular, the wide field of view of MIR camera of SPICA will allow us to make a panoramic mapping of dusty galaxies over the proto-cluster fields down to faint objects such as LIRG class at z ∼ 2 or ULIRG class at z ∼ 4, based on the rest-frame 8 µm feature. It will also be possible to quantify the obscured active galactic nuclei (AGNs) based on the rest-frame MIR colors. Recent studies suggest that the SF–M* relation is independent of environment since z ∼ 2 as far as the SFRs are derived from Hα luminosity alone (Koyama et al. 2013b), but the SPICA will be able to determine if it is really true when we consider the activity completely hidden by dust.

This work is based on observations with AKARI, a JAXA project with the participation of ESA. Our optical/NIR data are collected with the Subaru Telescope, operated by National Astronomical Observatory of Japan (NAOJ).

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Environmental Dependence of Galaxy Properties Revealed by AKARI and SPICA

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ABSTRACT

We have investigated the dependence of galaxy properties on their surrounding environments with AKARI/IRC. We found less star-forming galaxies tend to be in dense region at \( z = 0.8 \) whereas at \( z > 0.8 \) universe, the star formation are more active in denser region, consistent with the previous work. As an indicator of star formation, we used \( 8 \mu m \) to \( 4.5 \mu m \) flux ratio, which is reduced by the radiation from Active Galactic Nuclei so that it can trace pure star forming galaxies. Such a useful indicator could be used by only AKARI which has a continuous wavelength coverage between 2-24 \( \mu m \). In future work we suggest to extend this work to \( z = 3.5 \) universe using SPICA which has also continuous wavelength coverage at mid-infrared and has a great spatial resolution, which is needed to avoid source blend in dense regions.

1. UNCERTAINTIES IN ENVIRONMENTAL STUDIES

Although galaxies have been growing with their surrounding environment, we do not know the influence of the environment on the galaxy evolution. In the local universe, galaxies in dense regions tend to be massive, quiescent, and composed of old stars, which indicates they had formed a large amount of stars in the past. Recently, it is found that \( z \sim 1 \) galaxies in denser regions have higher star formation rates (Elbaz et al. 2007; Cooper et al. 2008), which is called reversal of environmental effect.

However, this reversal is still in debate; Popesso et al. (2011) shows that when Active Galactic Nuclei (AGNs) are excluded from the sample, the reversal disappears. Patel et al. (2009) found no reversal in a galaxy cluster at \( z \sim 0.8 \). The main reasons for this ambiguity are 1.) an AGN contamination influences the efficacy of standard indicators of the star formation rates, and 2.) an influence of individual galaxy cluster properties might cause systematic uncertainties.

2. ENVIRONMENTAL EFFECT USING AKARI NEP SURVEY

The AKARI NEP-deep survey (Matsuhara et al. 2006) has unique advantages to overcome these uncertainties. The AKARI/IRC (Onaka et al. 2007) continuous filter coverage at 2-24 \( \mu m \) with nine photometric bands enables us to measure the \( 8\mu m \) to \( 4.5 \mu m \) luminosity ratios, which can only be increased by star formation, not by AGN since it increases the luminosity of both bands.

The catalogue of this survey has recently been updated by Murata et al. (2013), who devised new image analysis methods and removed many of contaminations in the previous images. In the revised catalogue, the detection limits of all the mid-infrared bands were improved by \( \sim 20\% \), the source extraction is more than 99\% reliable, and the total number of detected objects was increased by \( \sim 2000 \) compared to the previous version of the catalogue to 9560.

To calculate the local galaxy density, we have estimated photometric redshift with an accuracy of \( \Delta z/(1+z) \sim 0.04 \) at \( z < 0.8 \) and \( \sim 0.05 \) at \( z > 0.8 \) using optical to near-infrared data taken by CFHT/MegaCam(\( u'g'r'i'z' \)) and WIRCam(\( YJKs \)). The calculation was performed using the LePhare code with COSMOS SED templates (Ilbert et al. 2009)

Using the photometric redshift estimated above, we calculated the local galaxy density, assuming the galaxies with the same redshift within 0.05(1 + \( z \)) are at the same epoch. We found dense galaxy regions in the AKARI NEP-deep field at each redshift as shown in Figure 2, where galaxies at \( z = 0.4, 0.7, \) and 1.0 are indicated by magenta, green, and blue points. We calculated the \( 8 \mu m \) to \( 4.5 \mu m \) luminosity ratios for these galaxies, and compare them with their local over-densities. The results are shown in Figure 3. At \( z = 4 \), the luminosity ratio decreases with the density, consistent with trend in the local universe. The galaxies at \( z = 0.7 \) has a similar trend. In contrast, galaxies at \( z = 1.0 \) has an opposite trend; the luminosity ratio increases with the density, indicating the reversal of the environmental effect, consistent with the previous studies.

However, these results still have some difficulties. 1.) Some objects are blended with nearby galaxies, for which we cannot estimate the luminosity ratio accurately. 2.) A significant fraction of galaxies are not detected at optical to near-infrared band, preventing us from calculating the photometric redshift. 3.) The AKARI NEP-deep field does not contain extremely dense region, so that the galaxy properties in these region are still unknown. 4.) We cannot explore the environmental dependence of galaxy properties at higher redshifts, where galaxies are more affected by their environment.
Figure 1. The photometric redshift accuracy calculated using optical to near-infrared data. The accuracy is $-0.013 \pm 0.04$ for $z < 0.8$ and $-0.029 \pm 0.052$ for $z > 0.8$.

Figure 2. The galaxies identified to be in dense regions. The magenta, green, and blue points indicate the galaxies at $z = 0.4, 0.7, \text{and } 1.0$.

3. FUTURE STUDIES WITH SPICA

Making use of the SPICA’s advantages, we can overcome these uncertainties and explore the environmental dependence of galaxy properties in detail. This is because i.) The sharp spatial resolution can detect galaxies without blending even in the densest region. ii.) The spectral mapping with SAFARI enables us to calculate accurate density even objects without optical detection. iii.) The wide field of view will find galaxies in various kinds of environment. iv.) The high sensitivity
Figure 3. The environmental effects of the 8 µm to 4.5 µm luminosity ratios. At $z < 0.8$ the luminosity ratios decrease with over density, while at $z > 0.8$ the trend is reversed.

and continuous filter coverage at mid-infrared enable us to understand the environmental effect up to $z \sim 3.5$. For these purposes, deep legacy survey should be carried out with the unique advantages of the SPICA.

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FIR Extended Emission from Cold Gas and Dust in Blue Compact Dwarf Galaxies: the Anomalous Cases of POX 186 and UM 461

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ABSTRACT

FIR observation of BCD galaxies with Herschel has revealed a wealth of new insights in these objects which are thought to resemble high-redshift forming galaxies. Dust and cold gas showed to be colder, in more or less quantities than expected and of uncertain origin. However, not unlike in the local universe, not all the dust or the cold gas is accounted for, making it more challenging. SPICA and its factor 10 to 100 in sensitivity will allow to image the faint extended cold gas/dusty disks in BCDGs in addition to detect faint C and O lines only marginally or not at all detected by Herschel.

1. TWO BCDGS OUT OF NORMS

Blue Compact Dwarf Galaxies (BCDGs) are objects considered both as local analogs to high redshift early forming galaxies and as, paradoxically, left-overs from the cosmological history. Low metallicity, low dust content, relatively high star formation rates (wrt to total mass), large gas-to-star ratios, dwarf galaxies have been observed over two decades at all wavelengths to understand their evolution, how they survived the various cosmological events that punctuated the cosmological history. Recently combining high sensitivity and spatial resolution Herschel observations (covering at the wavelength range between 50 µm and 500 µm) with previous MIPS observations, it was shown that the dust properties as a function of the star-formation rate and metallicity in low metallicity dwarf galaxies (12 + log(O/H) < 8.1) behave very differently from higher metallicity dwarf galaxies and other normal galaxies.

UM 461 and POX 186 are two different BCDGs with almost opposite properties: UM 461 is a low metallicity gas rich with an underlying old stellar population (< 5 Gyrs) dwarf galaxy (Figure 1 Right, Lagos et al. (2011); Doublier et al. (2001)) while POX 186 is a low metallicity gas poor with no apparent underlying old stellar population ultra compact dwarf galaxy (Figure 1 Left, Corbin & Vacca (2002); Doublier et al. (2000)).

2. DUST PROPERTIES IN POX 186 AND UM 461

POX 186 and UM 461 (Figure 2) were observed as part of the “Dwarf Galaxies Survey” (PI: S. Madden, Madden et al. (2013)). For both objects the following data were obtained using the Herschel observatory with PACS: 70 µm, 100 µm and 160 µm and SPIRE 250 µm, 350 µm and 500 µm. The details of the data processing, photometry and spectral energy distribution fit is given in Rémy-Ruyer et al. (2013) and Rémy-Ruyer et al. (2013 in prep). The MIPS data at 24 µm were taken from Bendo et al. (2012).

2.1. SED

In the MIR + FIR, POX 186 does not show the same features as in the visible (Figure 2, Left). The galaxy displays a cold tail whose origin is unclear: cold gas/dust tail/arm. POX 186 is an archetypical “dark galaxy”.

POX 186 and UM 461 are plotted on Figure 3. Only upper limits could be obtained for POX 186 at 350 µm and 500 µm. This sets a lower limit for the dust and/or cold gas component temperatures. The blue symbols represent the fitted SED

Figure 1. Left: POX 186: HST VRI Right: UM 461: K band
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Figure 2. RGB composite image: 24 µm MIPS and Herschel PACS 100 µm +SPIRE 250 µm Left: POX 186 Right: UM 461

under the following assumptions: single dust component described by a modified Black-Body emission (see Rémy-Ruyer et al. (2013 in prep) for all details). The black line represents the modified BB models for the given dust mass, dust temperature and dust emissivity.

For POX 186, the observed SED appears to depart from the model at long wavelengths. The flat observed SED is indicative of very different components influencing the energy distribution in the MIR and FIR. As seen in the two images: visible (Figure 1 Left) and MIR+FIR (Figure 2, Left) there seems to be a warm component corresponding to the central star forming region, and much colder and extended underlying disk of gas/dust. However, the integrated photometry includes both regions and higher resolution with higher sensitivity would allow us to disentangle the various components.

UM 461 shows two distinct components in the visible and near infrared whose properties are different such as stellar population, star formation age and history. The Eastern star formation region shows much “younger” characteristics than the West star forming region (Figure 2, Right). The distinctions are also reflected in the MIR+FIR range (Figure 3, Left). One region (West) is much colder than the other (East).

The observed SED cannot be reproduced with a single dust component as shown in Figure 3, Right. The fit diverges at both end of the energy distribution.

Contrary to POX 186, UM 461 shows the indication of hosting a warmer dust component possibly associated to the younger star formation located East. UM 461 could be a local counterpart of the high redshift SINSs galaxies inside which self-gravitating star forming regions temporarily form, then merge back into the galaxy disk.

2.2. Anomalous Objects

In Figure 5, the curves give theoretical Herschel flux ratios for simulated modified black bodies for \( \beta = [0.0, 2.5] \) and temperatures \( T = [0, 40] K \) in 2 K bins and \( T = [40,100] K \) in 10 K bins (black dots). Lines of constant temperature are indicated as dotted lines (see Rémy-Ruyer et al. (2013 in prep)).

Note that POX 168 and UM 461 amongst the most metal poor galaxies (from 0.03 to 0.20 Z_\odot) are very faint and even not detected anymore at longer wavelength. However, when detected their MIR properties differ from the bulk of dwarf galaxies. The dust composition, temperature and spatial distribution may be very different due to the very low metallicity and the particulars of the star formation event.
FIR Extended Emission from Cold Gas and Dust in BCDGs

**Figure 4.** UM 461: 2-components modified BB SED

**Figure 5.** Left PACS/PACS diagram: F70/F100 versus F100/F160. The colours correspond to different metallicity bins. Crosses and downward triangles represent DGS and KINGFISH galaxies, respectively. Right Colour-colour diagram: PACS/SPIRE diagram: F100/F250 versus F250/F500.

3. SAFARI

In coordination with interferometric submm-radio telescopes (ALMA in the southern hemisphere, Plateau de Bures) to cover the SED colder components at high spatial resolution, SPICA represents the perfect follow up tool for local BCDGs, and to search and study higher redshift (z ∼ 0.5–1) dwarfs. It will allow to spatially resolve both galaxies and structures and detect down to 210 µm all components responsible for the anomalous SED shape and allow multiple components fitting

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UV-Bright Nearby Early Type Galaxies Observed in the Mid-Infrared: Evidence for a Multi-Stage formation History by Way of WISE and GALEX Imaging

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ABSTRACT
At \( z \lesssim 0.1 \), 10\% of massive elliptical galaxies exhibit a substantial excess of ultraviolet emission over what is expected from their old stellar populations (the ‘UVX’). We explore the source and radial distribution of UVX in 49 nearby E/S0-type galaxies by measuring their extended photometry in the UV to mid-IR with GALEX, SDSS and WISE. We find a 1 magnitude separation of color between the inner and outer regions. Via careful modelling, we show that this color difference is most readily explained by a \( \sim 0.5 \) to 2 Gyr age difference. This is consistent with ‘inside-out’ formation: rapid star formation in the core at \( > 4 \) Gyr ago, and at least one later stage starburst event coinciding with \( z \sim 1 \).

1. BACKGROUND AND SAMPLE
That some early type galaxies (ETGs) are strong emitters of UV is a decades-old mystery. In ETGs, the UVX appears as a sudden increase in the flux in spectral energy distributions (SEDs) blueward of 2500 Å. Possible sources of UVX include recent star formation, metal-poor \( > 10 \) Gyr-old horizontal branch (HB) stars, younger metal-rich HB stars, or a combination of these (see O’Connell 1999, for a review). By understanding how ETGs evolved to their present state, we can determine the major sources of mass-building over cosmological history. The theories need to integrate many factors, including the morphologies and age-metallicity differences observed between more and less massive ETGs. Mergers play an important role in explaining these factors. For example, dissipational (gas-rich) mergers would seed new star formation, while a dissipationless (gas-poor) merger would add mass through minor merging with quiescent systems. Merging is suspected to play a roll in an inside-out cessation, a core forms through very rapid starbursts at high redshifts, fueled by wet-merging. At later epochs, major multi-stage growth form the outer regions via minor mergers and accretion of hot gas from the immediate environment (e.g., Daddi et al. 2005; Nelson et al. 2012).

We use imaging from the recently completed Wide-field Infrared Survey Explorer (WISE) mid-IR imaging to explore the UV to mid-IR color-space of ETGs with UVX. The two objectives in our study are to: 1) use photometry between the UV and mid-IR to constrain the stellar populations contributing to the UV emission, and 2) use radial information to interpret how these galaxies may have assembled their stellar mass.

ETG Sample and Data Analysis. From the GALEX-Ultraviolet Atlas of Nearby Galaxies (Gil de Paz et al. 2007), we selected by morphological type E or S0, resulting in a sample of 125 galaxies all at \( z < 0.06 \). Our final sample resulted in 49 reliable objects, at a mean redshift of 0.02. We present here photometry measured in the GALEX FUV/NUV, SDSS \( r \), and WISE 3.4 \( \mu \)m bands.

We consider three possible sources for the observed UV excess in ETGs: 1) a significant population of BHB/EHB stars \((t_{\text{age}} \geq 2 \text{ Gyr and } T_{\text{eff}} \geq 14000 \text{ K})\), where EHBs are the combined BHB phase and higher \( T_{\text{eff}} \); 2) a substantial population of hot young stars from a recent starburst \((t_{\text{age}} \sim 500 \text{ Myr and } 1 < Z < 1.5Z_{\odot}, T_{\text{eff}} > 10000 \text{ K})\); 3) a significant population of very hot, post main-sequence metal-poor stars \((t_{\text{age}} \geq 9 \text{ Gyr and } Z < 0.5Z_{\odot})\). We seek to distinguish between these possibilities by comparing their predicted UV/optical/mid-IR colors. To do so, we use the Flexible Stellar Population Synthesis models (FSPS; Conroy et al. 2009; Conroy & Gunn 2010) to create composite stellar population (CSP) models. For a full explanation of sample selection and data analysis see Petty et al. (2013).

2. ETG RADIAL COLOR DISTRIBUTION AND MULTI-STAGE FORMATION
We find strong color gradients for NUV–r, and NUV–[3.4]. By dividing the flux for each galaxy into inner and outer regions (inner half-light, and outer 50–90\% of the total flux), we plot in Figure 1-(a) the histograms of NUV–r and...
Figure 1. (a) Distributions of NUV–r and NUV–[3.4] colors at the inner half-light ($R_{in}$ white) and outer radii ($R_{out}$ grey). The hatches denote a subpopulation of highly elliptical galaxies ($b/a < 0.6$). (b) Color plots with the distribution of inner/outer colors (dashed contour is the outer color distribution). Different parameter combinations of FSPS templates overlay the contours at ages 2 (top), 5 (middle) and 10 (bottom) Gyr. (c) The stacked distributions of $\Delta$(NUV–[3.4]) with different BHB fractions at the inner and outer radii as labeled. For example, the dark grey labeled 0/0.25 refers to the color at $f_{BHB} = 0$ and 0.25 for $R_{in}$ and $R_{out}$, respectively. (d) Estimated ages for $R_{in}/R_{out}$ considering the different CSP parameter combinations. Symbols are: $\tau = 0.2$ Gyr (black), 0.6 Gyr (blue), and 1 Gyr (magenta); $0.25Z_\odot$ (double circles), $1Z_\odot$ double diamonds, other $1.5Z_\odot$. The dotted lines trace metallicities along a fixed $f_{BHB}$ and $\tau$ with $Z$.

NUV–[3.4] colors at the inner ($R_{in}$) and outer ($R_{out}$) radii, and these show a statistically significant color separation of approximately 1 mag. The averages are: NUV–r $= 5.7 \pm 0.2$ and $4.9 \pm 0.1$ for $R_{in}$ and $R_{out}$, respectively; and NUV–[3.4] $= 6.1 \pm 0.2$ and $5.1 \pm 0.2$ for $R_{in}$ and $R_{out}$, respectively.

In Figure 1-(b) we take isochrones of the FSPS synthetic photometry at $t_{age} = 2$ (top), 5 (middle), and 10 Gyr (bottom), and plot them in FUV–NUV, NUV–r, NUV–[3.4] color-space. The FSPS lines overlay the grey-scale contours that include both the $R_{in}$ and $R_{out}$ colors of the ETG sample, and outline the distribution of colors for $R_{out}$ with the dashed contour lines. The density peaks are clearly separated. Dust may be ruled out as the origin of this separation from the direction of the orange vectors. The 2 Gyr plots indicate that the colors for the inner regions could only be explained by super-solar metallicities $> 1.5Z_\odot$. Enforcing the same age across the whole galaxy, then the outer regions are more likely to host a 1–1.5 $Z_\odot$ stellar population with a moderate BHB fraction. At 5 Gyr (middle plots), the $R_{in}$ colors could be caused by higher metallicity/moderate BHB fractions, and the outer regions would have a lower metallicity and higher numbers of BHBs. At 10 Gyr, the isochrones give narrower ranges and the metallicity dependence is stark: $R_{in}$ would be dominated by 1–1.5 $Z_\odot$ stellar population and an insignificant BHB fraction; $R_{out}$ would be dominated by a $< 1Z_\odot$ stellar population, and may include slightly more BHBs. We also note that for 2–5 Gyr the dominating SFH is $\tau = 0.2–0.6$; at 10 Gyr the range is widened to all $\tau$.

In Figure 1-(c) we test if BHB fraction can solely cause the 1-mag color difference observed in NUV–[3.4], using estimated ages from fitting the FSPS templates to the ETG colors. The models with BHB fractions $\gtrsim 0.25$ in the outer radii are more likely to have a 1-mag color difference (these are shown in light-blue, dark and light grey).

In Figure 1-(d) we show the effects that BHB fraction, metallicity and star formation history have on the estimated ages ($t_{age,in}$) and $t_{age,out}$). Each data point is a weighted average of the entire ETG sample, testing different parameter configurations (e.g., one point for $f_{BHB} = 0$, $\tau = 0.2$, and $Z = 1Z_\odot$). We do not separate the temperature boosts here, since Figure 1-(d) indicates that the effects on color are negligible for this analysis.

The points reflect the assumption that both the inner and outer regions are evolving with the same set of parameters. For example, the magenta square ($Z = 1.5Z_\odot$, $f_{BHB} = 0.5$, and $\tau = 1$), easily identified as the outlier, is fixing the prior that the parameter combinations are the same for the inner and outer regions. In other words, each point is the $t_{age}$ coordinate for the inner and outer regions having the same metallicity, BHB fraction, and $\tau$. With this assumption, we find that nearly all points are below the equality line, and many (12 points) with $\Delta t_{age} > 1$ Gyr.

In order for the inner and outer regions to have equal ages, then the inner and outer regions must have a certain set of properties. Over half of the points within errors of the equal age line, have low metallicity (double circles for $Z = 0.25Z_\odot$),
UV-BRIGHT ETGs OBSERVED IN THE MID-IR

and some fraction of BHBs (diamonds and squares). This constrains the possible scenarios that could lead to the observed color difference.

Conclusions. In Petty et al. (2013), the analysis, results and conclusions are discussed in depth. Here we highlight the key results: I. WISE and GALEX colors FUV–NUV and NUV–[3.4] are highly effective in separating the parameters which drive the observed colors. The 49 ETGs in this sample exhibit a strong color difference with bluer colors on the outside of the galaxies in both UV-opt and UV-mid-IR. We extract the photometry for the inner half-light and outer 50–90 % and find a clear color difference: $R_{in}/R_{out} \text{ NUV–}r = 5.7/4.9$, and NUV–[3.4] $= 6.1/5.1$. II. We find that the different regions are significantly different in age, metallicities, and/or the existence of BHBs. We discussed two formation scenarios based on our results: 1) if the bulge and disk coevolved, the metallicities must be significantly different ($0.25 Z_\odot$ in the outer regions, $> 1 Z_\odot$ in the centers); 2) the ETGs formed in an inside-out process with at least 2 major stages of growth $\geq 1$ Gyr apart.

III. Our age estimates indicate that the second scenario is most likely. The average ages are estimated to be $7.0 \pm 0.3$ Gyr (inner) and $6.2 \pm 0.2$ Gyr (outer), with a minimum of $2.6$ Gyr. Even when we assume homogeneity of parameters over radius, there is evidence of multi-stage evolution where the outer regions are likely to have formed at least $0.8$ Gyr after the inner regions ($-0.3 < \Delta t_{age} < 1.9$ Gyr). IV. Since the estimated ages are beyond the lifetimes of star forming regions to contribute significantly to the UV emission, we assume that BHBs or EHBs are the primary source of the UVX. The average colors fall within the ranges predicted for BHB fractions greater than $0.25$ in NUV–[3.4] in the outer regions.

3. SPICA OBSERVATIONS OF ETGS

With the proposed specifications of the Focal Place Camera, we could achieve much higher resolution and depth than is currently available with WISE data. The current sample here could be used as a template for looking at moderate to higher redshift quiescent galaxies. The outer diffuse IR emission of these galaxies is extremely difficult to detect for more distant galaxies, because of significant surface brightness dimming. We could use the FPC for resolved radial profile photometry to try to distinguish at what point these galaxies present a strong color difference between the nucleus and outer regions. Multiple mid-IR filters would more finely disentangle BHB/metallicity degeneracies. Depending on the choice of filters one could, within $0.2$ Gyr, create age radial profiles, even with just GALEX and SPICA.

This publication makes use of data products from the Wide-field Infrared Survey Explorer. The publication is based on observations made with the NASA Galaxy Evolution Explorer.

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Semi-analytic Model of Galaxy Formation in the Infrared: Predictions for SPICA

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ABSTRACT

Understanding the galaxy dust emission is very important to obtain a full picture of galaxy formation, since it contains rich information about hidden star formation activity, physical properties of interstellar dust, and their role in galaxy formation. From the analysis of infrared spectral energy distribution (SED) of local galaxies which were observed by AKARI, we have found that a dust temperature averaged over the entire galaxy is strongly correlated with total infrared surface brightness, rather than total infrared luminosity. Combining this correlation with our cosmological galaxy formation model, we have computed dust SED of mock galaxies. By using this model, we present can theoretical predictions on the evolution of dusty universe.

1. INTRODUCTION

It is one of the most important issues in astronomy that understanding how the cosmological structures, such as galaxies, galaxy clusters and large-scale structures, have been formed and evolved. In order to fully understand the history of cosmological structure formation, we need to approach a variety of statistical natures of galaxies, such as luminosity functions in various wavelengths and correlations between several physical quantities, making full use of the multi-band observations and precise theoretical model. To explore the cosmological galaxy formation history hidden by dust, we use a so called “semi-analytical model (SAM)” of galaxy formation. If we would like to expand a SAM to IR to submm range, the key is how to theoretically calculate spectral energy distribution (SED) of dust emission. In this work we model the dust SED using the tight correlation between the surface density of total infrared luminosity and dust temperature, which is recently found by (Totani et al. 2011). In the following section we will show the our preliminary results.

2. MODEL

The detailed description of the basic model, the Mitaka model is given by Nagashima & Yoshii (2004). The model compute merging history of dark matter (DM) halos based on the standard structure formation theory driven by cold DM and include several important physical processes related to the evolution of baryons in DM halos such as radiative gas cooling, star formation, supernova feedback, galaxy merger, stellar population synthesis, chemical evolution, and extinction by interstellar dust.

The model can quantitatively reproduce a wide variety of observed characteristics of local galaxies, including luminosity functions and scaling relations among various observables such as magnitude, colors, surface brightness, size, gas mass-to-light ratio, and metallicity (Nagashima & Yoshii 2004); however, the dust radiation process does not included in our model and the model can not predict the FIR to submm properties of galaxies. Recently, we have found the tight correlation between the total infrared surface brightness and dust temperature from the analysis of infrared spectral energy distribution (SED) of local galaxies which were observed by AKARI (Totani et al. 2011). In this work, combining this correlation and mock galaxy catalog produced by the Mitaka model, we investigated the cosmological history of galaxy formation hidden by dust.

3. RESULTS

First, in Figure 1 we show the local luminosity function for the total IR, and the luminosity functions at 250 µm, 350 µm, and 500 µm, respectively. The data points are obtained by Vaccari et al. (2010). It can be seen that our model very well reproduces the observations at all wavelengths.

Figure 2 represents the differential number count of star forming galaxies at 100 µm. The data points are obtained by Magnelli et al. (2013). The model could reproduce the observed number count; therefore it can be say that our model is consistent with the observed trend of cosmic evolution of dusty star forming galaxies.
Figure 1. The local total IR luminosity functions (upper-left), and the luminosity functions at 250 $\mu$m (upper-right), 350 $\mu$m (bottom-left), and 500 $\mu$m (bottom-right), respectively. Data points are obtained by Vaccari et al. (2010). Our model well reproduces the observations in each band.

Figure 2. The differential number count at 100 $\mu$m. It can be seen that our model roughly well reproduces the observations at all flux ranges. Data points are obtained by Magnelli et al. (2013).

Figure 3 represents the redshift evolution of cosmic star formation rate density. In this Figure, we show the two theoretical predictions: one is estimated from UV luminosity density, and the other is estimated from the sum of UV and IR luminosity densities. It can be seen that there are large amount of star formation activity hidden by dust, especially at high redshift. According to the our preliminary estimation, SPICA SAFARI can easily detect numerous number of high-$z$
Figure 3. The redshift evolution of cosmic star formation rate density. The magenta solid line represents the our model prediction estimated from UV luminosity density, while the black solid line represents the results estimated from the sum of UV and total IR luminosity densities. Therefore the difference of these two lines denote the amount of star formation activity hidden by dust. The data points are obtained by Hopkins et al. (2004), Pascale et al. (2009), Rodighiero et al. (2010), Karim et al. (2011), Cucciati et al. (2012), Bouwens et al. (2007), Bouwens et al. (2011), Verma et al. (2007), and Ouchi et al. (2004).

\((z \sim 4)\) galaxies in FIR to submm range. Future facilities such as ALMA, TMT, and \textit{SPICA}, will give us many useful insights on the early stage of galaxy formation hidden by dust.

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Estimation of the Confusion Limit for SPICA

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ABSTRACT

Since the most fundamental limit to detect very distant objects is the source confusion, the estimation of the source confusion limit of SPICA is very important to decide the observational strategy. We estimated the confusion limit of SPICA from 5 to 200 \( \mu m \). For the mid- and far-IR (MIR and FIR) galaxy counts, we used an updated version of the empirical galaxy number count model of Takeuchi et al. (2001). At 5 \( \mu m \), we used a semi-analytic galaxy evolution model “\( \nu GC \)” to construct the galaxy number counts. Based on his, confusion limits for SPICA were estimated by the analytic formulation that can deal with angular clustering of the galaxies (Takeuchi & Ishii 2004).

1. INTRODUCTION

Despite of the fundamental importance of the IR, it is the wavelength at which astronomers are still suffering a poor spatial resolution determined by diffraction. This is because IR telescopes should be operated at a very high altitude or in space, since the IR photons cannot penetrate the Earth atmosphere. The diameter of the telescopes is, then, inevitably limited by the size of balloons or rockets. This makes the IR to be one of the final frontiers in astronomical observations. The Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a part of the JAXA future science program, in collaboration with ESA. The wavelength coverage of SPICA will be \( \lambda = 5–210 \mu m \). The advent of SPICA will provide a unique opportunity to explore the ultra high-\( z \) Universe at the IR with a high photometric sensitivity and unprecedentedly high angular resolution. It is, then, important to estimate the source confusion limit which determines the fundamental detection limit of a telescope. The confusion limit is determined by the sky surface density and clustering property of the sources (Takeuchi & Ishii 2004, hereafter T04, and references therein). In this work, we estimate the confusion limit of SPICA by the formulae developed by T04, which can include the effect of inhomogeneous distribution of the sources and angular clustering. All the details will be shown in our main paper (Takeuchi et al. 2013, in preparation).

2. INFRARED NUMBER COUNTS AND CONFUSION LIMITS

We use the theoretical formulae developed by T04 to estimate the confusion limit of SPICA. The advantage of their formulae is that we can include the effect of the angular source clustering. Details are found in T04 and we do not show the equations here. However, we stress that the redshift information of IR galaxies is not necessary to calculate the confusion limits. Actually, only the fit to the differential counts determines the confusion limit estimation. Since we do not know the counts deeper than the detection limits of current surveys, we need a model counts going down to very faint flux densities at all the wavelengths considered. We explain the adopted count models in this work.

2.1. MIR–FIR–Millimeter Counts

Takeuchi et al. (2001) have constructed an empirical IR galaxy count model to reproduce the observed counts and the CIB spectrum. Hence, we just tuned this model to successfully reproduce the MIR–FIR galaxy number counts and the CIB, especially at the latest FIR measurement presented by Matsuura et al. (2011). The counts are shown in Figure 1.

2.2. NIR Counts

Since the IR galaxy model of Takeuchi et al. (2001) does not include the stellar emission component, we need to deal with the counts at the NIR with a different model, since even at the rest 4.5 \( \mu m \), we observe the redshifted stellar radiation of distant galaxies rather than dust emission. Nagashima et al. (2005) constructed “the Numerical Galaxy Catalog (\( \nu GC \))”, based on a semianalytic model of galaxy formation. Their strong feedback (SFB) model is in much better agreement with near-infrared (\( K' \)-band) faint galaxy number counts and redshift distribution than the WFB one (see their Figure 19). Since this is suitable for our purpose, we mainly used the SFB model.
2.3. Clustering Model of IR Galaxies

Since the redshifts of galaxies we consider here will be very high, the clustering is diluted by superposition along the line of sight (e.g. Peebles 1980). We examined the clustering effect on the result, and found that it is really negligible for ultra high-\(z\) galaxies expected to be observed by \(\text{SPICA}\). Then we do not discuss it here (see Takeuchi et al. 2013, in preparation).

2.4. Settings for \(\text{SPICA}\)

We adopt a simple assumption for the optics of \(\text{SPICA}\) in this work. We calculated the cases with the diameter \(\phi_{\text{mirror}} = 2.9, 3.1, 3.3, \text{ and } 3.5 \text{ m}\). The optics is assumed to be axisymmetric and free from aberration. The main mirror is occulted by the second mirror. This effect, as well as the occultation by spiders of the second mirror, is handled simply by assuming the occultation fraction \(f_{\text{occ}}\). A pure Airy beam corresponding to the effective area of the main mirror, i.e., reduced by the occultation by the second mirror, is assumed. The fraction of \(f_{\text{occ}} = 0.1\) (goal) and 0.125 are calculated. In this case, the effective area of the telescope \(A_{\text{eff}}\) becomes

\[
A_{\text{eff}} = A_{\text{mirror}} (1 - f_{\text{occ}}) .
\]

3. RESULT AND DISCUSSION

We first show the case of \(\phi = 3.5 \text{ m}\) in Figure 2. We show the results for the occultation fraction \(f_{\text{occ}} = 0.125\) and 0.1 in Figure 2. The confusion limit of \(\text{SPICA}\) at longer wavelengths (\(\lambda = 150\text{–}200 \mu\text{m}\)) does not change so significantly, since the increase of the diffraction limit and decrease of the IR galaxy number counts roughly balance at these wavelengths. At wavelengths shorter than \(\lambda = 150 \mu\text{m}\), the confusion limit starts to decrease more steeply toward 50 \(\mu\text{m}\). This is because the number counts become lower toward shorter wavelengths, because both diffraction and number counts decrease. Around 30 \(\mu\text{m}\), there is a “shoulder” of the confusion. This is a complicated effect caused by the combination of the PAH features and upturn of the continuum of hot dust emission (see, e.g., T01). Then, the confusion limit decreases very rapidly toward 10 \(\mu\text{m}\). For the SFB model of Nagashima et al. (2005), the confusion limit still decreases toward NIR.

Then, we show the \(\text{SPICA}\) confusion limits with \(\phi = 2.9, 3.1, 3.3, \text{ and } 3.5 \text{ m}\) in the right panel of Figure 3. The effect of the telescope aperture is the largest at \(\lambda \approx 12 \mu\text{m}\), and rather large at 5 \(\mu\text{m}\). At these wavelengths, the difference between the limit for \(\phi = 2.9 \text{ m}\) and 3.5 \(\mu\text{m}\) is a factor of five. In contrast, the difference is a factor of 1.5 or smaller at \(\lambda \geq 50 \mu\text{m}\).
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This means that the survey depth is more strongly affected by the final decision of the mirror diameter at the MIR wavelengths, and right-hand panel shows the limits at the FIR wavelengths.

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SESSION 2:
THE CYCLING OF MATTER
BETWEEN STARS, GALAXIES AND
THE INTERGALACTIC MEDIUM
The Cycling of Matter between Stars, the Interstellar Medium, and the Intergalactic Medium

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ABSTRACT

The evolution of the interstellar medium is driven by a number of complex processes which are deeply interwoven, including mass accretion from nearby (dwarf) systems and the intergalactic medium, mass ejection into the halo and intergalactic medium, stellar mass injection into the interstellar medium, star formation, mechanical energy input by stellar winds & supernova explosions, and radiative energy input. These processes are mediated by dust and molecules in an only partially understood way. This complex feedback between stars and the medium they are formed in drives the evolution of galaxies and their observational characteristics.

SPICA is set to expand studies of the origin and evolution of the interstellar medium and its role in the evolution of galaxies to the era of vigorous star formation in the Universe at redshifts between 1 and 3. Yet, our understanding of what these observations tell us about what really happens at those epochs will depend very much on our understanding of the microscopic physical and chemical processes and their dependence on the local conditions. These are best studied in the local universe. In order to reap the full benefits of SPICA, a concerted program of key observations is required that study the physics and chemistry of the ISM locally and leverage this to probe the far Universe.

1. INTRODUCTION

The origin and evolution of galaxies are closely tied to the cyclic processes in which stars eject gas and dust into the interstellar medium (ISM), while at the same time gas and dust clouds in the ISM collapse gravitationally to form stars. The ISM is the birthplace of stars, but stars regulate the structure of the gas, and therefore influence the star formation rate. Winds from low mass stars — hence, the past star formation rate — control the total mass balance of interstellar gas and contribute substantially to the injection of dust, an important opacity source, and Polycyclic Aromatic Hydrocarbon molecules (PAHs), an important heating agent of interstellar gas. High mass stars (i.e., the present star formation rate) dominate the mechanical energy injection into the ISM, through stellar winds and supernova explosions, and thus the turbulent pressure which helps support clouds against galactic- and self-gravity. Through the formation of the hot coronal phase, massive stars regulate the thermal pressure as well. Massive stars also control the FUV photon energy budget and the cosmic ray flux, which are important heating, ionization, and dissociation sources of the interstellar gas. Massive stars are also the source of intermediate mass elements which play an important role in interstellar dust. Eventually, it is the dust opacity which allows molecule formation and survival. The enhanced cooling by molecules is crucial in the onset of gravitational instability of molecular clouds.

Clearly, therefore, there is a complex feedback between stars and the ISM. And it is this feedback that determines the structure, composition, chemical evolution, and observational characteristics of the interstellar medium in the Milky Way and in other galaxies all the way back to the first stars and galaxies that formed at redshifts > 5. If we want to understand this interaction, we have to understand the fundamental physical processes that link interstellar gas to the mechanical and FUV photon energy inputs from stars.

SPICA provides a challenging opportunity to study the origin and evolution of the ISM of galaxies. As a powertool, SPICA provides access to key tracers of the interstellar medium including atomic and ionic fine-structure lines and molecular rotational lines — that can probe the physical conditions of the different components and phases of the ISM —, the emission features of PAH molecules — that play such an important role in the energy and ionization balance of interstellar gas as well as trace the interaction regions of massive stars with their environments —, and dust absorption and emission features as well as continuum — that trace the characteristics and origin of dust as well as acts as a proxy for gas. SPICA will be able to do so through the era of vigorous star formation in the history of the Universe (redshifts 1–3) when most stars were born and galaxy assembled. The challenge will be to validate and calibrate these tracers in the local Universe and to link them to the processes that drive the evolution of the ISM of galaxies.

In this review, I will focus on two key questions: What are the sources of gas and dust? & What processes play a role in the lifecycle between stars and the ISM? I choose these two questions because the infrared can shine unique light on them. I will end with a short outline of some key issues that can be addressed well by SPICA.
2. THE GAS AND DUST BUDGETS OF GALAXIES

Stars in the last stages of their evolution return much of their material to the ISM. For most stars, as these ejecta expand and cool, small dust grains nucleate and grow when the temperature drops to about 1500 – 1000 K, depending on the material and the chemical kinetics (Cherchneff 2000; Cherchneff & Dwek 2010). This dust, heated by stellar radiation, dominates the spectral energy distribution (SED) of the star and the mid- and far-infrared emission provides an excellent tracer of the mass. Fits to these SEDs provide then a handle on the dust injection rate, which can be translated into a gas mass loss rate adopting a dust-to-gas ratio and a velocity (Srinivasan et al. 2009). The gas can also be traced directly through molecular observations. Molecular excitation and uncertain abundances hamper analysis of these lines in terms of mass loss rates but the multitude of molecular lines can overcome this (Olofsson 2008). For some, mainly massive stars (OB & Wolf Rayet stars), mass loss is better traced by UV resonance lines, optical/IR wind emission lines, IR/radio thermal emission from the gas. For these sources, detailed empirical scaling laws have been derived linking the mass loss rate to the properties of the star (Vink et al. 2000).

The mass budget of the ISM is summarized in Figure 1 (Tielens 2005). Stars pollute the Milky Way with ≃ 2 M⊙/yr of gas and associated dust and molecules. The gas return is dominated by the numerous low mass stars during their Asymptotic Giant Branch phase. Supernovae from massive stellar progenitors contribute only some 10% of the gas mass compared to low mass stars but a comparable amount of heavy elements, reflecting their factor 10 enrichment by nucleosynthesis. The timescale for stars to replenish the local interstellar gas mass is 5 × 10⁹ years. This is very comparable to the star formation rate which converts the available gas mass into stars on a timescale of 3 × 10⁹ years. The galactic fountain, setting up the circulation between the halo and the disk, involves more gas (e.g., ≃ 5 M⊙/yr). The Milky Way grows due to accretion of nearby dwarf galaxies — the Magellanic stream provides a prime example — but this cannibalism is only of minor importance for the overall mass balance. The G-star problem indicates that the Milky Way may have been accreting some 1 M⊙/yr of metal-poor intergalactic gas over much of its history. Finally, the gas disk is very extended and this gas may slowly flow inwards replenishing gas lost to star formation in the inner disk. Unfortunately, existing evidence for radial motion may actually reflect non-axisymmetric distribution of gas in space or velocity and limits on inflow are very forgiving (= 5 km/s; Blitz, private communication). Table 1 adopts 1 km/s. It should be recognized that the magnitude of the various contributions to this mass budget are uncertain. Nevertheless, all of the processes involved are relatively rapid compared to the lifetime of the Milky Way and hence a quasisteady state has been established, balancing stellar mass injection and intergalactic mass accretion with star formation and mass loss. It should be recognized, though, that some of these processes are highly punctuated, driven by temporal interaction with nearby systems, and steady state may only apply averaged over long timespans.

Observations show that AGB stars are important contributors to the stardust budget of the Milky Way (Figure 1), returning some 6 × 10⁻³ M⊙ yr⁻¹ in solid form. By comparison, red supergiants, the descendants of massive stars, return only a paltry 1.5 × 10⁻⁴ M⊙ yr⁻¹ of dust. The contribution of SNe to the dust mass budget is unclear. If all the condensible material were turned into dust, type II SNe might contribute some 9 × 10⁻³ M⊙ yr⁻¹. Observationally, dust is known to form typically between 300 and 1000 days after the SN explosion as revealed by a sudden drop in optical light, a concomittant increase in IR emission, and the development of a pronounced blue-red asymmetry in the emission line profiles of the ejecta (Wooden et al. 1993; Lucy et al. 1989). However, IR studies of core collapse SNe implied less than 5 × 10⁻³ M⊙ of dust (somewhat dependent on the adopted grain material properties, very sensitive to the adopted clumpy distribution of the ejecta, and widely varying between SNe), corresponding to an efficiency of ≃ 10⁻³ – 10⁻¹ (Wooden et al. 1993; Sugarman et al. 2006; Ercolano et al. 2007; Meikle et al. 2007). Young supernova remnants (SNR) provide another view of the dust formation efficiency of SNe and one that indicates much higher dust formation efficiencies. Spitzer studies of the young (≃ 330 yr) supernova remnant, Cas A, revealed a warm dust mass of 0.025 M⊙ in the volume processed by the reverse shock (Rho et al. 2008). A Herschel study adds to that 0.075 M⊙ of cold dust mass interior to the reverse shock (Barlow et al. 2010). The total dust mass (≃ 0.1 M⊙) should be compared to the estimated total ejected mass of 2–4 M⊙, much of this in the form of oxygen (≃ 2 M⊙) which will not condense (Willingale et al. 2002; Vink et al. 1996). In analogy to the
well-studied type Ib SN 1993J, some 0.6 $M_\odot$ of condensible elements (C, Mg, Si, S & Fe) were ejected during the SN explosion of Cas A (Thielemann et al. 1996), corresponding to a very high dust formation efficiency of ~ 0.2. Likewise, Herschel observations of the extremely young SNR associated with SN 1987A — which has just entered the reverse shock phase as the ejecta slammed into the previous stellar wind remnant some 10 years after the explosion — reveal ~ 0.5 $M_\odot$ of cold dust (Matsuura et al. 2011); many orders of magnitude larger than estimated from observations during the dust condensation period of ~ 500–1000 days ($10^4$–$10^5$; Wooden et al. 1993). Given the bewildering zoo of SNe types and the uncertainties and conflicting observational results on dust formation in these environments, the contribution of SNe to the dust budget can presently only be guessed at but this anecdotal evidence suggests that it is high. Figure 1 assumes that all of the condensibles form dust and type II SNe are then slightly more important than AGB stars for the dust budget.

Figure 1 also includes a contribution of dust formed in the inner regions of protoplanetary disks and entrained and ejected by the protostellar wind. This estimate is also at the high end as it is based upon the assumption that 1/3 of the accreting mass is ejected as a wind (Shu & Shang 1997) and that all condensibles form dust. Other estimates of protostellar wind characteristics typically result in a ~ 3 times smaller wind mass loss rate (Hartmann 1995). It should also be kept in mind that, for the dust budget, protostellar winds are only a “pseudo” source of dust. The wind likely originates from the inner region where all preexisting dust has sublimated and recondensed. The net addition of dust may then actually be negative (carbon will not condense as dust in these environments). Certainly, in terms of the stardust budget of the ISM, astration by protostars presents a sink.

The main uncertainty in these mass injection rates has not yet been mentioned. Derived mass-loss rates depend directly on the distance and these are very uncertain for galactic objects. The SAGE/Spitzer and Heritage/Herschel programs have mapped the Small and Large Magellanic Clouds in all photometric bands between 3 and 500 μm and — because the distance is well known — the dust budget of these low metallicity dwarf galaxies has been well determined on a galaxy-wide scale (Srinivasan et al. 2009; Matsuura et al. 2009; Riedel et al. 2012). Results of these studies are summarized in Table 1. Perusal of this data reveals interesting similarities and differences between these galaxies. In particular, at the measured star formation rate, the existing gas reservoir will be consumed in some $3 \times 10^5$ yr for the Milky Way and the LMC, but that timescale is ~ $10^{10}$ yr for the SMC. This gas reservoir will be replenished by stellar injection on timescales of ~ $5 \times 10^9$ yr for the Milky Way and the LMC; so the gas content of these two galaxies is roughly in steady state. For the SMC, the relevant timescales are comparable ($10^{10}$ yr) to the Hubble time and indeed the SMC is quite gas-rich compared to its stellar mass. Now, in contrast to the Milky Way, the gas budget of the SMC and LMC is dominated by SNe and not AGB stars. These dwarf galaxies are still undergoing strong bursts of star formation (Harris & Zaritsky 2009); e.g., the star formation rate of the LMC increased very rapidly some 5 Gyr ago and hence low mass stars when this burst started (or later)— formed at the start of this burst or later — have not yet had time to evolve onto the AGB. As a corollary, the measured dust injection rate by AGB stars cannot have provided the observed dust content of the SMC and LMC (Table 1). In contrast, SNe could have, if they are indeed efficiently producing dust (see above). Alternatively, for the Milky Way, we

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**Table 1. Inventory of the ISM**

<table>
<thead>
<tr>
<th>Component</th>
<th>Milky Way</th>
<th>LMC</th>
<th>SMC</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of dark halo</td>
<td>$1 \times 10^{12}$</td>
<td>$\approx 1\times 3 \times 10^{10}$</td>
<td>$\approx 1.5 \times 10^9$</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Stellar Mass</td>
<td>$5 \times 10^{10}$</td>
<td>$1.7 \times 10^9$</td>
<td>$3.7 \times 10^8$</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISM mass</td>
<td>$7.5 \times 10^9$</td>
<td>$5.2 \times 10^8$</td>
<td>$4.2 \times 10^8$</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>Star formation rate</td>
<td>2</td>
<td>$\approx 0.2$</td>
<td>$\approx 0.04$</td>
<td>$M_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>RSG &amp; AGB Mass Loss</td>
<td>1</td>
<td>$4 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$M_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>SNe</td>
<td>$2 \times 10^{-1}$</td>
<td>$\approx 10^{-1}$</td>
<td>$\approx 3 \times 10^{-2}$</td>
<td>$M_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>Z</td>
<td>1$^1$</td>
<td>0.5</td>
<td>$0.1 - 0.2$</td>
<td>$Z_\odot$</td>
</tr>
<tr>
<td>Dust</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>ISM mass$^2$</td>
<td>$6 \times 10^7$</td>
<td>$\leq 3.5 \times 10^6$</td>
<td>$\geq 3 \times 10^5$</td>
<td>$M_\odot$</td>
</tr>
<tr>
<td>RSG &amp; AGB Mass Loss</td>
<td>$6 \times 10^{-3}$</td>
<td>$2 \times 10^{-5}$</td>
<td>$7 \times 10^{-6}$</td>
<td>$M_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>SNe production$^3$</td>
<td>$9 \times 10^{-3}$</td>
<td>$4 \times 10^{-3}$</td>
<td>(?)</td>
<td>$1 - 40 \times 10^{-6}$</td>
</tr>
<tr>
<td>Dust destruction by SNe</td>
<td>$\approx 6 \times 10^{-3}$</td>
<td></td>
<td></td>
<td>$M_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>Stellar astration of dust$^4$</td>
<td>$2 \times 10^{-2}$</td>
<td>$\approx 3.5 \times 10^{-3}$</td>
<td>$10^{-3}$ (?)</td>
<td>$M_\odot$ yr$^{-1}$</td>
</tr>
</tbody>
</table>

$^1$ The metallicity of the Milky Way shows a gradient of ~0.06 dex per kpc in the primary elements. $^2$ From COBE measurements of the IR emission for the Milky Way and 160 μm PACS/Herschel measurements for the LMC/SMC. $^3$ Assuming complete condensation of all dust forming elements. $^4$ Winds from young stellar objects may also inject newly formed dust into the ISM and this may amount to about 1/3 of this value. References: Tielens (2005); Srinivasan et al. (2009); Matsuura et al. (2009); Riedel et al. (2012); Matsuura et al. (2013); Meixner et al. (2013); Dwel et al. (1997)
Figure 2. The mid-infrared spectra of the PhotoDissociation Region in the Orion Bar and in the Planetary Nebula, NGC 7027 are dominated by a rich set of infrared emission features. Assignments of these features with vibrational modes of PAH molecules are labeled at the top. These PAH features are perched on broad plateaus attributed to clusters of PAHs and on a mid-infrared continuum likely due to nanograins. Figure adapted from Peeters et al. (2002).

know that accretion of refractory elements such as Si, Mg, Fe on dust is very rapid in diffuse clouds (Savage & Sembach 1996; Tielens 1998) and hence much of the dust mass of the LMC and SMC may result from accretion on a few stardust grains injected by AGB stars.

3. THE ROLE OF PAHS IN THE ISM

The infrared spectra of almost all interstellar objects — including regions of massive star formation such as H II regions and reflection nebulae (Figure 2), carbon-rich stars in the last phases of their evolution such as post-Asymptotic-Giant-Branch stars and planetary nebulae, surfaces of dark clouds, the planet forming disks of young stellar objects, the general interstellar medium, galactic nuclei, and (ultra)luminous infrared galaxies — are dominated by strong, broad emission features at 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 \( \mu m \) (Figure 2; Peeters et al. 2002; Hony et al. 2001; Armus et al. 2007; Kaneda et al. 2013; Kim et al. 2012; Mori et al. 2012)). These strong emission features are accompanied by a plethora of weaker bands at 3.4, 5.2, 5.7, 6.0, 7.4, 12.0, 13.5, 14.2, 15.8, 16.4, 17.0, 17.4 \( \mu m \) and are perched on very broad plateaus and a continuum that is sharply rising towards longer wavelength (for a review, see Tielens (2008). These features are ubiquitous in the interstellar medium on all scales from planet forming disks around young stellar objects to the scale of whole galaxies. It is clear that the carriers represent an important component of the ISM.

These spectral features are very characteristics in peak position for polycyclic aromatic hydrocarbon materials and they are generally ascribed to IR fluorescence of UV-pumped large Polycyclic Aromatic Hydrocarbon molecules (PAHs; Allamandola et al. 1989; Puget & Leger 1989; Tielens 2008). There are three pieces of evidence supporting the assignment of these features to large molecules (50–100 C-atoms) rather than “bulk” materials (e.g., 10–300 nm grains). (1) In order to emit in the mid-IR, the carrier(s) of the IR emission features must be much hotter than the 15 K that characterizes the far-IR emission due to 10–300 nm grains in radiative equilibrium with the interstellar radiation field. Hence, a fluorescence process is implied in which a single photon highly excites the molecule, which then relaxes through the emission of IR photons. Analysis of the energetics involved implies then molecular-sized carriers (50–100 C-atoms). (2) Several of the IR emission features (e.g., the 6.2 & 11.2 \( \mu m \) features) show a pronounced redshifted profile. Such a profile is characteristic for anharmonicity; again a distinct signature for emission by highly vibrationally excited molecules (Barker et al. 1987; Cook & Saykally 1998; Pech et al. 2002). (3) The feature to continuum ratio is very high, exceeding 20 in many sources. This is quite typical for molecular compounds; bulk (carbonaceous) materials, in contrast, invariably have intrinsic feature-to-continuum ratios that are much less.

Observations of the IR emission features and the spectroscopic, physical and chemical characteristics of interstellar PAHs have recently been reviewed elsewhere (Tielens 2008). Here, I highlight one aspect: the observed variations in the relative strength of the CH (3.3 and 11.2 \( \mu m \) features) to the CC modes (6.2 and 7.7 \( \mu m \) features). This illustrates well how observations of the IR emission features can be used to determine the physical conditions in regions of star formation. Such variations have been observed when comparing different sources as well as when comparing different positions within the same source (Galliano et al. 2008). The two spectra in Figure 2 illustrate these variations well. Extensive laboratory studies and quantum chemical calculations have demonstrated that, while peak positions can shift somewhat, the intrinsic
THE CYCLING OF MATTER IN THE UNIVERSE

Figure 3. The observed ratio of the 6.2 to 11.2 μm bands — a measure of the degree of ionization of PAHs — is related to the ionization parameter, \( \gamma = G_0 T^{1/2}/n_e \) for a few well-studied PDRs, where the physical conditions — the strength of the UV radiation field, \( G_0 \), the electron density, \( n_e \), and, the temperature, \( T \) — have been well determined from a multitude of atomic fine-structure lines and molecular rotational lines. The degree of ionization of PAHs increases to the right as either \( G_0 \) increases or \( n_e \) decreases. The temperature, \( T \), enters through the velocity dependence of the Coulomb focusing factor. Figure taken from Galliano et al. (2008).

The mid-infrared spectra of the PhotoDissociation Region in the Orion Bar and in the Planetary Nebula, NGC 7027 are shown in Figure 2. The observed variations in the intrinsic feature-to-continuum ratios that are much less for molecular compounds; bulk (carbonaceous) materials, in contrast, invariably have higher ratios. This is quite typical for molecular compounds; bulk (carbonaceous) materials, in contrast, invariably have higher ratios.

4. THE DYNAMICS OF THE ISM

The mechanical energy input through expanding supernova ejecta and — to a lesser extent — by stellar winds has a profound influence on the structure of the ISM by generating turbulent motions of the H I and by sweeping up and shocking the surrounding interstellar gas to very high temperatures. Thus, while the total mechanical energy injected by massive stars into the ISM of the Milky Way is only a small fraction of the radiative energy budget \( L_{\text{mech}} \approx 2 \times 10^8 \, \text{L}_\odot \) versus \( L_{\text{rad}} \approx 4 \times 10^{10} \, \text{L}_\odot \), the interstellar medium reacts to this mechanical energy by becoming very turbulent, the gas disk puffs up, and part of the volume becomes filled with hot gas. The latter may, even in the plane, become a dominant, separate phase of the ISM, the Hot Ionized (intercloud) Medium (HIM) in which the Warm Neutral/Ionized Medium and Cold Neutral Medium (e.g., diffuse clouds) are embedded. The importance of mechanical energy input for the structure of the ISM has been long recognized through UV absorption lines of highly ionized species e.g., O vi), N V, X-ray emission of hot gas, and large scale H I structures such as chimneys (Snowden et al. 1997; Heiles 1994; McCray & Snow 1979).

4.1. Interstellar Bubbles

Large scale, infrared surveys such as GLIMPSE and MIPSGAL with Spitzer, Hi-GAL with Herschel, and WISE have used dust emission as a tracer of the structure of the ISM of our galaxy and this has revealed that the ISM is a bubbly cauldron of activity where young, massive stars are strongly interacting with their environment (Figure 4; Churchwell et al. 2006). Assisted by volunteers from the general public, in excess of 5,000 “bubbles” have now been identified in IR images of the disk of our Milky Way galaxy (Simpson et al. 2012). These bubbles consist of bright 8 μm emission shells surrounding regions of bright 24 μm emission. These structures are thought to represent wind-blowen-bubbles (Everett & Churchwell 2010) where the shock driven by the fast wind from a massive star \( v_w \sim 2000 \, \text{km/s}; \ 10^{-5} \, \text{M}_\odot/\text{yr} \) sweeps up the surrounding medium into a dense shell while the reverse shock heats the wind material to a high temperature \( 3 \times 10^7 \, \text{K}; \ \text{Weaver et al. (1977)} \). Gas near the inner boundary of this dense shell is then photo-ionized by the star and
Figure 4. A small portion of the GLIMPSE/MIPSGAL survey of the galactic plane reveals a myriad of bubbles (Churchwell et al. 2006). IRAC 8.0-micron light is green and MIPS 24-micron light is red.

Figure 5. Left: Multiwavelength image of the 30 Dor region in the LMC. Hot gas created by stellar winds and supernova explosions is traced by the X-ray emission (blue). Gas photo-ionized by the ~ 2400 massive OB stars in this super star cluster glows in the Hα line (Red). The surrounding photodissociation region is traced by the IR emission from PAHs (green). This is an early stage of the formation of a superbubble. Eventually, such a superbubble will break out of the plane of the LMC. Right: A multi-wavelength, Chandra, Hubble, & Spitzer view of the M82 galaxy reveals a galactic wind — originating in the nucleus — venting out to distances of ~ 5 kpc into the halo. This wind, driven by the hot gas created by many SNe and traced by X-ray emission (blue), entrains gas and dust from the disk. The PAHs in these cloudlets are set aglow by UV star light (red). Shocked intercloud gas recombines and emits — among others — in Hα (orange). The galactic disk is traced by the bluest visible light (yellow-green).

emits in, for example, Hα. Dust inside this ionized gas volume gets heated to a high temperature and emits in the mid-IR (e.g., 24 µm). PAHs in the surrounding photodissociation region are set aglow by FUV photons in the mid-IR emission features (Figure 4). Interpreting these structures as wind-blown-bubbles has some issues, though, as the expected, bright X-ray emission from the hot gas filling the bubbles has been notoriously difficult to observe and, indeed, for those sources where it has been observed, the X-ray emitting gas contains only a small fraction of the energy and mass of the stellar winds (Townsley et al. 2003). In addition, dust is not expected to survive under the harsh conditions of the hot bubble gas (Everett & Churchwell 2010). Furthermore, bubbles are also associated with stars that are suspected to have very weak winds; e.g., the wind mechanical energy is some 2% of the radiative energy for an O5 star but only 0.3 % for a B0 star. As an alternative interpretation, the observed structure of these bubbles may reflect the initial expansion of (radiatively) ionized gas into a medium with a pronounced density gradient followed by pressure release in a champagne flow into a surrounding low density environment when these bubbles burst (Ochsendorf et al., in preparation). The gas dynamics in combination with radiation pressure on the dust can then generate dust waves dominating the IR morphology of the region.

4.2. Galactic Winds & Halo-plane Interaction

Eventually, the massive stars blowing these bubbles will go supernova and a strong supernova shockwave will expand and sweep up the surrounding medium. A reverse shock will be driven into the ejecta heating the gas to ≃ 3 × 10^7 K (Figure 5). Massive stars are generally born in OB associations containing typically some 100 OB stars. The coalescence and rejuvenation of the hot gas by each successive SN will drive the formation and expansion of a superbubble. When this superbubble breaks out of the (cloud) disk, the energy will be vented into the halo — the galactic fountain — mixing material to great height and over large distances within the disk (c.f., Norman & Ikeuchi (1989)). Figure 5 shows a more extreme example of such a break-out associated with the moderate starburst in the nucleus of M82. Studies of IR emission from edge on galaxies have revealed that this levitation of dust is a common characteristic (Irwin et al. 2007; Thompson et al. 2004; Howk & Savage 1997; Burgdorf et al. 2007).
Figure 6. The mechanical luminosity derived from the observed supernova rate (assuming $10^{51}$ erg/SN) or the stellar wind is compared to the local interstellar medium pressure for a few well-chosen sources. The latter has been determine from observations of density/temperature sensitive atomic and/or molecular transitions. W4 has a well-developed superbubble, which has not (yet) broken out of the plane. R136 (and 30 Dor) are in the early stages of developing a superbubble. M82 has a well-developed galactic wind originating in the numerous super star clusters in the nucleus. The ULIRG, Arp 220, has not (yet) developed a galactic wind. The line indicates Equation (4) for a coupling efficiency of $\xi = 0.1$.

The extreme star formation associated with the formation of super star clusters has thus a profound influence on the ecology of a galaxy and its subsequent evolution. To set the scale, a mini-starburst, such as R136 in the 30 Dor region has formed some 50 very massive stars and corresponds to a star formation rate, $SFR \sim 10^{-2} M_\odot/yr$. The whole 30 Dor region has been forming stars over a longer period (tens of millions of years) and is characterized by a $SFR \approx 7 \times 10^{-2} M_\odot/yr$ (Doran et al. 2013). The nuclear starburst in M82 contains the equivalent of some 100 R136 and has a $SFR \sim 1 M_\odot/yr$. A ULIRG, such as Arp 220, has some 10,000 R136 and a $SFR \sim 10^2 M_\odot/yr$. Using a population synthesis model such as Starburst99 (Leitherer et al. 1999), these star formation rates can be translated into the radiative and mechanical energy input; viz.,

$$N_{Lyc} = 2 \times 10^{53} \left(\frac{SFR}{M_\odot/yr}\right) \text{ s}^{-1},$$  
$$\dot{M}_* = 0.26 \times 10^{53} \left(\frac{SFR}{M_\odot/yr}\right) \text{ M}_\odot/yr,$$
$$L_{Mech} = 2 \times 10^8 \left(\frac{SFR}{M_\odot/yr}\right) L_\odot.$$  

Actually, of course, observations of the total infrared luminosity, the H$\alpha$ or Pa$\alpha$ line, are used to determine the star formation rate through equation (1) and similar ones. Equations (2) and (3) can then be used to determine the mass loss rate by massive stars and the mechanical luminosity. This does presume that the observed luminosity of a region reflects star formation activity rather than AGN activity. The importance of AGN activity may be judged from X-ray emission — but high column densities may hamper their detection —, from mid-IR emission lines from highly ionized species, or from the equivalent width of the PAH features (Genzel et al. 1998). Given the high obscuration that can be associated with extreme regions of star formation in galactic nuclei, much effort has been spent on developing other quantitative indicators for the star formation rate and validating them, using studies of local regions of star formation. These include the luminosity in the PAH features (Calzetti et al. 2007) and gas tracers of PDRs such as the CO lines (Tacconi et al. 2013).

We can also define a “blow-out” criteria; the minimum mechanical luminosity required for a superbubble to break out of the galactic disk,

$$L_{Mech} = 7 \times 10^7 \left(\frac{H}{\text{kpc}}\right)^2 \left(\frac{P}{10^7 \text{K cm}^{-3}}\right) \left(\frac{T}{10 \text{ K}}\right) \left(\frac{0.1}{\xi}\right) L_\odot,$$

with $H$, $P$, and $T$ the scale height, pressure, and temperature of the gas in the disk and $\xi$ the thermalization efficiency of the mechanical energy. The latter is estimated to be $\sim 0.1$ (Veilleux et al. 2005). Figure 6 collects data on a few well-chosen examples of star formation and superbubble formation. We note that regions of extreme star formation, such as ULIRGs, are characterized by high interstellar pressures, but nevertheless this data illustrates that breakout is happening/imminent.
Tielens

in all these environments. Regions of extreme star formation are therefore natural pollutants of galactic halo’s and the intergalactic medium and the break out process will eventually limit extreme starbursts in ULIRG environments.

5. **SPICA’S VISION**

The evolution of the interstellar medium is driven by a number of complex processes which are deeply interwoven, including mass accretion, stellar mass injection, star formation, mechanical energy input by stellar winds & supernova explosions, and radiative energy input. The resulting ISM is highly structured where different phases interact and interchange dynamically on a rapid timescale. Moreover, the properties of the ISM are expected to vary systematically reflecting the local (stellar/ISM) conditions.

Dust and PAHs can be effective and quantitative tracers of many of these processes and infrared observations are key to this. Because of space limitations, I have not highlighted in this review IR observations of interstellar gas. The mid- and far-IR is home to key atomic and ionic fine-structure lines including [O I], [O III], [C II], [N II], [N III], [S I], [S III], [S IV], [Ar II], [Ar III], [Ne II], [Ne III], and [Si II] as well as the molecular rotational lines of H₂ and CO. Combined, these transitions are excellent tracers of the physical conditions of the emitting gas and hence can probe the physical conditions in warm interstellar regions.

Large molecules and dust also play a role in many of these processes but these links are only partially understood. Specifically, PAHs and dust couple gas thermodynamically to the non-ionizing stellar light through the photo-electric effect and dynamically through radiation pressure.

As the next generation infrared observatory, **SPICA** is well poised to address both aspects of ISM research using dust and PAH emission to trace the cyclical interrelationship of stars and the interstellar medium as well as quantify the detailed physics that drives this evolution in the near Universe and then use those relationships to understand the evolution of galaxies in the far Universe. Specifically, **SPICA** will be able to address many of the key questions in this field quantitatively and I am, particularly, looking forward to answers to the following:

- What are the characteristics of interstellar dust and how does that depend on metallicity, star formation activity, ISM conditions? How similar/different is dust formed in regions of extreme star formation from “local” dust and what does that tell us about the characteristics of dust in the earliest galaxies?
- What is the role of PAHs and very small grains in the energy & ionization balance of the ISM? And how does that influence the structure of the ISM and the star formation activity?
- What is the role of mechanical energy — SNR & turbulence — in the energy balance and phase structure of the ISM? How do supernova shocks process dust and PAHs and how does this couple back to the structure of the ISM and the star formation activity?
- What is the role of the Halo and the IGM in the mass, pressure, & energy budgets of the ISM?
- How can we best trace the conditions for star formation over the history of the Universe?

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Interstellar Dust and PAHs in Our Galaxy and Nearby Galaxies: from AKARI to SPICA

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ABSTRACT

AKARI has revealed various phenomena on the evolution of dust grains, including polycyclic aromatic hydrocarbons (PAHs), through processing in the interstellar space of our Galaxy and nearby galaxies. In particular the mid- to far-infrared (far-IR) all-sky diffuse maps show that PAHs are widely distributed in the Galactic plane, similarly to large grains but with significant spatial variations in their abundance ratios. Following AKARI, SPICA will elucidate the whole story of the evolution of dust grains in space. The most outstanding uniqueness of SPICA is high-sensitivity spectral mapping in a continuous mid- to far-IR range, which matches very well with the AKARI heritage. The spectral range includes most of the fundamental vibration modes of minerals, organic matter, and ices. The continuous spectral coverage, not hampered by the atmospheric absorption, is essential to unambiguously identify relatively broad spectral features inherent to solid particles. Among the proposed instruments, the SCI (SPICA Coronagraph Instrument) is indispensable to study a small-scale structure around a central bright source. It is particularly important to investigate materials surrounding dusty AGNs in distant galaxies or young stars in nearby starforming regions, where we can study the properties of dust grains in early Universe and in planetary formation sites, respectively.

1. INTRODUCTION

With AKARI (Murakami et al. 2007), we have performed a systematic study of interstellar dust grains in various environments of galaxies including our Galaxy (Kaneda et al. 2009). Because of its unique capabilities, such as near- and far-infrared (far-IR) spectroscopy, and all-sky coverage in the mid- and far-IR, AKARI has revealed various phenomena on the evolution of carbonaceous grains including polycyclic aromatic hydrocarbons (PAHs), through processing in the interstellar space. For example, the AKARI near- and far-IR spectroscopy have indicated structural changes of hydrocarbon particles and formation of graphite grains, respectively, in harsh environments of galaxies. In addition to such spectral datasets, the 9 µm diffuse map is the world-first all-sky map of the PAH emission (Figure 1), which has revealed that PAHs are widely distributed in the Galactic plane, similarly to large grains but with significant spatial variations in their abundance ratios.

Hence AKARI provides global and unbiased views of interstellar dust and PAHs in our Galaxy and nearby galaxies thanks to the all-sky coverage, but not their detailed properties due to its rather poor spatial resolution and limited spectroscopic capabilities. Spectral mapping data of individual targets provided by SPICA with its high spatial resolution and continuous wavelength coverage are perfect complements to the AKARI heritage. In this paper, we review the results obtained from our AKARI observations on the processing of interstellar dust grains in various environments of our Galaxy and nearby galaxies. Then we discuss our future prospect for a study of this topic using a combination of the focal-plane instruments of SPICA.

2. OUR GALAXY AS SEEN BY AKARI

Figure 1 shows a diffuse map of the Galactic plane in the AKARI 9 µm band, along with the spectral response curves of the AKARI 9 µm and 18 µm bands in comparison with those of the WISE bands at similar wavelengths. It is notable that the AKARI 9 µm band covers the major PAH emission features very efficiently. Similarly we obtain diffuse maps of the Galactic plane in the AKARI 18, 65, 90, 140, and 160 µm bands, which represent distributions of warm and cool interstellar dust components. The quality of those AKARI all-sky images has been much improved from that of the IRAS images.
Utilizing the AKARI all-sky point-source catalogs, we identified C-rich and O-rich AGB stars, based on the color-color diagrams of the 9 and 18 µm band fluxes with the 2MASS J, H, and K band fluxes (Ishihara et al. 2011). As for their spatial distributions, we find that the O-rich AGBs are more concentrated toward the Galactic center, while the C-rich AGBs are rather uniformly distributed throughout the Galactic plane. From the AKARI diffuse maps of the Galactic plane, however, we find that interstellar PAHs and far-IR dust are similar in the spatial distribution on both global and local scales. Because it is generally thought that silicate grains, a major far-IR dust component, are supplied into the interstellar space by O-rich stars, while PAHs are produced by C-rich stars, the result indicates that products and their suppliers have different spatial distributions.

Figure 1 also shows the positions of near-IR (2–5 µm) spectroscopic observations, most of which were performed during the AKARI warm mission phase after the boil-off of liquid helium cryogen. In particular, the properties of hydrocarbon grains can be probed by the AKARI near-IR spectroscopy of the 3.3 µm main feature and 3.4–3.6 µm sub-features. Both of them are attributed to the C-H vibration mode of carbonaceous grains. The former is due to aromatic (sp²) hydrocarbons, while the latter is probably attributed to aliphatic (sp³) hydrocarbons (Duley & Williams 1981). They are likely to come from mixed aromatic-aliphatic organic nano-particles (Kwok & Zhang 2011). It has been believed that their intensity ratios do not vary much in the ISM. However AKARI reveals that they considerably change, depending on interstellar conditions, which implies structural changes of the organic matter. Those spectral variations seem to be related with the spatial variations in the ratios of the PAH to far-IR intensities which are revealed by the Galactic diffuse maps (Kaneda et al. 2012).

For study of the ISM with SPICA, we will select particular regions based on the AKARI all-sky maps (also exploiting other databases such as Herschel/HIGAL and Spitzer/GLIMPSE). Probing the properties of circumstellar and interstellar dust with spectral mapping observations, we understand the lifecycle of matter within our Galaxy.

3. NEARBY GALAXIES AS SEEN BY AKARI

External galaxies provide much wider ranges of physical conditions for the ISM. Among them, nearby galaxies, which are spatially resolved well with SPICA, are important targets to understand large-scale circulations of matter in galaxies. Figure 2 shows the distribution of the PAH emission in the starburst galaxy M 82, which is widely extended toward the halo regions. In M 82, copious amounts of large grains and PAHs are flowing out of the disk through galactic superwinds. We found that there is an excellent correlation between the PAH and Hα distributions (Kaneda et al. 2010). The spectropolarimetry showed that Hα is significantly (5–15 %) polarized (Yoshida et al. 2011), which suggests that Hα photons from the galactic disk are scattered by PAHs in the halo. Moreover it was found that the estimated dust flow velocity decreases with the height from the disk, which implies that PAHs may be falling back toward the disk (Yoshida et al. 2011).

Using the AKARI near-IR spectroscopy, we clearly detect the PAH 3.3 µm emission and the 3.4–3.6 µm features in the halo regions, which are located at a distance of 2 kpc away from the galactic center, thus confirming the presence of very small PAHs even in the harsh environment of the M 82 halo (Yamagishi et al. 2012). The observed spectral properties are quite different from those commonly understood; the 3.4–3.6 µm features are unusually abundant in the halo, suggesting the dominance of aliphatic structures over aromatic ones by shattering of hydrogenated amorphous carbon grains in shocks. Hence, for nearby active galaxies, spectral mapping with SPICA will reveal dust processing through material circulation on a galactic scale, although M 82 is obviously too bright for SPICA.

PAHs and dust in elliptical galaxies provide us with another extreme case representing the end of the lifecycle of matter. With Spitzer and AKARI, we find that the PAH emission in elliptical galaxies exhibits unusual band ratios (Kaneda et al. 2008); the usually strongest 7.7 µm feature is notably weak, whereas the 3.3 µm and 11.3 µm features are relatively strong.
DUST IN GALAXIES: FROM AKARI TO SPICA

Figure 2. Contour maps of M 82 in the AKARI 7 \(\mu m\) (PAH) band overlaid on (left) the 2MASS \(J\) band and (right) H\(\alpha\) images (Kaneda et al. 2010).

We conclude that neutral PAHs, rather than ionized ones, become dominant in very soft radiation fields, typical of elliptical galaxies, which causes the faint C-C vibration features at 6–8 \(\mu m\). It should be noted that the PAH 3.3 \(\mu m\) and 11.3 \(\mu m\) emission does not represent any star-forming activity in this case.

Figure 3 shows the spatial distributions of large grains and PAHs in the elliptical galaxies, NGC 4125 and NGC 4589. The distribution of the PAH 11.3 \(\mu m\) emission was obtained with the Spitzer/IRS spectral mapping observations (Kaneda et al. 2011), while that of the dust emission was obtained by the AKARI/FIS slow-scan observations. The figure reveals that the PAHs exist only near the galactic centers, while the large grains are distributed more widely, even considering the difference in spatial resolution. Recently we obtain the far-IR deep imaging data of these galaxies with the Herschel/PACS in our open time program. The lower panels in Figure 3 show the 100 \(\mu m\) images after optimized high-pass filtering; far-IR dust emissions in both galaxies are spatially resolved well, exhibiting distributions quite similar to PAHs. Since PAHs are likely to be old remnants originating in mass losses from intermediate-mass stars, while large silicate grains are currently being produced from low-mass old stars, this similarity may have deep physical implications for evolution of the ISM in old galaxies. A problem is that the sensitivity of Herschel is not high for extended emission due to high IR background from its warm telescope; The cold telescope of SPICA is indispensable to explore diffuse dust components in faint galaxies such as elliptical galaxies to understand the end of the lifecycle of matter.

4. FROM AKARI TO SPICA

Following AKARI, SPICA will elucidate the whole story of the evolution of solid matter (i.e. dust grains) in space. The most outstanding uniqueness of SPICA is high-sensitivity spectral mapping in a continuous mid- to far-IR range, which matches very well with the above AKARI heritage. The spectral range includes most of the fundamental vibration modes of minerals, organic matter, and ices. The continuous spectral coverage, not hampered by the atmospheric absorption, is essential to unambiguously identify relatively broad spectral features inherent to solid particles. Among the proposed instruments, the SCI (SPICA Coronagraph Instrument) is indispensable to study a small-scale structure around a central bright source. It is particularly important to investigate materials surrounding dusty AGNs in distant galaxies or young stars in nearby star-forming regions, where we can study the properties of dust grains in early Universe and in planetary formation sites, respectively. Dust grains are created and supplied into the interstellar space mostly by evolved stars through mass loss, the formation site of which could also be probed in detail by the SCI.

It is physically straightforward that the mid-IR wavelength range of SPICA is most suitable for detection of materials with temperatures of about 100 K. Such warm materials are often found in compact regions surrounding the central sources that heat or excite the ambient material. For example, planet-forming disks around Sun-like stars and dusty tori around typical AGNs have equilibrium temperatures of \(\sim 100\) K at \(\sim 10\) AU and \(\sim 100\) pc, respectively, from the central sources. They correspond to a spatial scale of 1″ at distances of 10 pc and 20 Mpc for the star and AGN, respectively. Since \(\lambda /D\) is 0″7 at a wavelength of 10 \(\mu m\), this spatial separation is rather too close for SPICA, and therefore, due to diffraction, signals from central bright sources would severely contaminate their outskirts regions which are to be studied with SPICA. This situation is schematically shown in Figure 4. The SCI can reconcile the mismatch between the SPICA’s unique spectral region and the characteristic spatial scale. Considering the balance between heating (proportional to \(r^{-2}\)) and cooling rates (proportional to \(T^4\)), the angular size of a region with temperature \(T\) increases with \(T^{-1/2}\) and thus \(\lambda_{peak}^2\), the square of the peak wavelength of the thermal emission to be observed and spatially resolved. Since the angular resolution is degraded in proportion to \(\sim \lambda /D\), coronagraphy at shorter wavelengths is much more compelling than that at longer wavelengths.
Figure 3. Upper: AKARI 90 µm band (white contours), Spitzer/IRS PAH 11.3 µm spectral mapping (red contours), and AKARI 3 µm band (green) images of the elliptical galaxies NGC 4125 and NGC 4589. Lower: The Herschel/PACS 100 µm maps of the same galaxies.

Figure 4. Schematic image to show why we need a mid-IR coronagraph to study warm materials around a central source.

5. CONCLUDING REMARKS

With the unique capabilities of all-sky survey and near-IR spectroscopy, AKARI reveals various phenomena about dust grains on large spatial scales in galaxies including our own. With better angular resolution and low IR background, SPICA will connect small- and large-scale phenomena. Spectral imaging with continuous 4–210 µm coverage will unravel the whole story of the evolution of solid matter in space from early Universe to planet formation.

We thank all the members of the AKARI projects, particularly those belonging to the working group for the mission program, “ISM in our Galaxy and nearby galaxies (ISMGN)”. AKARI is a JAXA project with the participation of ESA.
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The Properties and the Structure of the ISM of Low Metallicity Dwarf Galaxies: From Herschel to SPICA

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ABSTRACT

Herschel has brought new light on the structure and properties of the gas and dust in low metallicity galaxies. The sensitivity of SPICA will leap beyond Herschel to revolutionise this study, where crucial observational constraints on the dust and gas properties of the extremely low metallicity galaxies has been lacking. We review our current knowledge of the low metallicity dust and gas properties in terms of where Herschel and Spitzer have brought us and how SPICA will go even further in this field.

1. INTRODUCTION: DWARF GALAXIES SURVEYS

The gas and dust spectral energy distribution (SED) that a galaxy presents today is its fossil footprint harboring clues to the processes governing its evolution through cosmic time. In order to reconstruct the history of the galaxy, in lieu of capturing snapshots of any one galaxy throughout its evolutionary history, we can study large numbers of galaxies possessing wide ranges of properties, including metallicity, star formation activity and morphology, for example, and attempt to reconstruct the effect of these variables on the evolution of galaxies. This requires characterising the various gas phases with the appropriate variety of tracers and sampling the dust emission over a wide range of wavelengths. Only then can we have enough constraints to follow the dust and gas evolution in galaxies.

While our comprehension of the gas and dust properties in metal-rich or moderately metal-poor galaxies has been growing at a fast pace due to the very successful infrared (IR) space missions IRAS, ISO, Spitzer, AKARI and Herschel, as well as recent ground-based millimetre (mm) and submillimetre (submm) telescopes, the number statistics of studies that include the low metallicity dwarf galaxies, in particular, have been suffering, mainly from lack of sufficient sensitivity. The Dwarf Galaxy Survey (DG: Madden et al. 2013), has compiled a large observational data base of 48 low metallicity galaxies, motivated by the new PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) 55 to 500 μm photometry and spectroscopy observations onboard the Herschel Space Observatory (Pilbratt et al. 2010).

Surmising dust and gas properties of low metallicity galaxies has been an enigmatic undertaking. For one thing, assessing the molecular gas content in dwarf galaxies has been a difficult issue due to the formidable challenge in detecting CO in these galaxies (e.g. Schruba et al. 2012; Cormier et al. 2013, and references within). Also, even before Herschel the presence of a submm excess over the expected Rayleigh-Jeans behavior had been noted in the SEDs of some low metallicity galaxies detected at 850/870 μm with SCUBA on JCMT and with LABOCA on APEX (e.g. Galliano et al. 2003, 2005; Bendo et al. 2006; Galametz et al. 2009; Zhu et al. 2009; Galametz et al. 2011). The origin of this submm excess is still under investigation (see Galametz et al. 2011, for discussion).

2. DUST PROPERTIES AND METALLICITY

The dust properties of the DGS have been modeled by Rémy-Ruyer et al. (2013a) (Figure 1, for example) and compared with the Herschel KINGFISH survey, consisting of mostly metal-rich galaxies (Kennicutt et al. 2011; Dale et al. 2012). The full DGS + KINGFISH samples, 109 galaxies together ranging over 2 dex in metallicities, are modeled to determine the dust mass, dust temperature ($T_{\text{dust}}$) and emissivity index ($\beta$) to investigate the effects of metallicity on the dust properties.

The overall $T_{\text{dust}}$ of the low metallicity galaxies spans a broader range in temperature and a higher mean $T_{\text{dust}}$ of 32 K, with a few extreme cases as high as 90 K. This is in contrast to the higher metallicity KINGFISH galaxies which span a narrower temperature distribution and a lower mean $T_{\text{dust}}$ of 23 K. A trend of increasing $T_{\text{dust}}$ with decreasing metallicity can be noted (Rémy-Ruyer et al. 2013a). In contrast, the distribution of $\beta$ is widely varying for both galaxy samples with no obvious trend in metallicity.

With dust masses accurately measured for galaxies of a broad metallicity range, it is possible to characterize the impact of metallicity on the gas-to-dust mass ratio (G/D). This was possible for the moderately low metallicity to more metal-rich galaxies (for $12 + \log (\text{O/H}) > 8$) before Herschel, but the behavior of metal enrichment in the ISM for the lower metallicity galaxies was uncertain due to observational constraints. Rémy-Ruyer et al. (2013b) show the broad scatter observed in G/D over 2 dex range of metallicity and a steep rise in the G/D for the lower metallicities, consistent with chemical evolution models, that require grain growth in the ISM as a source of dust production as well as episodic star formation history.
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Figure 1. Left: Metallicity range of the DGS and KINGFISH samples. Right: The full SED of the dwarf galaxy, NGC 1705, modeled by Rémy-Ruyer et al. (2013a) using the Galliano et al. (2011) model. Note the excess beyond that of the SED model, appearing at 1.2 mm.

Figure 2. Dust properties of the DGS and KINGFISH samples. Histogram of $T_{\text{dust}}$ distribution with metallicity (left) and $\beta$ (right). The color scale represents the metallicity values.

(Asano et al. 2013, Zhukovska et al., in preparation): dust production becomes more efficient when enough dust can accumulate, and this occurs in the observations and models at around $12 + \log (O/H) \sim 7.5$ (Figure 3).

3. FIR FINE STRUCTURE LINES AND LOW METALLICITY ISM

The DGS galaxies were surveyed in the most important FIR fine structure lines, such as 158 $\mu$m [C II], 63 and 145 $\mu$m [O I], 88 $\mu$m [O III] and more rarely, due to sensitivity limits, 57 $\mu$m [N III], 122 and 205 $\mu$m [N II] (see Madden et al. 2013, for more details of the DGS observations). These important cooling lines are diagnostics to probe the FUV flux, the gas density and temperature and the filling factor of the ionized gas and photodissociation regions (PDRs; e.g. Wolfire et al. 1990; Kaufman et al. 2006; Le Petit et al. 2006). The photoelectric effect is normally the dominant source of gas heating in PDRs and [C II] usually ranks foremost in the PDR cooling lines, followed by the 63 $\mu$m [O I]. Thus the [C II]/$L_{\text{FIR}}$ (or ([C II]+ [O I])/$L_{\text{FIR}}$) indicates the efficiency of photoelectric heating. Figure 4 (left) shows the ([C II]+ [O I])/$L_{\text{FIR}}$ vs. $L_{\text{FIR}}$ of dwarf galaxies is higher than those of galaxies in other surveys, of mostly metal-rich galaxies. These relatively larger efficiency factors, from 1% to 2%, can be a consequence of relatively normal PDR gas densities (often on the order of $10^3$ to $10^4$ cm$^{-3}$) and low average ambient radiation fields over full galaxy scales, resulting in a relatively low ionization parameter. Note, in contrast, the effect of the FIR line deficit seen in the most luminous sources (e.g. Luhman et al. 2003; Graciá-Carpio et al. 2011; Díaz-Santos et al. 2013; Farrah et al. 2013) where dustier H II regions are present leading to a high ionization factor globally. On the other hand, the 88 $\mu$m [O III] line is the brightest FIR cooling line in the dwarf galaxies — not the [C II] line, as in the normal metallicity galaxies. The predominance of the [O III] line which requires an ionization energy of 35 eV, demonstrates the ease at which such hard photons can traverse the ISM on full galaxy scales (see also Cormier et al. 2012; Lebouteiller et al. 2012), highlighting the different nature and structure of the ISM of low metallicity galaxies.
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Figure 3. Comparison of the observed G/D for the DGS + KINGFISH galaxies compared to models of Asano et al. (2013) (left) and Zhukovska et al. (in preparation) (right) for various star formation time scales (τ) and star formation histories. From the recent study of Rémy-Ruyer et al. (2013b).

Figure 4. Left: ([C II]+[O I])/L_{TIR} vs L_{TIR} and Right: [C II]/L_{FIR} vs CO(1–0)/L_{FIR} for the dwarf galaxies and other more metal-rich samples.

The dwarf galaxies also show extreme [C II]/CO ratios (Figure 4 right): while most normal star forming galaxies are observed to have [C II]/CO ~ 1000 to 4000, the low metallicity galaxies can reach much higher ratios — up to an order of magnitude higher, or more, in [C II]/CO over galaxy-wide scales. Such relatively high [C II] values may be indicative of a reservoir of gas, possibly molecular, not traced by CO: the CO-dark molecular gas, which may be present in the C∗-emitting region, where the CO is photodissociated but the H2 remains self-shielded from the dissociating photons (e.g. Glover & Jappsen 2007; Wolfire et al. 2010). This was first uncovered in a few low metallicity galaxies using [C II] (e.g. Poglitsch et al. 1995; Israel et al. 1996; Madden et al. 1997), but Herschel has increased the sample for deeper studies and SPICA will take the study of this phenomenon to much large samples of extremely low metallicity, where CO is very difficult to detect, if at all.

4. PROBING THE COMPLEX LOW METALLICITY ISM - THE SPICA DWARF GALAXY SURVEY

The challenge for SPICA is to take the next step to obtain the wide range of MIR and FIR cooling lines to be able to model the various phases of the gas and dust over full galaxy scales as well as obtaining much large sample of low metallicity dwarf galaxies, to obtain a more precise prescription of the role of metallicity in governing the evolution of galaxies. Herschel has successfully opened up wide the window into this subject and can be exploited to build a most comprehensive observing programs for SPICA. To execute this will entail reaching for a large number of the lowest metallicity galaxies. Due to sensitivity, Herschel was able to target only a handful of extremely low metallicity galaxies: less than 1/20Z☉ in...
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photometry ($12 + \log (O/H) < 7.8$; Figure 1) and of these 20% were not detectable with PACS 160 µm. 10% of our full sample was not detectable in spectroscopy at all, and only 20% were detected with 5 FIR fine structure lines and only one or two of the brightest FIR fine structure lines, if at all, in the lowest metallicity galaxies. Having observational constraints for the MIR through FIR continuum to accurately model the dust properties (Figure 1) for large numbers of the lowest metallicity galaxies would be a breakthrough with SPICA. Many ambiguities remain in the interpretation of the behavior of the $G/D$ ratio at these low metallicities, specifically metallicities less than $12 + \log (O/H)$ (about $1/8 Z_{\odot}$; Figure 3).

Using limiting MIR and FIR gas diagnostics to deduce the conditions for star formation and the structure of the galaxy is effectively averaging ensembles of PDRs and physically different gas phases mixed in a telescope beam. The challenge in moving forward with interpretation is to cover a range of diagnostics having varying critical densities and ionization potentials, to be able to characterise the PDRs and dense and diffuse ionized gas and neutral atomic and molecular gas which have very different filling factors even for the range of dwarf galaxies Herschel has surveyed. Analysis of these various phases comprising galaxies can not be done without considering the gas and dust tracers together. An example of one of the most thorough analysis that has been approached, given the wide selection of diagnostics for any one galaxy, is demonstrated in Cormier et al. (2012, 2013) with 17 FIR fine structure lines and CO observations as well as the photometry constraints to model the full dust SED of Haro 11. This is the brightest low metallicity galaxy in the DGS sample and 7 FIR lines were obtained with PACS as well as all of the higher energy ionic lines with the Spitzer IRS. Cormier et al. (2012) was able to determine the mass fraction of different phases of this unresolved galaxy. Only with sufficient observational constraints was this possible, but now will be possible for large numbers of galaxies, with the increased sensitivity of SPICA.

Statistical surveys with SPICA will follow from Euclid (launch expected 2018) which will survey 15000 sqdegree, detecting $10^{12}$ galaxies of which about $10^5$ should be dwarfs: to as low as $10^5 L_{\odot}$ out to 100 Mpc with a limiting magnitude, $M_g$, of $\sim 24.5$ whereas Herschel was $\sim 20.0$. If SPICA surveys 500 dwarf galaxies of similar characteristics as the lowest metallicity galaxies detected by Herschel (SBS0335−052 and Izw18), the FIR SAFARI spectrometer on SPICA would require 500 h to simultaneously detect the 7 brightest FIR lines and continuum. The MIR camera, MCS (12 to 28 µm), which would observe the PAH bands, $H_2$ lines, ionic lines plus warmer dust continuum, would use 100 to 500 h to complete the survey. Similarly, to map the extended Local Group galaxies, such as NGC 6822, NGC 4214, IC 10, would require on the order of $\sim 10^4 h$ with SAFARI while mapping galaxies the size of the SMC or M31 ($5^2 \times 2^2$ deg) would use 300 to 500 h. The LMC (8 deg $\times 8$ deg), on the other hand, would require more than 2 months if mapped completely. Mapping 1 deg $\times 1$ deg pieces of the LMC with SAFARI would take $\sim 30^4 h$, which would allow a wide rage of ISM and star formation properties to be probed in the LMC. Spectroscopy with PACS on Herschel and IRS on Spitzer acquired very limited regions in the LMC and SMC, each of several arcmin$^2$ at most. Only with large statistically-important surveys with SPICA observing a large array of important diagnostic MIR to FIR lines, and with more efficient mapping characteristics, will we be able to accurately assess the impact of metallicity on the evolution of the dust and gas of galaxies.

None of this research would be possible without the dedicated effort of the Herschel PACS GT and SPIRE GT SAG 2 teams in producing science-quality data, with particular acknowledgement to Maud Galametz, George Bendo, Hélène Roussel, Matt Smith, Marc Sauvage, Eckhard Sturm and Albrecht Poglitsch. This research was supported in part by the Agence Nationale de la Recherche (ANR) through the programme SYMPATICO (Program Blanc Projet ANR-11-BS56-0023).

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Herschel Planetary Nebula Survey (HerPlaNS)

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ABSTRACT

Herschel Planetary Nebula Survey (HerPlaNS) is a far-IR imaging and spectroscopic survey of planetary nebulae, performed with the Herschel Space Observatory, aiming at understanding the energetics and shaping history of the circumstellar nebulae. Below we briefly demonstrate the breadth and depth of the HerPlaNS data set using one of the targets, NGC 6781, as an example, and explore expectations in the era of SPICA, the next-generation far-IR mission.

1. HERSCHEL PLANETARY NEBULA SURVEY (HERPLANS)

The Herschel Planetary Nebula Survey (HerPlaNS) is an open-time program of the Herschel Space Observatory (Pilbratt et al. 2010) conducted by a team of about 30 astronomers.1 Our chief objective is to examine the spatially-resolved far-IR characteristics of planetary nebulae (PNs; Table 1) as energetic systems of gas and dust by mastering the telescope’s mapping and spectroscopic capabilities. Far-IR observations allow simultaneous probing of the dust component via thermal continuum emission and the gas component via far-IR fine-structure and molecular line emission without much extinction. The spatially-resolved energetics as a function of location in these nebulae will provide more insights about the evolution of the central star and circumstellar shells. In this contribution, we present a brief overview of the survey and its data products, summarizing the potential of the data set using NGC 6781 as an example (§2), and hint at expectations for the era of SPICA (§3). A complete account of the present summary is found elsewhere (Ueta et al. 2014).

2. HERPLANS DATA DEMONSTRATION WITH NGC 6781

Table 1. List of HerPlaNS Target PNs

<table>
<thead>
<tr>
<th>Name</th>
<th>PN G</th>
<th>Morpha</th>
<th>D (kpc)</th>
<th>R (pc)</th>
<th>Age (10^3 yr)</th>
<th>T_e (10^3 K)</th>
<th>H2</th>
<th>X-Raysb</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 40</td>
<td>120.0+09.8</td>
<td>Bbsh</td>
<td>1.0</td>
<td>0.11</td>
<td>4</td>
<td>48</td>
<td>N</td>
<td>D</td>
</tr>
<tr>
<td>NGC 2392</td>
<td>197.8+17.3</td>
<td>Rsai</td>
<td>1.3</td>
<td>0.14</td>
<td>3</td>
<td>47</td>
<td>N</td>
<td>D, P</td>
</tr>
<tr>
<td>NGC 3242</td>
<td>261.0+32.0</td>
<td>Ecspa</td>
<td>1.0</td>
<td>0.10</td>
<td>4</td>
<td>89</td>
<td>N</td>
<td>D</td>
</tr>
<tr>
<td>NGC 6445</td>
<td>008.0+03.9</td>
<td>Mpi</td>
<td>1.4</td>
<td>0.14</td>
<td>3</td>
<td>170</td>
<td>Y</td>
<td>P</td>
</tr>
<tr>
<td>NGC 6543</td>
<td>096.4+29.9</td>
<td>Mcspa</td>
<td>1.5</td>
<td>0.09</td>
<td>5</td>
<td>48</td>
<td>N</td>
<td>D, P</td>
</tr>
<tr>
<td>NGC 6720</td>
<td>063.1+13.9</td>
<td>Ecsh</td>
<td>0.7</td>
<td>0.13</td>
<td>6</td>
<td>148</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>NGC 6781</td>
<td>041.8+02.9</td>
<td>Bth</td>
<td>1.0</td>
<td>0.32</td>
<td>26</td>
<td>112</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>NGC 6826</td>
<td>083.5+12.7</td>
<td>Ecsha</td>
<td>1.30</td>
<td>0.08</td>
<td>5</td>
<td>50</td>
<td>N</td>
<td>D, P</td>
</tr>
<tr>
<td>NGC 7009</td>
<td>037.7−34.5</td>
<td>Lbspa</td>
<td>1.5</td>
<td>0.09</td>
<td>3</td>
<td>87</td>
<td>N</td>
<td>D, P</td>
</tr>
<tr>
<td>NGC 7026</td>
<td>089.0+03.3</td>
<td>Bs</td>
<td>1.7</td>
<td>0.16</td>
<td>&lt; 1</td>
<td>80</td>
<td>N</td>
<td>D, P</td>
</tr>
<tr>
<td>Mz 3d</td>
<td>331.7−01.0</td>
<td>Bps</td>
<td>1−3</td>
<td>0.1−0.2</td>
<td>0.6−2</td>
<td>32</td>
<td>Y</td>
<td>D, P</td>
</tr>
</tbody>
</table>

(a) According to the morphological classification by Sahai et al. (2011). (b) The HerPlaNS sample is a subset of the Chandra X-ray Planetary Nebula Survey (Kastner et al. 2012): D - diffuse, P - point-source X-ray detection. (c) Not a ChanPlaNS target PN; data from Gruendl et al. (2006). The PSF of XMM-Newton does not allow clear determination of the presence of a point source. (d) Not a ChanPlaNS target PN; may be a symbiotic/PN mimic (Frew 2008); data from Kastner et al. (2003).

NGC 6781 is a PN near the end of the interior nuclear burning phase, whose central star (CSPN) is of 110 kK (Frew 2008) and 385 L\(_{\odot}\) at 950 \(\pm 143\) pc away (Schwarz & Monteiro 2006). Comparison of these parameters with evolutionary tracks of Vassiliadis & Wood (1994) suggests that the initial and present masses of the central star are 1.5 and 0.6 M\(_{\odot}\), respectively, and the age of the PN since the AGB turn-off is \(3 \times 10^4\) yr.

The optical nebula of NGC 6781 shows a signature “ring” of 50′′ radius within a diffuse, low-emission nebula extending \(190′′ \times 160′′\) (Mavromatakis et al. 2001; Phillips et al. 2011). Morpho-kinematic observations in molecular lines (Bachiller et al. 1993; Hiriart 2005) indicated that the nebula is a nearly pole-on cylinder with an equatorial enhancement (i.e., barrel) with the \(4 \times 10^4\) yr dynamical age at adopted 950 pc.

Hence, the spatially-resolved data of NGC 6781 will reveal variations nebular quantities in the equatorial plane as a function of radius, taking into account the height of the bipolar structure along the direction of the line of sight.

### 2.1. Broadband Imaging: Diagnostics via Dust Continuum

HerPlaNS broadband imaging consists of PACS dual-band imaging at 70 and 160 \(\mu m\) over a \(600′′ \times 600′′\) field and SPIRE triple-band imaging at 250, 350, and 500 \(\mu m\) over a \(240′′ \times 480′′\) field. Far-IR images of NGC 6781 (Figure 1, left) reveal the signature ring of the near pole-on cylindrical barrel in all five far-IR bands. The total fluxes are measured by aperture photometry with the 3-\(\sigma\)sky threshold (Table 2).

The surface brightness distribution at 70 \(\mu m\) is co-spatial with low-ionization optical line emission. The emission peaks at the eastern and western rims represent the pivot points of the inclined barrel. The brighter southern rim shows the higher-temperature inner barrel wall in the cavity, while the dimmer northern rim shows the lower-temperature outer barrel wall. This surface brightness imbalance becomes less at longer wavelengths where the optical depth is low and the “ring”

Table 2. Far-IR Image Characteristics and Photometry of NGC 6781

<table>
<thead>
<tr>
<th>Band</th>
<th>(\lambda) ((\mu m))</th>
<th>(\Delta \lambda) ((\mu m))</th>
<th>(I_{\text{peak}}) (mJy arcsec(^{-2}))</th>
<th>(\sigma_{\text{sky}}) (mJy arcsec(^{-2}))</th>
<th>(F_{\nu}) (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACS Blue</td>
<td>70</td>
<td>25</td>
<td>11.623</td>
<td>0.022</td>
<td>65.42 (\pm 3.28)</td>
</tr>
<tr>
<td>PACS Red</td>
<td>160</td>
<td>85</td>
<td>6.68</td>
<td>0.06</td>
<td>64.88 (\pm 3.28)</td>
</tr>
<tr>
<td>SPIRE PSW</td>
<td>250</td>
<td>76</td>
<td>2.41</td>
<td>0.06</td>
<td>30.04 (\pm 4.60)</td>
</tr>
<tr>
<td>SPIRE PMW</td>
<td>350</td>
<td>103</td>
<td>0.982</td>
<td>0.042</td>
<td>14.56 (\pm 2.25)</td>
</tr>
<tr>
<td>SPIRE PLW</td>
<td>500</td>
<td>200</td>
<td>0.327</td>
<td>0.046</td>
<td>6.41 (\pm 1.02)</td>
</tr>
</tbody>
</table>
looks more complete. The extent of the far-IR emission is about the same as the diffuse [N II] emission of a deep exposure image (about 100″ radius at 5-σ; Mavromatakis et al. 2001). Hence, the diffuse line emission is probably caused by dust grains scattering the line emission.

By fitting these emission maps with the power-law dust emissivity ($S_{\nu} \propto \nu^\beta B_\nu(T_{\text{dust}})$, where $\beta$ is the emissivity index and $T_{\text{dust}}$ is the temperature), we successively derive the $\beta$, $T_{\text{dust}}$, optical depth, and dust column mass density maps (Figure 1, right). The high $T_{\text{dust}}$ region ($\geq$ 40 K) is co-spatial with the [O III] λ5007 line emission, delineating the inner highly-ionized region of barrel wall directly visible to us. The $\beta$ map is almost entirely unity, suggesting that the far-IR emitting dust is carbon-based (Volk & Kwok 1988), which is consistent with the previous optical line abundance analyses (Liu et al. 2004b) and the absence of silicate dust features in the mid-IR spectra (e.g., Phillips et al. 2011).

Because far-IR thermal dust continuum is optically thin ($\tau_{160 \mu m} = 10^{-5}$ to $10^{-6}$ on the “ring”), the dust column mass density map probes the whole nebula depth along the line of sight, corroborating the pole-on barrel structure previously only inferred and modeled with optical data. By integrating over the entire nebula, the total amount of far-IR emitting dust is determined to be $M_{\text{dust}} = 3.8 \times 10^{-3} M_\odot$ and roughly 50% of this mass seems to be contained in the cylindrical barrel.

2.2. Spatio-Spectroscopy: Diagnostics via Gas Emission

HerPlaNS spectroscopy includes PACS integral-field-unit range-scan spectroscopy in the B2A band (51–72 $\mu$m), B2B band (70–105 $\mu$m), and R1 bands (103–145 $\mu$m and 140–220 $\mu$m), achieving the spectral coverage of 51–220 $\mu$m resulting in 25 spectra over a 47″×47″ field and SPIRE Fourier-transform spectrometer spectroscopy to cover 194–672 $\mu$m resulting in 35 spectra in the SSW band (194–313 $\mu$m) and 19 spectra in the SLW band (303–672 $\mu$m) sparsely sampled over a field of a ∼120″ radius.

Figure 2 shows spectra for the whole 51–672 $\mu$m at two spatial pointings (at the center and eastern rim). At both pointings, continuum is detected at about $\lesssim 10$ mJy arcsec$^{-2}$ in the PACS range and less than a few mJy arcsec$^{-2}$ in the SPIRE range. Thermal dust continuum emission in the PACS range is generally stronger at the eastern rim, but is about the same at both pointings in the SPIRE range. This indicates that the central highly-ionized barrel cavity is completely surrounded by a colder dusty envelope.

Besides continuum, a number of ionic and atomic lines in the PACS range, and a number of CO rotational transitions and other molecular species are seen in the SPIRE range. The relative line strengths of the two pointings suggest that the central cavity is more strongly ionized. While rich in lines, we determine that line contamination in broadband mapping is less than 5% based on these spectra.

Moreover, PACS/SPIRE spectra taken by arrays of spaxels/bolometers can be rendered into spectral line maps by integrating the data cube over specific emission lines (Figure 3). Such line maps provide us with a new means to perform far-IR line diagnostics in a spatially-resolved manner and constrain the physical stratification of the medium. In the case of NGC 6781, two pointings are adjacent to each other, and hence, a single mosaic map covering most of the mid-section of the nebula can be recovered.

Using far-IR line ratio maps (e.g., [O III] 52 μm/88 μm and [N II] 122 μm/205 μm) augmented with other optical-to-far-IR line ratio maps (e.g., [O III] λ5007/88 μm and [N II] 16583/122 μm), the electron temperature ($T_e$) and electron density ($n_e$) maps can be derived by solving the equation of statistical equilibrium for the lowest several excitation levels of these atoms (Liu et al. 2001, 2004a,b). Moreover, these ($T_e$, $n_e$) maps can be translated into ionic/elemental abundance maps with various ionization correction factors (Liu et al. 2001; Vamvatira-Nakou et al. 2013). For NGC 6781, we collapsed these maps into 1-D profiles along the RA direction in the end (Figure 3).
The $T_e$ profiles reveal constant $T_e$ ($\sim 9,000$ K) in the highly-ionized barrel cavity, surrounded by the $T_e$ maximum ($\sim 10,500$ K) beyond which $T_e$ tapers off. The $n_e$ profiles show a high-ionization gas $n_e$/$[\text{O III}]$ at constant ($+$; $\sim 400$ cm$^{-3}$) and a low-ionization gas $n_e$/$[\text{N II}]$ with a radially increasing trend ($+$; $100–600$ cm$^{-3}$).

The ionic abundance profiles reveal the physical stratification: the highly ionized cavity ($\lesssim 30''$) in which energetic photons ionize O$^+$ ($> 35.12$ eV), the inner barrel wall (between $30''$ and $40''$) where still energetic photons ionize N$^+$ ($> 29.60$ eV), and the barrel wall peak and beyond ($\gtrsim 50''$) where only less energetic photons ionize N$^0$ and C$^0$ ($< 29.60$ eV). There should be photo-dissociation regions farther out, but they are not detected in the present data. If they were, we could have performed similar line diagnostics exclusively for the photo-dissociation regions with surface brightness maps in neutral N ($[\text{N I}]$/$\mu$ line intensity map) and in neutral H ($\text{H I}$ at 21 cm), for example.

The CNO elemental abundances are roughly the same. The average elemental abundances relative to H are 8.9 for C, 8.2 for N, and 8.9 for O (0.5, 0.4, and 0.2 dex more than solar, respectively; Grevesse et al. 2010). The marginal N overabundance disqualifies NGC 6781 from being Peimbert Type I (N/O $\gtrsim 0.5$; Peimbert & Torres-Peimbert 1983), i.e., the CSPN is less than 2 M$_\odot$ initial mass. The C-rich stellar ejecta appear to be accumulating at the barrel wall: the rise of C/O near the wall does not seem to reflect the evolutionary epoch where C becomes more abundant in the CSPN.

3. EXPECTATIONS FOR THE ERA OF SPICA

As briefly reviewed, spatially-resolved far-IR data from Herschel have just enabled us to decipher the physical stratifications in relatively isolated dusty gaseous systems. These insights will enhance the understanding of not only the PN physics itself but also the general far-IR line diagnostics used for systems that are not necessarily spatially resolved (e.g., luminous infrared galaxies; for which many excellent reports can be found in the present proceedings issue). To continue making progress in the era of SPICA, while improving upon sensitivity is a must, particular attention to the spatial integrity and fidelity of the data must also be drawn to achieve the full extra success.

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Understanding the Role of Massive Stars on the Dusty ISM Environment in Galaxies with SPICA

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ABSTRACT

In this article, some key science cases of SPICA are discussed focusing on (1) the dust formation associated with mass loss activities of evolved massive stars (e.g., Wolf-Rayet stars) before the SN explosion and (2) the dust formation in the ejecta of SNe and its evolution (destruction and/or grain growth) in a timescale of a few – a few tens years from its synthesis.

1. INTRODUCTION

Due to the short (< a few tens Myr) lifetime during the main sequence, massive stars can supply nucleo-synthesized materials into the interstellar space relatively in a short timescale and can be regarded as a strong candidate for the dust budget in the early universe. One of the major processes of dust formation by massive stars is the dust condensation in the ejecta of core-collapse supernova (SN) explosions (Kozasa et al. 1991; Todini & Ferrara 2001; Nozawa et al. 2003). Although formation of 0.1–1 solar mass (M⊙) of dust per typical SN is needed to explain the dust content in the early universe (Morgan & Edmunds 2003), the amount of newly formed dust in the ejecta of a supernova obtained from the near- to mid-infrared observations of young SNe (< a few years) with AKARI and Spitzer remains only in the range of 10⁻³–10⁻⁵ M⊙ (Sakon et al. 2009; Mattila et al. 2008; Meikle et al. 2007; Kotak et al. 2009). On the other hand, recent far-infrared observations of SN1987A in the Large Magellanic Clouds and some Galactic SNRs by Herschel have revealed the presence of nearly 1 M⊙ of dust in a remnant (Matsuura et al. 2011; Gomez et al. 2012; Barlow et al. 2010). There is an apparent large gap in measured dust mass between MIR observations of young SNe (t < a few years) and FIR observations of young SNRs.

Recently, SNe in the “transitional” phases between the SNe younger than a few years and the young SNRs older than several tens years after the SN explosion have started gaining attention. Tanaka et al. (2012) have searched for those SNe in the “transitional” phase in the archival near- to mid-infrared imaging data of nearby galaxies obtained with AKARI/Infrared-Camera (IRC) and Spitzer. They have reported the detection of infrared emission at the position of SN 1978K (t ∼ 30 yr) in NGC 1313. They attribute this emission to 1.3 × 10⁻³ M⊙ of shocked circumstellar silicate dust rather than newly formed dust in the SN ejecta nor the swept-up interstellar dust.

In order to understand the role of SNe as the dust budgets in the universe, the following three dust populations that may contribute to the observed infrared spectral energy distribution (SED) of a SN should be separately examined; (1) the dust formed in the ejecta of SNe (hereafter, SN dust), (2) the dust formed by the pre-SN stellar wind, which is now located in the circumstellar region (hereafter, CS dust), and (3) the interstellar dust swept up by the SN ejecta (hereafter IS dust). In this paper, we discuss some key science cases of SPICA focusing on the life cycle of dust in massive stars before and after the SN explosion.

2. DUST FORMATION IN THE SN EJECTA AND ITS EVOLUTION

As for SNe in nearby galaxies except for those in Magellanic Clouds, we would not be able to get any spatially resolved geometric information of three dust populations (i.e., SN dust, CS dust and IS dust) even with the spatial resolution of JWST and SPICA. Under this condition, in order to carry out the spectral decomposition of emissions from those three dust populations properly, multi-epoch observations of dusty SNe on a timescale of several — a few tens years after the explosion are indispensable. It should be noted that observational simultaneity in wide spectral range from mid- to far-infrared is crucial for such time-varying phenomena and only SPICA can fulfill those purposes.

As discussed in Tanaka et al. (2012), SNe in the “transitional” phases in nearby galaxies will provide us unique opportunity to study the origin of dust in the early universe. Since the mass of the swept-up IS dust estimated for such “transitional” phase SNe is less than an order of ∼ 10⁻⁶ M⊙, SPICA/MCS (Kataza et al. 2012) and SAFARI (Roelfsema et al. 2012) will be able to study the properties of shocked CS dust and SN dust. If the contribution of CS dust emission is small, the SN dust will be detected at the wavelengths longer than 30 μm (see Tanaka et al. 2012). These observations...
will lead us to measure the reliable mass of SN dust by taking account of the possible grain growth and/or destruction that may take place in a timescale of several tens years after the SN explosion. In particular, MCS/Wide Field Camera (WFC; Wada et al. 2010) and SAFARI will be sensitive to the 10^{-4} M_{\odot} of dust cooled below 100 K even at 25 Mpc, which will be crucial to conclusively answer to the question of whether or not SNe can be the efficient dust budget in the early universe.

Systematic spectroscopic monitoring observations of young SNe in nearby galaxies (<10 Mpc) with SPICA/MCS and SAFARI will be crucial to study the chemical and physical properties of newly formed SN dust and pre-existing CS dust. MCS/Medium Resolution Spectrometer (MRS; see Sakon et al. 2012a) provides us unique capability to demonstrate the process of interaction between the SN ejecta gas and circumstellar medium taking advantage of its excellent line sensitivity in wide mid-infrared spectral range from 12 µm to 38 µm. Moreover, MCS/MRS will be sensitive enough to detect 10^{-3} M_{\odot} of dust at >150 K at a distance of 5 Mpc and will offer unique capability to diagnose the chemical compositions of the constituent dust species and to examine the temporal evolution of the physical properties of each dust component in detail.

3. DUST FORMATION IN THE PRE-SN STELLAR WIND

Recent observations of dust-forming type-Ib supernova 2006jc made with AKARI and Spitzer have shown that the amount of newly-formed dust in the SN ejecta of SN 2006jc is in the range of only 10^{-4}–10^{-5} M_{\odot} (Sakon et al. 2009; Mattila et al. 2008). At the same time, however, they recognize the presence of pre-existing circumstellar dust possibly formed in the mass loss wind associated with the events prior to the SN explosion. These results suggest that the dust condensation not only in the SN ejecta but also in the mass loss wind during the pre-explosion phase can contribute to the process of dust enrichment in the early universe. However, it is suggested that the metal-free massive stars in the early universe may die without losing a large fraction of its mass (Baraffe et al. 2001) and the origin of dust in the early universe still remains puzzling. Although there has been no evidence, so far, of dust formation in a smooth wind flow of a single Wolf-Rayet star (Cherchneff & Dwek 2010), WR binary system, in particular WC+O systems with eccentric orbits, can periodically produce dust in two winds’ collision zone whenever the secondary passes by the periastron point of the primary (Williams 1995) even in low metallicity environment. In addition, more abundant massive binary systems are expected to be born in early universe (Machida 2008). The CS dust structures around the SN progenitor must be formed and characterized as a result of the mass loss activities before the SN explosion. Therefore, dust formation history in such WR binary systems shall be clarified to understand the geometrical and compositional properties of circumstellar dust structures surrounding the type I/b/c SN progenitors.

Marchenko et al. (2002) have pointed out the survival of dust produced by WR+O binary systems for more than 100 years. If this is the case, the dust can travel farther from the WR+O core into the ISM and part of it can survive the later SN explosion event. Therefore, whether or not such WR binary systems would have made significant contribution toward supplying dust in the early universe has to be examined from the observational point of view.

For example, WR 140 is a long-period, colliding-wind binary located at the distance of 1.1 kpc (WC7 class Wolf-Rayet star+O4 type star, P = 7.93 yr, e = 0.881; Marchenko et al. 2003; Williams 2009). So far, interesting features in the light curves at multi-wavelengths were reported whenever the O-type companion star passed through the densest region of the carbon-rich WR wind (i.e., “spectroscopic events” in 1993, 2001 and 2009). This event is often accompanied by dust formation. Marchenko & Moffat (2007) presented the high-quality 12.5 µm image of WR 140 taken with Michelle/Gemini-North in November/December 2003. They detected the concentric dust arc-like structures, which are unequivocally linked with the 1993 and 2001 dust formation episodes (Marchenko & Moffat 2007). In the case of WR 140, the dust produced during a spectroscopic event travels 3 arcsec from the WR+O core and is cooled to 300 K after one orbital period (~10 yr) from its formation. After ten orbital periods (~100 yr) from its formation, the dust reaches at 30 arcsec away from the WR+O core and is cooled to ~100 K if grain growth is not taken into account. Therefore, sensitive spectroscopic mapping capability in wide spectral range covering from mid- to far-infrared is indispensable to understand the 100 years’ scale evolution of circumstellar dust around WR 140.

There are several other WC 4-9 stars that are known as the episodic dust-makers with the recurrence period of a few — a few tens years (Williams 1995). Integral Field Unit (IFU) spectroscopic observations of those targets with MCS/MRS shall provide us valuable opportunity to investigate the properties of circumstellar dust formed around the Type-Ib/c SN progenitors. The latest specification of MCS/MRS provides us two dimensional spectroscopic capability with a wide field of view (FOV) of 12’’x8’’(Sakon et al. 2013). Moreover, since the same FOV is shared between MRS-S and MRS-L by means of a beamsplitter installed in the foreoptics, the continuous 12–38 µm spectrum with moderate spectral resolution (R = 1000–3000) is obtained by a single pointed observation (Sakon et al. 2012a, see Figure 1). With those capabilities, MCS/MRS, combined with SAFARI, shall give us conclusive answers to the questions of (1) if the scale of mass loss and dust formation be homogeneous at every periastron passage and (2) how the synthesized dust pass through the mass evolution and chemical composition denaturation until it reaches the interstellar space.

4. CONCLUSION

Some key science cases of SPICA focusing on the dusty SNe and their progenitors are discussed. The universe seen by SPICA is no longer static but dynamic. Therefore, observational simultaneity over a wide spectral range is critical for those targets. Continuous spectral coverage from the mid- to the far-infrared is essential for SPICA, since this cannot be

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Figure 1. An example plan for the IFU spectral mapping observations of WR 140 with MCS/MRS. FOV positions are shown over the mid-infrared image of WR 140 obtained with Subaru/COMICS on June 2011 (Sakon et al. 2012b) to cover the whole circumstellar dust structures formed as a result of the past periastron events over ~100 years (top). The geometric configurations of the slitlets for MRS-S and MRS-L in a shared FOV are shown schematically (bottom).

achieved by JWST. The proposed observations should revolutionize our understanding of cosmic dust enrichment by the massive stars that characterise the ISM environment of the early universe.

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SPICA’s Promise for Supernovae and Supernova Remnant Studies

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ABSTRACT

Spitzer and Herschel have started to reveal that SNe can form a significant mass of dust and molecules. The number of SNe studied so far is still limited. Moreover Spitzer and Herschel measurements have shown that multi-wavelength and monitoring observations are critical to build a comprehensive picture of dust and molecular formation in SNe. Equipped with near- to far-infrared imaging and spectroscopic instruments, the SPICA mission will enable a more fuller picture of supernovae and supernova remnants, potentially resolving if SNe can be a major source of dust in the interstellar medium of galaxies.

1. INTRODUCTION

In the last decade, infrared and submillimeter surveys of galaxies have found a substantial mass of dust in galaxies from the Local Universe, nearby galaxies to high-redshift galaxies (e.g. Bertoldi et al. 2003; Dunne et al. 2011). It is still unknown how the interstellar medium (ISM) of galaxies acquires such a large mass of dust. Theories of dust evolution modelling of high-redshift galaxies have suggested and proposed that a large mass of dust formation in supernovae (SNe) can explain dust in galaxies, particularly those in high-redshift galaxies. Recent observations with the Herschel Space Observatory began to reveal that core-collapse SNe can also form a significant mass of dust (0.1–0.7 M⊙; e.g. Barlow et al. 2010; Matsuura et al. 2011; Gomez et al. 2012). These studies have lead us to propose major questions of dust production in supernovae:

Q1: What are the effective dust masses formed in SNe?
Q2: What is the time scale of dust formation in SNe?
Q3: What are the important physical and chemical processes involved in dust formation in SNe?
Q4: How much of dust could be destroyed by SN shocks?

Future observations with SPICA have a potential to answer these important questions.

2. DUST FORMATION IN SNE

Recently, far-infrared and submillimeter observations of SNe and SN remnants have found 0.1–0.7 M⊙ of dust in core-collapse SNe. That is much larger than the previously reported dust mass found in the early epoch after the SN explosions (10^{-4}–10^{-3} M⊙; e.g. Wooden et al. 1993; Sugerman et al. 2006). Gall et al. (2011) reported that the inferred dust masses of SNe and SN remnants appear to have a correlation with estimated dust temperatures. Also dust mass is correlated with the wavelength where the dust thermal emission has been detected. Near- and mid-infrared observations tend to find dust-mass in the range of 10^{-6}–10^{-4} M⊙, while far-infrared and submillimeter observations tend to find the mass range up to 1 M⊙. The cause of this correlation is undetermined. It might suggest an increasing dust mass in time as the SNe become cooler. Multi-wavelength and monitoring observations of SNe and SN remnants from near-infrared and far-infrared wavelength is essential to find the cause of these correlations, leading us to determine the effective dust masses formed in SNe and SN remnants.

SN 1987A is the closest SN whose explosion was detected in the past 400 years, and has provided a unique opportunity to monitor the time evolution of a SN remnant after the explosion. Wooden et al. (1993) reported the detection of dust in SN 1987A at mid-infrared wavelength about 2 years after the explosion with an inferred dust mass of about 10^{-4} M⊙. Spatially resolved Gemini mid-infrared images showed that mid-infrared dust thermal emission originated from the ring of SN 1987A, which indicated that the mid-infrared excess at d ~ 6000 days is from the progenitor dust rather than dust formed after the SN explosion (Bouchet et al. 2006). They also reported the dust mass of ~ 10^{-4} M⊙ from Spitzer observations.

Herschel also found far-infrared dust emission from SN 1987A (Matsuura et al. 2011) during the Magellanic Cloud survey (Meixner et al. 2013). The inferred dust mass was 0.4–0.7 M⊙, and we concluded that the only plausible explanation of such a large dust mass is dust formation in the SN ejecta, where a large mass of refractory elements became available. That assumption will be tested by an ALMA high angular resolution image.

So far SN 1987A is the only case where the time evolution of dust formation and thermal emission have been monitored. It is not yet determined why the dust mass in SN 1987A has increased: it might be gradual grain formation in time, or grains are located in clumps, which are optically thick in mid-infrared wavelength, distorting the dust masses we see today.
Theories have proposed that dust grains condense almost instantly once the gas temperature drops to the sublimation temperature (Nozawa et al. 2003; Sarangi & Cherchneff 2013). If this theory is correct, mid-infrared observations in early days should be completely optically thick, hiding a large amount of dust, but there is no such an indication so far in SN 1987A (Ercolano et al. 2007). Future SPICA observations of newly exploded SNe can test these hypothesis.

MCS has potential to detect over a few hundred of SNe within 500 Mpc in 5 years. The number of far-infrared detection would be relatively modest, 7 SNe within 10 Mpc during a 5 year mission mainly due to the confusion limit, though potentially SNe up to 40 Mpc may be detected.

3. MOLECULES IN SNE

While explosions of SNe generate an enormous energy $10^{53}$ ergs (McCray 2003), gas in the ejecta cools down gradually, by adiabatic cooling and later with line and dust thermal emission (Jerkstrand et al. 2011). Models predicted that the gas temperature drops to 80 K only after 8 years in the case of SN 1987A (Jerkstrand et al. 2011). From molecules that have been detected SN ejecta, in early epoch in near-infrared (e.g. Spyromilio et al. 1988; Kotak et al. 2006) and in submillimeter and millimeter wavelength after 20 years of the explosions (Kamenetzky et al. 2013). Molecules have been detected in the young SN remnant, Cas A (Rho et al. 2012; Wallström et al. 2013) and they suggested that CO molecules are formed in the gas after the passage of reverse shocks. Similar to dust formation, the estimated CO mass seems to have increased in time within 25 years, but little observations of CO in between these 20 years makes it difficult to determine how molecules have formed in time. In contrast, chemical models predict CO formation is completed within 500 days after SN explosions (Sarangi & Cherchneff 2013). If that is the case, a large cold CO mass must be hidden from near-infrared observations in early epoch.

Using SPICA capability of detecting molecular lines from near-infrared to far-infrared, molecular chemistry in SN remnants can be investigated. Figure 1 demonstrates how the strong CO transitions can change from near-infrared to far-infrared in time. The temperature and the extent of gas were taken from the model of Nozawa et al. (2003) and the radiative transfer code from Matsuura et al. (2002) was used. These observations will reveal the time evolution of chemistry and thermal dynamical in SNe.

So far, the number of SNe where molecular lines are detected is limited. CO lines have been detected only from 9 SNe and 1 Cas A at near-infrared wavelength. Far-infrared CO lines have been detected only from SN 1987A and Cas A. Additionally SiO bands at 8 µm have been detected in 3 SNe.

The MCS on board the SPICA has a potential to detect SNe exploded up to 200 Mpc, providing potential of detecting near-infrared CO and SiO bands over 100 SNe. The SAFARI can detect SNe found up to 7 Mpc, and high-$J$ CO transitions could be detected in about 5 SNe within the 5 year mission.

4. FAR-INFRARED LINES IN SNE

Models predicted that far-infrared atomic lines are important cooling lines for SN ejecta (Jerkstrand et al. 2011). Among important cooling lines, only handful lines have been observed in SN ejecta (Bouchet et al. 2006), making lack of constraints on physical process within SNe after the explosions. SPICA SAFARI will be able to detect these important cooling lines, such as $[O\text{I}] 63\,\text{µm}$ for the first time. The expected number of SNe is about 5 within the 5 year SPICA mission.
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The Interstellar Dust Reservoir: \textit{SPICA}'s View on Dust Production and the Interstellar Medium in Galaxies

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Abstract

Typical galaxies emit about one third of their energy in the infrared. The origin of this emission reprocessed starlight absorbed by interstellar dust grains and reradiated as thermal emission in the infrared. In particularly dusty galaxies, such as starburst galaxies, the fraction of energy emitted in the infrared can be as high as 90\%. Dust emission is found to be an excellent tracer of the beginning and end stages of a star's life, where dust is being produced by post-main-sequence stars, subsequently added to the interstellar dust reservoir, and eventually being consumed by star and planet formation. This work reviews the current understanding of the size and properties of this interstellar dust reservoir, by using the Large Magellanic Cloud as an example, and what can be learned about the dust properties and star formation in galaxies from this dust reservoir, using \textit{SPICA}, building on previous work performed with the \textit{Herschel} and \textit{Spitzer} Space Telescopes, as well as the Infrared Space Observatory.

1. THE DUST RESERVOIR IN GALAXIES

1.1. Sources and Sinks in the Large Magellanic Cloud

The Large Magellanic Cloud (LMC) was imaged using \textit{Spitzer} (SAGE; Meixner et al. 2006) and \textit{Herschel} (HERITAGE; Meixner et al. 2013) using all non-overlapping photometric bands available on these telescopes. The combined SAGE-HERITAGE survey, often referred to as Mega-SAGE, covers the wavelength range from 3.6 to 500 µm. The four \textit{Spitzer}-IRAC bands (3.6–8.0 µm) mainly show circumstellar dust emission from stellar point sources, and extended emission due to polycyclic aromatic hydrocarbons (PAHs), thus forming a good tracer of the production and consumption of dust in post- and pre-main-sequence stars, while the \textit{Spitzer}-MIPS and \textit{Herschel} images show the dust mass in the interstellar medium (ISM). The MIPS 24 µm band represents a transition, while dominated by extended emission due to interstellar dust, extremely dusty point sources are clearly detectable in this band too. It is these point sources with 24 µm detections that dominated the dust production and consumption budget.

Building on a series of previous estimates and methods to determine dust production rates by evolved stars, Riebel et al. (2012) estimate a total dust production rate of \(\sim 2.1 \times 10^{-5} \, M_\odot \, yr^{-1}\) from the \textit{Spitzer}-IRAC and MIPS data. This rate should be contrasted against the dust mass in the interstellar medium of the LMC, \(\sim 10^6 \, M_\odot \, yr^{-1}\), derived from the \textit{Herschel} observations Skibba et al. (2012), and the dust consumption in star formation \(\sim 1.9 \times 10^{-3}\); Skibba et al. (2012), assuming a dust-to-gas ratio of 1/200. Taking these numbers at face value, it becomes clear that evolved stars do not produce sufficient dust to replenish the interstellar medium, on the residence time scale of dust in the interstellar medium \(\sim 2.5 \, Gyr\); Tielens 1990). Moreover, the much higher dust consumption rate in comparison to the dust production rate even suggests that the dust reservoir in the interstellar medium of the LMC is currently being depleted. This would imply that until fairly recently, the dust production rate was much higher than at the present day, or, alternatively that we are missing a significant source of dust production in this equation.

Three alternatives suggest themselves: i) The dust production in supernovae has not been considered in the estimates of dust production by evolved stars in the LMC (e.g. Riebel et al. 2012), due to low number statistics, but estimates suggest that it could be similar to the production by Asymptotic Giant Branch stars (e.g. Whittet 2003). Indeed, Dunne et al. (2003) argued that supernova remnant Cas A has produced 2–4 \(M_\odot\) of dust, although it has since been shown that the bulk of the dust mass detected is part of a foreground cloud (Krause et al. 2004). From observations of contemporary supernovae in external galaxies, Sugerman et al. (2006) showed that a more realistic number of dust production may lie around \(10^{-3} \sim 10^{-2} \, M_\odot\), although \textit{Herschel} observations of SN 1987A show that it has already produced 0.5 \(M_\odot\) in the first 25 years (Matsuura et al. 2011). ii) Dust production in the interstellar medium is efficient, and the source of interstellar dust is not stellar. This has been explored by Zhukovska et al. (2008) and by Jones (2005), and seems to be a viable option. Zhukovska et al. (2008) estimate that the dust production in the interstellar medium in the Solar Neighborhood exceeds the dust production by evolved stars after as little as 1 Gyr. iii) Dust production by extreme Asymptotic Giant Branch (AGB) stars may be overlooked. Searches for dusty evolved stars rely on classifying point infrared (IRAC, 2MASS) point sources (e.g. Boyer et al. 2011), which are subsequently being fitted against a dust shell model grid to determine the integrated dust production rate (e.g. Sargent et al. 2011; Srinivasan et al. 2011). From this procedure it becomes clear that the dust
production is dominated by the reddest objects, the so-called extreme AGB stars. Indeed, Riebel et al. (2012) found that this small number (4%) of extremely red sources account for 75% of the total dust production. This immediately raises the question how many even dustier and redder sources are present, and how they can be detected. With the peak of their spectral energy distributions (SEDs) shifting to even longer wavelengths they can no longer be picked up in the near- or mid-infrared, and far-infrared detections are required. At these wavelengths, the point spread function (PSF) becomes very large, and the point sources need to be bright to stand out over the extended emission due to interstellar dust within the beam. At the distance of the LMC, this is generally not the case, and Boyer et al. (2010) demonstrated that only a small number of known evolved stars in the LMC have counterparts in the Herschel data.

1.2. The Composition of Stellar Dust

Including spectroscopy in the analysis of evolved stars enables us to dissect the dust production not only by type of AGB star (carbon-rich or oxygen-rich), but to narrow down the mineralogical components in the freshly produced dust. Although a huge amount of variation exists, and still needs to be further explored, studies like those done by Sargent et al. (2010) and Srinivasan et al. (2010) modeled representative oxygen-rich and carbon-rich AGB star spectra for the LMC, and determined typical compositions. Combining this with the dust production rate derived from model grid fitting as above, allows for a determination of the total dust production split out by mineral. It is found that in the LMC, of the dust produced by AGB stars and Red Supergiants, 77 wt.% is in the form of amorphous carbon, 11% in the form of silicon carbide (SiC), 12% in amorphous silicates, and a small fraction of < 1% of the freshly produced dust may be in the form of crystalline silicates (Kemper 2013).

Although most extreme AGB stars turn out to be carbon-rich, the exact composition of dust produced by these stars is hard to determine due to the high optical depth in the circumstellar dust shells. The composition of only the optically thin outer layer can be optimally probed (Speck et al. in prep.), so the SiC/amorphous carbon ratio in the vast majority of the dust mass produced by extreme AGB stars remains unknown, although one may assume that it remains constant throughout the mass losing phase of the star.

As stated before, supernovae may be important dust sources too, but so far little is known about the composition of the dust in these environments. One of the few studies that have looked into this is done by Rho et al. (2008), who derived a multi-component composition dominated by amorphous silicates for Cas A in an attempt to fit the main spectral feature at 21 μm.

The interstellar dust of our own Milky Way shows a different composition from what is produced by evolved stars; the majority of the dust is in the form of amorphous silicates, and a smaller fraction in amorphous carbon (Tielens et al. 2005). Only trace amounts of SiC (~ 2.6–4.2%; Min et al. 2007) and crystalline silicates (< 2% Kemper et al. 2004) can be present. The LMC ISM is similar in composition to the Galactic ISM, because the ultraviolet extinction curve between the Milky Way and the LMC is virtually identical, including the relative strength of the 2175 Å bump (Fitzpatrick 1986), meaning similar ratios between carbon-rich and oxygen-rich dust in both galaxies. The discrepancy between ISM dust and stellar dust composition is consistent with the idea that in both galaxies dust formation in denser parts of the ISM itself may dominate the overall dust production, however, there is a contribution from evolved stars that needs to be considered.

2. OBSERVING CIRCUMSTELLAR AND INTERSTELLAR DUST WITH SPICA

2.1. The Dust Reservoir in Local Group Galaxies as Observed by SPICA

The Mid-Infrared Camera and Spectrograph (MCS) on board of SPICA will operate at 5–38 μm, and this wavelength range will be extended to the near-infrared with the Focal Plane Camera (FPC) which covers the 0.7–5 μm range, providing continuous band coverage from 0.7–38 μm at a spectral resolution $R \approx 5–10$. The long wavelength instrument SAFARI will operate at 34–210 μm, and has two modes that are suitable for SED construction: first, the spectroscopic SED mode, with $R \approx 50$, which will allow us to get SEDs from all pixels in a map; and, second, – the more useful option for surveys of the dust budget in galaxies – the photometric mode which covers the SAFARI wavelength range in three broad bands. Thus SPICA uniquely provides a full wavelength coverage from 0.7–210 μm in photometric bands, where for instance Spitzer has gaps in the wavelength coverage. In particular the gap between the IRAC-[8.0] and MIPS-[24] band has been hampering the photometric classification of carbon-rich and oxygen-rich AGB stars, as prominent broad spectral features are available in this range (the 9.7 μm silicate feature, and the 11.3 μm SiC feature). The silicate band can also be used for further constraining the optical depth and thus the mass-loss rate of oxygen-rich AGB stars. The photometric bands available on the suite of instruments on board of SPICA will overcome these problems and can take advantage of the diagnostic power of broad spectral features due to dust, because of the continuous wavelength coverage.

With SPICA it will become possible to do studies of the interstellar dust reservoir and dust injection by evolved stars in galaxies beyond the Magellanic Clouds. Studying external galaxies allows for taking in a global view of the dust reservoir and dust producing stars in the entire galaxy, without having to account for interstellar extinction. Obvious candidates are M31 and M33, the two other spiral galaxies, besides the Milky Way, in the Local Group, at distances of 752 ± 27 kpc (Riess et al. 2012) and 840 kpc (Freedman et al. 1991), respectively. Although M31 is the closest one of the two, it is more inclined, and it will be harder to avoid crowding and confusion, compared to M33.

Thus, an exciting possibility is to set up a survey of M31 (or M33) to make an inventory of the stellar content, particularly focused on dusty objects, in a similar fashion as the SAGE-LMC survey (Meixner et al. 2006). We have performed some...
initial estimates and found that a $1\degree \times 3\degree$ region encompassing the entirety of M31 can be mapped with 600 pointings using MCS. If we employ 4 filters (two in WFC-L, and two in WFC-S), and do observations in 2 epochs to check for spurious point sources and variability, we find that with the minimum amount of integration time per frame we can perform these observations in $\sim 400$ hours. The WFC-S and WFC-L modes can be used at the same time, as can the FPC-S instrument, with a slight sky offset. This setup does not cover the full spectral range, but a factor of 5 increase in total time would cover all MCS filters, leading to a project time of $\sim 2000$ hours for the $1\degree \times 3\degree$ area covering M31 on the sky. Reductions in integration time can be made again by deciding to cover only half or a quarter of M31, and extrapolating the statistics on the stellar population.

Figure 1 shows the color-magnitude diagrams (CMD) for the point sources detected in the SAGE-LMC survey, classified by Boyer et al. (2011) into different types of evolved dust producing stars. The bands presented in these diagram are within the MCS wavelength range, and a closely matching MCS equivalent can be identified in the currently proposed filter set. The sample has been placed at the M31 distance and compared with the detection limits of the proposed survey. For the shortest integration times available on MCS, the detection limits for the WFC-S bands are virtually the same for the SAGE-LMC project and the M31 survey proposed in this work, in terms of detectability of the type of object. The detection limit is indicated by a gray line in each of the panels of Figure 1. However at longer wavelengths, it turns out that the current detection limit for the proposed survey would not detect the same stellar population in M31 as it did in the SAGE-LMC survey, by at least 2 magnitudes. It appears that the choice of filters with $R \approx 10$ are too narrow to go deep, especially in comparison with MIPS-[24], and perhaps an additional set of 2 or 3 broad band filters for the WFC-L mode would remedy this, making the WFC-L as much of an improvement over MIPS-[24] as that WFC-S has been improved over IRAC-[4.5] and IRAC-[5.8].

2.2. Spectroscopy with the Mid-infrared Camera and Spectrograph (MCS)

The currently proposed MCS instrument includes two spectroscopic modes: the High Resolution Spectrograph (HRS-L), which will operate at 12–18 $\mu$m, with $R \approx 20,000$–30,000, and the Medium Resolution Spectrograph, which will operate at 12.2–23.0 $\mu$m, with $R \approx 2000$ (MRS-S) and at 23.0–37.5 $\mu$m, with $R \approx 1000$ (MRS-L). For the purpose of studying solid state features, the spectral resolution offered by the MRS is sufficient to do a detailed analysis of the mineralogy. Unfortunately, the wavelength coverage of the MRS mode does not include a number of important spectral features:

- The Si-O stretching mode in amorphous and crystalline silicates around 9.7 $\mu$m.
- Features due to polycyclic aromatic hydrocarbons (PAHs) from 6–12 $\mu$m.
- Two out of the four identified bands of C$_{60}$, namely those at 7.0 and 8.5 $\mu$m.
- Ice features at 4.2 $\mu$m due to CO$_2$; 6.0 $\mu$m due to H$_2$O and 6.8 $\mu$m due to a still unidentified carrier
- Absorption lines from C$_2$H$_2$ and other molecules related to dust formation.
- Spectral features due to alumina, oxides and quartz.
- The 11.3 $\mu$m feature due to SiC.

The wavelength range shortward of 12.2 $\mu$m is covered by a grism in WFC-S, with an intended spectral resolution of $R \approx 50$. While this may, in some cases, be sufficient to detect the presence of these features, it is not possible to do any compositional analysis, such as for instance the crystalline fraction of silicates, which is revealed by the shape of the resonance. For such an analysis, the observations should match the spectral resolution of laboratory data, which is...
µsilicates only show broad resonances due to the Si-O stretching mode at 9.7 µm. The degree of processing for different objects is dominated by water ice, with its infrared absorption features at 3.4, 8.5, 17.4 and 18.89 µm. SAFARI will operate at 34–210 µm, with different spectral bands providing complementary information about the dust and ice resonances.

The detection of narrow features, such as the C2H2 absorption lines, or the C60 narrow emission bands, becomes virtually impossible at R = 50. Thus, we recommend the insertion of a R = 200 grism in the WFC-S filter wheel, with a wavelength coverage of 5.0–12.2 µm. Perhaps this may have to be divided over two grisms, to avoid problems with the dispersion.

There are a number of other interesting dust and ice resonances that are included in the MRS wavelength coverage. Here we highlight a few examples, to illustrate the discovery space that can be further explored with the MRS mode on the MCS.

First, carbon dioxide (CO2) in its pure form has a double-peaked resonance around 15.2 µm (Ehrenfreund et al. 1999). This double-peaked structure becomes less pronounced or disappears altogether when the a-polar CO2 ice is embedded in polar H2O-rich ices. The depth of the trough between the two peaks can provide information about the amount of thermal processing, and thus about the degree of separation between the two ice components (CO2 and H2O) in embedded objects, such as the envelopes of young stars. Moreover, the 15.2 µm resonance due to CO2 develops a shoulder on the red side and gradually shifts towards longer wavelengths overall, when it is mixed with methanol (CH3OH) (Ehrenfreund et al. 1999). For instance, Zasowski et al. (2009) have shown that studying the exact shape of the 15.2 micron absorption feature due to CO2 at a resolution of R ≈ 600 can indeed be used as a tool to determine the composition of the ice mixture, and establish the degree of processing for different objects. Specifically, they find that in a sample of 16 Class I/II objects the typical ice composition is dominated by water ice, with ∼12% CO2, and up to ∼10% of methanol ice. The ice absorption features at shorter wavelengths (6–12 µm) also provided constraints on further ice components.

A second topic of great interest in the wavelength range covered by MRS is the thermal processing of silicates. Silicates observed in the interstellar medium are probably not of stoichiometric composition, and show many lattice defects, often referred to in the astromineralogy community as being amorphous (see e.g. Kemper et al. 2004). These amorphous silicates only show broad resonances due to the Si-O stretching mode at 9.7 µm, and the O-Si-O bending mode at 18 µm. However, when silicates are exposed to temperatures above the glass temperature (≈ 1000 K), annealing occurs, and the silicates may become crystalline. The spectral signature of crystalline silicates is quite different, and show a wealth of narrower resonances due to increased regularity in the lattice (See Figure 1 of Molster & Kemper 2005). Although it is known that an increased level of crystallinity is due to exposure of the silicates to high temperatures, it is not clear whether this is due to annealing of amorphous silicates, as for instance modeled by Sogawa & Kozasa (1999), or from direct condensation in the gas phase (See Figure 2). Recently, Jones et al. (2012) used a sample of oxygen-rich AGB stars from the Milky Way, the LMC and the SMC, representing three different metallicities, to show that the transition between sources showing crystalline silicates or sources without them, is much sharper for the dust mass-loss rate, than for the gas mass-loss rate, suggesting that annealing (heating of amorphous silicates) is the dominant crystallization mechanism.

Finally, a recent exciting discovery is the detection of interstellar C60 (Cami et al. 2010), by its infrared resonances at 7.0, 8.5, 17.4 and 18.89 µm. The line strengths in these four bands provide clues to the excitation and formation mechanisms of this enigmatic molecule (Bernard-Salas et al. 2012; Micelotta et al. 2012), and its chemical closeness to PAHs may also help understand the formation of these pre-biotic molecules.

2.3. Spectroscopy with SAFARI

With the SAFARI instrument, the 38–55 µm range is spectrally accessible for the first time in well over a decade, after the Infrared Space Observatory (ISO) was able to do this. SAFARI will operate at 34–210 µm, with different spectral
resolutions, namely $R \approx 50$, $R \approx 500$ and $R \approx 2000$. Especially $R \approx 500$ is very suitable for mineralogical studies in interstellar and circumstellar environments, and here we highlight three of possible research areas that can be further explored.

First, in 2002, the presence of carbonates in two planetary nebulae was discovered using the features of dolomite at 62 $\mu$m and calcite at 92 $\mu$m (Kemper et al. 2002). This was the first extrasolar detection of these minerals, and their discovery in this non-parent-body environment suggest a formation path in the absence of liquid water. An archival search of the spectra of young stellar objects observed with ISO-LWS revealed a further 17 detections of carbonates (Chiavassa et al. 2005), but additional detections with Herschel have not been reported yet, due to the difficulty of detecting broad bands in the PACS spectroscopy. With SAFARI a systematic survey into the occurrence of these resonances can be performed.

Second, in the SAFARI wavelength range, two water ice features, at 43 and 63 $\mu$m may appear in emission. Previously, these emission features have been observed towards YSOs (Malfait et al. 1999) and post-AGB stars (Hoogzaad et al. 2002) with ISO-LWS. Water ice is less volatile than CO$_2$ ice, sticking to dust grains at higher temperatures, and the ratio between the CO$_2$/H$_2$O mass fractions informs us about the amount of thermal processing of the ice. Moreover, the shape and appearance of the 43 and 63 $\mu$m resonances depend on the lattice structure of the water ice, providing further information on the formation and processing history.

Finally, SAFARI will offer a further opportunity to study the 69 $\mu$m resonance due to forsterite, initially discovered with ISO-LWS. This crystalline silicate feature is very sensitive in peak position to both composition (Fe-content) and dust temperature (Molster et al. 2002), and provides a valuable constraint to dust models based on crystalline silicate detections at shorter wavelengths. This feature is narrow enough that it could reliably be detected with Herschel-PACS (Sturm et al. 2010), but so far it has only been analyzed for a handful of objects, allowing for further discovery space to be filled in by SAFARI observations.

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HELGA: Dust, Gas and Star Formation in M31

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ABSTRACT

We present the results of the Herschel Exploitation of Local Galaxy Andromeda (HELGA) project, which, when combined with existing radio, infrared, UV and other data, allows us to explore at high spatial resolution the dust content and star-formation activity in our nearest large galaxy.

1. INTRODUCTION

The Andromeda galaxy (M31) is, at 785 kpc the nearest large galaxy to the Milky Way (MW) and the other dominant member of the local group. 18.2 hours of combined Herschel SPIRE and PACS guaranteed time was used to make a large 2.5° × 5.5° image of the galaxy in 5 bands at 100, 160, 250, 350 and 500 µm, in January 2011. The resultant image has become iconic in publicity material for Herschel and the European Space Agency (ESA) and was even used extensively in a live BBC broadcast, “Stargazing Live.” HELGA was proposed for science however, not just for PR, and the wealth of complementary imaging available across the whole electromagnetic spectrum allows for a very detailed analysis of our nearest giant galaxy neighbour.

2. DUST MORPHOLOGY (FRITZ ET AL. 2012)

The Herschel data was presented in HELGA I by Fritz et al. (2012). The first task was to separate genuine M31 emission from galactic foreground emission in our HELGA maps (Figure 1). We use H I maps from Thilker et al. (2004) and Braun et al. (2009) to achieve this. However the recession velocity and rotation of M31 is such that the measured recession velocity of some regions is zero, so is difficult to disentangle from MW cirrus. In HELGA I we discuss in detail how we identify foreground to produce a cirrus-free map to be used in further HELGA papers.

The cirrus-free image (Figure 1) shows very clearly the well-known 10 and 15 kpc ring structure but also two additional previously unidentified rings at around 21, 26 and possibly also 31 kpc.

3. ENERGY DISTRIBUTIONS AND DUST PROPERTIES (SMITH ET AL. 2012)

In HELGA II by Smith et al. (2012) we conduct pixel by pixel fits to the SEDs across M31, using all 5 PACS and SPIRE bands plus the Spitzer 70 µm flux as an upper limit. All images were smoothed to the resolution of the 500 µm map (36′′) and only pixels where the S/N in all 6 bands was greater than 5 were used, which still left us with 4000 individual fitted pixels.

All pixels were well fit by a single modified black body function (Figure 2) with no evidence for excess cool dust such as has been found in Dwarf galaxies such as NGC1705 (O’Halloran et al. 2010). By combining our dust distribution map with the atomic Hydrogen data of Braun et al. (2009), and molecular gas derived from the CO image of Nieten et al. (2006) we also construct a gas to dust ratio distribution, shown in Figure 3, which varies from around 20 in the centre of the galaxy to 200 in the outer regions. This distribution fits an exponential profile and matches extremely well the metallicity variation in M31 which is convincing evidence that dust does indeed trace the metal distribution, at least in this particular galaxy. If we wish to derive a total gas mass estimated form the dust emission therefore we must scale by the metallicity.

Figure 1. Left: the full field at 250 µm showing lots of structure outside the main disk which could be associated with M31 or could be foreground MW cirrus. Right: Cirrus-free image of M31.
**GEAR AND FORD**

**Figure 2.** Top: The dust mass distribution of M31 from Smith et al. (2012). Bottom: 2 sample SED fits showing good single-temperature fits with no sign of an excess of cool dust.

**Figure 3.** Right: The variation of gas to dust ratio as a function of radius in M31. The best fit line has a gradient of 0.0496 dex kpc$^{-1}$ which matches very well the inverse of the metallicity gradient of $-0.06 \pm 0.03$ dex kpc$^{-1}$. Left: variation of dust beta index as a function of radius in M31 (Smith et al. 2012).

The other major result from this paper is that the properties of the emitting dust seem to vary significantly with radius. In Figure 3 we show the variation in fitted dust emissivity index beta as a function of radius, with a dramatic change in properties at around 3.1 kpc (see also Draine et al. 2013) for reasons that are as yet unclear.

**4. STAR FORMATION IN M31 (FORD ET AL. 2013)**

In HELGA III (Ford et al. 2013) we explore the rate of star formation and its efficiency in M31. We use UV emission measured by GALEX to trace unobscured hot young stars, and the 24 $\mu$m Spitzer flux to trace obscured star-formation. After correcting the FUV and 24 $\mu$m emission for contamination from an old stellar population, traced by 3.6 $\mu$m emission, we can construct the total star formation rate from both obscured and unobscured stars (following Leroy et al. 2008). We obtain a total star formation rate in M31 of $\sim 0.25 M_\odot$ yr$^{-1}$, significantly lower than in the Milky Way. We can also use
the total FIR emission as a measure of total obscured star formation, this results in roughly a factor two higher estimate for the total SFR, which suggests that a large fraction of the FIR emission is being heated by the general interstellar radiation field in M31 rather than directly by young stars. However the overall FIR morphology still traces very well the same star-formation distribution as does the (UV+24 $\mu$m) method, as seen in Figure 4.

In HELGA III we also compare our maps of star formation with the atomic and molecular gas maps of Braun et al. (2009) and Nieten et al. (2006) to investigate the Kennicutt-Schmidt star formation law and its variation in M31. Kennicutt (1998) and many subsequent studies have suggested that the rate of star formation is related to the surface brightness of total gas by the relation, $\Sigma_{\text{SFR}} = A\Sigma_G^N$, where $N$ is the K-S index, measured to be 1.4 in Kennicutt (1998) for whole galaxies. We find in M31 that if we use the total gas mass from atomic + molecular gas that the K-S index $N \sim 2.0$, which is consistent with higher values found previously. However if we use only the molecular gas, which many have argued is a better tracer of where star formation will occur, the K-S index, $N$, falls to $\sim 0.6$, i.e. star formation in M31 may be significantly less efficient in more dense regions, at least on the sub-kpc scales probed by HELGA.

5. DISTRIBUTION AND PROPERTIES OF MOLECULAR CLOUDS (KIRK ET AL. 2013)

In HELGA IV (Kirk et al. 2013) we extract a catalogue of giant molecular cloud complexes (GMCs) and compare their properties to GMCs in the Milky Way. We use the 350 $\mu$m image, whose resolution of 24"5 corresponds to 93 pc at M31, i.e. the scale of complexes rather than individual molecular clouds. 236 individual sources were identified and their properties catalogued. As shown in Figure 5, these look very similar to Milky Way GMC complexes.
Figure 6. Comparison of SPIRE 350 $\mu$m results to BIMA interferometric sources. Left-panel based on Figure 1 of Sheth et al. (2008). Middle-panel based on Figure 3 Field A from Rosolowsky (2007). The dots show the positions of interferometry CO clouds. The large dashed circle shows the limit of the Sheth et al. (2008) map. The thick-black contours show the location and extent of sources from this paper. The greyscale and contours are SPIRE 350 $\mu$m data. The contours are spaced at 5$\sigma$ intervals. The smaller right-hand panel shows the location of the other two panels (Kirk et al. 2013).

Figure 7. Left: 3-colour SPIRE image of M31 deprojected assuming an inclination of 77°. Right: The 10 and 15 kpc Rings are shown by dotted circles. GMCs associated with the arms are shown by open markers, GMCs associated with Arm B are differentiated by the cross over their marker. The best-fit logarithmic spirals are shown by the solid line (Arm A) and the dashed line (Arm B). The Baade (1963) arm crossing regions are annotated (Kirk et al. 2013).

There is only a very limited amount of higher angular resolution interferometric imaging available for M31, however for the two regions that have been studied by Rosolowsky (2007) and Sheth et al. (2008) (Figure 6) we can see that the objects we identify break up into individual molecular clouds, proving that we are finding GMC complexes.

6. OVERALL STRUCTURE OF M31

Finally in HELGA IV we also look at the overall structure of M31. We can deproject the SPIRE image to show us what M31 would look like face-on, shown in Figure 7.

We then show that the structure can be well fit by 2 rings at 10.5 and 15.5 kpc respectively, plus 2 logarithmic spiral arms, all slightly offset from each other, as shown in Figure 7.
HELGA: DUST, GAS AND STAR FORMATION IN M31

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The Synergy with SPICA and ALMA — for a Robust AGN Diagnostic —

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ABSTRACT

Here we show the results of our ALMA cycle 0 observation toward the nearby type-I Seyfert nucleus in NGC 1097. We observed some typical dense gas tracers such as HCN (J=4–3) and HCO+ (J=4–3). We find that the HCN (J=4–3)/HCO+ (J=4–3) and HCN (J=4–3)/CS (J=7–6) integrated intensity ratios are enhanced in AGNs including NGC 1097 compared to nearby starburst galaxies and Galactic star forming regions. Multi-line/transition analysis of HCN and HCO+ emissions reveal that these lines are emitted from dense (104.5 ≤ nH2 [cm−3] ≤ 106) and hot (70 ≤ Tk [K] ≤ 550) regions, and that HCN to HCO+ abundance ratio is high (4–20). We introduce a “high-temperature chemistry” to explain the observed properties. Finally, we briefly discuss the possible future studies with ALMA and SPICA on AGN science.

1. INTRODUCTION

How did galaxies evolve to form their wide physical/chemical variety observed today? This is one of the essential problems in modern astronomy. Especially, a supermassive black hole in the center of a galaxy is known to coevolve with its host galaxy (e.g., Kormendy & Ho 2013), although the mechanism of the coevolution is unknown. To study these problems, it is necessary to reveal how some powerful heating mechanisms such as active galactic nuclei (AGNs) and starbursts (SBs) affect each other, and also their host galaxies. However, prior to study the effect of each heating mechanism, we have to construct a robust method to diagnose such mechanisms observationally. Historically, optical and IR astronomy have presented many sophisticated diagnostic methods utilizing the different physical/chemical properties of atomic lines. However, these wavelengths suffer dust extinction and thus can not penetrate deep into the dusty nuclei in e.g., ultra-luminous infrared galaxies = ULIRGs.

This problem of dust extinction can be overcome in mm/submm wavelengths. Based on this perspective, we have identified HCN-enhancement in intensity with respect to, e.g., HCO+ and CO, as the most promising indicator of AGNs (e.g., Kohno 2005). However, the cause of this HCN-enhancement is not clear because many different processes can contribute to the phenomenon in active environments, including high gas densities, high temperatures, and/or non-standard molecular abundances. In addition to these causes, a non-collisional excitation such as IR-pumping by the re-radiation from UV/X-ray heated dust can produce vibrationally excited lines and severely affect the rotational lines, which makes it difficult to deal the line intensities qualitatively.

To discuss the cause of the HCN-enhancement in detail, we observed the nuclear region of the nearby (D = 14.5 Mpc) Seyfert galaxy NGC 1097 by submillimeter dense gas tracers such as HCN (J=4–3) and HCO+ (J=4–3) by the Atacama Large Millimeter/submillimeter Array (ALMA). This galaxy hosts a type-I Seyfert nucleus, though it is a low luminous one (L2–10 keV = 4.4 × 1040 erg s−1, Lbol = 8.6 × 1041 erg s−1 at D = 14.5 Mpc; Nemmen et al. 2006). This nucleus is surrounded by a brilliant SB ring with a radius of ∼700 pc, which is luminous at various wavelengths. The molecular condensation at the nucleus shows elevated HCN to HCO+ abundance ratio (RHCO+/HCN) of ∼2 for both J=1–0 (Kohno et al. 2003) and 3–2 (Hsieh et al. 2012) transitions, suggesting that the physical/chemical properties would be dominated by the AGN in this nucleus. Here, we show a digest of the results of our observations in this paper. The details are extensively discussed in Izumi et al. (2013).

2. OBSERVATION

We observed NGC 1097 with the band 7 (∼350 GHz) receiver on ALMA using the 2SB dual-polarization setup, in the cycle 0 (ID=2011.0.00108.S, PI: K. Kohno). The observation was performed in a compact configuration and the total observing time was ∼2.1 hrs including overheads. Weather conditions were good throughout the observation with a system temperature of 150–200 K. The image reconstruction was done with the task CLEAN in CASA and analyzed with MIRIAD both in standard manners. Using natural weighting, the achieved synthesized beam is 1″5 × 1″2, P.A. = −72.4 deg for HCN (J=4–3), for example. This angular resolution (corresponds to ∼100 pc) is enough to separate the emission from the AGN and the circumnuclear SB ring in NGC 1097. Achieved rms noises are ∼2.1 mJy beam−1 and ∼2.3 mJy beam−1 in the LSB and the USB, at velocity resolutions of 8.6 km s−1 and 8.3 km s−1, respectively.
Among several line emissions in band 7, we focus on the extremely high HCN ($J=4–3$) to CS ($J=7–6$) integrated intensity ratio ($R_{\text{HCN/CS}}$), which is $>12.7$ in brightness temperature scale. In addition, the HCN ($J=4–3$) to HCO$^+$ ($J=4–3$) integrated intensity ratio ($R_{\text{HCN/HCO}^+}$) is also high ($\sim2.1$) in this nucleus, which is the same trend as the low-$J$ transitions (Kohno et al. 2003). We searched the literature (Bayet et al. 2008, 2009; Iono et al. 2013; Imanishi & Nakanishi 2013; Knudsen et al. 2007; Pérez-Beaupuits et al. 2009; Schilke et al. 1997; Seaquist & Frayer 2000) to check whether such a ratio is commonly observed or not, and the results are summarized in Figure 1. Note that one advantage of this diagram over the previous diagnostic diagram using HCN ($J=1–0$) line (Kohno 2005) is that it is much more applicable to high redshift galaxies because its lines are still within the frequency coverage of ALMA up to redshift $z \sim 3$.

At first inspection, we find that SB galaxies, Galactic star forming regions, and SB-dominated ULIRG (NGC 1614) are located in the bottom-left region of the diagram. On the other hand, the two AGN-host galaxies, NGC 1097 and NGC 1068, are located in the top-right, although NGC 1097 has a compact nuclear star-forming region and the low angular resolutions of the NGC 1068 observations are likely contaminated by the circumnuclear SB ring. VV114 East Nucleus (ULIRG/AGN+SB) shows somewhat higher ratios than those in SB galaxies. Therefore, from this diagram, one might deduce that a galaxy which has a larger AGN contribution tends to reside in the top-right region more. However, this is a tentative view as we do not have clear theoretical evidence to support the use of this diagram, and it is based on a few samples. Therefore, we need large samples and theoretical models to test extensively this diagram. Note that NGC 4418 shows line ratios comparable to those in SB galaxies, though the energy budget in the nuclear region of NGC 4418 seems to be dominated by a buried AGN (Imanishi et al. 2004; Spoon et al. 2001). One possible explanation for this situation would be IR-pumping, which could significantly affect the molecular rotational populations. Actually, a clear absorption feature of HCN at 14.0 $\mu$m and a vibrationally excited HCN emission are detected in this nucleus (Lahuis et al. 2007; Sakamoto et al. 2010).

To reveal the cause of the HCN-enhancement, we investigated the physical conditions (gas density $= n_{\text{H}_2}$, kinetic temperature $= T_{\text{kin}}$, and abundance (we estimate it by using the molecular column density $= N_{\text{mol}}$)) of typical dense gas tracers, HCN and HCO$^+$, by using RADEX (van der Tak et al. 2007). RADEX uses an escape probability approximation to solve the non-LTE excitation in a homogeneous (single temperature, single density), single component medium. Here, we used the $J=4–3$ (this work) and $3–2$ (Hsieh et al. 2012) transitions of HCN and HCO$^+$ for the simulation.

To conduct the simulation, we varied the gas kinetic temperature within a range of $T_{\text{kin}} = 10–600$ K ($dT_{\text{kin}} = +10$ K), and a gas density of $n_{\text{H}_2} = 10^2–10^7$ cm$^{-3}$ ($dn_{\text{H}_2} = \times10^{0.25}$). In addition, a ratio of gas density to velocity gradient, or equivalently gas column density to line velocity width, was changed as $N_{\text{HCO}^+}/dV$ [cm$^{-2}$ (km s$^{-1}$)$^{-1}$] = $2.0 \times 10^9$ to $2.0 \times 10^{14}$, and HCN to HCO$^+$ abundance ratio ([HCN]/[HCO$^+$]) was changed as 1, 2, ..., 15, 20, 30, ..., 100. The $T_{\text{bg}} = 2.73$ K background emission was also added to the calculation. Under these conditions, we ran RADEX and then carried out $\chi^2$ tests to search for the best parameters to reproduce the observed intensity ratios.
The Synergy with SPICA and ALMA

Figure 2. A schematic picture of the high temperature gas phase chemistry especially about H$_2$O (left) and HCN (right). These molecules are effectively formed as the temperature gets higher.

As a result, we conclude that these HCN and HCO$^+$ emissions come from hot ($70 \leq T_{\text{kin}}$ [K] $\leq 550$) and dense ($10^{4.5} \leq n_{\text{H}_2}$ [cm$^{-3}$] $\leq 10^6$) molecular clouds, where the [HCN]/[HCO$^+$] is enhanced to 4–20.

5. INTERPRETATION OF OUR RESULTS — FROM MOLECULAR GAS PHASE CHEMISTRY

One possible interpretation of our results is based on a “high temperature chemistry” (Figure 2), which has been proposed in, e.g., Harada et al. (2010). This kind of chemistry suggests that the abundance of H$_2$O is enhanced in high temperature environments, especially at $T \geq 300$ K, by the hydrogenation of atomic O. Thus the abundances of O and/or OH are suppressed in such hot regions. The fractional abundances of our interested molecules under such conditions are discussed below.

HCN: The hydrogenation from CN with H$_2$, CN + H$_2$ → HCN + H, is an endothermic reaction which has a relatively low reaction barrier of $\gamma = 820$ K, thus the HCN abundance is effectively enhanced in high temperature environments. Also, the decrease in O atom due to the formation of water would lead to relatively carbon-rich conditions, which would also act to enhance HCN abundance.

HCO$^+$: This ion species is generally created as CO + H$_2^+$ → HCO$^+$ + H$_2$. However, after the temperature increases and the creation of water and HCN are promoted, protonated species of these molecules tend to take up much of the positive charge in the form of H$_2$O$^+$ and HCNH$^+$, rather than H$_2^+$ and HCO$^+$, by reactions of, for example, H$_2$O + H$_2^+$ → H$_2$O$^+$ + H$_2$, H$_2$O + HCO$^+$ → H$_2$O$^+$ + CO. These reactions would prevent the HCO$^+$ formation and/or decrease the HCO$^+$ abundance.

As described above, the enhanced HCN abundance with respect to HCO$^+$, which can explain the observed AGN-specific properties, can be expected in high temperature environments. However, it is doubtful whether such a low-luminosity AGN in NGC 1097 can heat the surrounding ISM to several hundred kelvin at a tens of parsec scale. Probably, we should expect non-radiative heating mechanism such as shock waves associated with the AGN (jet or outflow) to be important in heating the gas in this nucleus, though such a jet component or a sign of shock heating has not been observed so far. Clearly, we need an observation with higher angular resolution and sensitivity.

6. SUMMARY AND FUTURE PROSPECTS WITH SPICA

In this paper, we present high resolution (~ 100 pc) ALMA observations of the 350 GHz band including HCN ($J$=4–3) and HCO$^+$ ($J$=4–3) emissions from the type-1 Seyfert nucleus of NGC 1097. The conclusions are summarized as follows:

- The HCN ($J$=4–3) to CS ($J$=7–6) and HCN ($J$=4–3) to HCO$^+$ ($J$=4–3) integrated intensity ratios are higher in AGNs than in SB environments. Although the sample is small, we consider these line ratios are effective discriminator between AGN and SB activities, and thus constructed a tentative diagnostic diagram.
- We ran non-LTE simulations by RADEX to constrain the excitation parameters of the HCN and HCO$^+$ lines. The $\chi^2$ tests using the $J$=4–3 and 3–2 lines show that these emissions come from dense ($10^{4.5} \leq n_{\text{H}_2}$ [cm$^{-3}$] $\leq 10^6$), and hot ($70 \leq T_{\text{kin}}$ [K] $\leq 550$) environments, and [HCN]/[HCO$^+$] is estimated to be 4–20.
- We introduce a chemical layouts based on a high temperature chemistry to explain the observed HCN-enhancement, although the heating source is still not clear. Another heating source separate from the radiative heating, such as shocks associated with the AGN, is suggested to exist.

We confirmed that multi-$J$ modeling including HCN and HCO$^+$ by using ALMA is a powerful tool to investigate the physical/chemical properties of dense molecular medium around an AGN. We will apply this method to other key
molecules and other galaxies in future ALMA observations, which can be combined with SPICA to produce synergistic effects. For example, Kawakatu et al. (2007) predicted the existence of massive gas reservoir (massive gas torus) with a mass of $\sim 10^8$–$10^9 \, M_\odot$ extending over a $\sim 100$ pc scale around the central supermassive black hole (SMBH) in galaxies. They concluded that the gas mass to black hole mass ratio, and the geometry of the massive torus reflect the growth history of SMBH (Figure 3). To test this scheme, the fast survey speed of SPICA will play an important role in finding AGNs with various activities at various eras by using optical/IR diagnostic method. On the other hand, ALMA can follow up those galaxies in detail thanks to its extremely high angular resolution and sensitivity, and can measure the mass and the geometry of the expected massive gas tori. Clearly, the synergy of these two telescopes is the key to revealing the evolutionary history of SMBHs, and then to shedding a light on the dark side of the universe.

This paper makes use of the following ALMA data: ADS/JAO. ALMA#2011.0.00108.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in co-operation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

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PAH Emission from H II Regions in the SAGE-spec Spitzer Program

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ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are some of the important components of the interstellar medium being both abundant and ubiquitous. We present the preliminary results on PAH emission in H II regions in the Large Magellanic Cloud using the spectroscopic data taken by Infrared Spectrograph (IRS; 5–38 µm), a part of the SAGE-Spec Spitzer Legacy program. The SAGE-Spec program provides the IRS mapping data of ten H II regions combining them with the archival data of 30 Dor. Among the eleven H II regions, an exemplary spectrum of an H II region (LHA 120-N 11: DEM L34) is presented. The integrated spectrum shows prominent PAH features at 6.2, 7 to 9, and 11.3 µm as well as a weak PAH feature at 12.7 µm. Several ionic lines such as [S IV] 10.51, [Ne II] 12. 81, and [Ne III] 15.56 µm, are also detected, which probe the ionization and/or density of the gas. PAH band ratios are examined over the region, and we investigate the correlation between the band ratios and the radiation field strength. Finally, we propose how the nature of PAHs and their correlation to the local environment can be extensively explored by SPICA.

1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are commonly considered to be the carriers of mid-infrared (MIR) emission bands that have been observed toward diverse objects (for a recent review, see Tielens 2008). PAHs are heated by UV photons and (re)emit rich spectral features mostly between 3 and 20 µm which are sensitive to local physical conditions. They have frequent interactions with ions, electrons, and other molecules as well as dust grains. Thus, PAHs play an important role on the energy balance and the ionization balance in the ISM, and it is important to understand the behavior of PAHs with given environment.

Madden et al. (2006) obtained infrared spectra of a number of galaxies with a wide range of metallicities using Infrared Space Observatory. The intensity of the PAH emission seen in these spectra shows strong dependence on metallicity of the host galaxies. In low-metallicity environments, very weak or no PAH emission is detected. In particular, it is unexpected to observe the paucity of PAH emission in some star-forming galaxies with low metallicities in the context that PAH emission is often used as an indicator of star formation. The effect of the metallicity-dependence of PAH emission has been examined in more detail. For example, Calzetti et al. (2007) derived 8 µm PAH emission luminosities of star-forming regions in nearby galaxies using the Spitzer IRAC 8 µm band and addressed the correlation between the PAH emission and the Pa α (1.8756 µm) emission line. They found the good correlation between them, especially for those with Galactic metallicity, but the relation shows deviations when lower-metallicity objects are included. This is likely to be due to the paucity of PAH emission in low metallicity.

Another important nature of PAHs is that the relative strength of different PAH emission bands vary significantly. Galliano et al. (2008) modeled PAH band ratios of various objects and found that there is a universal linear trend between the ratio of 7.7 µm band to 11.3 µm band and the ratio of 6.2 µm band to 11.3 µm band. Interestingly, the band ratios measured in spatially resolved regions of a galaxy vary as much as the range of the variety seen from various types of galaxies. This is an important aspect because if the physical conditions of a specific area are disentangled, observed PAH features can be interpreted accordingly. In fact, the band ratios are known to reflect the local physical conditions such as radiation field strength or gas density. Therefore, it is important to understand how PAH emission behave in different environments such as low metallicity environment by observing PAH emission in spatially resolved and well-characterized regions.

The Large Magellanic Cloud (LMC) is an ideal target since the LMC provides an opportunity to look at low metallicity environment (∼ 0.5 Z⊙) in close proximity (50 kpc). H II regions have plenty of UV photons to heat PAHs (but may destroy PAHs, too), so various PAH features have been observed frequently. Together with diagnostics of the physical conditions, H II regions in the LMC enable us to investigate PAH emission in detail.
2. SPITZER SAGE-SPEC PROGRAM

Various surveys toward the LMC at a range of wavelengths have been carried out (e.g., HERITAGE; Meixner et al. 2010). As a Spitzer Legacy Program, there is a photometric survey in the infrared of the LMC, Surveying the Agents of Galaxy Evolution (SAGE-LMC; Meixner et al. 2006). Following the SAGE-LMC, SAGE-Spec (Kemper et al. 2010) is the spectroscopic survey of the LMC to examine the life cycle of dust and gas in the LMC. The Spitzer SAGE-Spec program consists of 224.6 hr of spectroscopic observations using Spitzer IRS (5–38 µm) and MIPS-SED (70–90 µm) observing modes to target 196 point sources as well as 20 extended regions, 10 H II regions and 10 atomic/molecular diffuse regions (Figure 1). In addition, the SAGE-Spec sample is extended by archival IRS staring mode observations as well as the archival IRS/MIPS-SED maps of the 30 Doradus H II region (Indebetouw et al. 2009) and two diffuse regions. In total, 11 H II regions and 12 diffuse regions are included in the SAGE-Spec (for more information on targets, see Table 6 in Kemper et al. 2010), and spectral maps of the 23 extended sources are obtained by IRS mapping mode and MIPS SED mode. All H II regions are mapped in strips that cover a width of 1’ and the length being the diameter of each H II region (the maximum length of the strip is limited to 5.4’). This mapping strategy allows us to examine the spatial variations of spectral features inside the H II regions.

3. PRELIMINARY RESULTS OF H II REGIONS

As a representative for the 11 H II regions, the integrated spectrum of one H II region (LHA 120-N 11; DEM L34) is shown in Figure 2. The spectrum shows prominent PAH features at 6.2, 7.7, 8.6, and 11.3 µm features and a weak 12.7 µm feature. Strong ionic lines such as [S IV] 10.51, [Ne II] 12.81, [Ne III] 15.56 µm are seen, which are diagnostics of the
PAH EMISSION FROM H II REGIONS IN SAGE-Spec

Figure 2. An exemplary integrated IRS spectrum of an H II region (LHA 120-N 11; DEM L34). Different colors indicate different orders of IRS; Short-Low 1st order (blue), Short-Low 2nd order (violet), Long-Low 1st order (green), Long-Low 2nd order (cyan).

physical conditions in the region. For example, the ratio of [S IV] 10.51 μm to [Ne II] 12.81 μm can be used as an indicator of radiation field strength similar to [Ne III] 15.56/[Ne III] 12.81 (Groves et al. 2008). This ratio is useful because both lines are observed by the same order (Short-Low 1st order: shown in blue in Figure 2), so deriving the ratio and examining their spatial distribution is straightforward. Beside the emission features, the dust continuum is dominant at longer wavelengths. While the integrated spectrum represents the IR emission features of the region, two-dimensional spectral maps provide the spatial distributions of emission features and the correlations between different features. PAH band ratios (e.g., $I_{6.2}/I_{11.3}$) are known to be sensitive to their charge state, which is physically related to the ionization/recombination ratio of the gas (e.g., Galliano et al. 2008). We compare the PAH band ratio map ($I_{7.7}/I_{11.3}$) to the line ratio map ([S IV]/[Ne II]). There seems to be a rough correlation between the PAH band ratios and the line ratios, but there are deviations from the correlation, too. This will be further discussed in Hony et al. (2013, in preparation).

4. PERSPECTIVE ON SPICA

SPICA (Space Infrared Telescope for Cosmology and Astrophysics; Nakagawa et al. 2011) is a next-generation infrared astronomy mission. Its cooled (< 6 K) large (3-m class) telescope will be able to offer superior sensitivity and high spatial resolution. One of the key instruments, the Mid-infrared Camera and Spectrometer (MCS) onboard SPICA will cover various PAH features. The MCS consists of three parts; the Wide Field Camera (WFC), the Mid Resolution Spectrograph (MRS), and the High Resolution Spectrograph (HRS). The MRS will perform integral-field unit (IFU) spectroscopy by image slicers providing a field of view of 12′′ × 8′′. It covers a wide wavelength range from 12.2 to 37.5 μm with a spectral resolution of $R \approx 1100$–3000 and has good spatial resolutions (0′′.32/pixel or 0′′.44/pixel). These unique capabilities of the MRS will play a key role in studying spatial variations of PAH features, sub-features of PAH emission, and PAH emission in distant objects. Major PAH features are located at 3.3, 6.2, 7.7, 8.6, and 11.2 μm, and these features in distant galaxies (i.e., $z \sim 1–3$) will be nicely covered by the MRS. PAH features have been detected in high-redshift galaxies, for example, Teplitz et al. (2007) observed two sources at $z = 1.09$ and $z = 2.69$ by Spitzer, both of which show prominent PAH features at 6.2, 7.7, and 8.6 μm. Using the MRS, the PAH features will be detected from more (fainter) objects at high-redshift and can be compared with the same features seen in local universe. In particular, the low metallicity environment in the LMC is representative for a typical low-mass galaxy at $z \approx 2$ (Panter et al. 2008), so we can study the variation such galaxies in a nearby analog in much more spatial detail.

Besides the features mentioned above, there are various PAH features at longer wavelengths, such as the 12.7 and 16.4 μm features and broad emission plateau from 15 to 19 μm. The reflection nebula NGC 7023 shows several PAH features in the high-resolution 15–20 μm spectrum obtained with the Spitzer IRS (Sellgren et al. 2007), which are likely to originate from large PAHs. It is noticeable that the 18.9 μm feature is locally distributed around the central heating source unlike other features seen in NGC 7023, and this indicates that it could be attributed to highly ionized PAHs. To examine these features in more detail, good spectral resolutions, high sensitivities together with efficient spectral mappings are required, which will be achieved by MRS.
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In addition to the MRS, a WFC-SH grism ($R = 200$) covering 4 to 13 $\mu$m will be useful to study PAH emission in the Milky Way, Magellanic Clouds, and nearby galaxies, and the MCS-WFC will provide morphologies of emission features in various MIR bands that can be compared with spectroscopic data. Finally, PAH studies will be strengthened by combining with capabilities of other instruments onboard SPICA; FPC-S (Focal Plane Camera-Science: 0.7–5 $\mu$m imaging and spectroscopy) to observe PAH emission at shorter wavelengths and SAFARI (SpicA FAR-infrared Instrument: 34–210 $\mu$m) to examine correlations between PAHs and warm/cold dust. It is expected that SPICA will open a new era for the research field related to PAH emission.

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**SPICA Observations in the Era of Ground-Based THz Astronomy**

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**ABSTRACT**

When SPICA starts observations, some ground-based terahertz (THz) telescopes will be in operation by targeting atmospheric windows around 1–1.5 THz. Among future ground-based THz facilities we focus on the Greenland Telescope (GLT), whose dish size and angular resolution are 12 m and 4′′ (at 1.5 THz). The largest advantage of those ground-based telescopes is better angular resolutions, although the sensitivity is worse than SPICA. Based on some scientific cases discussed for the GLT, we discuss how SPICA can collaborate with ground-based THz telescopes. The shorter-wavelength coverage of SPICA than the GLT is suitable for improving dust temperature estimates, and identifying some important chemical species. A high angular resolution of the GLT is crucial to produce high-resolution map or to overcome the confusion limit of SPICA. Flexible ToO (Target of Opportunity)-type observations are also worth considering for SPICA.

1. **INTRODUCTION**

The Terahertz (THz) frequency band is a largely unexplored domain in radio astronomy. The Greenland Telescope (GLT; Grimes & Blundell 2012; Inoue 2013) will provide a unique opportunity to explore THz windows around 1–1.5 THz. In addition to its main mission to image the black hole shadow in M87 as part of a submillimeter (submm) interferometer, the GLT is also capable to serve as a powerful single element telescope for a great fraction of time. Currently, the GLT is planned to start observations around 2016.

The merit of ground-based THz observations is that we can use a large telescope. The diameter of the GLT is 12 m, so that the angular resolution achieved is 4′′ at 1.5 THz, while the diffraction limit of 3.5-m-class space telescopes such as Herschel and SPICA is ~12′′ at ~1.5 THz. Therefore, compared with space telescopes such as Herschel and SPICA, the GLT is suitable for objects whose interesting structures in THz have an angular scale of a few arcsec.

In the following sections, we first explain unique science cases carried out by the GLT. Based on these cases, we describe possible collaboration between SPICA and the GLT. Although we focus on the GLT, the ideas described in this contribution can be applied to any ground-based THz telescopes to be constructed in the future, such as CCAT.1

2. **THZ SCIENCE CASES FOR THE GLT**

A major advantage of moving to higher frequencies into the THz regime is that thermal dust continuum emission will be measured around its peak in the spectral energy distribution (SED). Moreover the GLT angular resolution (4′′ at 1.5 THz) enable us to spatially resolve the individual star formation sites within nearby molecular clouds (d < 1 kpc). These two points would be big advantages especially searching for less massive pre- and proto-stellar populations (e.g., brown dwarf mass or even less massive sources) and constrain the core mass function at the lower mass end. Furthermore, in combination with multi-frequency data, this will allow us to measure SEDs of pre- and proto-stellar sources and determine their cool-gas temperatures ~10 K, thus providing access to the earliest evolutionary phases of star formation.

Dust continuum observations in the THz regime will also play an important role for nearby galaxies. Dust emission is often used as a tracer for star-formation activities. Here, determining the dust temperature is paramount. Combining lower frequency bands with the 1.5 THz dust emission will significantly improve dust temperature estimates. Moreover, we emphasize that the GLT 1.5 THz achieves an angular resolution comparable to submm interferometric data taken by the Submillimeter Array (SMA) (Figure 1). No THz facilities have ever had such a resolution.

Spectral line studies will complement the THz continuum observations. A wealth of interesting but unexplored lines are in the THz windows (Table 1). High-J molecular lines (e.g., CO, HCN) will probe extremely hot (300–500 K) molecular regions in the vicinities (<10 AU) of forming protostars. Line profiles will reveal gas motions in these regions. CONDOR

1 http://www.ccatobservatory.org/
Figure 1. Contour: SMA 880 µm continuum brightness of a nearby dwarf galaxy He 2-10 (see Hirashita 2013, for details). The beam of the subcompact configuration of SMA is shown in the lower right corner. Gray scale: Hubble Space Telescope Advanced Camera for Surveys optical images at F550M band. The spatial resolution of the GLT at 1.5 THz (4") is also shown in the upper left corner.

on APEX already detected the CO ($J = 13-12$) line at 1.50 THz toward Orion FIR 4, measuring the very hot molecular gas ($\sim 200$ K) concentrated around the high-mass protostar without contamination from the more extended outflow (Wiedner et al. 2006). Additional lines accessible in the THz windows will be groups of atomic fine-structure lines (e.g., [N II], [C II]), tracing diffuse transitional regions from ionized or atomic gas to molecular gas in the interstellar medium, and pure rotational lines (e.g., CH), tracing chemically basic light molecules.

<table>
<thead>
<tr>
<th>Species</th>
<th>Frequency (THz)</th>
<th>Transition</th>
<th>Excitation energy (K)</th>
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<td>$^{3}P_0–^{3}P_1$</td>
<td>—</td>
</tr>
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</table>

In the field of very-high-energy (VHE) phenomena, THz continuum observations can help to constrain the mechanism and region of origin of the VHE in active galactic nuclei (AGNs). In particular, current multi-frequency monitoring campaigns from optical to X- and gamma-rays lack observations in the THz window for a complete SED to constrain the underlying physics of the origin of VHE. THz/submm observations will also help advancing gamma-ray burst (GRB) research. THz continuum observations will provide clean measurements of the source intensity, without being affected by scintillation and extinction. Afterglow properties can be constrained with THz observations because the forward-shock...
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synchrotron peak frequency is falling to lower frequencies with time. Catching the shock in the THz range, and comparing these data with optical and infrared wavelengths will set constraints on the fireball model by constraining the density profile around the GRB. A systematic reverse-shock emission search with the GLT is also imperative to explore the first stars in the early Universe (at redshifts $z \sim 10–30$), because the luminosity of reverse-shock emission is expected to be 100 times brighter than that of forward shock emission. For this purpose, a rapid-responding system is necessary for the GLT.

3. POSSIBLE COLLABORATIONS BETWEEN SPICA AND THE GLT

The good angular resolution (4″ at 1.5 THz) is one of the largest advantages of the GLT, and this is also true for other future ground-based THz telescopes. SPICA can achieve the same resolution at 50 μm. Therefore, the spatial resolution of SPICA mid-infrared observations matches that of the GLT. The high resolution of the GLT has also an advantage in comparing with interferometric data at longer wavelengths (Figure 1).

Another general feature of ground-based facilities is that they are capable of executing time-consuming observations. In contrast, space observatories are not suitable for time-consuming projects because of their limited lifetimes. Therefore, if we have found interesting objects by the GLT, they are viable targets of SPICA.

Below, we describe possible collaboration items between SPICA and the GLT for some of the specific science cases reviewed in Section 2. We choose (i) warm environments, (ii) dust formation and evolution, and (iii) time-variable sources as viable topics for such a collaboration.

3.1. Warm Environments

One of the unique points in THz observations is capability of observing highly excited CO, which is a tracer of dense and warm gas (hydrogen number density $\gtrsim 10^3$ cm$^{-3}$ and temperature 300–500 K). Such a highly excited tracer is suitable to probe the vicinity of protostars and AGNs. On the other hand, mid-infrared spectroscopy is one of the strongest tools for investigating various chemical species in various environments. For example, an AGN with high excitation CO lines (NGC 1068; Hailey-Dunsheath et al. 2012) emits strong HCN lines (Krips et al. 2011), but so far there is no definite explanation for it. SPICA can target this kind of AGNs to observe vibration-rotation absorption bands of some molecular species (such as HCN 14 μm Lahuis et al. 2007), further constraining the emission mechanism.

The [N II] 1.46 THz (205 μm) can also be observed by the GLT. By SPICA, we can additionally observe [O I] 63 μm and [C II] 158 μm. These atomic lines trace diffuse (30–100 cm$^{-3}$), transitional regions from ionized or atomic gas to molecular gas in the ISM, so that they are unique tracers of H II regions, photo-dissociation regions, and the surface of molecular clouds. In particular, obtaining the radiation field intensity (Pineda et al. 2010) and density (Oberst et al. 2011), and extracting kinematic information from the line profiles are crucial steps to reveal the cloud formation and disruption processes.

3.2. Dust Formation and Evolution

Precise measurement of dust mass is a crucial step in clarifying the dust enrichment in the Universe. There are two major uncertainties in measuring dust mass: one is the dust temperature and the other is the dust mass absorption coefficient.

The dust temperature is most precisely determined if we observe at wavelengths near the dust SED peak, which is located around 100 μm depending on the dust temperature. Although the THz windows accessible for the GLT contribute to improving dust temperature estimates significantly, adding a shorter wavelength such as 100 μm is desirable for further precision. Therefore, follow-up observations of GLT sources by SPICA around 100 μm contribute to improving dust mass estimates. By combining the better estimate of dust temperature by SPICA and the better spatial resolution of the GLT, we can make a high-resolution dust temperature map.

The uncertainty in the mass absorption coefficient may be overcome by knowing the dust species from mid-infrared spectroscopic observations by SPICA. Indeed, Markwick-Kemper et al. (2007) determine the mineralogical composition of dust in an AGN environment (a broad absorption line quasar PG 2112+059) by fitting the dust spectral features. Since such an identification of dust species is difficult for THz featureless continuum, SPICA mid-infrared observations will provide unique information on dust species.

In Figure 2, we show another example of spectral fitting: the observed SED of a planetary nebula NGC 6781 overlaid with the best-fit CLOUDY (Ferland et al. 2013) model (Otsuka et al., in preparation). In particular, the wavelength range covered by SPICA and the GLT is important for the dust emission. Thus, combination of SPICA and the GLT will contribute to precise determination of the dust mass contained in mass-loss objects such as planetary nebulae, asymptotic giant branch stars, etc., to better understand the total dust supply rate by those sources in the Galaxy. THz (and submm) measurements by the GLT is of fundamental importance in determining the cold dust mass, which has the largest contribution to the total dust mass.

For high-redshift galaxy surveys, it is worth noting that SPICA still has a problem of confusion limit for far-infrared continuum observations. Therefore, a high-resolution follow-up observations by the GLT is crucial to isolate spatially contaminated sources.
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Figure 2. The best-fit SED calculated by CLOUDY overlaid on the photometric (dots: INT/WFC, 2MASS, Spitzer IRAC, AKARI PSC, Herschel PACS and SPIRE) and spectroscopic data (WHT/ISIS, Spitzer IRS, Herschel PACS and SPIRE) for a planetary nebula NGC 6781 (Otsuka et al., in preparation).

3.3. Time-Variable Sources

Blasars are unique objects to understand AGN activities, such as jets. Measurements of synchrotron-self-absorption SED are especially important to determine the magnetic field strengths associated with the energetic phenomena. However, the far-infrared–submm region is the unexplored part in the SED (Abdo et al. 2011). Therefore, a possibility of simultaneous observations between SPICA and a ground-based submm telescope is interesting in filling the SED gap in the far-infrared–submm region. For this purpose, it is worth considering a flexible operation mode for SPICA such as a ToO (target of opportunity) mode. Campaign observations of GRBs and SNe between SPICA and the GLT are also interesting if there is such a flexible operation mode.

4. SUMMARY

We will be able to carry out fruitful collaborations between SPICA and the GLT by utilizing the following complementary characteristics: SPICA has a coverage of wavelengths shorter than 200 μm while the GLT has a higher resolution at >200 μm. Specifically, the GLT can overcome the confusion limit of SPICA at far-infrared wavelengths, while SPICA can follow up GLT objects at ∼100 μm, obtaining better estimates of dust temperature and dust mass. Moreover, SPICA can clarify dust species and physical states of the ISM by mid-infrared spectroscopic observations, which are capable of detecting plenty of lines and features. Flexible ToO-type operations are also worth considering for SPICA.

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**From Exoplanets to Distant Galaxies: SPICA’s New Window**

**SPICA AND GROUND-BASED THz ASTRONOMY**


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Study on the Interstellar OH Radical in Mid-Infrared

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ABSTRACT

The powerful spectroscopic capability of \textit{SPICA} in mid- and far-infrared bands will certainly open a totally new window to understand the universe through chemical diversity. Huge amount of molecular lines can be detected in this wavelength, but most of them have never been studied before although they must contain abundant very new information on the interstellar conditions. The OH radical is one of the key molecules to be observed in the interstellar space related to shock process, which also forms H$_2$O, SiO, and other major molecular species. Except OH maser emissions at around 1.7 GHz, its thermal emission has not been studied much because its transition wavelengths are mostly in mid- and far-infrared. The OH fractional abundance relative to H$_2$ is expected be enhanced more than two orders of magnitudes behind the shock but it is also detected in cool, extended clouds. Observations of the OH transitions in \textit{SPICA}’s wavelengths towards various Galactic and extragalactic astronomical sources will certainly provide exciting new results, especially in relation to prevalent shock related phenomena.

1. \textit{SPICA AND SENSITIVE SPECTROSCOPIC OBSERVATIONS}

The Japanese-led mission \textit{SPICA} is the next-generation, space infrared observatory which will be consisted of a 3.2-meter cryogenically cooled (6 K) telescope and state-of-the art detectors (Nakagawa et al. 2011). Under this extremely low background level environment, \textit{SPICA} will provide high spatial resolution and unprecedented sensitivity in the mid- and far-infrared. Its powerful spectroscopic capability in this wavelength, which is expected to be more than an order of magnitude better in sensitivity compared to PACS of \textit{Herschel} (Pilbratt et al. 2010), will certainly open a totally new window to understand the universe through chemical diversity.

In the mid- and far-infrared bands, there exist various molecular transitions from vibrational states (mostly resulted from the stretching or bending modes), rotational-vibrational states, and high-energy rotational states. Compared to the electronic and rotational states of molecular lines, these infrared transitions have not been studied much not only for the relatively weak lines, but also for the major transitions. Figure 1 shows a sample of the spectral line survey obtained with \textit{ISO} (Kessler et al. 1996) toward an asymptotic giant branch star, CRL 618, evolving toward the planetary nebula stage (Herpin & Cernicharo 2000). This figure clearly shows the importance of the infrared transitions from the major molecules to understand the physical properties of astronomical objects. The hydroxyl radical (OH) is one of those major molecules which needs to be studied much further considering its importance in the interstellar processes.

In addition, high sensitivity spectroscopic studies in the \textit{SPICA}’s mid- and far-infrared bands will certainly reveal enormous number of weak lines. Most of these lines have never been studied before, but they must contain huge amount of unexpected important information which may change our fundamental view of the universe. This article is to stress the importance of the sensitive spectroscopic observations in the \textit{SPICA}’s band.

2. OH RADICAL

OH is one of the first radicals detected in the diffuse gas clouds. Radicals contain at least one unpaired electron which often make them highly reactive and unstable. Free radicals are too short-lived to be observed in the terrestrial environment, but many of them are now observed in space as important tracers of interstellar processes (Kwok 2007).

The energy diagram for the OH molecule is shown in Figure 2 (Wampfler et al. 2013). The + and − notations refer to the total parity of the Λ doublets. Due to an unpaired electron (S = 1/2) and the magnetic moment of the nuclei the levels further split into two hyperfine states. The ground state of OH is $^2\Pi_{3/2,1/2}$, which emits four maser lines at around 1.7 GHz (two main lines: 1665 & 1667 MHz and two satellite lines: 1612 & 1720 MHz). These OH maser lines have been studied towards many star-forming regions as important tracers of the shocked gas.

Except these maser lines, however, other important transitions from OH have wavelengths mostly in the infrared bands which hinders easy access in the ground. Although some of the OH infrared transitions have been observed previously with space telescopes, such as \textit{KAO, ISO, Herschel}, or \textit{SOFIA}, studies for OH are still very limited compared to its importance in the space.

We have tested the OH excitation using an LVG-like code of van der Tak et al. (2007). Excitation of OH is mainly controlled by either collisions or radiative pumping, but not by both, and a part of the results is shown in Figure 3. As indicated in the panel, $T_{\text{kin}} = 100$ and 200 K, and $n_{\text{H}_2} = 10^4$ and $10^5$ cm$^{-3}$ have been assumed. These results are the cases...
Figure 1. Continuum-subtracted spectra of CRL 618 (long-wavelength detectors of ISO). The plot indicates a Gaussian fit to this feature (Figure 1 of Herpin & Cernicharo 2000).

of the total OH column density of $1.0 \times 10^{18} \text{ cm}^{-2}$ with a linewidth of 5 km s$^{-1}$. We are preparing an elaborate model for the OH excitation for some of its transitions to be used as meaningful tracers of interstellar conditions (Park et al., in preparation).

Shock is everywhere in space. Almost all objects in the space are associated with shock, such as supernova remnants (SNRs), expanding hot gas, HII regions, circumstellar envelopes, (proto-)planetary nebulae, star formation regions, etc. Among interstellar molecules, OH, H$_2$O, and SiO are thought to be good shock tracers, as they are also observed as masers. OH is a key molecule in the formation of these species.

In dense quiet gas phase, where ion-molecule reactions dominate, OH usually forms by the hydrogen abstraction sequence followed by the dissociative recombination of H$_3$O$^+$ (Jensen et al. 2000). This results in the fractional abundance of OH, $f_{\text{OH}} \approx 10^{-8}$, relative to total H$_2$, in the density of $n_{\text{H}_2} = 10^4 - 10^6$ cm$^{-3}$. Elevated kinetic temperature in the shocked region, however, enables the endothermic reactions to be processed which were inactive in the quiet gas region, and enhances $f_{\text{OH}}$ to be more than 2 orders of magnitudes ($\geq 10^{-6}$).

At $T_{\text{kin}}$ above $\sim 300$ K, important production reactions of OH, H$_2$O, and SiO become O + H$_2$ $\rightarrow$ OH + H, OH + H$_2$ $\rightarrow$ H$_2$O + H, and Si + OH $\rightarrow$ SiO + H (Neufeld & Dalgarno 1989; Pineau des Forets & Flower 1996). Immediately behind a shock, H$_2$O is formed fast and contains most of the oxygen, but it is more easily dissociated than OH by photons, and quickly depleted to the grain surface in denser regions. SiO is an unambiguous shock tracer, since Si is highly depleted in the quiet phase (by larger than 1000) and needs to be sputtered or desorbed from grain mantles, or
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Figure 2. OH transitions. Wavelengths are given in units of microns (Figure 1 of Wampfler et al. 2013).

destroyed to be in the gas phase (Pineau des Forets & Flower 1996). OH is playing a key role in relation to the formation of these molecules, and among three molecules, OH is the only one also detected in cool, extended clouds.

In shock and PDRs, abundances are clearly enhanced mainly by the activation of endothermic neutral-neutral reactions. But there are significant difficulties to interpret these regions using these shock tracers. It is not only because of different predictions by different models, but also because emission from these regions are resulted from the mixed effects caused by different physical conditions, chemical variations, or radiative transfer. We definitely need to have more data to understand these sources, especially in the mid- and far-infrared region, since many of the molecular lines emitted from shock regions lie in this wavelength.

3. OUR GALACTIC CENTER

Interstellar molecular lines observed in the mid- and far-infrared region will provide important information to understand the properties of various Galactic and extragalactic sources. Chemical information of the observed lines are essential to understand physical conditions of, for example, complicated massive star-forming regions, embedded deeply inside...
Figure 3. Sample results of the OH excitation model calculated by using the modified code of van der Tak et al. (2007).

dense GMCs (e.g., Minh et al. 2010, 2011), since there are not many probes available to investigate these regions. Here we introduce our Galactic center, as a candidate for the study of shock features with OH and/or other shock tracers, which will provide important clues to understand this extremely complicated region. Especially we do not have many evidences indicating apparent interactions among various different components which are crucial to understand the nature and evolution of this region.
Study on the Interstellar OH Radical in Mid-Infrared

\[ \text{NH}_3 \]

\[ \text{Figure 4. NH}_3 (6, 6) \] observational results made with Green Bank Telescope. Two panels in the bottom-left are color-coded channel maps for main gas condensations, the 50 km s\(^{-1}\) and the 20 km s\(^{-1}\) clouds (left) and newly found streaming gas components (right). The velocity scale is shown as a color bar on top of these panels. Spectra obtained towards the position, F, M, and I are shown in the upper-right side. Gaussian fit results are overlapped with the observed spectra. See details of this figure in Minh et al. (2013).

Neutral gas near the Galactic center is predominantly molecular. Most of the gas within \( \sim 20 \) pc (in projection) from Sgr A\(^*\) is concentrated into two massive clouds, called M\(\sim 0.02 - 0.07 \) (also referred to as the "50 km s\(^{-1}\) cloud") and M\(\sim 0.13 - 0.8 \) (the "20 km s\(^{-1}\) cloud") according to their galactic coordinates (Guesten et al. 1981). These two clouds have comparable masses (\( \sim 5 \times 10^5 M_\odot \)) and linear dimensions (\( \sim 10 - 15 \) pc), and they have a complicated morphological structure (e.g., Guesten et al. 1981; Armstrong & Barrett 1985). The large linewidths of the observed transitions indicate the existence of a high degree of turbulence. Subsequent to early absorption line observations of OH and H\(_2\)CO, spectral lines and dust emissions from these clouds have been studied extensively (e.g., Snyder et al. 1969; Guesten et al. 1981; Minh et al. 1992), and it has been found that the physical and chemical properties of these molecular clouds differ substantially from those in the galactic disk.

This molecular gas has been thought to interact with the central components in the inner 10 pc of our Galactic Center, such as the circumnuclear disk (CND) or the SNR Sgr A East (e.g., Ho et al. 1991; Coil & Ho 1999). The CND is a ring-like, dense (\( \geq 10^5 \) cm\(^{-3}\)), highly turbulent (\( \Delta v \geq 40 \) km s\(^{-1}\)), and clumpy molecular gas, which surrounds Sgr A\(^*\) with an inner edge at \( \sim 1.5 \) pc and an outer edge at \( \sim 3 - 4 \) pc (e.g., Liu et al. 2013, and references therein). Sgr A East is an expanding shell of a synchrotron emission that lies behind Sgr A\(^*\); it is thought to interact with the CND and also with the ambient 50 km s\(^{-1}\) cloud. Sgr A East appears to be pushing the gas away from its nucleus, forming ridges of material on all sides; however, some material, such as the NH\(_3\) filamentary streamers, may also move toward the nucleus and possibly feed the nucleus.

As shown in Figure 4, we recently found that there exist various streaming components associated with the CND near our Galactic center which are apparently located out of the galactic plane and have highly eccentric orbits (Minh et al. 2013). Some of these streaming components are expected to be sources that feed the CND of our Galactic center directly and episodically. However, the structure and evolution of these components have not yet known well which may provide a crucial clue to understand the infall of gas to Sgr A\(^*\), the supermassive black hole (SMBH, mass ~ \( 2 \times 10^6 M_\odot \); Reid et al. 1999; Ghez et al. 2005), and the formation of highly eccentric young stellar clusters located very near to SMBH.

This study could be extended toward the northeast region outside Figure 4, where a number of unusual non-thermal filaments (NTFs), referred to as streaks, threads, and filaments, have been found (e.g., Yusef-Zadeh et al. 1984; Lang et al. 1999). These features have lengths of tens of parsecs, yet widths of only less than 0.5 pc, orientation roughly perpendicular to the Galactic plane. Studies on the association between NTFs and both ionized and molecular gas components will
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provide an important clue to understand the nature of NTFs. We expect that emissions from OH or other shock tracers, especially in infrared, will certainly provide fundamental information to understand this important but complicated region.

4. SUMMARY

The next-generation, space infrared observatory, SPICA, is going to have a powerful spectroscopic capability in mid- and far-infrared bands. We expect that huge amount of molecular lines will be detected in this wavelength, which will certainly open a totally new window to understand the universe through chemical diversity. A considerable amount of the detected lines has never been studied before, but must contain abundant very new information on the interstellar conditions. This article is just to stress the importance of spectroscopic measurements in mid- and far-infrared bands, and the OH radical is introduced as an example of the important species to be studied. OH is one of the key molecules to be observed in the interstellar space related to shock process, which also forms H$_2$O, SiO, and other major molecular species. The OH fractional abundance relative to H$_2$ is expected be enhanced more than two orders of magnitudes behind the shock but it is also detected in cool, extended clouds. Except OH maser emissions at around 1.7 GHz, however, its thermal emission has not been studied much because its transition wavelengths are mostly in mid- and far-infrared. We test the OH excitation model to be used as a tool to trace the specific physical conditions. Observations of the OH transitions in SPICA’s wavelengths towards various Galactic and extragalactic astronomical sources will certainly provide exciting new results, especially in relation to prevalent shock related phenomena. Here we introduced our Galactic center as a possible candidate source for the study of this kind.

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Evidence of Hot-Bottom-Burning in Extreme OH/IR Stars

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ABSTRACT

Observations by Herschel Space Observatory of extreme OH/IR stars indicate that these objects currently undergo a phase of very high mass loss – superwind. We derived relatively low 12C/13C ratios which is indicative of the hot-bottom burning process. Further evidence from the observed oxygen isotopes (16O/17O/18O) also support this idea. We conclude that these stars are massive (M ≥ 5 M⊙) AGB stars. With SPICA-SAFARI, it will be possible to observe these isotopic ratios in a number of these stars as they contribute significant gas and dust mass return to the interstellar medium of our galaxy.

1. INTRODUCTION

One of the important characteristics of a star which evolves onto the asymptotic giant branch (AGB) is the star is losing much of its initial mass in a form of cool, low-velocity stellar wind. As a result, it develops an extended circumstellar envelope of dust and gas and eventually evolve to become a planetary nebula (e.g., Iben & Renzini 1983; Habing 1996). It has been postulated that towards the end of the AGB phase, mass loss rate increases (Vassiliadis & Wood 1993).

Since all stars with an initial mass between 0.8–8 M⊙ pass through the AGB phase. It is difficult to determine the initial stellar mass of an AGB star. However, chemistry in the circumstellar envelope gives clues to rough initial masses. For stars with a mass below ~ 3 M⊙, the third dredge-up can convert initially oxygen-rich star to a carbon star, i.e., C/O is larger than 1. Stars with a mass larger than ~ 4 M⊙, the hot-bottom burning (HBB) starts and convert carbon to nitrogen hence reducing the C/O ratio to below unity (Boothroyd et al. 1993). Signatures of HBB are the low 12C/13C and 18O/16O ratios as well as Li overabundance in circumstellar envelopes (Sackmann & Boothroyd 1992; Lattanzio et al. 1996).

Figure 1. Spectral energy distributions of the sampled stars. The solid lines are the model, dots are observations from IRAS LRS, ISO and Herschel-PACS and SPIRE while the filled circles are from IRAS PSC and open circles and crosses are ground based observations.
In this paper, we present observations of a few extreme OH/IR stars, AGB stars which show deep silicate dust absorption at 10 and 20 μm as well as strong OH maser emission, observed by *Herschel Space Observatory* (hereafter *Herschel*, Pilbratt et al. 2010) using the heterodyne instrument HIFI (de Graauw et al. 2010).

### 2. MASS LOSS RATES

By fitting the spectral energy distributions (Figure 1), we derived high dust mass loss rates for our sample stars (See Table 1). Assuming that mass loss is due to a momentum-driven wind, we calculate the (dynamical) gas mass loss rate which is driven by the dust to the observed terminal velocity, $M_{\text{dyn}}$. As can be seen, these values are a few $10^{-4} M_\odot$ yr$^{-1}$, except for WX Psc which has the silicate 10 μm in self-absorption.

In modelling the gas mass loss rate, we fit the CO rotational emission lines obtained with *Herschel*-HIFI, as well as complementary ground-based observations to probe the warm inner part and cool outer envelope, respectively. A constant mass loss rate derived from a dust-driven wind hugely overestimate the line fluxes for low transitions (e.g., $J = 1–0$ and 2–1). In order to reconcile the model with the infrared and CO observations, we conclude that 4 out of 5 stars have undergone a recent increase in their mass loss rates, a superwind. This increase results in the high dust optical depth as

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**Table 1.** Parameters for modelling the dust and gas mass loss rates in the sample stars, the radii of the superwind ($r_{sw}$), and the derived $^{12}\text{C}^{13}\text{C}$ ratios.

<table>
<thead>
<tr>
<th></th>
<th>WX Psc</th>
<th>OH 127.8+0.0</th>
<th>AFGL 5379</th>
<th>OH 26.5+0.6</th>
<th>OH 30.1–0.7</th>
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<td>$T_r$ (K)</td>
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<td>$R_e$ (cm)</td>
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<td>$9.0 \times 10^{13}$</td>
<td>$5.0 \times 10^{13}$</td>
<td>$6.0 \times 10^{13}$</td>
<td>$5.0 \times 10^{13}$</td>
</tr>
<tr>
<td>$v_e$ (km s$^{-1}$)</td>
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<td>12.7</td>
<td>18.3</td>
<td>15.0</td>
<td>18.1</td>
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<td>$D$ (kpc)</td>
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<td>2.8</td>
<td>0.58</td>
<td>1.37</td>
<td>1.75</td>
</tr>
<tr>
<td>$M$ ($M_\odot$ yr$^{-1}$)</td>
<td>$1.8 \times 10^{-7}$</td>
<td>$2.0 \times 10^{-6}$</td>
<td>$1.6 \times 10^{-6}$</td>
<td>$2.0 \times 10^{-6}$</td>
<td>$1.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$M_{\text{dyn}}$ ($M_\odot$ yr$^{-1}$)</td>
<td>$1.9 \times 10^{-5}$</td>
<td>$9.2 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>$r_{sw}$ (cm)</td>
<td>—</td>
<td>$1.2 \times 10^{16}$</td>
<td>$1.0 \times 10^{16}$</td>
<td>$9.0 \times 10^{15}$</td>
<td>$2.5 \times 10^{16}$</td>
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<tr>
<td>$^{12}\text{C}^{13}\text{C}$</td>
<td>$10 \pm 4$</td>
<td>$2 \pm 1$</td>
<td>$27 \pm 11$</td>
<td>$10 \pm 16$</td>
<td>$4 \pm 1$</td>
</tr>
</tbody>
</table>
In order to reconcile the model with the infrared and CO observations, we conclude that 4 out of 5 stars have a specific abundance. The dashed lines show the range of uncertainty in the abundance.

The abundance of silicate transitions at 10µm and 20µm as observed with Herschel-HIFI, as well as complementary ground-based observations to probe the warm inner part and cool outer envelope, respectively. A constant value for the CNO cycle of 4. It is noted that although CNO cycle operates in low mass stars, it is more efficient in higher mass stars.

Our HIFI observations included frequency settings which admitted three isotopologues of the same transition of an ortho-H$_2$O and a para-H$_2$O for AFGL 5379 (bottom) and OH 26.5+0.6 (top). The vertical line marks the rest frequency of the H$_2$O emission lines. Note the absence of the H$_2^{18}$O in both transitions.

seen in the silicate absorption bands while the outer, cooler part of the circumstellar envelope is due to tenuous mass loss prior to the superwind.

### 3. ISOTOPIC RATIOS

We also obtained spectra of $^{13}$CO for some of our stars. Delfosse et al. (1997) observed a number of extreme OH/IR stars with the IRAM telescope which we used to derive the carbon isotopic ratios. Due to the high optical depth of the $^{12}$CO (and possibly $^{13}$CO) lines, these values have large uncertainties. However, these numbers are close to the equilibrium value for the CNO cycle of 4. It is noted that although CNO cycle operates in low mass stars, it is more efficient in higher mass stars.

Our HIFI observations included frequency settings which admitted three isotopologues of the same transition of an ortho-H$_2$O $3_{1,2}-3_{0,3}$ and the ground state para-H$_2$O $1_{1,1}-0_{0,0}$ for OH 26.5+0.6 and AFGL 5379 (Figure 3). Both transitions show strong emission from the H$_2^{16}$O and H$_2^{18}$O while the H$_2^{13}$O lines are not detected above the noise. This is also a consequence of HBB which quickly destroys the $^{18}$O isotope leaving the other two isotopes unchanged.

Lattanzio et al. (1996) showed a calculation for a 6 M$_\odot$ with a solar composition which has a similar outcome that we observed in these two stars. We conclude then that these OH/IR stars are massive ($M \geq 5 M_\odot$) AGB stars.

### 4. FUTURE OBSERVATIONS WITH SPICA

It is almost impossible to observe H$_2$O from the ground hence Herschel has been instrumental in the study of this molecules in evolved stars. With SPICA, we will be able to extend our study to cover many more objects which are losing mass at a very high rate. The SAFARI instrument will be able to resolve most of the strong H$_2$O isotopologues which is
inaccessible from the ground, as well as CO lines. These stars are important since their mass loss affects the chemical evolution of our galaxy, both in terms of molecular and dust enrichment.

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Identifying the Chemistry of the Dust around AGB Stars in Nearby Galaxies

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ABSTRACT

Asymptotic giant branch (AGB) stars are significant contributors to the chemical enrichment of the interstellar medium (ISM) of galaxies. It is therefore essential to constrain the AGB contribution to the dust budget in galaxies. Recent estimates of the total AGB dust injection rate to the Large and Small Magellanic Clouds (LMC and SMC; Riebel et al. 2012; Boyer et al. 2012, Srinivasan et al. in prep) have used data from the Spitzer Space Telescope SAGE (Surveying the Agents of Galaxy Evolution; Meixner et al. 2006) and SAGE-SMC (Gordon et al. 2011) surveys. When sorted by dust chemistry, the data allow for a comparison of O-rich and carbonaceous dust production rates. In the LMC, for instance, the rate of dust production from carbon stars is two and a half times that from oxygen-rich AGBs. A reliable determination of the fractional contributions of the two types of dust would serve as input to models of chemical evolution. However, the Spitzer IRAC photometric bands do not sufficiently probe the characteristic mid-infrared spectral features that can distinguish O-rich AGBs from carbon stars — namely, the 9.7 μm silicate feature and 11.3 μm silicon carbide feature. With the continuous spectral coverage in the ~4–30 μm range, SPICA has the potential to distinguish these two types of chemistries. In this contribution, synthetic photometry from the model grid of AGB stars, GRAMS (Sargent et al. 2011; Srinivasan et al. 2011), will be used to discuss the science possibilities that SPICA might offer this study.

1. THE AGB DUST BUDGET IN NEARBY GALAXIES

Low- and intermediate-mass (0.8–8 M_⊙) stars go through the asymptotic giant branch (AGB) stage towards the end of their lives. During this phase of the star’s lifetime, the products of shell hydrogen and helium burning are mixed into the outer layers by huge convective zones. Surface pulsations levitate the material to cooler regions where they form gas molecules and, further on, solid particles (dust). Radiation pressure on the dust grains then drives an efficient outflow (e.g., Woitke 2006; Bladh & Höfner 2012). The mass-loss rate increases as the star evolves along the AGB, and can exceed 10^{-4} M_⊙ yr^{-1}. Stars can thus lose a significant fraction of their mass, in the form of gas and dust, during the AGB phase. The ejecta are mixed into the interstellar medium (ISM) where the dust can be incorporated into the next generation of stars. By affecting the subsequent star formation while simultaneously increasing the metal content in the ISM, the amount of AGB mass loss provides an important constraint to galactic chemical evolution and population synthesis models.

Perhaps the most important constituent of the dredged-up matter is 12C, which quickly combines with any existing oxygen atoms to form CO. The subsequent chemistry of the circumstellar shell is dependent on the slight overabundance of either O or C. With progressive dredge-up episodes, the abundance of carbon relative to oxygen (the C/O ratio) exceeds unity leading to the formation of carbon stars for initial masses of up to ~4 M_⊙, depending on the metallicity. Given their mass range, carbon stars are numerous at low metallicities; however, individual massive O-rich AGBs have large dust production rates (DPRs) by virtue of their mass. In order to estimate the relative contributions of carbonaceous material and silicate/metal oxides, it is necessary to sort the AGB population based on circumstellar chemistry. While it is easy to identify optically thin O-rich and C-rich AGBs from their near-infrared (NIR) colours, the identification of dusty sources (the so-called “extreme” AGBs) requires mid-infrared data (see, e.g., Figure 5 in Boyer et al. 2011). Even with this information, it is not straightforward to determine the circumstellar chemistry — the extreme AGB population consists of a mixture of O-rich AGBs and carbon stars. Based on their masses, it is expected that most of these stars are carbon-rich; however, even a handful of massive O-rich extremes in this population can contribute significantly to the dust budget. The chemistry of the dust can be confirmed with mid-infrared (MIR) spectra owing to the typical prominent spectral signatures of AGB dust — the silicate feature at 9.7 μm in O-rich stars, and the silicon carbide feature at 11.3 μm for carbon stars. In practice, such spectra are available only for a small fraction of the AGB population; estimates of the integrated dust budget rely largely on photometric data.

Studies of Galactic AGB stars are affected by moderate to high line-of-sight extinction, resulting in uncertain distance and luminosity estimates. Among nearby galaxies, the Magellanic Clouds are ideal for AGB studies because of their proximity, viewing angle and low extinction along their lines of sight. The Clouds were imaged as part of the Spitzer Space Telescope SAGE (Meixner et al. 2006) and SAGE-SMC (Gordon et al. 2011) surveys. The SAGE-Spec program (Kemper et al. 2010) obtained follow-up MIR spectra for a subset of SAGE point sources. The evolved-star candidates extracted from these data were used to calculate the dust budget based on empirical relations between the DPR and broadband MIR properties such as the colour (Matsuura et al. 2009, 2013) and the excess flux from dust (Srinivasan et al. 2009; Boyer et al.
Figure 1. The SAGE-Spec spectra of an O-rich AGB (blue) with silicate emission and two carbon stars with SiC in emission (red) and in absorption (pink), and the spectrum of an S-type star from Smolders et al. (2012) with strong alumina emission (orange). The vertical dashed lines show the approximate location and extent of the SiC feature and molecular absorption due to acetylene and HCN in carbon stars. The filter response curves for the IRAC and MIPS 24 \( \mu \text{m} \) bands (green) are compared to the SPICA MCS-S filter set (vertical solid lines). The continuous coverage of this wavelength range by the SPICA MCS-S filters (solid vertical lines), unlike the IRAC and MIPS 24 \( \mu \text{m} \) filters (filter response curves in green), recovers the silicate as well as the SiC and alumina features. In addition, the SPICA bands are also able to detect strong \( \text{C}_2\text{H}_2 \) absorption at 13.7 \( \mu \text{m} \).

2012). While such empirical relationships enable quick estimates for the cumulative DPR, they assume that the trends determined from a handful of well-studied sources apply over the entire range of spectral energy distributions (SEDs) of the evolved star population.

While radiative transfer modelling of the individual SEDs, taking into account all the available information (i.e., spectra along with preferably multi-epoch photometry to constrain the variability of the sources; see, e.g., Sargent et al. 2010; Srinivasan et al. 2010), provides more accurate estimates of the DPR, such individual modelling is unrealistic for large datasets. As a compromise, SEDs could be fit to a pre-computed grid of radiative transfer models that spans the range of observed parameters for dusty evolved stars. This was the motivation for the Grid of Red supergiant and AGB Models (GRAMS; Sargent et al. 2011; Srinivasan et al. 2011). The GRAMS grid contains over 66000 models with silicate dust and about 12000 models with a mixture of amorphous carbon and 10% SiC by mass, and the models reproduce the range of observed MIR properties of LMC AGB and red supergiant (RSG) stars. Riebel et al. (2012) used the GRAMS grid to fit the SEDs of LMC evolved star candidates. They found that (a) the total dust return from AGB and RSG stars to the ISM is about \( 2.1 \times 10^{-5} \text{M}_\odot \text{yr}^{-1} \), (b) the return from carbon stars is 2.5 times that from O-rich AGBs and RSGs, (c) carbon stars comprise more than 95% of the extreme AGB population, and (d) although the extreme AGBs amount for only \( \leq 5 \% \) of the evolved star population, they contribute \( \geq 75 \% \) of the dust return. A similar study for the SMC is in progress (Srinivasan et al., in preparation).

2. AGB SCIENCE WITH SPICA

As previously mentioned, it is important to classify the evolved star candidates by chemical type in order to determine the relative contributions of carbonaceous and oxygen-rich dust. The main hindrance to MIR colour-based classifications of Spitzer datasets is the absence of filters that can efficiently probe the 9.7 \( \mu \text{m} \) silicate in O-rich AGBs and the 11.3 \( \mu \text{m} \) SiC features in carbon stars. While these features may contribute slightly to the IRAC 8 \( \mu \text{m} \) band (similarly, the silicate feature at \( \sim 18 \mu \text{m} \) may affect the flux in the MIPS 24 \( \mu \text{m} \) band), it is not easy to constrain the dust parameters such as optical depth and DPR with just these bands. If available, Spitzer data can be complemented with either AKARI or WISE observations, both of which offer bands in the \( \sim 11–12 \mu \text{m} \) range. The continuous coverage over the 0.7–38 \( \mu \text{m} \)
the ISM is about 2 and about 12000 models with a mixture of amorphous carbon and 10 % SiC by mass, and the models reproduce the range of observations, both of which offer bands in the WISE optical depth and DPR, with just these bands. If available, Spitzer data can be complemented with either SiC feature at 11–12 µm in carbon stars. While these features may contribute slightly to the Spitzer 8 µm progress (Srinivasan et al., in preparation). (GRAMS; Sargent et al. 2011; Srinivasan et al. 2011). The GRAMS grid contains over 66000 models with silicate dust observed parameters for dusty evolved stars. This was the motivation for the Spitzer of only SPICA IRAC and MIPS 24 µm bands are also able to detect strong C2H2 bands in AGB stars. In addition, the features due to other molecules such as HCN and C2H2 can be captured by filters centred around 11.2 µm. For this reason, it is recommended that the MCS include a narrow-band filter centred around 11.2 µm. Despite this difficulty, the SPICA MCS filter set can be used to separate O-rich and C-rich features in AGB stars. This is illustrated in Figure 2 (left panel), where the flux in the S6 filter (centred at ~9.7 µm, see Figure 1) is plotted against the [S5]–[S8] colour, which is a measure of the continuum around the silicate feature for O-rich AGBs. The SAGE-Spec sources with the 9.7 µm silicate feature in emission separate out from the carbon stars on this diagram.

In addition to O- and C-rich chemistries, it may also be possible to identify regions in colour-colour space that occupied by S-type AGB stars — sources with C/O ratios close to unity. To demonstrate this, photometry in the SPICA bands synthesised from IRS spectra of galactic S-type stars from the Smolders et al. (2012) sample is compared with the GRAMS models in Figure 2 (right panel). S-type stars and galactic O-rich AGBs also feature broad Al2O3 emission at ~11.2 µm; as with the SiC feature, the alumina feature is split across two adjacent MCS filters in the current configuration (Figure 1). A narrow-band filter would therefore be useful for both features.

2.1. Customising the SPICA MCS for AGB Chemical Classification

The specification for the SPICA MCS-S filter set consists of ten filters covering wavelengths from about 3.3 µm to 24 µm (see Sakon, these proceedings, for more details on these filters). This current configuration is well-suited for identifying most AGB features in the MIR. In addition, the five filters on the FPC can be used to constrain the photospheric contribution to the SED.

Figure 1 compares the Spitzer IRS spectra of different types of AGB stars. The silicate features at 9.7 µm and 18 µm, outside the range of the IRAC and MIPS 24 µm filters, are covered by the MCS filter set. The 11.3 µm SiC feature straddles two filters. Moreover, it is difficult to estimate the continuum in LMC carbon stars around the SiC feature due to molecular absorption features (e.g., the strong C2H2 feature at 13.7 µm). For this reason, it is recommended that the MCS include a narrow-band filter centred around 11.2 µm. Despite this difficulty, the SPICA MCS filter set can be used to separate O-rich and C-rich features in AGB stars. This is illustrated in Figure 2 (left panel), where the flux in the S6 filter (centred at ~9.7 µm, see Figure 1) is plotted against the [S5]–[S8] colour, which is a measure of the continuum around the silicate feature for O-rich AGBs. The SAGE-Spec sources with the 9.7 µm silicate feature in emission separate out from the carbon stars on this diagram.

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2.2. Circumstellar Molecules

Dusty AGB stars in low-metallicity populations such as the LMC show prominent molecular absorption features in the MIR. These features are attributed to a molecular layer in the circumstellar shell and, in principle, they can be used to find the column density and gas:dust ratio in these sources (see, e.g., Matsuura et al. 2006; Sargent et al. 2010; Srinivasan et al. 2010). However, the ~4.4–6 µm CO band is at the edge of the Spitzer IRS spectrum, which hampers accurate parameter estimates. The band centred at ~4.4 µm in the MCS-S filter set may be able to provide a rough estimate of the CO feature strength in AGB stars. In addition, the features due to other molecules such as HCN and C2H2 can be captured by filters centred at 8.0 µm and 14.6 µm (Figure 1).

The SPICA MCS filters will help in the chemical classification of AGB stars, even when such classification is difficult based on near-infrared colours. The filters will also provide tighter constraints on the optical depth and dust-production rates by targeting prominent AGB dust features. The current specification for the filters works well for this purpose, but a narrow-band filter around 11.2 µm would be a great addition to this set for the broad silicon carbide and alumina features.

![Figure 2](https://example.com/figure2.png)

**Figure 2. Left:** SAGE-Spec O-rich AGBs with 9.7 µm silicate emission (circles) are well separated from carbon stars (squares) in a plot showing the flux in the S6 filter versus the [S5]–[S8] colour. The flux in the S6 filter is proportional to the silicate feature strength, and the colour is a measure of the pseudo-continuum around the feature. **Right:** The Smolders et al. (2012) S-type stars (green circles) occupy a small region on this SPICA MCS colour-colour diagram. SAGE-Spec carbon stars (triangles) and O-rich AGB stars with silicate emission (squares) as well as the GRAMS O-rich (black circles) and C-rich (red) models are also shown for comparison.

range offered by the Focal Plane Camera (FPC) and Mid-Infrared Camera and Spectrograph (MCS) instruments on board SPICA is ideal for AGB-star studies.
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centred in this wavelength range. The SPICA MCS filter set, along with the FPC, offers a great opportunity for galaxy-wide studies of AGB populations in nearby galaxies (see, e.g., Zhao-Geisler, these proceedings).

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Probing the Formation of Relativistic Jets in Real-Time with SPICA

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ABSTRACT

The time domain remains, in many respects, the least explored of parameter spaces in astronomical studies. The purpose of this article is to encourage the SPICA community to consider the potential of rapid infrared timing observations. The specific example considered is that of variable emission from relativistic jets in compact accreting objects, whose formation and powering mechanisms we still do not understand. Infrared observations have the potential to give us fundamental insight on the conditions required for jet formation in accreting stellar-mass black holes. This is because particle acceleration is thought to be magnetically-driven, and the spectral transition between optically-thin and self-absorbed jet synchrotron radiation lies in the infrared. We review recent observations from WISE showing that we have the capability to measure key physical parameters of the jet, and their time-dependence on rapidly-changing conditions in the accretion flow around the black hole (on timescales of just a few seconds). SPICA will provide a breakthrough in this field because of its sensitivity and broadband coverage, and we detail an example SPICA observation on short (tens of milliseconds) timescales. We believe that SPICA has the potential to make great impact on time domain science, and we discuss some technical requirements that will enable this.

1. INTRODUCTION

Black holes are fundamentally simple objects. Only two parameters – mass and spin – are required for their unique characterization. Yet, they host a variety of complex and extreme astrophysical phenomena in the vicinity. Accretion of gas drives their growth and much of their observed radiative power. Outflows in the form of relativistic ‘jets’ and winds remove angular momentum, and are responsible for mechanical and thermal feedback which is now known to play a key role in galaxy evolution.

Jets have been observed to extend linearly over scales as large as ~Mpc from black holes (BHs) of the supermassive variety. Yet, many basic questions remain unanswered. For instance, what conditions give rise to a jet in some BHs and not others? And what fraction of the accretion energy is carried away by the jet as radiatively-invisible feedback? It is believed that magnetic fields likely play a key role in jet formation (see, e.g., articles in Belloni 2010). But in order to understand this role, it is first necessary to measure the field strengths (B) at the base of the jets where they are formed above BHs.

2. JETS IN STELLAR MASS BLACK HOLES

The scaling with mass of BH physics means that it is easier to study the response of jets to varying conditions in the accreting material in stellar mass BH and neutron star binaries (Figure 1), rather than in their supermassive cousins.1

According to the ‘standard’ model of emission from compact jets (Blandford & Königl 1979), a peak in the flux density of jet emission is expected at a frequency dependent on the B field and inversely dependent on the size of the jet base (R). This peak occurs because of magnetic and particle flux conservation, leading to each region in the jet being characterized by a frequency that decreases with distance from the base. The sum envelope of all components is an inverted spectrum (∝ν−α) up to a peak frequency associated with the optically thick-to-thin break (ν_b). At higher frequencies, optically-thin synchrotron (∝ν_0) tells us the jet particle distribution. Some of the best current constraints show that ν_break in BH binaries can straddle the entire infrared regime and more (e.g. Migliari et al. 2010; Rahoui et al. 2011; Gandhi et al. 2011; Corbel et al. 2013; Russell et al. 2013). See, e.g. the broadband jet break in the BH binary GX 339–4 around 10 μm shown in Figure 2.

In addition, broadband detections of GX 339–4 over multiple epochs with the WISE mission (Wright et al. 2010) have shown that ν_break can change dramatically (by factors of at least ~10) in just a few hours, and probably much faster. In

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1 e.g. a timescale of 1 s for a 10 M_⊙ BH is equivalent to several months for a 10^8 M_⊙ supermassive BH. The former is much more amenable to observations.

Figure 1. Artist’s illustration of an accreting stellar-mass black hole. The black hole accretes material from a companion donor star. Energy is extracted in the accretion disk and a fraction of the material is ejected in extended bipolar relativistic jets. Credit: NASA. It is not possible to spatially resolve these components (except the extended jet in some binaries), so variability studies provide the best clues to the inferred structure.

Figure 2. Broadband quasi-simultaneous spectral energy distribution (SED) of the BH binary GX 339–4 during its 2010 active state (Gandhi et al. 2011). The mid-infrared peak probed by WISE is where the jet synchrotron spectral break ($\nu_{\text{break}}$) lies. The thick dashed line shows the approximate 5σ sensitivity limit of the MCS/WFC in only 10 ms (extrapolated from MCS factsheet, assuming Poisson noise scaling). This 10 ms sensitivity level is roughly comparable to the present WISE sensitivity with exposure times of about 8–9 s, over a wider wavelength regime than WISE. Continuous fast timing with SPICA on these timescales will allow us to probe entirely new parameter space. For comparison, the approximate 1 hour 5σ sensitivity level is shown by the lower thin, dashed line.

fact, Figure 3 in Gandhi et al. (2011) find variability on the shortest WISE cycle time of 11 s. This means that either $B$ or $R$ must be undergoing similar vacillations, on timescales faster than have been considered before. We are likely seeing the inner jet responding to stochastic variability in the accretion flow that feeds it, giving direct ‘real-time’ constraints on the disk–jet connection through mid-infrared observations.

Yet, if we ask what are the physically most interesting timescales for probing such a connection, these turn out to be on the order of fractions of a second (corresponding to the dynamical time in the inner disk or the light travel time from the disk to the expected base of the jet) for a typical 10 M$_\odot$ BH. There is plenty of evidence for X-ray variability on these timescales. Recent observations have also found optical and near-infrared variations on fast sub-second timescales (see Figure 3), at least part of which is correlated with the X-rays (Kanbach et al. 2001; Gandhi et al. 2008; Durant et al. 2009;

**Fast Timing Studies with SPICA**

**Figure 3.** (Left) The first mid-infrared light curve of a stellar-mass BH jet. The data are for GX 339–4 from the WISE mission and span about 24 hours at 13 epochs of observation (each with integration times of ~8–9 s, spaced by a minimum of 11 s (and usually by multiples of ~95 mins, the satellite orbital time). These fully simultaneous observations in four bands W1–4 enabled first direct measurements of $\nu_{\text{break}}$ in a black hole binary (Gandhi et al. 2011). (Right) A short 30 seconds–long segment of optical and X-ray lightcurves of the same binary in 2010, with rapid sampling of 50 ms (Gandhi et al. 2010). The optical data (g’, r’ filters) are from VLT/ULTRACAM; X-rays from RXTE. As compared to these data, the mid-infrared sampling on the left remains very poor, but this can change with SPICA.

Gandhi et al. 2010; Casella et al. 2010; Durant et al. 2011). So the next step has to be the search for fast (sub-second) mid-infrared variations that are correlated with X-rays.

3. **THE NEED FOR SPICA**

The above results highlight the utility of the infrared regime for jet studies in stellar-mass BHs. However, most accreting stellar-mass binaries still remain undetected in the infrared. This is due to a combination of several reasons. Strong emission from accreting, stellar or surrounding material can dominate fainter jet radiation over the infrared–X-ray regime in many sources (e.g. Russell et al. 2006). In addition, the transient nature of activity in many binaries makes it difficult to catch them contemporaneously with multiple observatories necessary to probe broadband emission and isolate the jet. Finally, there has simply been a lack of monitoring instruments sensitive enough to detect infrared jet emission at sub-mJy flux levels, where most binaries are.

**SPICA’s** infrared coverage over a broad infrared regime, as well as its superb sensitivity (Nakagawa et al. 2011), make it ideal for jet timing studies.

4. **An Example SPICA Observation**

Here is a detailed example of the kind of observation to break new ground in this field.

1. One would wait for a Galactic binary to go into outburst, and trigger **SPICA** observations based upon some X-ray, radio or other multi-wavelength activity threshold. There are various monitoring missions (e.g. **MAXI**) well-suited for deciding when to trigger.

2. **SPICA/MCS** instrument (Kataza et al. 2012) will be used in imaging or low-resolution mode, simultaneously with the near-infrared FPC (Lee et al. 2012), covering ~0.7–38 μm. The main aim is to cover the widest possible range of infrared wavelengths, simultaneously. Note that **SAFARI** (Roelfsema et al. 2012) may also be used separately after **MCS** observations. These will be non-simultaneous but still useful because of the broadband nature of jet emission.

3. The simultaneous data will be used to locate $\nu_{\text{break}}$ over the entire near- to mid-infrared (or more) regime covered, which, in turn, will determine physical parameters of the jet including $B$ and $R$ (see Gandhi et al. 2011, for details).
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4. **SPICA** has the potential to carry out such measurements on timescales of a fraction of a second. For instance, if the option of windowing and reading out only a small portion of the detector centered on the target can be implemented, this will enable continuous fast timing light curves to be measured. If detector readout time scales with pixel area, a $\sim 10\times 10$ pixel ($1.4'\times1.4'$) window on the MCS could yield an on-source time of $\sim 10$ ms for the short wavelength arm, for instance. Extrapolating from the current expectation of the 1 hour imaging sensitivity assuming Poisson statistics scaling, the signal:noise achievable even on this short time will be sufficient for bright transient outbursts of some binaries (See Figure 2). This assumes that the high zodiacal sky background dominates the noise.

5. The final pièce de résistance will be to coordinate the **SPICA** observation with strictly-simultaneous observations at another wavelength. For instance, an X-ray facility such as Astro-H (Takahashi et al. 2012) can be used to probe the accreting matter, while **SPICA** measures the response of the jet in real-time, enabling us to watch the interplay of accretion and outflows unfold before our (telescopic) eyes.

5. **FAST TIMING WITH SPICA: REQUIREMENTS AND POTENTIAL**

**SPICA** already possesses the most crucial requirements for the fast timing science described herein: the ability to observe simultaneously over a broad wavelength regime, and the requisite sensitivity. Below are some additional requirements, none of which are particularly challenging if included in the initial mission planning stages now.

- A provision should be made for Target of opportunity (ToO) observations. For the science described herein, a reaction time of up to a few days will be acceptable.
- The option of being able to window the detector will be very useful to increase the cycle time of exposures. Characterization of the ‘dead time’ between consecutive exposures and any extra sources of noise on fast sampling times should also be carried out. Reaching down to $\sim 10$ ms cycle times may be challenging, but if arbitrary window sizes and shapes can be coded in the detector control software, that would increase the versatility of the instrument significantly.
- Finally, coordination between different missions requires accurate clock calibrations for both relative and absolute timing. X-ray missions routinely achieve timing accuracies of fractions of a millisecond. Calibration of the on-board clock should not be an overly demanding task if this is planned for in advance.

Such provisions will extend **SPICA**’s reach into the time domain, allowing science ranging from exoplanet transits, to asteroseismology, pulsars and blazars, to name a few.

6. **SUMMARY**

**SPICA** has huge potential for the study of transient phenomena, expanding its reach into the hot, non-thermal universe. The infrared regime is particularly important for the science of relativistic jets described herein, but a little bit of planning will allow **SPICA** to make its mark on time domain studies in general.

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FAST TIMING STUDIES WITH SPICA

Cool Dust in the Environments of Evolved Massive Stars: Wolf-Rayet Stars at High Galactic Latitudes

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ABSTRACT

As very massive stars evolve, they pass through several evolutionary stages of fast and slow wind mass loss towards their expected end as supernovae. The precise evolutionary path of massive stars of various masses above $20 M_\odot$ is unclear and may be highly affected by the presence of binary companions. An excellent probe of the evolution of evolved massive stars, such as Wolf-Rayet stars, is their circumstellar environment. In particular, knowledge of the amount of mass loss, structure of ejecta, timescales for mass loss and ejecta chemistry indicate the likely state of the massive star in prior evolutionary phases, as the evolutionary phases leave their imprint on the surroundings. Here we present the results of studies with the Herschel PACS and SPIRE instruments at wavelengths between 70 and 500 $\mu$m together with AKARI/FIS data at 90 and 140 $\mu$m to investigate the environments of Wolf-Rayet stars in an attempt to distinguish the cool and massive component of the expelled material from earlier mass-loss phases of Wolf-Rayet stars with implications on likely ejecta formation mechanisms and stellar histories. Studies of objects at higher galactic latitudes reduces problems with unrelated structures along the line of sight.

1. INTRODUCTION

This presentation provides a report on investigations undertaken with optical emission-line, AKARI/FIS (Kawada et al 2007) and Herschel Space Observatory/PACS (Pilbratt et al 2010; Poglitsch et al 2010) data that resolve the materials in the vicinity of Wolf-Rayet (WR) stars at high galactic latitudes. WR stars are believed to be evolved very massive stars, having started on the main sequence with masses $> 20 M_\odot$. With typically significant mass lost in ejecta either from a single or binary star system a WR star can end up with a mass of less than half its initial mass in a relatively short high-mass loss rate phase (Langer 2012). Despite the apparently large mass loss, not all WR stars show circumstellar ejecta materials in the form of rings or shells in optical emission line surveys (Marston 1997), although these surveys are not very deep or uniform. In this paper we present the initial results of a review of galactic WR stars that are well out of the plane of the galaxy and which have notable extended structures. The high galactic latitudes allow us to better associate structures local to the stars as opposed to other systems along the line of sight. The main thrust of the work – using deeper optical emission line images, plus infrared AKARI and Herschel data – is to determine the existence, structure and amount of extended materials associated with outflows/ejecta of the WR stars and the likely origin scenarios.

2. THE SAMPLE WOLF-RAYET ENVIRONMENTS

In this presentation we consider two of our sample WR stars for particular attention.

1. WR16 (Anon): This is a WN8h star with an almost perfectly circular ring nebula approximately 7’ across (Marston et al 1994). Investigations have shown CO materials surrounding the ring nebula and quite clearly associated with it. Filaments outside the ring nebula show nitrogen enrichment but a clear lack of sulphur line emission (Marston et al 1999; Stock et al 2011).

2. WR40 (RCW 58): This is also a WN8h star with a prominent ring nebula (RCW 58) shaped like an eye. Optical spectra show that it is the ring is expanding at around 50 km/s (Smith et al 1984). Abundances suggest that the materials are again nitrogen rich and believed to be ejected from the surface of the star. Optical H$\alpha$ and [O III] emission line images show remarkable morphological differences with the [O III] having a larger extent, especially around the “waist” of the eye. This has been interpreted as being due to a fast-moving wind passing through a very clumpy shell. Ablation of materials in the wind via mass-loading (Hartquist et al 1986) lead to elongated radial structures. Some of this material becomes highly excited and can end up external to the main ejecta nebula (Marston 1995; Gruendl et al 2000).

3. WR16 (ANON): STRUCTURES AT VARIOUS SCALES

The SUPERCOSMOS Southern Halpna Survey (SHS: Parker et al 2005) provides a deeper H$\alpha$ image than produced in the nebula discovery image of Marston et al (1994). Both the inner nebula and a region of 100’ x 100’ are shown in Figure 1Left. This shows the very extended structures surrounding the star. The filaments to the north of the main ring were shown to have nitrogen enrichment and fill a similar volume to the $^{12}$CO J=1-0 emission reported by Marston et
Figure 1. Left: WR16 and nebula Anon as seen by SUPER COSMOS SHS image 100′ across. The almost spherical ring at the centre has been enlarged in inset. Right: Three colour *Herschel*/PACS image 70 μm - blue, 100 μm - green, 160 μm - red. Hot dust evident in inner shell. Peaks in emission outside the inner shell coincide with decreased Hα emission areas.

al (1999). This further confirms that the strong, almost spherical, ring structure is forming within very extended ejecta material around WR16 containing significant mass.

The *Herschel*/PACS broad band maps of the central 30′ show what is quite a standard situation for nebula shells surrounding hot stars. The 70 μm emission is very prominent, with more extended emission seen at the longer 100 and 160 μm wavelengths (Figure 1 Right). The far-infrared emission outside the spherical shell appear predominantly in between Hα peaks.

The more extended 140 μm (WIDE-L) *AKARI*/FIS map gives clear indications of emission surrounding the inner “warm” nebula suggesting cool gas and dust associated with the CO emitting ejecta (Marston & Morris 2009). A suggestion of an outer shell some 30 arc minutes radius around the WR star.

4. WR40 (RCW 58): STRUCTURES AT VARIOUS SCALES

There are several images of the nebula RCW 58 in Hα emission in various papers. The Hα image of Gruendl et al (2000) clearly illustrates the linear, radial structures. Our *Herschel*/PACS images at 70, 100 and 160 μm indicate the close relationship between the warm dust (particularly prominent at 70 μm) and the optical Hα emission, and exhibits significant clumping. Previous lower resolution *AKARI* data was not able to show the dust shell broken up in this way. Low-level *Herschel*/PACS emission to the north east of the ring nebula suggests some material has been blown out from the shell. This is consistent with the ablation of shell materials by the fast WR wind (Figure 2 Left). The low-level PACS emission is also coincident with low-level longer wavelength emission seen in SPIRE maps (not shown in this presentation).

A strip taken across the nebula using the *AKARI*/FIS shows the ring prominently at the shorter wavelength of 90 μm but two ridges of higher-level 140 μm emission at approximately 15′ to north east and southwest of the star. This hints at a larger shell structure of cool materials around the WR star (Figure 2 Right). This is inconsistent with the possible ~3deg diameter shell suggested in IRAS images (Marston 1996) but may be associated with an earlier phase of the star, such as an O star phase.

5. CONCLUSIONS

Deeper optical images than previously used, together with far-infrared imaging show distinctly different structures for nebulae of similar sizes around the stars WR16 and WR40. Here we reveal that there is a very extensive set of material up to 30′ from the central star which are centred on the star. These extend beyond the inner, almost spherical, ring nebula and are entirely coincident with molecular emission and nitrogen enriched materials suggesting extensive ejecta (Stock et al 2011). The multiple rings and arcs suggest several ejection phases prior to becoming a WR star.

Around the star WR40 the immediate ring nebula is lenticular and clumpy shaped with the far-infrared emission following closely the Hα emission. Low-level far-infrared dust emission outside the shell indicate ablated dust from the fast wind of the WR star penetrating the ring nebula which also creates an outer [O III] shell, as previously seen in optical images (Marston 1995; Gruendl et al 2000). External ejecta materials are not obvious and it suggests that the majority of the ejecta for this object reside in the prominent ring nebula, in contrast to WR16 (Anon).

Significant cool dust is noted around two high latitude WR stars (and others). The extended materials around WR16 (Anon) and the nebula RCW 58 around WR40 clearly have their origins in ejecta materials that come from a stellar
Cool Dust Around WR Stars

**Figure 2.** Left: WR40 and RCW 58 as seen in 3-colours by Herschel/PACS image 70 μm - blue, 100 μm - green, 160 μm - red. Hot dust is evident in inner shell. Peaks in emission outside the inner shell coincide with decreased Hα emission areas. Right: Herschel data superimposed on extended AKARI/FIS emission at 140 μm (WIDE-L band).

evolutionary phase prior to that of WR. The mapping of cooler materials gives substance to the assertions of Marston (1995) and Gruendl et al (2000) that RCW 58 is in a dynamically more advanced evolutionary state where the WR wind has penetrated the ejecta completely.

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High Resolution 30 μm Imaging of the Homunculus Nebula of Eta Carinae

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ABSTRACT

We present a result of high-resolution 30 μm imaging observations of the Homunculus Nebula of Eta Carinae (η Car). The Homunculus Nebula is known to contain a large amount of cool dust (∼100 K) at polar lobes and an equatorial torus. While the distribution of the cool dust shows the past dust formation events on η Car such as giant eruptions and binary interactions, no spatially resolved images at long mid-infrared wavelengths (30–50 μm) have been obtained. We observed η Car with a mid-infrared camera MAX38 on the University of Tokyo Atacama 1.0-m telescope, and successfully obtained spatially resolved images of the Homunculus Nebula at 18.7, 31.7 and 37.3 μm. The observations revealed the structure of the massive equatorial torus which contains the dust of 0.09 M⊙. This amount is equal to approximately 80% of the total dust mass 0.12 M⊙ in the Homunculus Nebula. It is also found that the dust of 0.012 M⊙ exists inside the polar lobes. Assuming that the dust was constantly formed after the giant eruption occurred in 1843, the dust formation rate is estimated as 7 × 10⁻⁵ M⊙ yr⁻¹. This indicates that the binary interaction plays a significant role in the dust formation on η Car.

1. INTRODUCTION

Eta Carinae (η Car) is one of the best examples for understanding the dust formation in Luminous Blue Variables (LBVs). It has a remarkable circumstellar nebula called the “Homunculus” Nebula. This nebula is one of the most luminous objects in the infrared wavelengths, and the total infrared luminosity integrated from 2–200 μm is 4.3 × 10⁶ L⊙ at a distance of 2.3 kpc (Davidson & Humphreys 1997). The dust mass in the Homunculus Nebula is estimated to be 0.1–0.15 M⊙ (Morris et al. 1999). Its spectral energy distribution indicates that most of the dust has a temperature of ∼100 K. Observations beyond 30 μm with high spatial resolution are needed to examine these hypothesis.

2. OBSERVATIONS

The observations were made with MAX38 on the miniTAO telescope in October 3, 2010. The miniTAO telescope is located at the top of Cerro Chajnantor (Co.) in the Atacama Desert, Chile with an altitude of 5,640 m (Sako et al. 2008). The precipitable water vapor (PWV) is 0.4 to 1.3 mm at Co. Chajnantor. Thanks to the low PWV, we can carry out observations with the 30 μm wavelength region, which had never been observed from the ground-based telescopes (Miyata et al. 2008; Nakamura et al. 2010; Asano et al. 2012). Table 1 summarizes the observational parameters. The PWV values during the observations were between 0.5 to 1.0 mm. All frames were obtained with the chop-nod technique. The images of V1185 Sco were also obtained at 18.7 and 31.7 μm as references of point spread functions (PSFs).
Table 1. The parameters of the miniTAO/MAX38 observations (October 3, 2010)

<table>
<thead>
<tr>
<th>$\lambda$ ((\mu)m)</th>
<th>$\Delta\lambda$ ((\mu)m)</th>
<th>exp. time$^1$ (sec)</th>
<th>FWHM (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.7</td>
<td>0.9</td>
<td>50</td>
<td>4.7</td>
</tr>
<tr>
<td>31.7</td>
<td>2.2</td>
<td>100</td>
<td>8.0</td>
</tr>
<tr>
<td>37.3</td>
<td>2.4</td>
<td>50</td>
<td>9.3</td>
</tr>
</tbody>
</table>

$^1$ on-source time.

3. RESULTS

The images in each filter are shown in Figure 1. The infrared colors of [31.7]/[18.7] and [37.3]/[18.7] give good agreements with the ISO results within the margin of the uncertainty. The 18.7 \(\mu\)m image gives a picture of the bright infrared core and the bipolar lobes previously reported in the Q-band imaging (e.g. Smith et al. 2003), while the spatial resolution of our image is lower than those observations. The 31.3 \(\mu\)m and 37.3 \(\mu\)m images have the higher spatial resolution than any observation at these wavelengths. The images of 30 \(\mu\)m bands show that most of the flux comes from the bright infrared core. The spatial profile of 37.3 \(\mu\)m can be fitted with a Gaussian function with a FWHM of 12.0 arcseconds, or 130\% of the PSF size. This result indicates most of the cold dust components distributed around the bright infrared core.

Figure 2 shows a map of color temperature of the dust estimated from the deconvoluted 18.7 \(\mu\)m and 31.7 \(\mu\)m images. The deconvolution was done by the Richardson-Lucy method (Richardson 1972; Lucy 1974) using the reference PSFs. The dust emissivity was assumed to be in proportion to $\lambda^{-1}$ (e.g. Morris et al. 1999; Smith et al. 2003). A map of optical depth of the dust emission was also derived from the two images. The total flux is scaled to that of the ISO observation for each image. The optical depth map of the cool dust clearly shows that most of the cool dust component exists in the equatorial torus. In addition, the temperature map revealed that the cooler dust components exist inside each lobe. These components have temperatures of 120 K, which is considered to be in thermal equilibrium. Since the lobes were formed by the giant eruption in 1843, the dust inside the lobes should have been formed after the eruption.
The dust emissivity was assumed to be in proportion to $\lambda^{-2}$ for each image. The optical depth map of the cool dust clearly shows that most of the cool dust component exists in the ISO $\lambda=37.3 \mu m$ image, which has the higher spatial resolution than any observation at these wavelengths. The images of $\lambda=30\mu m$, $\lambda=31.7\mu m$, and $\lambda=37.3\mu m$ bands indicate that most of the flux comes from the bright infrared core and the bipolar lobes. The images of $\lambda=30\mu m$ can be fitted with a Gaussian function with a FWHM of 7 arcsec. The 18.7, 31.7, and 37.3 $\mu m$ bands show that most of the flux comes from the bright infrared core and the bipolar lobes previously reported in the Q-band imaging (e.g. Smith et al. 2003), while the spatial agreements with the results within the margin of the uncertainty. The 18.7 $\mu m$ image gives a picture of the bright infrared core.

Table 2 summarizes the estimated dust mass of each component based on our mid-infrared images, assuming the grain density $\rho \approx 3$ g cm$^{-3}$ and the dust size $a \approx 1 \mu m$. The result suggests that both of the giant eruptions and the binary interactions play important roles of dust formation. If the amount of dust inside the lobes was assumed to be constantly formed after the 1843’s event, the dust formation rate is estimated as $\sim 7 \times 10^{-5} M_\odot$ yr$^{-1}$. This rate is much higher than the dust formation rate of WR binaries, an order of $10^{-7}$–$10^{-6}$ $M_\odot$ yr$^{-1}$ (e.g. Marchenko et al. 2002). The efficient dust formation around $\eta$ Car may be caused by the high eccentricity of the binary system and/or the high mass loss rate of the primary star.

Table 2. The estimated dust temperature and mass in each region of the Homunculus Nebula.

<table>
<thead>
<tr>
<th>Region</th>
<th>Dust Temperature</th>
<th>Dust Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial torus</td>
<td>130 K</td>
<td>0.09 $M_\odot$</td>
</tr>
<tr>
<td>Polar lobes</td>
<td>170 K</td>
<td>0.015 $M_\odot$</td>
</tr>
<tr>
<td>Inside the lobes</td>
<td>120 K</td>
<td>0.012 $M_\odot$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.12 $M_\odot$</td>
</tr>
</tbody>
</table>

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[Fe II]-Bright Supernova Remnants in Our Galaxy and Nearby Galaxies

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ABSTRACT

We have performed extensive near-infrared [Fe II] line observations of supernova remnants (SNRs) in our Galaxy and nearby galaxies using various instruments and telescopes. Here, we introduce our recent results from our unbiased [Fe II] imaging survey of the Galactic plane, near-infrared high-resolution imaging and spectroscopy of SNRs, and [Fe II] imaging observations of nearby galaxies. The corresponding strong line and continuum emissions at mid-infrared wavelength can be explored by sensitive instruments on SPICA.

1. INTRODUCTION

Massive stars evolve fast. Thus, these relatively young stars are mainly distributed close to the Galactic plane, where most of high-mass star-forming clouds are located, and there they end their lives. As a result, the remains of stars, supernova remnants (SNRs), are frequently seen toward cloudy regions of the Milky way. This gives difficulties in observational studies of SNRs, because they often suffer strong extinction and confusion effects. A good method is to make observations in infrared wavelength, where extinction is less severe than optical and confusion can be suppressed due to advent of new imaging and spectroscopic instruments. Especially, infrared [Fe II] line emission is useful to trace shock-heated gas of SNR. Enhanced iron released either from destruction of dust grains, containing highly depleted elements, in shocked layer or from metal-rich ejecta of the progenitor star can be an origin of the emission. In addition, well-developed partially ionized zone behind the shock front can supply sufficient amount of iron in the singly excited state. In the near-infrared wavelength, model calculations of fast radiative shocks expect strong [Fe II] 1.26 and 1.64 µm lines (e.g. Hollenbach & McKee 1989; Koo 2013).

The strong [Fe II] emissions were detected at several SNRs using circular variable filter (CVF) after the development of astronomical infrared detectors. Low-resolution near-infrared spectra using coarse resolution apertures were obtained at MSH 15–52 (Seward et al. 1983), IC 443 (Graham et al. 1987), Kepler, RCW 103, and three SNRs (N 63A, N 49, and N 103B) in Large Magellanic Cloud (LMC) (Oliva et al. 1989), and Crab (Graham et al. 1990). Later, more sensitive spectroscopic observations were done for two very bright historical SNRs Cas A and Kepler (Gerardy & Fesen 2001). There are recent near-infrared observations using modern instruments, including our works. Some examples are 3C 391 (Reach et al. 2002), W 28, and W 44 (Reach et al. 2005), W 49B (Keohane et al. 2007), G11.2–0.3 (Koo et al. 2007; Moon et al. 2009; Lee et al. 2013a), 3C 396 (Lee et al. 2009), and IC 443 (Kokusho et al. 2013). Here, we introduce our near-infrared [Fe II] observations of SNRs in our Galaxy and nearby galaxies.

2. [Fe II]-BRIGHT SNRS IN OUR GALAXY

For the last two years, we have performed an unbiased Galactic plane imaging survey, covering 10° ≤ l ≤ 60° and |b| ≤ 1°, using [Fe II] 1.64 µm narrow band filter on the UKIRT telescope (Koo 2013). In the survey images, there are several interesting objects such as young stellar objects, H II regions, evolved stars, planetary nebulae, and SNRs. SNRs are one of the most remarkable objects in the [Fe II] 1.64 µm line images, due to their relatively large sizes and brightnesses. Numbers of SNRs, including known [Fe II]-emitting SNRs, are identified in the survey area (Lee et al. 2013b). In general, SNRs which have high mean-surface-brightnesses are bright at the [Fe II] 1.64 µm line images, when we define the mean-surface-brightness as the 1 GHz flux divided by its square size in the Green’s catalog (Green 2009). It suggests that [Fe II] line emission can be a tracer for SNRs in the complicated interstellar medium. Many of them are SNRs detected by the mid-infrared search of SNRs within the Spitzer IRAC Galactic plane survey field (Lee 2005; Reach et al. 2006). Therefore, near-infrared and mid-infrared observations of SNRs are tightly correlated each other, mostly due to strong radiatively lines at those wavelengths (e.g. Koo 2013). The similar region of the Galactic plane is surveyed by near-infrared Hα narrow band filter (Reach et al. 2002), W 28, and W 44 (Reach et al. 2005), W 49B (Keohane et al. 2007), G11.2–0.3 (Koo et al. 2007; Moon et al. 2009; Lee et al. 2013a), 3C 396 (Lee et al. 2009), and IC 443 (Kokusho et al. 2013). Here, we introduce our near-infrared [Fe II] observations of SNRs in our Galaxy and nearby galaxies.

In our previous study of 3C 396, we found interesting morphological characteristics of the near-infrared [Fe II] 1.64 µm and Hα 2.12 µm line (Froehlich et al. 2011). In many cases, [Fe II]-emitting SNR shows Hα line emission as well. In our previous study of 3C 396, we found interesting morphological characteristics of the near-infrared [Fe II] 1.64 µm and Hα 2.12 µm line images (Lee et al. 2009). The less-dense, atomic [Fe II] region is located inside the recombined molecular region, indicating that the distributions cannot be interpreted by a single shock. Instead, the observed morphological characteristics may be due to the pre-supernova structures generated by the mass-loss of the progenitor and related surrounding molecular cloud. On the other hand, we have observed a handful of [Fe II]-emitting SNRs on the southern hemisphere using the AAT telescope. Figure 1 shows two bright SNRs on the northern and southern hemispheres. The young core-collapse SNR G11.2–0.3
Figure 1. Near-infrared [Fe II] 1.64 \( \mu \)m narrow band images of two bright core-collapse SNRs. Left: G11.2–0.3 on the northern hemisphere taken by UKIRT telescope. Right: RCW 103 on the southern hemisphere taken by AAT telescope.

Figure 2. Near-infrared [Fe II] 1.64 \( \mu \)m line velocity channel maps of N 49 in LMC. The channel velocities cover \( \sim 100-500 \) km s\(^{-1}\). The bright infrared star on the north has the H-band magnitude of 10.6.

is one of the brightest [Fe II]-emitting SNRs in our Galaxy (Koo et al. 2007; Moon et al. 2009; Lee et al. 2013a). The bright [Fe II] emission originates mainly from the swept-up circumstellar material heated by shocks. Besides, there are faint [Fe II] emission from the fast-moving knots of the dense iron ejecta. The other young core-collapse SNR RCW 103 on the southern hemisphere has comparable brightness to G11.2–0.3. The two bright [Fe II] filaments distribute opposite (NW-SE) direction. Presently, we are working on near-infrared spectra toward positions of [Fe II] filaments to understand the origin and dynamics of the [Fe II]-emitting dense gas in RCW 103.

3. [Fe II]-BRIGHT SNRS IN NEARBY GALAXIES

We have performed near-infrared imaging and spectroscopic observations of SNRs in the nearest galaxy LMC using the AAT telescope. For two bright SNRs (N 49 and N 63A), we made spectral mapping observations. The [Fe II] line luminosity of N 49 is much higher than those of Galactic SNRs. Figure 2 shows velocity channel maps of N 49 constructed from the [Fe II] 1.64 \( \mu \)m line spectra. Some bright structures are resolved over the velocity range of \( \sim 100-500 \) km s\(^{-1}\), although the observed sensitivity and spectral resolution is not enough to see faint, detailed structures. The different morphologies at different channel maps indicate that the surroundings of N 49 are not simple. Whether such surroundings
[Fe II]-Bright Supernova Remnants

can make the strong [Fe II] emission is uncertain. Very recently, we have carried out near-infrared [Fe II] 1.64 μm narrow band imaging observations of nearby galaxies: M 31, M 33, M 51, M 74, M 83, M 101, NGC 247, NGC 4214, and NGC 4449 using the UKIRT telescope. The [Fe II] imaging observations successfully distinguish bright SNRs from H II regions and stellar components. For example, the [Fe II]-bright SNR G98-28 in M 33 is clearly isolated from the nearby giant H II region and other ionized gas clouds, which is unclear in Hα images. Moreover, the SNR also shows bright mid-infrared emission in the Spitzer IRAC and MIPS images. Because it is hard to explain bright emission over the broad infrared bands by pure line emission only, more sensitive high-resolution imaging and spectroscopic observations are necessary to understand the origin of the infrared emission detected at this [Fe II]-bright SNR in the nearby galaxy M 33.

4. SPICA OBSERVATIONS

We are working on infrared studies of SNRs in our Galaxy and nearby galaxies using various methods presently available. In addition to individual study of well-known SNRs, there will be large area surveys of our Galaxy and nearby galaxies using SPICA. We expect that SNRs can easily be identified in such surveys. Our efforts are essential to prepare studies of supernova explosion, evolution of SNR, dust formation in ejecta, SNR interaction with environment, and SNR shock physics using infrared instruments on SPICA.

This work is supported by a Grant-in-Aid for Japan Society of Promotion of Science (JSPS) fellows (No. 23-01322) and K-GMT Science Program Galaxy Ecology and Massive Stars at z=0 (GEMS0).

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Lee, H.-G. 2005, JKAS, 38, 385
**ABSTRACT**

We present the preliminary results of the flux calibration for extended sources observed with the Far-Infrared Surveyor (FIS) onboard the AKARI satellite. The circumstellar shells of evolved stars (particularly of AGB and post-AGB stars) retain the fossil record of their mass loss in the form of dust/gas density distributions and these shells have the potential to verify/constrain many theoretical aspects of stellar evolution and mass loss. Hence, it is critical to have an accurate surface brightness and flux calibration. The FIS has four photometric bands between 50–180 µm with two types of Ge:Ga array detectors. The Ge:Ga array is long known to have a slow transient response and FIS has already been characterized for point sources. To calibrate for extended sources, we used a method in which photometry is done in a contour aperture of the 3σ detection threshold above the background to encompass more than the PSF core. We show that the revised slow transient corrections for the short wavelength band have a similar functional form as for the point source corrections, whereas for the long wavelength band two distinct functional forms dependent on the source brightness.

1. **INTRODUCTION**

Mass loss is one of the processes by which stars liberate material into the surrounding space, and lower-mass evolved stars are expected to play a significant role in enriching the ISM with lighter elements as well as molecules and solid-state species (dust) that are critical to life (e.g., Sedlmayr 1994). Unfortunately, our understanding of the evolution of mass loss ejecta in the circumstellar shells remains qualitative at best, and therefore, observational characterization that contains theoretical models is urgently needed.

Probing of the intrinsically cold (below 100 K) circumstellar envelopes (CSEs) in the far-IR began in the 1980’s with the IRAS satellite (Neugebauer et al. 1984) showing the existence of the CSEs as a consequence of continuous/continual dusty mass loss (Young et al. 1993). In the 1990’s, observations made with ISO (Kessler et al. 1996) confirmed that these CSEs were rich in molecules and dust (e.g., Yamamura & de Jong 2000) and their far-IR maps showed internal structures as signatures of mass-loss modulations (e.g., Izumiura et al. 1996). Observations made in other wavelengths also indicated that variations in the rate of mass loss resulted in CSEs with multiple shells and axisymmetric structures (e.g., Ueta et al. 2000). In the early 21st century, the next generation of far-IR satellites, AKARI (Murakami et al. 2007), Spitzer (Werner et al. 2004), and Herschel (Pilbratt et al. 2010), became available with higher spatial resolution and greater sensitivities (e.g., Ueta et al. 2009).

2. **OBSERVATIONS AND DATA REDUCTION**

AKARI is the first Japanese satellite dedicated to infrared astronomy (Murakami et al. 2007). It was launched on 2006 February 21 (UT), began taking data 2006 April 13 and ran out of liquid-helium 2007 August 26. The post-helium mission continued until power failure in May 2011, and the last command to terminate the satellite was sent on 2011 November 24. The diameter of the telescope is 68.5 cm (Kaneda et al. 2007) and is cooled down to 6 K in a liquid-helium cryostat (Nakagawa et al. 2007) for reducing the thermal emission. The Far-Infrared Surveyor (FIS) is one of the two focal-plane instruments onboard AKARI (Kawada et al. 2007). It has four photometric bands between 50–180 µm with two types of Ge:Ga array devices: the Short-Wavelength (SW) and the Long-Wavelength (LW) detector.

MLHES (excavating Mass Loss History in Extended dust shells of Evolved Stars, PI: Yamamura) is one of the pointed-observation mission programs and has the primary goal to map the circumstellar shells of low-mass evolved stars in detail to excavate the ancient history of dusty mass loss. The MLHES data set is the largest collection (144 objects) of one of the most sensitive far-infrared (far-IR) images of the cold extended circumstellar dust shells of evolved stars and is the key to understanding the dusty mass loss phase of stellar evolution. Due to the intrinsically faint nature of the extended far-IR cold dust shells, it is critical to have an optimized data reduction method to minimize the measurement uncertainties. This was done by using a new imaging tool kit FAST (FIS-AKARI Slow-scan Tools). FAST is a program that allows for interactive assessment of the data quality and on-the-fly corrections.
Figure 1. The Observed over Expected flux ratio vs. the Peak/Sky surface brightness ratio shows the effect of the slow transient response from a contour aperture by using a contour aperture to account for extended emission.

Figure 2. The Observed over Expected flux ratio vs. the Total (Observed plus sky and dark) flux plot. The dashed lines represent the fit determined from Shirahata et al. (2009) and the gray is the fit for extended emission.

to the time-series data on a pixel-by-pixel bases in order to manually correct glitches that would have been missed in the pipeline process.

3. PHOTOMETRIC FLUX CALIBRATION

FIS uses Ge:Ga detectors, which are known to show a slow transient response at low temperature under low background flux conditions, which typically happen in the space environment (Kaneda et al. 2002, and references therein). The slow transient response is a time-delay in the detector response which is caused by quick changes of the incoming flux. The time constant of the slow response is typically 10–100 sec, and depends on both the background and the signal photon fluxes. It is known that the slow transient response is different for point sources and extended sources (Kawada et al. 2007).
Table 1. Preliminary correction functions for SW and LW arrays

<table>
<thead>
<tr>
<th>SW Band</th>
<th>$0.1 \text{ Jy} &lt; (TF) \leq 400 \text{ Jy}$</th>
<th>LW Band</th>
<th>$(TF) \leq \text{boundary}$</th>
<th>boundary $\leq (TF)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N60</td>
<td>$R = 0.638 \times (TF)^{-0.027}$</td>
<td>WIDE-L</td>
<td>$R = 0.210 \times (TF)^{0.071}$</td>
<td></td>
</tr>
<tr>
<td>WIDE-S</td>
<td>$R = 0.578 \times (TF)^{-0.071}$</td>
<td>N160</td>
<td>$R = 0.071 \times (TF)^{0.446}$</td>
<td></td>
</tr>
</tbody>
</table>

However it has only been quantified for point sources (Shirahata et al. 2009). For the method described by Shirahata et al. (2009), the point-source fluxes are measured only from the PSF core of the photometric calibration sources (solar system objects and stars) and the flux from the PSF wing is recovered by using an aperture correction scaling factor. Then the slow transient response correction was determined by comparing the ratio between the observed and expected fluxes and the total observed flux. This correction method, by design, works only on point sources because it assumes a specific surface brightness profile (i.e., a Gaussian PSF).

For extended sources, however, the total observed flux is not necessarily a good representation of the transient effect (i.e., a region of strong surface brightnesses may be extended). Thus, to accurately verify the extent of the slow transient response, we elected to use the peak to sky surface brightness ratio instead. Figure 1 shows the relation between the observed-to-expected source flux ratio and the peak-to-sky surface brightness ratio. Note that in our method, a contour aperture with a threshold of $3\sigma$ above the background was used to encompass more than the PSF core of the calibration point sources.

This figure suggests that (1) in the N60 and WIDE-S bands, observed fluxes are always underestimated (at about 50–60 %) irrespective of the degree of the slow transient response effect and (2) in the WIDE-L and N160 bands, observed fluxes are always underestimated (at about 50–60 %) for sources with the bright peak (peak/sky $\geq 4$ or 5) and the degree of underestimate of the observed flux is dependent on the peak/sky of the peak for faint sources (peak/sky $\leq 4$ or 5), respectively. When the peak is bright enough the entire PSF (core and wing) is detected by the detector. However, for less sensitive detectors in the WIDE-L and N160 bands, if the peak is not bright, then part of the PSF (most likely wing) may not be detected by the detector (and a larger correction factor is necessary).

To see how this manifests itself in the relationship between the observed/expected flux ratio ($R$) and the observed total flux ($TF$; observed plus sky and dark), because we need the correction factor as a function of the measured total flux, flux: Figure 2 displays the relation between $R$ and $TF$. The dashed lines represent the slow transient correction functions for point sources determined by Shirahata et al. (2009) while the gray lines represent the correction functions for extended sources, resulted from the present analysis. This figure also indicates that less sensitive WIDE-L and N160 bands are likely to fail to capture emission from the source when a source is not bright enough. This effect for the contour photometry was not properly accounted for in the analysis done by Shirahata et al. (2009). Hence, faint object fluxes will be underestimated if the Shirahata correction method is used in the contour photometry.

We determine that significant surface brightness/flux oversight happens for objects with peak/sky $\leq 4$ or $TF \leq 9$ Jy for the WIDE-L band and peak/sky $\leq 5$ or $TF \leq 13$ Jy for the N160 band. Based on our analysis, we propose to use the following flux correction scheme for extended photometry measurements as shown in Table 1. For the SW band, we suggest the power-law relations (positive exponents) between the total measured flux to the correction factor, while for the LW band we propose two methods, power-law relations (positive exponents) for dim objects and constant factors for bright sources.

RT would like to thank the East Asian and Pacific Summer Institute (EAPSI) fellowship program and NSF/JSPS for the opportunity to conduct part of this research at ISAS/JAXA, and AKARI team for allowing a fruitful international collaboration, the SPICA 2013 conference for letting us present our work and the LOC for providing travel funding. This research is based on observations with AKARI, a JAXA project with the participation of ESA.

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A Far-Infrared View of Astrospheres Around Young and Old Stars

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ABSTRACT

between their stellar winds and the surrounding medium can give rise to spectacular looking bow shocks or bow waves which are part of a star’s astrosphere. Though the basic physics are the same, the sizes and shapes of these astrospheres can vary drastically for different types of stars or different interstellar conditions. In this short contribution I will focus on recent observations of dust in astrospheres around both young hot stars and old cool stars and how these observations set the stage for more extensive spectroscopic imaging studies with new infrared facilities such as SPICA.

1. ASTROSPHERES

Astrospheres are the interaction interface between stellar winds of moving stars and the interstellar medium (ISM). A schematic view of an astrosphere is shown in Figure 1 (left panel) illustrating the different interfaces. The termination shock is where the free-flowing stellar wind meets the shocked medium. The bow shock is the interface between the shocked and ambient medium. These two layers of shocked medium are (initially) separated by the contact discontinuity. If radiative cooling is efficient the two layers “collapse” into a thin shell. The shape of this shell can be approximated by \( y(x) = x^2/3R_0 \) (van Buren et al. 1990) while the overall size is set by the equilibrium between ram pressure of the stellar wind and that of the interstellar medium. Here \( x \) and \( y \) are the coordinates perpendicular and parallel to the direction of motion. \( R_0 \) is stand-off distance defined as \( R_0 = \sqrt{\frac{4\pi \dot{M} v_{\text{wind}}^4}{\dot{M} v_{\text{wind}}^2 \rho_{\text{ISM}}}} \) (Wilkin 1996), and represents position of the stagnation point with respect to the star in the direction of motion.

Astrospheres, whether bow waves or bow shocks, are interesting astrophysical phenomena not only because the give rise to morphological diverse and beautiful structures (Figure 2) but also because their occurrence and characteristics can be used as laboratories to study, for example:

- Dust-grain interaction
- ISM properties
- Stellar mass-loss and space motion (e.g. to identify runaways)
- Stellar evolution (thermal pulses, binarity)
- Shock physics
- Grain processing (dust evolution from circumstellar to interstellar medium)

Figure 1. left: Illustration of the different components of an astrosphere. (Copyright held by N.L.J. Cox, Leuven (Belgium); reprinted with permission). right: Turbulent instabilities and relative space / wind speeds. (Copyright held by N.L.J. Cox, Leuven (Belgium), reprinted with permission).
2. THE PHYSICS OF ASTROSPHERES

In determining the emission mechanisms it is important to consider whether or not the bow shock is radiative or adiabatic. The cooling efficiency of shocked media influences the thickness of the shock layers making up the astrosphere: $\propto 1/$\text{Mach}$^2$.

Hydrodynamical simulations by van Marle et al. (2011) have shown that small grains ($< 0.1 \mu m$) closely follow gas distribution (i.e. the contact discontinuity), while medium sized grains travel into the shocked wind region. Large grains ($> 0.2 \mu m$) flow almost unhindered into the unshocked stellar wind.

Calculations and simulations predict that turbulent instabilities arise in these bow shocks whenever the star’s space velocity is much higher than that of the stellar wind (Dgani et al. 1996; Figure 1; right panel). This implies that turbulent instabilities arise primarily in fast moving stars with slow winds (such as red supergiants and AGB stars), and that for hot stars, even if a fast runaway moving at 100–200 km/s, with typical winds velocities above 1000 km/s, the interaction region will be fairly smooth.

3. FAR-INFRARED EMISSION FROM ASTROSPHERES: COOL AND HOT STARS

While IRAS showed that astrospheres frequently manifest themselves around early-type hot runaway stars (Van Buren & McCray 1988), Herschel revealed that such wind-ISM interaction regions are also common around cool evolved stars. Cox et al. (2012) found that 30% of nearby ($< 500$ pc) AGB stars and red super giants have a bow wave-type interaction region. Only a small fraction (few %) of the observed dust mass is estimated to be from swept-up ISM, while for massive young stars most of the dust in an astrosphere is swept-up interstellar material.

It is striking to realise the ease with which astrospheres are imaged at mid- to far-infrared wavelengths, as shown extensively with IRAS, textitSpitzer, WISE, and Herschel. In that sense it is also noteworthy that only a couple of stellar-wind ISM astrospheres have been imaged directly at other wavelengths. For a few early-type runaway stars H$\alpha$ emission has been detected (Kaper et al. 1997, Brown & Bomans 2005). No H$\alpha$ or other gas-line emission has been detected in the astrospheres of cool evolved stars, except for the notable exception of CW Leo’s bow shock for which far-UV emission (Sahai & Chronopoulos 2010) has been detected co-spatial with the dust emission (Ladjal et al. 2010). The presence of astrospheres around solar-type stars has been inferred from Ly$\alpha$ absorption line profiles (e.g. Wood 2004).

4. SPICA’S VIEW OF ASTROSPHERES?

Together, the MCS and SAFARI instruments foreseen for SPICA offer continuous spectral coverage from 5 to 200 $\mu m$ (Nakagawa et al. 2011). With SPICA it should be possible to acquire full SEDs of very low surface brightness ($< 1$ mJy/arcsec$^2$) extended IR emission of astrospheres to explore the hot & cold dust composition (mineralogy) and atomic and molecular gas abundance & excitation conditions for a large number of species. Figure 3 shows a few typical examples of cool stars with the SPICA field-of-view superimposed. It will be possible to obtain spectroscopic images of selected spatially resolved circumstellar envelopes (CSE) from AGB stars, and their faint interaction with the ISM. One potential concern is that AGB stars themselves are reasonably bright in the mid- to far-infrared. This requires quite a large dynamic range, pointing accuracy and good spatial resolution.

Herschel provided a legacy of photometric imaging surveys focused on the morphology, of which SPICA can take full advantage and concentrate on the physical condition of both gas and dust in the outflows and the surrounding interstellar medium including gas cooling, dust heating, dust processing (including formation, growth and destruction of grains, size alterations, crystallinity), dust mineralogy, turbulence, shocks, etcetera.
A Far-Infrared View of Astrospheres Around Young and Old Stars

Figure 3. SPICA field-of-view superimposed on Herschel PACS 70/160 µm infrared emission of detached shells and extended astrospheres of AGB stars and red super giants. Adapted from Kerschbaum et al. (2010), Cox et al. (2012), and Decin et al. (2012). Circumstellar envelopes and shells around evolved stars can have sizes of several arcmin. SAFARI’s large FoV and much improved sensitivity in spectroscopic modes will allow us to probe the outermost CSE regions and their faint interaction with the ISM. A colour version is provided in the online edition.


REFERENCES
Evolution of Dust Emission around PNe, from AKARI/Spitzer to SPICA

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ABSTRACT

The evolution of Polycyclic Aromatic Hydrocarbon (PAH) emission of carbon-rich Galactic planetary nebulae (PNe) is investigated based on AKARI/IRC and Spitzer/IRS observations. Systematic variations in band peak positions and relative intensities are discovered in terms of evolution of PNe. The results show that PAHs in evolved PNe tend to show similar features as interstellar PAHs. The SPICA/MRS will have the advantage to investigate the evolution of dust emission in the 15–40 μm region. We discuss potential observations with SPICA to develop our understanding of the evolution of dust emission.

1. EVOLUTION OF PAH EMISSION IN GALACTIC PNE

Planetary nebulae (PNe) are in the final phase of low- and intermediate-mass star evolution. They are typically surrounded by a large amount of dust which is formed during the asymptotic giant branch phase. Their circumstellar dust is finally injected into the interstellar medium. They are supposed to be one of the major dust suppliers in galaxies. Investigating the dust in PNe is important to understand the physics and chemistry of the interstellar matter.

The 2.5–14.0 μm spectra of 19 Galactic PNe which show carbon-rich dust features were obtained with the AKARI/Infrared Camera (IRC) and Spitzer/Infrared Spectrograph (IRS). The 2.5–5.0 μm spectra were obtained with the IRC using the grism spectroscopy mode, while the 5.0–14.0 μm spectra were obtained using the Short-Low (SL) module of the IRS. The intensity of PAH emission features are measured by spectral fitting. The spectral profile of the PAH features is approximated by a Lorentzian function. The peak position of the 6.2 μm PAH feature is also measured.

The variations in the PAH emission are investigated in terms of the PN evolution. Theoretical studies indicate that the effective temperature of a PN increases monotonically as the PN evolves (e.g., Blöcker 1995). Thus, the effective temperature obtained from the literature is used as an estimator of the evolutionary stage of PNe. The intensity ratio of the 7.7 to 11.3 μm features is shown in the top panel of Figure 1. The 7.7 to 11.3 μm intensity ratio is sensitive to the ionization fraction of PAHs (Bregman & Temi 2005), since the 7.7 μm feature becomes strong when PAHs are ionized. The ratio decreases as the effective temperature increases. It indicates that the PAH ionization fraction decreases with PN evolution. The intensity ratio of the 3.4 to 3.3 μm features is shown in the middle panel. The 3.4 μm feature is generally attributed to aliphatic components attached to PAHs (Joblin et al. 1996; Sloan et al. 1997). This ratio increases with increasing temperature, indicating that the amount of aliphatic components in PAHs increases as the PN evolves. The bottom panel shows the evolution of the peak wavelength of the 6.2 μm PAH feature. PAHs in the interstellar medium generally show the peak of the 6.2 μm feature around 6.22 μm, while PAHs in circumstellar regions typically show the peak at 6.24–6.28 μm (Peeters et al. 2002). The former emission feature is referred to as Class A and the latter as Class B. The figure indicates that the PAH emission evolves from Class B toward Class A along with the PN evolution. Thanks to the high sensitivity of the AKARI/IRC and Spitzer/IRS, a number of near- to mid-IR spectra were collected enough to statistically investigate the evolution of PAH emission in PNe. The origin of the evolution will be discussed in a separate paper (Ohsawa et al., in preparation).

2. POSSIBLE FUTURE OBSERVATIONS WITH SPICA

The Mid-IR Camera and Spectrometer (MCS) installed on-board SPICA has two special modules for spectroscopy, the Mid Resolution Spectrograph (MRS) and High Resolution Spectrograph (HRS). The MRS will explore the 12–38 μm range with a spectral resolution of R > 1000. The MRS will allow us to investigate some of the dust features in the mid-IR. Since image slicers are implemented, the MRS has the advantage to observe extended objects and investigate the spatial variation in the spectral profile of dust emission. In this paper, observations of crystalline silicates, fullerenes, and the 30 μm feature are proposed as future observations with the MRS.

Crystalline Silicate—Emission from crystalline silicate has narrow peaks in the mid-IR and silicates with a different crystalline structure, such as pyroxene and olivine, show a different spectral profile (e.g., Koike et al. 2003; Chihara et al.
Effective Tempature (K)

OHSAWA ET AL.

Figure 1. Top: the 7.7 to 11.3 μm intensity ratio, indicating the ionization fraction of PAHs. Middle: the 3.4 to 3.3 μm intensity ratio, indicating the aliphatic to aromatic ratio of PAHs. Bottom: the peak wavelength of the 6.2 μm feature, an indicator of the PAH emission class.

2002). Mid-IR spectroscopy enables us to identify the structure of silicate. There have been several studies on crystalline silicates focusing on the silicate feature around 10 μm. Emission around 10 μm is mostly attributed to hot (> 300 K) silicates. Spectroscopy in the 18–38 μm is more effective to identify the structure of warm (∼100 K) silicate. Observations of the 30 μm silicate feature may provide new insights into when and how the crystallization of silicates occurs.

Fullerene — Fullerene has been discovered in circumstellar (Cami et al. 2010) and interstellar (Sellgren et al. 2010) regions based on observations with the Spitzer/IRS. Although several studies have been made, their formation process and excitation mechanism still remain to be understood. Emission features of C_{60} and C_{70} appear around 17.6 and 18.9 μm and they are suitable targets for the MRS. A spatially-resolved observation of fullerene emission is important to identify their excitation mechanism (Bernard-Salas et al. 2012). The MRS will provide the 17–20 μm spectrum at the spatial resolution of ∼1''6, which will be useful to resolve the fullerene emitting region.

The 30 μm feature — The 30 μm feature is a broad emission feature which appears around 25–40 μm in a variety of evolved stars. The carrier of the feature is not identified. Magnesium sulfide (MgS) was proposed as a candidate (Goebel & Moseley 1985), as well as hydrogenated amorphous carbon (HAC, Duley 2000). Hony et al. (2002) have proposed that the 30 μm carrier could be heated by the infrared radiation or the carriers could be located far from the central star. The MCS has the potential to investigate the spatial distribution of the 30 μm feature. It would be useful to investigate the nature of the carrier of the 30 μm feature.
DUST EVOLUTION AROUND PNe

3. SUMMARY

The high sensitivity achieved by the *AKARI/IRC* and *Spitzer/IRS* has increased the number of objects which we can observe in the infrared. We were able to investigate the variation of the PAH emission in PNe in terms of the evolution of PNe. *SPICA* will achieve higher spatial resolution and sensitivity than *AKARI* and *Spitzer*. The MRS installed on-board *SPICA* has a great advantage to investigate the dust emission in the 15–40 μm range such as crystalline silicates, fullerenes, and MgS. The MRS will enable us to investigate the variations in these dust features along with PN evolution.

These results are in part based on observations with *AKARI*, a JAXA project with the participation of ESA and on archival data obtained with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. We fully appreciate all the people who worked in the operation and maintenance of those instruments. This work is supported in part by a Grant-in-Aid for Scientific Research (258492) by the Japan Society of Promotion of Science (JSPS).

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WISE J180956.27-330500.2: A Candidate AGB star with Ongoing Episodic Mass Loss

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ABSTRACT

Results of infrared photometries and dust shell modeling of a peculiar object WISE J180956.27−330500.2 are presented. The object has shown a significant time variation of its SED in the last 30 years. The variation is understood as a formation and expansion of massive dust shell since late 1990’s. The object was suspected to be a red star in the optical wavelengths before the mass ejection, which allows us to hypothesize that the object is possibly the first example of the AGB star just experiencing an episodic mass loss after a thermal pulse. Observation of this object with SPICA after some 10 years from now will bring us an important clue to understand the stellar evolution and mass loss, as well as the chemistry in the thick circumstellar envelopes.

1. INTRODUCTION

WISE J180956.27−330500.2 (hereafter WISE J1810) was discovered in the course of studying the WISE Preliminary Source Catalog as an object showing a peculiar infrared SED (Figure 1) with a very deep depression at WISE 3.4 µm band (Gandhi et al. 2012). The depression cannot be explained by an absorption of any kind of known molecular or dust component. Instead, we found that this peculiar SED of the object can be understood as a transient effect induced by an expanding and cooling dust envelope. No attention had been paid to WISE J1810 previously before our discovery, and therefore the nature of the object is not clear. The digitized photographic survey data show that the star was possibly red. Gandhi et al. (2012) proposed an idea that the object is in the late stage of stellar evolution and the dust shell was formed by a heavy mass loss that took place in late 1990’s. Mass loss from the AGB stars is a major source of heavy elements such as carbon and oxygen into the interstellar space and plays a key role on the chemical evolution of the universe. How the mass loss develops along the evolution of the star has been an important theme in astronomy.

There are a number of AGB stars showing far-IR excess in their SED. Far-IR or radio molecular line mapping around the stars detect extended, physically thin shells, indicating that these stars ejected a significant amount of matters in a short time period thousands years ago (e.g., Olofsson et al. 2000; Izumiura et al. 2011). This phenomenon is considered in relation with thermal pulse, an explosive nuclear burning in the helium shell in the AGB stars (e.g., Iben & Renzini 1983). WISE J1810 is possibly the first example of an episodic mass-loss for which we can make real-time observations. To clarify the nature of WISE J1810, we are carrying out follow-up observations in various wavelengths. In this article we present the recent photometry data and SED model fitting.

2. PHOTOMETRIC OBSERVATIONS

A set of far-IR–sub-mm photometric observations were carried out using the Herschel Space Observatory (Pilbratt et al. 2010) as a Director’s Discretionary Time (DDT) observation on October 1, 2012. We carried out imaging photometry using PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) at six wavelength, 70, 110, 160, 250, 350, and 500 µm. Data reduction was made using HIPE 11. The result are presented in Figure 2. The Herschel data are generally well consistent with the previous observations.

Near-infrared photometry was attempted by the Infrared Survey Facility (IRSF; Nagayama et al. 2003) at South Africa on September 29, 2012. SIRIUS camera observed J, H, and Ks band simultaneously. The total exposure time was 140 minutes, resulting the detection limit of 19.3 mag = 20 µJy, 18.5 mag = 41 µJy, and 18.5 mag = 27 µJy, for J, H, and Ks band, respectively. WISE J1810 was not detected in any of the bands, despite the fact that the object was Ks = 5.0 mag = 6.9 Jy at the 2MASS observation epoch. More than 13.5 mag diminishing in Ks band supports the presence of extremely thick dust envelope.
Figure 1. The SED of WISE J1810. The deep depression at 3–4 µm is not explained by any kind of absorption, and should be addressed to the time variation of the object. The optical fluxes shown by bars in the left indicate that the object was a red star.

Figure 2. Photometry results of WISE J1810 and dust shell models. Dust shell models are calculated for two separate phases: warm phase (2MASS observation epoch) and cool phase (AKARI–WISE–Herschel observation epoch), indicated in blue and red lines, respectively. Two kinds of dust components, oxygen-rich (left) and carbon-rich (right) cases are examined.

3. DUST SHELL MODELING: PRELIMINARY RESULTS

Dust shell models are constructed to derive physical parameters of the circumstellar shell around WISE J1810. We use DUSTY (Ivezić et al. 1999) for the calculation of dust radiative transfer. A spherical dust shell expanding with a constant velocity is assumed. Since we do not have any clues of dust composition of the shell, we examined two cases; warm silicate dust (Ossenkopf et al. 1992) for oxygen-rich dust shell and amorphous carbon (Hanner 1988) for carbon-rich shell. Nothing is known about the central star except for a speculation that the star is a red-giant (Gandhi et al. 2012). In addition, Gandhi et al. (2012) reported that the bolometric luminosity of the object has decreased by a factor of 4.7 between 2MASS and AKARI–WISE. In the current analysis we express this variation by changing the temperature of the central star. The radius of the central star is assumed to be 1.5 × 10^{13} cm (1 AU). The observed SED is divided into two datasets; one is the 2MASS data taken in 1998 and the others are AKARI, WISE, Herschel, and IRSF obtained recently (2006–2012). For the time being time variation in the recent several years is ignored.

The reasonable model SEDs are obtained and shown in Figure 2 and the model parameters are given in Table 1. In the both warm and cool phase the Wien side of the SED constrains the models rather severely and the parameter set for each case is quite unique. Distance is adjusted to scale the model flux to the observed flux.

4. DISCUSSION AND SUMMARY

Although the dust modeling is still preliminary, Figure 2 tells us several important aspects of WISE J1810. The oxygen-rich dust is preferred to account for the far-IR fluxes up to 70 µm. There is still an excess beyond 100 µm, which is likely
WISE J180956.27−330500.2

Table 1. The derived model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>O-rich case</th>
<th>C-rich case</th>
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</thead>
<tbody>
<tr>
<td>$T_{\text{star}}@1998$ [K]</td>
<td>3800</td>
<td>3750</td>
</tr>
<tr>
<td>$T_{\text{star}}@2010$ [K]</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$M_{\text{dust}}@1998$ [M$_{\odot}$]</td>
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<td>$9.5 \times 10^{-8}$</td>
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<tr>
<td>$M_{\text{dust}}@2010$ [M$_{\odot}$]</td>
<td>$3.3 \times 10^{-4}$</td>
<td>$4.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$R_{\text{shell}}@1998$ [R$_{\text{star}}$]</td>
<td>15–34</td>
<td>10–23</td>
</tr>
<tr>
<td>$R_{\text{shell}}@2010$ [R$_{\text{star}}$]</td>
<td>112–131</td>
<td>101–109</td>
</tr>
<tr>
<td>$V_{\text{exp}}$ [km/s]</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>Distance [kpc]</td>
<td>6.1</td>
<td>6.4</td>
</tr>
</tbody>
</table>

from the dust shells from the previous, moderate mass-loss. Fitting with multiple dust shell model must be an interesting subject.

The total dust mass in the shell for the carbon-rich case is reasonably consistent with those derived from the previous analysis of the extended shells by far-IR observations (e.g., Izumiura et al. 2011). If the shell is oxygen-rich, the total dust mass is significantly larger than that. The dust mass has increased from 1998 to 2010, indicating that the mass loss was still ongoing at the 2MASS epoch. From the expansion velocity estimated from the change of the shell radius and the thickness of the shell, we suggest that the intensive mass loss lasted only 1–2 years. It is much shorter than the expected high-luminosity period after the thermal pulse (Iben & Renzini 1983) and those expected from the far-IR observations. Further observational and theoretical studies are necessary to reveal the real nature of the phenomenon ongoing in this object.

SPICA observation of WISE J1810 will provide an essential clue to understand the nature of AGB evolution and mass loss. With an interval of some 10 years the object may be enter a new evolutionary phase. Continuous spectroscopic data in the mid- to far-IR range will be an important clue to study the evolutionary status of the object and the physical and chemical processes taking place in the thick dust shell.

Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. This research is based on observations with AKARI, a JAXA project with the participation of ESA. We thank to Mai Shirahata and Koji Tsumura to carry out the IRSF observations. Chris Pearson is acknowledged for his help on the SPIRE data reduction.

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Resolving the Mass Loss in Red Supergiants with the Very Large Telescope Interferometer and SPICA

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ABSTRACT

The mass-loss mechanism in red supergiants (RSGs) is one of the long-standing problems in stellar astrophysics. For solving this problem, it is crucial to probe the dynamics of the outer atmosphere. The milliarcsecond angular resolution achieved by IR long-baseline interferometry provides us with the only way to spatially resolve this key region. We present high spatial and high spectral resolution observations of the best-studied RSGs Betelgeuse and Antares in the 2.3 µm CO lines using ESO’s Very Large Telescope Interferometer (VLTI). We have succeeded in “velocity-resolved” aperture-synthesis imaging of the atmosphere of stars for the first time. This allows us to probe not only inhomogeneous structures over the surface of stars but also their kinematics, as routinely done in solar physics. We have detected vigorous upwelling and downdrafting motions of large CO gas clumps (as large as the radius of the stars) at up to 20–30 km s$^{-1}$ within 1.5 stellar radii. SPICA will provide a unique opportunity to probe the region farther away from the star, helping us to link the inhomogeneous, vigorous atmospheric motions to the physical properties of the circumstellar envelope.

1. INTRODUCTION

The mass loss in the red supergiant (RSG) phase significantly affects not only the evolution of massive stars but also the chemical enrichment of galaxies. Nevertheless, the mass-loss mechanism in RSGs is a long-standing problem in stellar astrophysics. While dust, pulsation, convection, and magnetohydrodynamical (MHD) waves are often considered to be candidates, there is currently no working theory for the mass loss in RSGs (e.g., Harper 2010).

For understanding the mass-loss mechanism in RSGs, it is crucial to study the dynamical structure of the outer atmosphere, where the energy and momentum for the wind acceleration are expected to be deposited. The outer atmosphere of RSGs has complicated, inhomogeneous structures, with the hot chromospheric plasma and the cool neutral/molecular gas coexisting within several stellar radii (e.g., Harper et al. 2001, and references therein). Inhomogeneous structures on the surface of RSGs are also spatially resolved by IR interferometry (e.g., Tuthill et al. 1997; Haubois et al. 2009). Kervella et al. (2009, 2011) and Marsh et al. (2001) reveal clumpy structures in the circumstellar envelope of the RSGs Betelgeuse and Antares. This inhomogeneous, multicomponent nature of the outer atmosphere and the circumstellar envelope is considered to be a key to understanding the driving mechanism of the mass loss.

However, milliarcsecond spatial resolution and high spectral resolution ($\gtrsim$6000) are required to spatially resolve the dynamical structure of the inhomogeneous atmosphere. The near-IR (1.3–2.4 µm) interferometric instrument AMBER at the ESO’s Very Large Telescope Interferometer (VLTI) is a unique instrument to achieve this (Petrov et al. 2007). With the spatially resolved 2-D spectrum of the RSG Betelgeuse in the CO first overtone lines obtained with VLTI/AMBER. The star is well resolved by our angular resolution (9.8 mas), which is shown by the vertical tick. The observed spatially unresolved (= normal) CO line spectrum of Betelgeuse is shown by the solid line. The extended outer atmosphere is seen as “spikes” in the CO lines. The atmosphere is more extended to the negative direction (PA = $-107^\circ$) than to the positive direction.

Figure 1.
Figure 2. Enlarged view of the spatially resolved 2-D spectrum of Betelgeuse for three CO lines. The star appears extended only in the blue wing and line center, not in the red wing of the CO lines. The observed spatially unresolved CO line spectrum of Betelgeuse is shown by the solid line.

currently available maximum baseline at VLTI, it is possible to have a spatial resolution of down to 1 mas and a spectral resolution of up to 12000.

2. VLTI/AMBER OBSERVATIONS OF THE RSGS BETELGEUSE AND ANTARES

Our VLTI/AMBER observations of Betelgeuse were the first study to spatially resolve this well-studied RSG in the individual CO first overtone lines near 2.3 $\mu$m (Ohnaka et al. 2009). The AMBER data revealed that the star is more extended in the CO lines than in the continuum and appears differently in the blue wing, line center, and red wing of the CO lines. Our modeling of the AMBER data showed that an inhomogeneous velocity field can make the star appear differently within the CO lines. However, with only six $u/v$ points, we could not determine how inhomogeneous the star appears.

Therefore, we observed Betelgeuse again one year later with better $u/v$ coverage. The almost linear $u/v$ coverage allowed us to reconstruct “1-D projection images” from 2.28 to 2.31 $\mu$m, which represent a 1-D intensity distribution of the star obtained by squashing the actual 2-D intensity distribution onto the projected baseline vector on the sky (see Ohnaka et al. 2011, for details). Figure 1 shows the observed spatially resolved 2-D spectrum of Betelgeuse. If one carried out long-slit spectroscopy placing the slit on the star using a 48 m telescope with an angular resolution of 9.8 mas, such a spatially resolved spectrum would be obtained. The figure reveals that the star is more extended in the CO lines, seen as “spikes” in the 2-D spectrum, suggesting an outer atmosphere extending to $\sim$1.3 stellar radii. The figure also shows that the outer atmosphere is more extended to the negative direction (corresponding to a position angle of $-107^\circ$) than to the positive direction. This is the first imaging of the extended outer atmosphere of an RSG in individual CO first overtone lines. The horizontal “wiggling” near the stellar disk center means that the photocenter of the star changes in the CO lines. Moreover, Figure 2 shows that the appearance of the outer atmosphere in each CO line is asymmetric with respect to the line center: it appears only in the blue wing and line center of the line but there is no trace of it in the red wing. Therefore, our high spatial and high spectral resolution AMBER observations enabled us to image how differently the star appears across the CO line profiles. Our modeling shows that the AMBER data can be explained by a model with an inhomogeneous velocity field, in which the CO gas within a region as large as the stellar radius is upwelling at 0–5 km s$^{-1}$, while the gas in the remaining region is downdrafting much faster at 20–30 km s$^{-1}$ (see Ohnaka et al. 2011, for details of the modeling).

We also observed another well-studied RSG Antares with VLTI/AMBER with the same instrumental set-up. We succeeded in reconstructing 2-D images within the individual CO first overtone lines, although with a strongly elongated...
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beam (Ohnaka et al. 2013). Furthermore, our AMBER imaging at two epochs reveals that the appearance of the star in the blue and red wing of the CO lines swapped completely within one year. Our modeling of the AMBER data of Antares suggests the vigorous, inhomogeneous gas motions in the outer atmosphere similar to Betelgeuse.

3. PROSPECTS WITH SPICA

Our “velocity-resolved” aperture-synthesis imaging of Betelgeuse and Antares with AMBER suggests that the material within 1.5 stellar radii is undergoing chaotic, vigorous motions without systematic outflows. To obtain a comprehensive picture of how the stellar winds are accelerated, it is important to link the dynamics of the inhomogeneous outer atmosphere to the physical properties of the region farther away from the star. SPICA’s coronagraphic instrument SCI will provide a unique opportunity to probe inhomogeneous or clumpy structures in the region at \( \gtrsim 10 \) stellar radii. High spectral resolution observations of molecular and atomic lines with MCS will also be useful for spatially resolving the dynamics of the circumstellar envelope. This will help us to unveil the nature of the mass loss from RSGs.

REFERENCES

**Herschel** Observations of the Shocked Gas in HH 54

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**ABSTRACT**

The star formation process is often revealed through the observations of molecular outflows. The ejection mechanism of these flows is most likely closely linked to the formation of protostellar disks. Swept up material from the parental cloud, excited in the interaction with the ambient medium, can be observed on parsec scale distances from the central source.

The Herbig-Haro object HH 54 is a shock that can be studied in detail using a very limited amount of **Herschel** time. It is located relatively nearby in the Chamaeleon II cloud, situated at a distance of 180 pc. The shocked region has an angular extent of roughly 30' and is not contaminated with emission from other nearby objects. The nature of the central source has, however, been a matter of debate. Several IRAS point sources have in the past been suggested to be the driving source of the HH 54 flow. Here, we present spatially resolved observations of CO carried out with SPIRE and PACS onboard **Herschel**. The observations show a complicated picture and provide the possibility to measure the true CO abundance in a spatially resolved region.

**1. INTRODUCTION**

The HH 54 shock is located at the edge of the nearby Chamaeleon II cloud at a distance of roughly 180 pc (Whittet et al. 1997). The region contains several visible HH objects and the knots move at high velocities towards the observer. The molecular gas is detected at velocities up to ~ −20 km s⁻¹ with respect to the vLSR and it is noteworthy that only blue-shifted emission has been detected from the HH 54 flow. The red-shifted part of the outflow has for unknown reasons not been detected and the nature of the central source is also shrouded in mystery.

Over the years, several suggestions have been put forward regarding the location of the central source, e.g. the Class I sources IRAS 1500−7658 and IRAS 12553−7651 (Caratti o Garatti et al. 2009; Bjerkeli et al. 2011, respectively). The region has been fairly well studied, both with space-based and ground-based facilities. Recently, observations of pure rotational H₂ transitions (Spitzer), low-J CO transitions (SEST, Odin, APEX, and Herschel-HIFI) and the 557 GHz ground state transition of o-H₂O (Herschel-HIFI) were presented (Neufeld et al. 2006; Bjerkeli et al. 2011).

Here, we present spectroscopic observations of the region, covering the wavelength range 50 to 670 μm. The observations were carried out at a high spatial resolution, providing valuable information on the morphology, temperature and density distribution in the shocked region. Combined with previously published H₂ data, we also measure the true CO abundance in the region.

**2. OBSERVATIONS AND RESULTS**

Between July 1 and December 30, 2012, 5 hours of OT2 observing time were used to observe the CO ladder using the PACS and SPIRE instruments. The observations were centered on HH 54 B (Sandell et al. 1987). In Figure 1, the spectrum obtained with PACS and SPIRE towards HH 54 is presented. Detected H₂O, CO, OH and O[II] lines are marked in this figure.

**3. TEMPERATURE, DENSITY AND THE ABUNDANCE OF CO WITH RESPECT TO H₂**

The spectroscopic observations of CO transitions with PACS and SPIRE show a spatial displacement with increasing J. Figure 2 shows the position of the emission maximum for each of the CO transitions from CO(4−3) to CO(18−17). This likely reveals the temperature gradient along the post-shock gas and provides valuable information on the nature of the exciting source of the outflow. The displacement, in the northeast - southwest direction, could indicate that IRAS 1500−7658 is the driving source of the HH54 flow, which was also suggested by Caratti o Garatti et al. (2009). This source is located 20' to the southwest from HH 54 at a projected distance of 1 pc. However, the apparent increase in temperature into the post-shock region is not easily reconcilable with that scenario.

The CO data were analysed in conjunction with the previously published H₂ data using the LTE approach. From this analysis it is clear that the H₂ emission trace a warmer gas component than the CO emission. Unlike results from previous studies of outflows, the higher J CO lines seem to trace gas of relatively low temperature. Only one single temperature (∼ 200 K) component is needed to explain the CO observations. Consequently, the H₂ gas is significantly warmer and at
Figure 1. FIR spectrum obtained with PACS and SPIRE (lower panel) towards the position of HH 54 B. Detected CO, H$_2$O, OH and O[I] lines are marked with the colours red, blue, black and green, respectively.

Figure 2. Colourmap show the CO column density in the observed region under the assumption of LTE. The green dots show the position of the emission maximum for each CO transition (from Gaussian fits). $J$ is increasing from northeast to southwest. The error bars refer to the Gaussian fitting to each emission map. Offsets are with respect to HH 54 B.

least the higher excited lines do not seem to be of the same origin as the CO emitting gas. Like in the case of other outflow observations carried out with Herschel, most recent shock models do not easily explain the observations.
Figure 3. The upper panel shows the temperature of H\textsubscript{2} (solid black line) and CO (dashed red line) versus offset from the position of HH 54 B in the northeast - southwest direction. The temperature of the CO emitting gas is increasing in the southwest direction. The lower panel shows the column density of the two molecules with respect to offset.

Assuming that the ground state transitions of H\textsubscript{2} trace a colder gas component (suggested from H\textsubscript{2} rotation diagrams), we can obtain a rough estimate on the variation of the CO abundance in the region. The computed column densities are presented in Figure 3 along with the temperature distribution for the two species. Offsets in this figure are from the (0,0) position in the northeast to southwest direction. The abundance of CO with respect to H\textsubscript{2} varies between $1 \times 10^{-4}$ and $2 \times 10^{-4}$ from the northeast to the southwest.

REFERENCES

Observations of Circumstellar Ices around Extragalactic Young Stellar Objects with SPICA

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ABSTRACT

Spectroscopic observations with SPICA will provide us invaluable opportunities to study the chemical properties of circumstellar solids in various galactic environments beyond the Milky Way. In this proceedings, we discuss scientific importance and feasibility of spectroscopic observations of ices and dust around YSOs in nearby galaxies with SPICA.

1. INTRODUCTION

Chemical diversity of materials that forms stars and planets in the universe is one of the important topics of present-day astronomy. Star- and planet-formation activities can occur in various galaxies which differ in many ways such as size, shape and environment. It is thus important to understand how galactic characteristics affect the properties of materials around young stellar objects (YSOs). Particularly, the effect of galactic metallicity on the chemical evolution of interstellar and circumstellar materials is of great interest since cosmic metallicity is increasing with time evolution of the universe. However, observations of YSOs in the early metal-poor galaxies are very difficult due to an enormous distance.

The Large and Small Magellanic Clouds are the nearest low-metallicity galaxies (50 kpc for LMC and 60 kpc for SMC). There are two main reasons to study YSOs in the Magellanic Clouds. First, YSOs in the Magellanic Clouds enable us to investigate how the different metallicity environments affect the properties of circumstellar materials. Metallicities of the LMC and the SMC are known to be approximately 1/2 and 1/5 compared to the solar neighborhood. Next, YSOs in the Magellanic Clouds enable us to investigate the properties of circumstellar materials as a function of the stellar luminosity because the distance to the galaxy is well-determined. Also, the face-on geometry of the LMC allows us to compare the distribution of YSOs and the ISM on a two-dimensional map.

Figure 1. AKARI/IRC (thick) and Spitzer/IRS (thin) infrared spectrum of an embedded high-mass YSO in the LMC. The positions of detected spectral features are labeled with the central wavelength of each feature in micron. Wavelength coverages of spectroscopic instruments proposed to SPICA are also shown. The AKARI spectrum is taken from Shimonishi et al. (2010) and the Spitzer spectrum is from Spitzer Heritage Archive, respectively.
Spectroscopic properties of embedded YSOs in the LMC and SMC have been investigated intensively in these few years with the advent of high-sensitivity infrared satellites such as AKARI and Spitzer. An example of an infrared spectrum of an embedded high-mass YSO in the LMC is shown in Figure 1 together with the spectroscopic capabilities of several instruments proposed to SPICA. Near-infrared ice absorption bands are discussed in detail with AKARI toward a number of embedded YSO samples in the LMC and SMC (Shimonishi et al. 2008, 2010, 2012; Shimonishi 2012). Mid-infrared ice bands are investigated by Spitzer toward a large number of YSO samples (e.g., Seale et al. 2011; Oliveira et al. 2013). These studies have shown that ices around YSOs in the Magellanic Clouds possess different properties in terms of molecular abundances. For example, Shimonishi et al. (2010) reported that the column density ratio of the two major ice species, CO$_2$/H$_2$O, is systematically higher in the LMC compared to Galactic counterparts, owing to the harsh radiation environment of the LMC. The results are quite important if we are to understand the chemical diversity of circumstellar materials in various galactic environments, including extremely metal-poor environments as in the early universe.

Ices in dense molecular clouds are considered to be a major reservoir of heavy elements, molecules and various organic compounds that are essential for the presence of life. Chemical reactions on the dust surface are an important process for the formation of molecules in low temperature environment. Solid-state chemistry is also believed to affect various astrochemical phenomena such as hot core/corino chemistry through the sublimation of ice mantles. Therefore, in order to understand the chemical diversity of star-/planet-forming regions in the universe, it is very important to investigate properties of solids in various galactic environments.

2. INFRARED SPECTROSCOPIC STUDY OF EXTRAGALACTIC YSOS IN THE SPICA ERA

Currently, spectroscopic observations of YSOs in the LMC and SMC are limited to a portion of high-mass YSOs and achievable spatial resolution is $\sim$1–2 pc scale for space observations. Significant advances in the infrared spectroscopic
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capability with SPICA will allow us to investigate the chemical properties of solids around extragalactic YSOs in more detail and toward a larger number of samples.

Figure 2 (left) shows theoretically-predicted infrared flux and color of YSOs at the distance of the LMC (based on the SED model by Robitaille et al. (2007)). It is shown that infrared spectroscopic sensitivity of SPICA MCS enables us to obtain the spectral information of high- and intermediate-mass YSOs in the Magellanic Clouds. The low-resolution spectroscopic mode with FPS-S LVF enables us to detect low-mass YSOs in the LMC. Furthermore, it is possible to obtain spectral information of high-mass YSOs even at the distance of the Andromeda Galaxy (M31) thanks to the high-sensitivity expected for SPICA (Figure 2 right). SPICA will clarify how interstellar environment of the individual galaxy affects the properties of circumstellar materials of YSOs.

Improved spectral resolution of SPICA MCS will provide us new knowledge about chemical compositions of ice mantles in diverse extragalactic environments. Currently, the detectable ice species toward extragalactic YSOs are limited to abundant molecules that show relatively strong absorption bands (e.g., H$_2$O, CO$_2$, CO). Medium- or high-resolution spectroscopy with MCS allows detailed comparison of observed and laboratory ice profiles and simultaneous analyses of gas-phase absorption lines located near ice absorption bands. This will help shed light on the chemical pathways for molecular formation by solid-state reactions. In addition, SPICA should constrain the formation efficiency of complex molecules in ice mantles under low-metallicity environment through the observations minor ice species such as CH$_3$OH.

3. SUMMARY

Infrared observations of extragalactic YSOs and relevant astrochemical studies are now at the dawn of a new era. In this proceeding, we review a part of scientific results which was obtained in the AKARI era and discuss possible future observations with SPICA. Massive infrared photometric and spectroscopic databases for the Magellanic Clouds obtained by AKARI (Kato et al. 2012; Shimonishi et al. 2013) and Spitzer (Meixner et al. 2006; Woods et al. 2011) should help plan unique observation strategies in the SPICA era. As a natural extension of infrared studies from AKARI to SPICA, it will play a very important role for understanding of the chemical diversity of solids in galactic scales.

We would like to thank all the members of AKARI and SPICA science/instrument team. This research is based on observations with AKARI, a JAXA project with the participation of ESA.

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Exploring the Ice-Forming Interstellar Environment in Nearby Galaxies with **SPICA**

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**ABSTRACT**

Absorption features due to interstellar ices are important probes of the interstellar environment. However, ices in nearby galaxies have not been fully studied yet. With the **AKARI** near-infrared spectroscopy, we systematically observed 120 nearby galaxies, and detected **H**\(_2\)O ice at 3.05 \(\mu\)m from 36 galaxies and **CO**\(_2\) ice at 4.27 \(\mu\)m from 9 galaxies. We find that ices are formed in the dust-rich and star-forming environment, and that **CO**\(_2\) ice may be efficiently formed due to massive star formation activities. With **SPICA**, we propose spectral mapping observations of ices for the **AKARI** sample galaxies. Based on the results, we will reveal spatial variations of the ice-forming interstellar environments within galaxies in detail.

1. INTRODUCTION

Absorption features due to interstellar ices are observed in near- and mid-infrared spectra (e.g., **H**\(_2\)O ice at 3.05 \(\mu\)m and **CO**\(_2\) ice at 4.27 \(\mu\)m). Ices are formed on the surface of dust grains in dense molecular clouds. The ice features are thought to be useful probes of the interstellar environment such as temperature, chemistry, and the radiation field. In this context, **CO**\(_2\) ice is an important one since it is a secondary product unlike **H**\(_2\)O ice which is primarily formed on dust grains via surface reactions (Oba et al. 2012). The possible formation process is **H**\(_2\)O + **CO** + \(h\nu\) \(\rightarrow\) **CO**\(_2\) + 2H, where \(h\nu\) indicates far-UV photons (Watanabe & Kouchi 2002). Therefore, the abundance of **CO**\(_2\) relative to **H**\(_2\)O ice may have information on the UV radiation field. However, only a handful of observations were performed for **CO**\(_2\) ice especially in nearby galaxies due to the atmospheric absorption. In this study, we systematically observed **H**\(_2\)O and **CO**\(_2\) ices in nearby galaxies with **AKARI**. Based on the results, we construct the sample of galaxies where ices are detected, and explore the ice-forming interstellar environment.

2. OBSERVATION

We used the grism slit spectroscopic mode of the **AKARI**/IRC to obtain near-infrared spectra between 2.5 and 5 \(\mu\)m, which have the spectral resolution of \(R \sim 100\). We analyzed the spectra of 211 regions in 120 galaxies which are observed in the framework of the **AKARI** mission program ISMGN (Kaneda et al. 2009) during 2006–2010. For example, our

![Figure 1](image.png)

**Figure 1.** Example of the observed spectra for NGC 3256. The red curve and blue arrows represent the best-fit continuum model and the spectral ranges used to fit the continuum model, respectively.
sample includes the following famous nearby galaxies; M 31, NGC 253, NGC 6946, M 101, M 51, NGC 2768, Centaurus A (Cen A), IC 10, and NGC 205.

3. RESULTS AND DISCUSSION

Figure 1 shows an example of the observed spectra, which shows absorption features due to H$_2$O and CO$_2$ ices as well as several emission features. We search for the absorption features due to the ices based on the following method. First, we fit a continuum spectrum by a multi-temperature (200, 400, 800, 1600, and 3200 K) blackbody model. Then we obtain an optical depth spectrum and fit it by the model spectra of H$_2$O and CO$_2$ ices. We derive the column density, $N$, from the equation $N = \int \tau \, d\nu / A$, where $A$, $\tau$, and $\nu$ are the band strength of each ice feature (Gerakines et al. 1995), an optical depth, and a wavenumber, respectively. As a result, we detect H$_2$O ice from 36 galaxies (>3$\sigma$) and CO$_2$ ice from 9 galaxies (>2$\sigma$) out of 120 galaxies.

Figure 2 shows the numbers of the galaxies where the H$_2$O and CO$_2$ ices are detected, classified in the three morphological types: late type, early type, and irregular. As can be seen in the figure, the ices are detected in late type galaxies with a high rate, while the detection is relatively rare in early type and irregular galaxies. As a global trend, late type galaxies show active star formation activities with abundant dust and gas, while early type galaxies do not. Therefore the ices may be present in the active and dust/gas-rich environment.

Next, we examine the role of star formation activities in the formation of the ices. Figure 3 shows the fractional numbers of the regions with the H$_2$O and CO$_2$ ices detected, with only the H$_2$O ice detected, and without ice detection as a function of the Br$\alpha$ intensity. These histograms clearly show that the regions with the CO$_2$ ice show higher Br$\alpha$ intensities than the others. Thus star formation activities may be essential to form the CO$_2$ ice, which supports the formation process of the CO$_2$ ice described in Watanabe & Kouchi (2002).

Finally, we examine the relation between the abundance of the CO$_2$ ice and star formation activities with the spatial information. Figures 4(a) and 4(b) show the maps of the column densities of the H$_2$O and CO$_2$ ices for the starburst galaxy M 82 (Yamagishi et al. 2013). In the figures, there is a clear difference in the spatial distributions of the ices; H$_2$O ice is widely distributed, while CO$_2$ ice is concentrated near the galactic center. This result suggests the difference in the UV radiation field in the galactic center and other regions. Figure 4(c) shows the CO$_2$/H$_2$O abundance ratios plotted against the PAH 3.3 $\mu$m/Br$\alpha$ ratios, in which there is a clear negative correlation. We furthermore find that CO$_2$/H$_2$O abundance ratios are high in the galactic center. The PAH 3.3 $\mu$m/Br$\alpha$ ratio represents the softness of the UV radiation field which depends on the number of massive stars. Thus massive star formation activities in the galactic center may cause the high CO$_2$/H$_2$O abundance ratios. Here it is notable that interstellar UV photons cannot penetrate into dense molecular clouds. A possible origin of the UV photons is the interactions between cosmic-rays and molecular hydrogen.
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**Figure 4.** Column density maps of (a) H$_2$O and (b) CO$_2$ ices in M 82 in units of 10$^{17}$ cm$^{-2}$. (c) The CO$_2$/H$_2$O abundance ratios plotted against the PAH 3.3 $\mu$m/Br$\alpha$ ratios. The contours in (a) and (b) are taken from the AKARI 7 $\mu$m image.

which produce far-UV photons (Prasad & Tarafdar 1983). Many supernova remnants due to the starburst activities may increase the cosmic-ray energy density in the galactic center.

### 4. PROSPECTS FOR SPICA

In order to expand the study of the interstellar ices with AKARI, we propose spectral mapping observations of the AKARI sample galaxies with high spatial resolution. The study in M 82 indicates that spatial information is critical to discuss the relation between the abundance of the ices and the interstellar environment. Hence with SPICA, we will observe H$_2$O ice at 6 and 13 $\mu$m, CO$_2$ ice at 15 $\mu$m and several emission features in the mid- and far-infrared. We establish reliable tracers of massive star formation activity in the mid- or far-infrared (e.g., PAH 11.3 $\mu$m/[Ne II], PAH 17 $\mu$m/[Si II], and [C II]/[O III]) as we used the PAH 3.3 $\mu$m/Br$\alpha$ ratio in the near-infrared. Comparing the spatial distributions of the ices with those of the tracers, we will reveal spatial variations of the ice-forming interstellar environments within the galaxies in detail.

### 5. SUMMARY

We systematically observed 120 galaxies with AKARI near-infrared spectroscopy, and detected H$_2$O ice from 36 galaxies and CO$_2$ ice from 9 galaxies. We find that the ices are detected in the star-forming and dust/gas-rich galaxies, and furthermore that CO$_2$ ice is formed in regions which show massive star formation activities. In M 82, CO$_2$ ice is abundant relative to H$_2$O ice in the galactic center, which may be caused by the massive star formation activities. Increase of cosmic-ray induced UV photons due to the starburst activities may cause the high CO$_2$/H$_2$O ice abundance ratios. Spectral mapping with SPICA is crucial to expand our study of the interstellar ices, and explore the spatial variation of the ice-forming interstellar environment within a galaxy in detail.

This work is based on observations with AKARI, a JAXA project with the participation of ESA. This work is supported by Grants-in-Aid for Japan Society for the Promotion of Science Fellows No. 23005457 and Grant-in-Aid for Scientific Research No. 22340043.

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Diffuse Galactic Light in a Field of Translucent Cloud MBM32 at High Galactic Latitude

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ABSTRACT

We have conducted multi-color optical imaging toward a high-Galactic cloud, and correlated the intensity of diffuse optical light to the 100 $\mu$m intensity $S(100 \mu m)$. A $\chi^2$-minimum technique was employed to fit a linear function of $S(100 \mu m)$ to the observed correlation and derive the slope parameter of the best fit-function $\Delta(DGL)/\Delta(100 \mu m)$. Combining our slope values and published ones, we show that the slope parameter values vary from cloud to cloud. Because the slope parameter decreases as $S(100 \mu m)$ increases, we suggest that a non-linear DGL model including a negative quadratic term of $S(100 \mu m)$ be fitted to the observed correlation.

1. INTRODUCTION

The extragalactic background light (EBL) from the optical to near-infrared is the cumulative emission of galaxies, intergalactic gas and stars, AGNs as well as emission from other exotic sources not common at the present epoch such as pregalactic objects (population III) and decaying unknown-particles. The claimed detections of the EBL at near-infrared wavelengths give 3–10 times greater values than the integrated intensities expected from galaxy counts. This may indicate that the EBL is dominated by a new, unknown emission component, or that the measurements of those claimed values are biased by incomplete subtraction of foreground emission such as zodiacal light and diffuse galactic light (DGL).

Based on our recent work by Ienaka et al. (2013), we present a study of the DGL, one of the important foregrounds, which is scattered light by interstellar dust grains illuminated by the interstellar radiation field (ISRF).

2. OBSERVATIONS

The optical data toward translucent cloud MBM32 at $(l, b) = (147, 41)$ have been acquired at four photometric bands, $B, g, V,$ and $R$. The observations were conducted on the 105cm Schmidt telescope at Kiso observatory1 using the 2KCCD camera with 2048 $\times$ 2048 pixels. The Sun and the Moon were more than 35 degrees below the horizon during the observations. The field of view of the camera is 50 $\times$ 50$''$ with a pixel scale of 1$''$5 pixel$^{-1}$. The average seeing was $\sim$3$''$3. The area of high-quality is approximately 45$'$ $\times$ 40$'$, smaller than the field of view of the camera due to using dithering.

The left panel in Figure 1 indicates the observed field by the white square superimposed on the IRAS/DIRBE 100 $\mu$m map (Schlegel et al. 1998), and the right shows optical pseudo color mages. In order to reduce the effects of large-scale

Figure 1. Left: Optical field at MBM32 superimposed on the IRAS/DIRBE 100 $\mu$m map (Ienaka et al. 2013). The solid square represents the observed field. Right: The optical pseudo color image synthesized from $B/g/V/R$ imaging. North is up, east to the left. The field is approximately 45$'$ $\times$ 40$'$.

1 Kiso observatory is operated by the Institute of Astronomy, the University of Tokyo
Kawara et al.

Figure 2. Correlation of the intensity of the diffuse optical light against 100 \( \mu m \) intensity (Ienaka et al. 2013). The red solid lines represent the linear functions recovered from the \( \chi^2 \) minimum analysis, while the red dashed lines represent the quadratic functions.

Figure 3. The correlation slopes \( b(\lambda) = \Delta S_\nu(\lambda)/\Delta S_\nu(100 \, \mu m) \) as a function of wavelengths (Ienaka et al. 2013).

non-uniformity in the flat-fielding, we observed the field at two different telescope attitudes by flipping the telescope around the right ascension axis in such a way that the difference in hour angle is 180 degrees, thereby rotating the image plane on the detector by 180 degrees. The diffuse optical light component was measured by rejecting stars and galaxies from the images.

3. RESULTS

Figure 2 plots the intensity of diffuse optical light, \( S_\nu(\lambda) \), as a function of 100 \( \mu m \) intensity, \( S_\nu(100 \, \mu m) \). \( S_\nu(\lambda) \) clearly correlates with \( S_\nu(100 \, \mu m) \) at all the bands. We now fit to the data a linear function defined as: \( S_\nu(\lambda) = a(\lambda) + b(\lambda)S_\nu(100 \, \mu m) \), where the slope parameter at wavelength \( \lambda \) is \( b(\lambda) = \Delta S_\nu(\lambda)/\Delta S_\nu(100 \, \mu m) \), and the constant parameter \( a(\lambda) \) represents components independent of the DGL (i.e., atmospheric airglow, zodiacal light, and the EBL). A minimum \( \chi^2 \) analysis was performed to obtain \( a(\lambda) \) and \( b(\lambda) \). Figure 3 plots \( b(\lambda) \) as a function of wavelength along with the published data, which are taken form Witt et al. (2008), Matsuoka et al. (2011), Brandt & Draine (2012), Laureijs et al. (1987), Guhathakurta & Tyson (1989), Paley et al. (1991), and Zagury et al. (1999), as well as the model spectrum from Brandt & Draine (2012). The figure indicates that \( b(\lambda) \) varies by a factor of 3–4.

4. DISCUSSION

Figure 4 (Ienaka et al. 2013) illustrates \( b(\lambda) \) as a function of \( S_\nu(100 \, \mu m) \), which indicates that \( b(\lambda) \) decreases as \( S_\nu(100 \, \mu m) \) increases. Sujatha et al. (2010) reported that \( b(\lambda) \) at far-UV wavelengths exponentially decreases with
with the published data, which are taken from Witt et al. (2008), Matsuoka et al. (2011), Brandt & Draine (2012), Laureijs et al. (1987), Guhathakurta & Tyson (1989), Paley et al. (1991), and Zagury et al. (1999), as well as the model spectrum \( \chi \) minimum clearly correlates with a parameter from the images.

The diffuse optical light component was measured by rejecting stars and galaxies around the right ascension axis in such a way that the difference in hour angle is 180 degrees, thereby rotating the image non-uniformity in the flat-fielding, we observed the field at two different telescope attitudes by flipping the telescope.

The data from Brandt & Draine (2012) shows that the lines represent the relation expected for albedos \( \omega_V =0.6, 0.7, \) and 0.8 from lower to upper (Ienaka et al. 2013).

\( S_\nu (100 \mu m) \) increasing. It is likely that such decrease is due to the absorption by dust along the line of sight. The optical depth in the optical is much less than in the far-UV, thus the \( b(\lambda) \) decrease appears to be linear against \( S_\nu (100 \mu m) \) at the optical. Therefore, it would be appropriate to fit a functional form of \( S_\nu (\lambda) = a(\lambda) + b(\lambda) S_\nu (100 \mu m) - c(\lambda) S_\nu (100 \mu m)^2 \) to the observed correlation.

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![Diagram](image_url)
Investigation of Property of Massive Star Clusters by mini-TAO, TAO and SPICA

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ABSTRACT

We built up a new observation system for investigation of massive star clusters. The tool is NIR imaging photometry by broad- and narrow-band filters installed in Atacama Near-InfraRed camera (ANIR). The observations of massive star clusters were carried out with mini-TAO 1 m telescope. As the results, almost all of known Wolf-Rayet (WR) stars or luminous-blue variables (LBVs) were confined and new candidates of progenitors of supernovae (SNe) were detected. Color-color diagram ([N207/Ks] vs [N187/Ks]) made from the images clearly shows a zone of 1.87 µm excess due to He II and Paschen-alpha emission that indicates WN-type WR stars and LBVs, and a zone of 2.07 µm excess due to C IV emission from WC-type WR stars. In other words, we found that various types of massive stars can be classified as zones on the diagram. Furthermore we will be able to reveal not only buried WR stars but also the constituent, age and evolution of massive star clusters. Identification of the components of clusters with mini-TAO, TAO 6.5 m and SPICA gives significant information to clarify the history of star formation (the birth and the evolution) of massive star clusters.

1. RESEARCH AND AIM : IMPORTANCE OF MASSIVE STARS

The Wolf-Rayet (WR) stars are thought to be the progenitors of supernovae. In addition, other types of massive stars are characterized by the generation and release of a variety of metal and release of enormous energy from them. Therefore, detail examinations of massive stars provide a significant information about not only progenitors of the supernovae but also the evolution of the interstellar medium and galaxies. However, the lifetime of massive stars is short and they changes their types in a short period of time. In addition, it is considered to be formed in an environment surrounded by a large amount of gas. That is, there are many mysteries in their birth and the evolution due to large extinction. For example, environment when they are formed, initial mass function (IMF) of a massive star cluster, the amount and mechanism of mass loss, discrepancy in the number of WR stars obtained in simulations and observations, and so on. The aim of our research is to discover new massive stars and to elucidate the evolutionary scenario of massive star clusters.

2. CURRENT OBSERVATIONS AND RESULTS

2.1. Observation

We propose near-infrared spectroscopic imaging observations, i.e, application of narrow band filters dedicated to emission lines characteristic of massive stars at wavelengths with less extinction, and efficient point source photometry by large format array.

The primary instrument for our purpose is ANIR (Motohara et al. 2008) with mini-TAO (The University of Tokyo Atacama Observatory; Minezaki et al. 2010) located at the summit of Cerro Chajnantor, an altitude of 5640 m at Atacama in northern Chile. ANIR is a simple imager that covers from 0.9 to 2.5 µm with four broad-band and four narrow-band filters. Owing to the high altitude and extremely low precipitable water vapor of the site, we can observe stably even 1.87 µm (including He II and Paα emission lines) range. By inserting a dichroic mirror in the front of the dewar window, it is also possible to carry out optical-NIR simultaneous imaging. NIR imaging observations of massive star clusters within Galaxy and LMC have been done by ANIR.

2.2. Color-color Diagram

We show the observational results of 3 massive star clusters near the Galactic center (GC): Quintuplet cluster, Arches cluster, and Sgr A* cluster (Figure 1), by Ks, N187 and N207 filters installed in ANIR. The latter 2 filters are mainly designed for the detection of emission lines from massive stars. After photometry for point sources of each band, color-color diagram are depicted (Figure 2). Based on the position of each source in the diagrams, we can classify the type of the detected sources. In this figure, WC type WR stars with [C IV] 2.07 µm and LBV or WN-type WR stars which are characterized by He II lines are distributed on right (-top) quadrant and central top area, respectively. In addition it is possible to detect the “red” objects further the lower left. Finally almost all cataloged objects are detected in this diagram. Further unidentified point sources that we found could be new massive stars.
Figure 1. Location of our three observed areas near galactic center (5.1′=11.9 pc for $R_0=8.0$ kpc) overlaid on the Paα image by Mauerhan et al. (2010) (39′×15′ = 91×35 pc).

Figure 2. The known WR stars (19, 21, and 19 WRs of Sgr A*, Quintuplet, Arches cluster area, respectively) plotted on the log($n_{187}$) vs. log($n_{207}$) diagram. Open and closed circles denote WN (including WN/WC) stars and WC stars, respectively. Each type of WR stars is distinguished by a zone on the diagram.

2.3. Detailed Classification by Type of Stars

For example we show the relations between the extinction-corrected $Ks$ magnitude and the excess of log($n_{187}$) ($n_{187}$ means the normalized $N_{187}/Ks$ ratio) for the WN and WN9/Ofpe stars in the three GC clusters in Figure 3. The absolute $Ks$ magnitude (corresponding to the extinction-corrected $Ks$) is indicated above the diagram. WN stars and WN9/Ofpe stars clearly show different sequences in this diagram. That is, WN sequence is located to the right of the figure. As the absolute $Ks$ magnitude becomes bright, the excess increases. In addition, the trend is the same for WN9/Ofpe stars, however the sequence is shifted to the left. On the other hand, a promising trend was not observed for the O-type stars, the excess value indicates a constant value for absolute $Ks$ magnitude.
Investigation of Property of Massive Star Clusters

![Diagram](image.png)

**Figure 3.** The relations between the extinction-corrected $K_s$ magnitude and the excess of $\log(n_{187})$ for the WN and WN9/Ofpe stars in the three cluster areas. Open and closed circles denote WN and WN9/Ofpe stars, respectively, and black dot denotes O-type stars (possibly supergiants). Cross denotes three LBV, and black diamond denotes the candidates of WN (or WN/Ofpe) stars detected on our images. The absolute $K_s$ magnitude (extinction and distance modulus are considered) is indicated above the diagram.

3. FUTURE OBSERVATION PLAN

3.1. NIR Survey Observation and Follow-up Spectroscopy

We plan the equipment of narrow-band filters $N187$, $N207$, $N218$ and $K_s$ broad-band in Simultaneous-color Wide-field Infrared Multi-object Spectrograph (SWIMS; Konishi et al. 2012) for TAO 6.5 m telescope. First, we will perform the classification of the tribe, the detection of known components of clusters, and the picking-up candidates of unknown massive post-MS by these filter sets. Next, the spectroscopic observations will be carried out using a spectroscopic function of SWIMS. As a result, investigation of the nature of the candidates will be achieved. Through the wide area survey of the northern and southern sky with the Subaru telescope (2015–2017) and TAO (2017∼), respectively, the exploration of survey of unprecedented area and the production of near-infrared catalog of massive stars will be achieved.

3.2. Research with SPICA

It is difficult to estimate the age of a star cluster. Some candidates of the massive post-MS (WR, LBV, BSG, YHG, etc...), MYSOs, and MIRAs are picked up by NIR imaging. The massive stars such as WR are at least 3 Myr old. How many massive stars exist in the cluster or near the cluster and how old are they? That is, to investigate components of the clusters and their lifetimes offers important information for the birth and the evolution of (massive star) clusters. **SPICA** (Nakagawa et al. 2011) has an important role for picking up multi components of a cluster by wide range imaging capability. The observation plans (bands and targets corresponding to each instrument) are shown in Table 1.

### Table 1. Observation plans

<table>
<thead>
<tr>
<th>Observation</th>
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<tbody>
<tr>
<td>NIR Narrow-band Imaging</td>
<td>mini-TAO/ANIR</td>
<td>Search for post MS</td>
</tr>
<tr>
<td>MIR (5–10 $\mu$m) Imaging</td>
<td>MCS/WFC-S &amp; FPC/FPC-S</td>
<td>Pick-up 500–1000 K object</td>
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<td>NIR Spectroscopy</td>
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SESSION 3: PLANET FORMATION AND DETECTION/CHARACTERIZATION OF EXOPLANETS
Studies of Exoplanets and Solar Systems with SPICA: An Overview

Michihiro Takami, Javier R. Goicoechea, Keigo Enya, Yuki Sarugaku, and SPICA Science Working Group

ABSTRACT

SPICA will be a powerful facility to help us understand the formation and evolution of our solar system and exoplanetary systems in 2020's. The wavelength coverage (5–210 µm) is optimal for observations of key targets including exoplanets, protoplanetary and debris disks, and solar system small bodies. At this coverage SPICA will offer several dramatic advantages, including extremely high sensitivity and excellent image quality with a cooled (~6 K) monolithic 3-m class mirror telescope, a variety of capabilities for spectroscopy and spectro-imaging, and an unprecedented high spectral resolution for mid-infrared spectroscopy free from telluric absorption and emission. We briefly summarize our discussions for possible science impacts on the above targets and research topics.

1. INTRODUCTION

One of the ultimate goals for modern astronomy and astrophysics is understanding the formation and evolution of our solar system and exoplanetary systems. We have made dramatic progress in the past decades, with discoveries of a number of exoplanetary systems and solar system small bodies (in particular “Trans-Neptunian Objects” or TNOs), and extensive studies of these objects and protoplanetary/debris disks. We also expect significant progress over the next decade with the advent of the Atacama Large Millimeter/sub-millimeter Array (ALMA) and James Webb Space Telescope (JWST), and also through detailed analysis of data recently obtained using the Herschel Space Observatory.

The SPace Infrared telescope for Cosmology and Astrophysics (SPICA) is a proposed mission for mid-to-far infrared (5–210 µm) astronomy, consisting of a single 3-m class aperture space telescope with cooled (~6 K) instrumentation. The instruments presently proposed for installations are the Mid-infrared Camera and Spectrograph (MCS), which includes the Wide-Field Camera (WFC), the Medium-Resolution Spectrograph (MRS), and the High-Resolution Spectrograph (HRS) (see Kataza et al., this volume); the SpicA FAR-infrared Instrument (SAFARI; Roelfsema et al., this volume); the SPICA Coronagraph Instrument (SCI; Enya et al., this volume); and the Focal Plane Camera for Science (FPC-S; Lee et al., this volume). See Nakagawa et al., this volume, for a summary of the specification for the mission and the above instruments. Figure 1 shows the spectral energy distributions (SEDs) of our target objects compared with the wavelength coverage of SPICA, JWST, Herschel and ALMA. The figure shows that SPICA will cover essential wavelengths for studies of these targets, particularly at the wavelengths where the most energy is emitted. Furthermore, studies with Spitzer Space Telescope, Herschel Space Observatory and ground-based telescope have confirmed a number of spectral features in the wavelength coverage of SPICA which are useful for detailed studies of the target objects (see later sections).

The strengths of SPICA compared with the other missions are: (1) extremely good sensitivity at 20–210 µm; (2) a capability for spectro-imaging with a Fourier type imaging spectrograph (SAFARI) at 34–210 µm; (3) a high spectral resolution (R ~ 30,000) at 12–18 µm provided by MCS-HRS; (4) capabilities for mid-infrared coronagraphic spectroscopy provided by SCI; and (5) a wide-field of view for imaging capabilities at 2–210 µm. Such specifications will complement JWST, which is expected to have an extremely good sensitivity at 20 µm or shorter wavelengths, and Herschel, which covered wavelengths up to 672 µm. At 57–210 µm SPICA is expected to improve the sensitivities provided by Herschel by a factor of 10–100, thereby significantly improving the studies of disks and solar system small bodies being made using the Herschel data.

The science cases for SPICA for the above targets have been extensively discussed over the past several years. The documents open to public include Swinyard et al. (2009); Goicoechea et al. (2009); Takami et al. (2010), and the White papers and the Yellow Books for which the European Consortium lead the publications. The internal documents with science cases include the Mission Required Documents for Japan Aerospace eXploration Agency (JAXA), and the proposals for individual instruments recently submitted to the international review committee. Based on the above documents and some recent additional discussions, we present a brief summary for the possible science impacts with SPICA based on the specifications being confirmed.
2. EXOPLANETS

In the last decade approximately 1000 exoplanets have been detected, mainly through measurements of radial velocity and photometry (i.e., the observations of transiting events) of parent stars\(^1\).\(^2\). The number of confirmed planets will significantly increase in the next few years due to the ~3000 candidates discovered during the Kepler mission\(^3\). While the majority of the exoplanets discovered to date seem to be gas giants like Jupiter and Saturn\(^4\), some exoplanets with lower masses seem to be icy and rocky planets. The detection limits for mass and radii are now comparable to Earth and Mercury, respectively (Barclay et al. 2013). The habitability of some exoplanets has also been discussed (e.g., Wang et al. 2013).

In addition to the above techniques, direct imaging (coronagraphy) of exoplanets has also been progressing rapidly (e.g., Currie et al. 2012; Kuzuhara et al. 2013). Despite the severe contrast problem of the parent stars, such observations have allowed us to observe young exoplanets with large orbital radii. This dimension is complementary to the radial velocity and transiting methods, which are sensitive to small radii, and valuable for testing theories of the formation of exoplanets (see, e.g., Ida et al., this volume).

Our challenge for the next decade should be detailed characterisation of exoplanets, in particular with spectroscopy. This will allow us to investigate their temperatures, surface gravity, atmospheric compositions, climates etc. While spectroscopic observations have been made of some “hot Jupiters” (e.g., Bean et al. 2013), gas giants with small orbital radii, astronomers have just begun to obtain spectra of exoplanets similar to those in our solar system (e.g., Konopacky et al. 2013). We expect that coronagraphic observations from the ground will allow us to observe spectra of many exoplanets over the next decades. However, overwhelming thermal emission from the telluric atmosphere and telescopes hampers observations in the mid-infrared, thereby excluding most of the relatively cool and old planets (\(t \sim 1\) Gyr or later) whose ages are closer to our solar system, and also icy giants analogous to Uranus and Neptune.

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\(^1\) http://www.exoplanet.eu/

\(^2\) http://phl.upr.edu/projects/habitable-exoplanets-catalog/

\(^3\) http://kepler.nasa.gov/
Studies of Exoplanets and Solar Systems with SPICA

Figure 2. Wavelengths of absorption lines and bandheads for various molecules which could be associated with the exoplanetary atmospheres (adapted from Tinetti et al. 2012). The wavelengths coverage of SPICA instruments, Spitzer and JWST are also shown. Of the instruments above only SPICA-SCI will be capable of direct spectroscopy of exoplanets.

Together with JWST-MIRI, SPICA-SCI will be a powerful tool to explore this dimension, i.e., coronagraphy in the mid-infrared. Observations using space telescopes are free from speckle and thermal noise caused by telluric atmosphere effects, thereby dramatically improving the sensitivity. While JWST will offer a better inner working angle, SPICA-SCI will offer a spectroscopic capability at 4–28 μm (R ∼ 200) as well as imaging. This will allow us to observe a number of absorption features associated with exoplanetary atmospheres (Figure 2) including major features such as H₂O, CO₂, CH₄, and NH₃ (e.g., Spiegel & Burrows 2012). These spectra will be extremely useful for improving theories for exoplanetary atmospheres, which currently have uncertainties for cloud formation and nonequilibrium chemical processes, leading us to derive fundamental parameters (mass, atmospheric compositions etc.) to constrain their formation theories. See also Kotani et al., this volume for details of possible studies.

In addition to coronagraphic imaging, photometric and spectroscopic capabilities will be useful for detailed studies of transiting exoplanets. See Narita et al., this volume and the Yellow Book for details.

3. GAS IN PROTOPLANETARY DISKS

Exoplanetary systems and our solar system are believed to have been formed in circumstellar disks of gas and dust (protoplanetary disks). The Hubble Space Telescope, ground-based 10-m telescopes, and millimeter/submillimeter interferometry have provided images of dozens of protoplanetary disks, some of which show potential signatures for ongoing planet formation such as disk holes (e.g., Andrews et al. 2011; Hashimoto et al. 2012) and spiral structures (e.g., Muto et al. 2012; Grady et al. 2013). The spectral energy distributions (SEDs) at UV to radio wavelengths have also been observed toward a number of the star+disk systems, and the disk structures have been discussed through modeling calculations (e.g., Espaillat et al. 2010).

The gas comprises most of the initial disk mass and may consequently play an important role in the formation and evolution of planetary systems, allowing gravitational instabilities to occur (Durisen et al. 2007, for a review), or providing gas drag on rocky materials (Nagasawa et al. 2007, for a review). A number of observational studies of gas disks have been made to date using millimeter/submillimeter interferometry (Dutrey et al. 2007, for a review), infrared spectroscopy from space and the ground (Najita et al. 2007; Pontoppidan et al. 2010; Dent et al. 2013), and optical high-resolution spectroscopy from the ground (Najita et al. 2007). The millimeter/submillimeter lines are associated with the regions on a few hundred AU scale (see Dutrey et al. 2007 for review), while those in the optical and infrared are associated with regions within a few AU of the central star.

The spectroscopic capabilities of SPICA at mid-to-far infrared wavelengths will be the best to extend the studies made so far, in particular those made using Spitzer and Herschel. Its extremely high sensitivities will allow us to investigate the dissipation of the gas disks in detail, in particular for t ∼ 10 Myr stars for which the dust disks are no longer observed. Indeed, SAFARI will offer a detection limit for far-IR lines of ∼ 3 × 10⁻¹⁹ W m⁻², improving the detection limits of the existing Herschel studies by a factor of 10. MCS-MRS will cover some lines which may be even more useful for investigating the dissipation of gas disks (Figure 3, left). Covering a number of emission lines observed using Spitzer and Herschel (e.g., [O I], [C II], H₂O, CO, OH, CH⁺, H₂) we will also be able to investigate the physical and chemical
Figure 3. (left) Predicted line fluxes by Gorti & Hollenbach (2004) for a $t = 10^7$ yr disk, overplotting the detection limits of SPICA for a 1-hr integration, 5-$\sigma$. Typical detection limits for the studies with Spitzer and Herschel (Lahuis et al. 2007; Fedele et al. 2013; Dent et al. 2013) are also shown. The Spitzer study by Lahuis et al. (2007) also covers the S I, Fe I and Fe II lines and typical detection limits are above the range of the plot. (right) Schematic view for a change in line profile due to disk clearing by a Jupiter-like planet.

conditions of such gas in detail. Furthermore, observations of HD lines at far-infrared wavelengths will constrain the masses for a large sample of protoplanetary disks (e.g., Bergin et al. 2013).

Furthermore, MCS-HRS will allow us to observe the velocity profiles of various emission lines, leading to the determination of the column density distribution and physical/chemical conditions as a function of radius. The spectral resolution and coverage of MCS-HRS ($R \sim 3 \times 10^4$ and 12–18 $\mu$m, respectively) are designed to (1) resolve kinematics comparable to the orbital motion of Jupiter in our solar system; and (2) make follow-up studies of emission bands extensively observed using Spitzer (H$_2$O, CO$_2$, HCN, C$_2$H$_2$ — see, e.g., Pontoppidan et al. 2010; Carr & Najita 2011). The high spectral resolution of MCS-HRS will also be useful for deblending many emission lines (Carr & Najita 2011). The observations of line profiles will hopefully allow us to trace kinematic evolution due to planet formation within a few AU of the disks (Figure 3, right).

4. DEBRIS DISKS

Debris disks have been observed toward a number of main sequence stars. A recent census using Herschel suggests that about 20% of nearby main sequence stars host such disks (e.g., Eiroa et al. 2013). Along with the Edgeworth-Kuiper and asteroid belts in our solar system, debris disks may be a useful fingerprint for the evolution of the associated exoplanetary systems (e.g., Wyatt 2008; Wyatt et al. 2012).

Observational studies have been traditionally made with infrared SEDs without direct spatial information. Most debris disks show a flux peak at a far-infrared wavelengths, thus these are considered as massive analogues to the Edgeworth-Kuiper belt in our solar system but with significantly larger dust masses. On the other hand, recent studies using Herschel, AKARI etc. have revealed new classes of debris disks significantly hotter or colder than the others, and their physical nature is being investigated (e.g., Fujiiwara et al. 2013; Eiroa et al. 2013) (see also Onaka et al., this volume). However, some or all of the Herschel detections of “cold disks” have been suspected to source confusion with extragalactic sources (e.g., Krivov et al. 2013; Gaspar & Rieke 2013). See also Sibthorpe, this volume, for source confusion of Herschel observations.

Structures in some disks have been resolved using a variety of telescopes from optical to millimeter wavelengths. These observations show that some disks are not uniform either in the radial and azimuthal directions (e.g., Acke et al. 2012). In particular, Herschel and ALMA have allowed us to separate out a warm dust component at the star, which may be analogous to the asteroid belt at our solar system, from the bright remaining component at large radii (e.g., Acke et al. 2012; Su et al. 2013).

The extremely good sensitivity, wide wavelength coverage, and capability of spectro-imaging of SPICA will enable us to extend the studies at mid-to-far infrared wavelengths made using Spitzer, Herschel and AKARI in recent years. SAFARI and MCS will allow us to obtain the images of the disks at mid-to-far infrared wavelengths, significantly improving the detection limits and also improving the angular resolution at mid-infrared wavelengths. The morphological information provided by such an instrument will be used to study the diversity and the evolution of debris disks. As discussed for Herschel studies, spatial information is also useful to entangle the degeneracy between the disk structure, dust temperature,
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grain size and compositions (Booth et al. 2013), thereby understanding their physical nature in more detail. The field of view of these instruments (2’×2’ for SAFARI, FIR; 5’×5’ for MCS-WFS) is sufficient to cover such disks in a single frame.

Determining the SEDs at a wide wavelength coverage, SPICA will also be able to (1) search for more “warm disks” and (2) investigate the nature of “cold disks”. The spectroscopic capability of SPICA will allow us to search for emission lines associated with gas (see, e.g., Moór et al. 2011; Riviere-Marichalar et al. 2012; Roberge et al. 2013, for some detections). This will hopefully establish these lines as useful probes to study physical/chemical conditions of the disks. The spectroscopic studies for solid features will also be intriguing, as described in the next section, together with those for protoplanetary disks.

5. MINERALOGY AND ICES IN DISKS

Dust is the major building block for solid material in planets, and is the major constituent of the terrestrial planets and the cores of giant-gaseous planets. Of the materials included in dust grains, silicate has been extensively studied to investigate the thermal history of protoplanetary disks and pre-solar nebula. Mid-infrared spectroscopy of silicate features has revealed that, while the silicate in the interstellar medium is amorphous (Kemper et al. 2004), crystalline components exist in some disks and comets (Henning 2010, for a review) (see also Koch et al. this volume). This implies that thermal annealing at ~1000 K occurred during the disk evolution, but the detailed mechanism is not clear. While the direct spatial information of their distribution may be useful for tackling this issue, such observations have been limited to the brightest disks (e.g., Okamoto et al. 2004).

A variety of ices associated with dust grains have been observed toward young stellar objects (van Dishoeck 2004, for a review), and it is likely these also exist in protoplanetary disks. Water ice is of the greatest among the ices, and is thereby responsible for a significant fraction of the total dust mass. The “snow line” due to water ice may be a key feature in disks when discussing the evolution of planetary systems (e.g., Nagasawa et al. 2007). Ices may also affect the atmospheric compositions of gas giants after comets are formed and fall onto the planets (Cavalié et al. 2013) and/or sustain life in extrasolar planetary systems. Despite its importance, water ice in protoplanetary disks (not the edge of the disk — e.g., Terada et al. 2012) is not readily observable; we must either observe (1) emission features at 44/62 µm or (2) absorption features in a spatially resolved disk. Both are extremely challenging, and there have been only a limited number of successful observations (Malfait et al. 1999; Honda et al. 2009).

The capabilities of spectroscopy and spectro-imaging at SPICA will be powerful tools for extending the above studies. Firstly, it will cover silicate features at a wide range of wavelengths at mid- to far-infrared (e.g., Malfait et al. 1998), leading to detailed understanding of silicate compositions in the individual disks. Since far-infrared features are expected for both protoplanetary and debris disks, these will be useful for conducting statistical studies for both types of disks and for discussing possible evolutionary schemes. Furthermore, SAFARI and SCI will allow the observations the spatial distributions of silicate features in bright debris disks. Detailed spectroscopy of silicate features will allow the determination of the abundance of minerals (i.e., the abundance of Fe, Mg etc.) in detail (e.g., Sturm et al. 2013), and will be useful for studying similarities and differences of their compositions in disks.

SAFARI will also be useful for observing ice features at 44/62 µm for a number of protoplanetary disks. After the Infrared Space Observatory (ISO), SAFARI will provide the unique opportunity to entirely cover the above feature. Spectro-imaging of the 44/62 µm ice features towards the brightest debris disks could be used to infer the presence or absence of the “snow-line” in the disks, the possible boundary between terrestrial and gas-giant planets. Finally, SPICA, as well as JWST, will offer observational capabilities for a variety of ice features in the mid-infrared associated with the edge-on disks.

6. SOLAR SYSTEM SMALL BODIES

Solar system small bodies (TNOs, comets, asteroids) are believed to contain clues for the initial or early stage of the formation of our solar system, and its dynamical evolution. Since the first discovery in 1992 (Jewitt & Luu 1993) more than a thousand TNOs have been discovered around and beyond the orbit of Neptune. Simulations show that kinematic interactions between the TNOs and planets may result in the formation of the asteroid belt and may supply water to the earth in the early stages of its evolution (Gomes et al. 2005; Levison et al. 2009). Discovery of an amino acid in cometary dust is providing a new clue for the formation of life in space (Elsila et al. 2009).

The size distributions and chemical compositions of solar system bodies are fundamental parameters for studying the Edgeworth-Kuiper and asteroid belts in our solar system. In principle the visible and thermal infrared brightness have to be measured to determine the size, albedo (the parameter for investigating the surface composition for a large number of samples) and thermal inertia of unresolved solid bodies. The measurement of the SED, which peaks at ~100 µm for TNOs, dramatically decreases the uncertainties in the determination of these parameters. Such observational studies have been conducted using Herschel, but the samples are limited to the brightest targets (e.g., Fornasier et al. 2013).

SPICA will be ideally suited to the observation of the SEDs for these targets, with unprecedentedly high sensitivity and accuracy. Indeed, SPICA will be able to measure the SEDs for most TNOs known to date (Figure 4.; see also Kiss et al., this volume) and also asteroids in the asteroid belt with diameters down to 50 m (Usui et al., this volume). Such observations of a large number of TNOs will probe the conditions of the “Initial Solar Nebula” in much greater detail than previously accomplished.
Figure 4. Detection limits of known outer solar system objects (SSOs) using SPICA and Herschel as a function of heliocentric distance and diameter (Yellow Book). The left and right plots show those for photometry and spectroscopy, respectively.

Furthermore, low-resolution spectroscopy of the 44/62 \( \mu \)m water ice features will facilitate the study of the water ice content and thermal history of the outer solar system. The wide spectral coverage of SPICA also contain a variety of features useful for studying comets, and also comet-like asteroids. Comparing the dust and gas features with those of debris disks, we will be able to obtain another clue about their similarities or differences.

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Studies of Exoplanets and Solar Systems with \textit{SPICA}

The Far-IR View of Star and Planet Forming Regions

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ABSTRACT

The far-IR range is a critical wavelength range to characterize the physical and chemical processes that transform the interstellar material into stars and planets. Objects in the earliest phases of stellar and planet evolution release most of their energy at these long wavelengths. In this contribution we briefly summarise some of the most relevant scientific advances achieved by the Herschel Space Observatory in the field. We also anticipate those that will be made possible by the large increase in sensitivity of SPICA cooled telescope. It is concluded that only through sensitive far-IR observations much beyond Herschel capabilities we will be able to constrain the mass, the energy budget and the water content of hundreds of protostars and planet-forming disks.

1. INTRODUCTION

Modern astrophysics is just beginning to provide answers to some of the most basic questions about our place in the Universe: Are Solar Systems like our own common among the millions of stars in the Milky Way and, if so, what implications does this have for the occurrence of planets that might give rise to life? The basic building blocks of a planetary system, gas and dust, emit efficiently at mid- and far-IR wavelengths (\( \sim 5 \) to \( 350 \) \( \mu \text{m} \)), a critical domain in which to unveil the processes that transform the interstellar material into stars and planets.

Due to the atmospheric opacity, the far-infrared domain (\( \sim 30–350 \) \( \mu \text{m} \)) has been one of the last spectral windows used in astrophysics. Indeed, observing at these long wavelengths with sufficient angular resolution and sensitivity represents a significant technological challenge that requires space telescopes equipped with sophisticated cryogenic instrumentation (down to a few mK) and very sensitive detector arrays.

The far-IR domain began to be fully exploited by the NED/UK/NASA’s IRAS telescope and the ESA’s Infrared Space Observatory, ISO. It has been successfully continued by NASA’s Spitzer, JAXA’s AKARI and most recently by the very successful Herschel Space Observatory, the largest telescope ever launched to space and a cornerstone mission of ESA with science instruments provided by European-led Principal Investigator consortia and with participation from NASA (Pilbratt et al. 2010).

Observations with the above space telescopes revolutionised our understanding of where and how stars are born. Objects in the early phases of star formation (SF), and in the first stages of planet formation (protoplanetary disks) release most of their energy in this domain. The far-IR range provides key spectral diagnostics physical conditions (atomic fine structure lines, high-\( J \) CO lines, etc.), chemical evolution (water and light hydrides), dust composition (minerals and ices) and dust column density. Therefore, observing in this critical domain we can constrain the mass of protostars and planet-forming disks, access to their most important gas cooling lines and ultimately, understand their nature and predict their evolution.

The power of SPICA, a large single-dish cooled telescope with unprecedented sensitivity, broadband coverage and large field-of-view, will drastically improve our understanding of the star and planet formation processes (at small spatial scales), its environment, and its link to galaxy evolution (SF at large scales). In order to progress in these fields, SED mapping of large areas of the sky, as well as more detailed spectroscopic studies of large samples of young stellar objects (YSOs) at sensitivities well below those achieved by Herschel are clearly needed. In this context, only a very sensitive instrument covering the critical “far-IR gap” (e.g., SAFARI) will be able to characterise the objects and the environments that are too obscured for the thee James Webb Space Telescope (JWST) to examine in the mid-IR, or too warm and extended to be efficiently observed by the thee Atacama Large Millimeter/submillimeter Array (ALMA).

2. LESSONS FROM HERSCHEL AND THE NEED TO GO BEYOND

In this contribution, we summarise some of the most important achievements of Herschel in the field of star and planet formation. This review is necessarily incomplete and descriptive. The goal is to present some areas where Herschel, by observing in the far-IR, has made unique contributions. We will conclude by discussing its limitations and how only a cooled telescope like SPICA will push the frontiers of our knowledge.
2.1. The Filamentary Structure of the ISM

*Herschel*’s photometric cameras had the ability to map several square degrees in the 70/100/160 μm (PACS) and 250/350/500 μm (SPIRE) bands. *Herschel* images confirmed that nearby interstellar clouds are systematically structured in networks of filaments, the *universal filamentary structure of the ISM* (e.g., André et al. 2010; Molinari et al. 2010). These filaments are reminiscent of the structures found in large-scale magneto-hydrodynamic turbulence simulations of the ISM (e.g., Padoan et al. 2001). The structure and properties of the diffuse ISM provide the initial conditions for the formation of dense giant molecular clouds (GMCs) where stars are born. The physics that governs the large- and small-scale structure of such diffuse clouds is a complex interplay between magnetic fields, turbulence, gravity and thermodynamics.

*Herschel* has provided spectacular large-scale images of diffuse clouds before the onset of SF, including high latitude clouds like the Polaris Flare (Miville-Deschênes et al. 2010). They unambiguously reveal the filamentary and clumpy structure of the ISM down to spatial scales of ~0.01 pc (10” angular resolution for a source at ~200 pc or ~0.1 pc for a source at 2 kpc). Sensitivity and high imaging speed in photometric mode were the key instrumental attributes of *Herschel* photometric cameras.

Studying the morphology of a few hundred filaments, most of them regions with on-going SF, the team of P. André et al. concluded that these filaments have the same characteristic width (~0.1 pc; Arzoumanian et al. 2011). Although their origin is not fully understood, this scale corresponds to the same scale below which turbulence becomes subsonic in diffuse, non-star forming gas. These findings clearly connect the fundamental properties and structures of the ISM with the regions where stars form.

2.2. From Filaments to Cores

Far-IR photometric surveys of nearby clouds further indicate that cold prestellar cores form primarily along dense filaments as they fragment (e.g., André et al. 2010; Molinari et al. 2010). From the observational point of view, prestellar cores are detected in lines of sight where the column density of material is above a given $A_V$ threshold (roughly above 8 magnitudes of extinction). With a knowledge of the dust properties and of the dust-to-gas conversion factor, one can translate the observed far-IR and submm continuum luminosities into total masses. *Herschel* observations show that despite of their relevance (prestellar cores collapse gravitationally and form stars) only ~2% of the cloud mass is in these cores. The “gas to stars conversion” is far from being an efficient process. Therefore, most of the cloud mass, ~85%, is contained in the extended component at lower extinctions ($A_V < 8$ mag). These more diffuse regions are dominated by the interstellar turbulence, magnetic field and UV-irradiation. These results also mean that understanding and characterising observationally the extended component of GMCs at large scales has a great relevance.

By studying the mass distribution of the observed prestellar cores, the *Herschel* teams were able to plot the so called “core mass function” (CMF). The CMF appears to resemble the stellar initial mass function (IMF) of stars (meaning of course that stars form from cores). Yet the CMF is: (1) shifted towards higher masses by a factor of $\times 3$ and is not well sampled down to masses corresponding to the mean mass of the log-normal IMF ($< 0.3 M_{\odot}$) and into the brown dwarf regime (e.g., Hennebelle & Chabrier works). Improved sensitivity in the far-IR domain will be critical to cover this important stellar population (the most numerous) and to fully understand the origin of the IMF.

Far-IR observations are extremely important to understand the first stages of protostellar evolution. In particular, they are critical to search for the “holy grail” of SF, the so-called *first hydrostatic cores* (FHSC). Prestellar cores are thought to collapse isothermally until become dense and opaque. At this point, the radiation of the central object gets trapped and the gas is heated up to ~2000 K. At these temperatures, molecular hydrogen (containing the bulk of the core mass) starts to be dissociated (see e.g., Commerçon et al. 2012). This is a crucial but short-lived (~10$^2$–10$^3$ years) evolutionary stage towards the formation of a Sun-like star. FHSCs are rare objects and thus they are difficult to identify without mapping very large areas of several SFRs. For nearby SFRs, FHSCs should be visible at 70 μm (e.g., with *Herschel*) but not at 24 μm (e.g., with *Spitzer*). FHSCs have a peculiar SED not compatible with a single cold grey-body (like that of a starless/prestellar core) nor with more evolved SEDs of Class-0 protostars. *Herschel* observations of the B1-bs core in Perseus have shown that this is a good FHSC candidate (Pezzuto et al. 2012). Broad-band far-IR and submm observations over entire SFRs are clearly needed to improve the number of detections.

2.3. From Deeply Embedded Protostars to Protoplanetary Disks

Understanding the physical processes involved in the earliest stages of stellar evolution requires to study the heating and cooling mechanisms that take place in YSOs. Beyond photometry, far-IR spectroscopic observations can uniquely probe the evolution of the physical and chemical structures in YSOs, from warm protostellar envelopes and their outflows to planet-forming disks around young stars (e.g., van Dishoeck et al. 2011).

The evolutionary sequence from Class-0 to Class-II protostars is characterised by strong changes in the physical conditions (density, temperature, ionisation...), with the gas composition and excitation changing accordingly. Protostellar evolution is complicated and it is not fully understood. The detection of the most important coolants of the warm/hot gas in YSOs (H$_2$, high-J CO, H$_2$O and O) allows a quantitative determination of the energy budget in these objects. Complete far-IR spectral scans of embedded protostars with *Herschel* show very rich spectra, with more than a hundred.
lines detected even at medium spectral resolution (Goicoechea et al. 2012, see Figure 1) and with a SED peaking in the far-IR. In combination with mid-IR spectra, the entire IR domain is the key piece to characterise the envelope, outflow and disk emission (Herczeg et al. 2012). The far-IR range is uniquely well suited for the detection of tens of lines from warm water vapour and to detect water ice features (44/62 µm bands). Following the water abundance from prestellar cores to planet-forming disks is specially relevant, both as a unique diagnostic tool of the physical conditions in warm/hot gas and also as the key molecule to define the potential habitability conditions later in planetary systems.

Detailed models of the far-IR atomic and molecular lines have been used to characterise the main heating mechanisms in YSOs: shocks, X-rays, UV radiation, etc. (e.g., van Kempen et al. 2010). Unfortunately, owing to the large integration times required to cover the complete far-IR range, Herschel/PACS has only been able to spectroscopically characterise a small sample of bright protostars (e.g., Karska et al. 2013; Manoj et al. 2013; Green et al. 2013). Besides, only for a very few YSOs, these objects have complementary mid-IR spectra (from Spitzer). The above limitations have prevented a more global characterisation of SFRs with a much larger statistical meaning.

2.4. The Formation of Planetary Systems

Planets form in the accretion disks that develop during the collapse and infall of massive protostellar envelopes (∼10,000AU) where stars are born. In this context, the formation of planetary systems can be seen as a by-product of the SF process. However, we still don’t fully understand how young gas-rich protoplanetary disks evolve into planetary systems. Circumstellar disks are very faint, so far difficult to study spectroscopically. Hence, we still have a very incomplete understanding of the formation mechanisms responsible of the great diversity of extra-solar planetary systems detected so far, and of the peculiar features of our own Solar System. These, of course, ultimately include the formation of Earths-like rocky planets with significant liquid water to support life.

The basic building blocks of any planet-forming disk (gas and dust) radiate predominantly in the far-IR band. Key spectral line diagnostics such as warm water vapour, HD, atomic oxygen or dust features can only be observed in this domain. For the first time, Herschel reached the sensitivity to carry out far-IR spectroscopy in a few bright protoplanetary disks (e.g., Thi et al. 2010; Fedele et al. 2012; Meeus et al. 2012). Interesting detections include the discovery of significant reservoirs of both cold and warm water vapour in planet-forming disks (Hogerheijde et al. 2011; Riviere-Marichalar et al. 2012). Together with the detection of [O I] 63 µm (the brightest line in disks), much more sensitive detections of water (vapour and ice) in hundreds of disks are needed to fully understand the processes that drive the position of the snow line, and thus the mechanisms that lead to the formation of rocky versus gaseous planets.

Figure 1. Far-IR continuum-subtracted spectrum of the Class 0 protostar Serpens SMM1 taken with Herschel/PACS (Goicoechea et al. 2012). The blue spectrum shows the same spectra as it would be observed in a “fast” low-resolution mode with SAFARI (R∼200 at 100 µm). A complete spectrum (∼34-210 µm) over a FoV of 2′×2′ could be obtained by SAFARI in only ∼30 sec (∼3 h and worse sensitivity with PACS). A higher spectral resolution spectrum (similar to PACS) and better adapted for the observation of planet-forming disks, can be obtained by SAFARI in ∼4 min.
Molecular hydrogen is the most abundant gas species in protoplanetary disks (containing ∼90% of the initial disk mass). However, H₂ is a symmetric molecule and it does not emit radiation efficiently. Instead, the deuterated isotopologue, HD (with its lowest rotational transitions at 112, 56 and 37 μm – not observable with JWST or ALMA) turns out to be the most powerful tracer of the disk total mass. Depending on the excitation conditions, the far-IR lines of HD can be many times more emissive than those of H₂. The only Herschel detection of HD (J =1–0 line at 112 μm) towards TW Hydae disk is a major discovery and implies a disk mass of more than 0.05 solar masses (Bergin et al. 2013). This is enough to form a planetary system like the Solar System despite the advanced age of TW Hya (∼10Myr). Indeed, HD is also an important constituent of Jupiter-like giant planets and it is also present in the atmospheres of Uranus and Neptune (Feuchtgruber et al. 2013). The detection of HD towards the closest protoplanetary disk (at ∼60 pc) required 7 h of integration time and pushed the detection limits of PACS. A factor ∼10 better line sensitivity will be needed to detect HD lines in protoplanetary disks at the distance of the closest SFRs. This will allow us to carry out a unique survey of disks with SAFARI and accurately constrain the mass of a statistically significant sample of planet-forming disks in different SFRs.

3. SPICA, A NEW GENERATION FAR-IR COOLED SPACE TELESCOPE

While the very successful Herschel mission demonstrates that only in the far-IR we can answer fundamental questions on the star and planet formation processes, Herschel has only shown the tip of the iceberg. This conclusion specially applies to the spectroscopic characterisation of YSOs and disks. The number of objects studied was clearly limited. Besides, the Herschel telescope was passively cooled to ∼80 K, thus only offering a modest increase in sensitivity compared to previous facilities in the far-IR range. The lack of sensitivity and of spectrometers designed to carry out large-mapping also precluded the spectroscopic characterisation of ISM clouds and SFRs globally.

In order to better explain the need for a new, much more sensitive telescope, one has to take into account the capabilities and scientific merit of the major astronomical infrastructures of the next decade. In ∼2025, ALMA will be in full operations, providing very high angular and spectral resolution observations in the submm and mm domains. ALMA will resolve the inner structures and the outflows of YSOs and it will observe planet-forming disks in great detail, being more sensitive to the low excitation molecular gas. ALMA, however, will not have access to the most important cooling lines of the warm/hot gas (high-J CO, H₂O, [C II], [O I], ...), it will not observe YSOs at their SED peak and it cannot observe mineral and ice features (the basic ingredients of a planetary system). Also important, ALMA is inefficient for large-scale mapping.

JWST will provide a major increase in angular resolution and sensitivity in the mid-IR domain, but JWST only covers the λ<28 μm range. Hence, it does not cover the critical far-IR band. Besides, it does not provide a high spectral resolution spectrometer in the mid-IR. Finally, JWST is not designed to have a coronagraph with spectroscopic capabilities to characterise young exoplanets directly. In the next decade, ELT and TMT-type optical and near-IR telescopes will also be built. Owing to the extinction at these short wavelengths, the regions where stars form will remain obscured.

After Herschel’s end of mission, windows of the far-IR domain will be still available for SOFIA stratospheric observations. However, the angular resolution and the sensitivity is not better, and key molecules like H₂O cannot be observed. All in all, it is clear that a very sensitive telescope is needed to cover the critical far-IR wavelength range between JWST and ALMA. In order to go significantly beyond Herschel capabilities, such a space telescope needs to be specialised both in large-scale spectral mapping and in providing detailed spectroscopic characterisation of individual YSOs and disks (i.e., observe faint lines, a few 10⁻¹⁹ W m⁻², on top of a ∼0.1–10 Jy continuum).

3.1. SPICA Observations of Star and Planet Forming Regions

SPICA’s large and cold aperture (∼3.2 m at <6 K) will provide a two order of magnitude sensitivity advantage over current far-IR facilities. In combination with a new generation of highly sensitive detector arrays, the low telescope background will allow us to achieve sky-limited sensitivity over the far-IR range. In its current design, the SAFARI instrument covers the far-IR band with a large, fully-sampled field-of-view of 2′×2′, both in photometry (48, 85 and 160 μm) and in spectroscopy (∼34–210 μm). The angular resolution of SPICA in the 48 μm band is ∼4″. As an spectrometer, SAFARI will offer a medium resolution mode (R∼2000/4000 at 100/50 μm) and a faster low-resolution mode (R∼200/400 at 100/50 μm). The latter one will be enough to efficiently detect the dust SED and the brightest cooling lines in very short times. Contrary to Herschel (very time-consuming and inefficient) this will allow us to map large areas of the sky in periodic intervals of time, opening new avenues for time-variability studies of protostars and protoplanetary disks in SFRs.

Transition from diffuse ISM clouds to GMCs:

SPICA will allow us to study the transition from diffuse clouds to GMCs where stars are form. By accessing the most important cooling lines of the ISM ([C II]158 μm) and the dust SED, we will be able to constrain the gas thermodynamics at large-scales and relate it to the the formation of filaments and their fragmentation. Dense filaments in SFRs are embedded in a more diffuse and turbulent medium that seems to be driven on larger scales. As we have seen, these more quiescent and extended regions constitute the bulk of the GMCs mass and play a critical role in their evolution. In spite of their relevance, the interfaces between the SF cores and the environment are less characterised spectroscopically and thus remain poorly understood. Many questions still need to be answered. How are GMCs formed and destroyed?
THE FAR-IR VIEW OF STAR AND PLANET FORMING REGIONS

Table 1. Herschel versus SPICA observations of YSOs in the far-IR.

<table>
<thead>
<tr>
<th>Class 0 protostar</th>
<th>Serpens SMM1 at 200 pc</th>
<th>Serpens SMM1 at 2 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Herschel/PACS</td>
<td>SPICA/SAFARI</td>
</tr>
<tr>
<td>Continuum at 100 μm</td>
<td>~250 Jy</td>
<td>~2.5 Jy</td>
</tr>
<tr>
<td>O163 μm (brightest line)</td>
<td>8E-15 W m^(-2)</td>
<td>8E-17 W m^(-2)</td>
</tr>
<tr>
<td>CO J=30-29 at 87.2 μm</td>
<td>7E-16 W m^(-2)</td>
<td>7E-18 W m^(-2)</td>
</tr>
<tr>
<td>Complete far-IR spectrum</td>
<td>~3h</td>
<td>~4 min</td>
</tr>
<tr>
<td>(R~2000 at 100 μm)</td>
<td>(rms~5E-18 W m^(-2))</td>
<td>(rms~1E-18 W m^(-2))</td>
</tr>
<tr>
<td>10′×10′ fully sampled map</td>
<td>~100 h for 1 line</td>
<td>&lt;3 h* (full far-IR band)</td>
</tr>
<tr>
<td>(R~2000 at 100 μm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10′×10′ fully sampled map</td>
<td>Not possible</td>
<td>&lt;1.5 h* (full far-IR band)</td>
</tr>
<tr>
<td>(R~200 at 100 μm)</td>
<td></td>
<td></td>
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</tbody>
</table>

*Assumes a pessimistic overhead of ~3 min between each consecutive FoV position.

How does SF affect their structure, evolution, and lifetime? (feedback). How does the environment determine the SF process? (fragmentation, efficiency ...)

While complete far-IR spectroscopic surveys of a handful of bright YSOs with Herschel provided the most complete information on the physical conditions and chemical content of individual sites of SF (hot cores, protostars, H II, etc.), they do not place the observations in the context of the large-scale emission (their environment). This has great relevance since it is the widespread gas and dust that set the initial conditions for SF. Contrary to Herschel, SPICA/SAFARI will map these faint extended regions both in the dust continuum and in bright cooling lines ([C II], [O I], [N II], ...), detecting individual objects and characterising their environment simultaneously. As noted earlier, ground-based submm telescopes such as ALMA cannot access the most important cooling lines of the warm/hot gas in YSOs. Nor can they observe the SED peak, which is essential to determine the dust temperature.

Spectral characterisation of protostars and planet-forming disks:
Mapping GMCs across the broad wavelength range of SPICA/SAFARI at multi-line mapping speeds orders of magnitude beyond the capabilities of Herschel, we will be able to completely sample a few appropriate SFRs for:
(a) short-lived first hydrostatic protostellar cores,
(b) protostars down to 0.01 M_{Sun} throughout the Class 0–I–II stages from 0.1–1 Myrs,
(c) planet-forming disks with a broad range of masses and evolutive stages.

The simultaneous observation of the complete SED, dust grain features and of a wealth of atomic fine structure, H_{2}O, high-J CO and HD lines will make SAFARI a unique instrument to constrain the mass, the energy budget and the water content of hundreds of YSOs and disks. Also very important, SPICA/MCS will be able to trace the hot gas and resolve the gas kinematics in many YSOs and disks, providing R~30,000 resolution at the wavelength of key H_{2} rotational lines and of some mid-IR vibrational bands from organic molecules.

In conclusion, complementing JWST and ALMA observations, SPICA will allow us to understand the nature of these objects and to critically test star/planet formation and evolution theories.

3.2. Observing with SPICA/SAFARI
As an example of the powerful SPICA/SAFARI capabilities (Roelofsema et al. 2012), Table 1 shows one of the few protostars (nearby and bright) for which a complete Herschel spectrum exists (Goicoechea et al. 2012). In comparison with Herschel (a handful of bright individual objects and a few small maps of very bright lines), SAFARI will be able to carry-out unbiased spectral-mapping surveys of entire SFRs. For the first time in the critical far-IR domain, this will allow us to characterise hundreds of protostars and planet-forming disks, together with their environment simultaneously.

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Results from the *Herschel* DIGIT Open Time Key Program

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on behalf of the DIGIT team

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ABSTRACT

Results obtained in the framework of the DIGIT (Dust, Ice and Gas in Time) *Herschel* open time key program are presented, with a focus on proto-planetary disks. The results summarized here show the richness of the infrared spectral range for the study of proto-planetary disks and the potential of *SPICA* in this area.

1. THE DIGIT OPEN TIME KEY PROGRAM

The DIGIT (Dust, Ice and Gas in Time) open time Key program (Principal investigator Neal J. Evans) uses the *Herschel* Space Observatory (Pilbratt et al. 2010) to study the evolution of young stellar objects towards planetary systems. The unprecedented sensitivity of *Herschel* allows for a comprehensive inventory of gas and solids in the environments of young stars, thus probing the changing physical and chemical conditions as star- and planet formation proceed. The DIGIT sample consists of 94 objects including protostars, Herbig Ae/Be stars, T Tauri stars, and weak-lined T Tauri stars. Many of the stars in the DIGIT sample are well characterized at other wavelengths; in particular *Spitzer* data are available. The new *Herschel* data can thus be put into the context of these existing data. Most *Herschel* observations were taken with the PACS instrument (Poglitsch et al. 2010), but also data with HIFI (de Graauw et al. 2010) and SPIRE photometry (Griffin et al. 2010) was obtained. First results of the DIGIT program were published by van Kempen et al. (2010) and Sturm et al. (2010). In several recent papers analyses are presented of the different categories of objects included in the DIGIT sample, e.g. weak-lined T Tauri stars (Cieza et al. 2013), proto-planetary disks (Fedele et al. 2013; Meeus et al. 2013), and embedded protostars (Green et al. 2013). A summary of results of the DIGIT program was presented by Bouwman & Evans (2012). Several other *Herschel* key programs also address the evolution of young stars, in particular the GASPS (Dent et al. 2013) and the WISH (van Dishoeck et al. 2011) programs. In this paper, we focus on results obtained for the proto-planetary disks sample. Figure 1 shows the infrared spectrum of one of the best studied objects in the sample, the Herbig Ae/Be star HD 100546.

![Figure 1](image.png)

Figure 1. Spectral energy distribution of the Herbig Ae/Be star HD100546, showing the *Spitzer* IRS spectrum, and the full PACS scan (Bouwman et al., in preparation). The inset shows the 69 μm forsterite band (Sturm et al. 2010).
DIGIT TEAM

2. EVOLUTION OF PROTO-PLANETARY DISKS

Planet formation has a profound influence on the structure and composition of proto-planetary disks, both of the gas and the solids. Small sub-micron sized grains that enter the disk from the molecular cloud grow by coagulation, and subsequently settle to the disk mid-plane. Radial and vertical mixing cause material to be transported from inner disk to outer disk regions, and from the mid-plane to the disk surface. Grain-grain collisions cause larger grains to be fragmented to smaller particles in a delicate balance between grain growth and destruction. In the inner disk chemical and thermal processing of primordial material takes place, (partially) erasing the memory of its origin. This processed material is mixed to the outer regions and becomes incorporated into planetesimals, that carry the imprint of these local conditions.

As planets form and migrate, they clear parts of the disk, creating gaps and holes. Such disks are often classified as transitional disks, as their spectral energy distribution shows a lack of emission in the near- and mid-infrared compared to continuous disks. Disk gaps complicate the accretion of gas and dust from the outer regions to the central young star, allowing for a widely varying spatial composition of the material in the disk. For instance, small grains can cross gaps more easily than larger grains, and proto-planets can cause azimuthally varying dust density and composition. Some disk gaps are found to be filled with gas (e.g. Casassus et al. 2013), while the signature for solid material is less obvious. The composition and chemistry that takes place in these disk gaps is interesting, since the material is less shielded from stellar photons due to the decrease in the local dust opacity.

The Herschel wavelength range is particularly suited to study the gas and dust emission from the warm disk surface layers and cooler material from e.g. the outer regions of proto-planetary disks, and thus complements the diagnostics provided by e.g. Spitzer, ALMA, and ground-based near-infrared spectroscopy and imaging. As an example, we show in Figure 1 the infrared spectrum of HD100546 (Bouwman et al., in preparation), showing both dust and gas emission from its proto-planetary disk.

3. GAS IN PROTO-PLANETARY DISKS: A DIGIT VIEW

Table 1 gives an overview of the gas species detected in the DIGIT sample, divided between the more massive Herbig Ae/Be stars and the T Tauri stars. The [C II] fine structure line was not covered in all spectra, and some of the emission may be of a diffuse nature and not associated with the disk.

The relatively low fraction of Herbig Ae/Be stars with H$_2$O detections (compared to T Tau stars) and the relatively higher detection rate of OH for these stars suggests that water may be dissociated to OH, perhaps as a result of the stronger radiation field of the more luminous Herbig Ae/Be stars. However we note that a substantial fraction of the Herbig Ae/Be stars in the DIGIT sample (previously classified as “flaring” or Meeus group I; Meeus et al. 2001) have recently been recognized to be transitional disks with substantial clearing of the inner disk regions (Honda et al. 2012; Maaskant et al. 2013), which may hamper a direct comparison to the T Tau stars in the sample. Fedele et al. (2012) model the OH and water emission in HD 163296 and find that it is most likely located in the upper layers of the disk atmosphere at distances of 15 to 20 AU from the star.

When applying PDR models to the detected fine structure line emission of [O I] and [C II], constraints on the gas densities and the radiation field can be derived (Fedele et al. 2013). The DIGIT data suggest typical densities of the order of 10$^5$ cm$^{-3}$ and G$_0$ between 10$^3$ and 10$^4$. Since some of the [C II] emission may be diffuse, these values are in some cases lower limits.

CO is sometimes detected to very high rotational quantum numbers, probing gas at high excitation. In the Herbig Ae/Be stars, modeling of the CO ladder shows that the gas and dust in the upper disk layers must be decoupled, with T$_{gas}$ larger than T$_{dust}$ (e.g. Bruderer et al. 2012). Interestingly, CO is detected only in the “flaring disks” among the Herbig Ae/Be stars (see Meeus et al. 2012). These objects also show strong PAH emission. As mentioned above, these “flaring” disks may in fact be transitional disks. In several of these “flaring” disks a lack of CO ro-vibrational emission from the inner disk regions has been reported, suggesting lower gas surface densities in the inner disk (Brittain et al. 2009; van der Plas et al. 2009). The detected CO emission in these disks is more likely associated with a disk wall at 10 to several tens of AU, and with the outer disk, or possibly CO gas in the disk gap.

Finally, CH$^+$ is detected in two Herbig Ae/Be stars. The first detection of CH$^+$ was reported by Thi et al. (2011) in HD100546, using data from the GASPS Herschel open time Key Program. They model the CH$^+$ in HD100546 using a physical/chemical disk model and find that the CH$^+$ is probably associated with the disk wall at ~13 AU, extending to ~30 AU. Using a slab model and an update of the flux calibration (resulting in different CH$^+$ line fluxes for HD 100546 compared to Thi et al. (2011)), Fedele et al. (2013) arrive at a location of the CH$^+$ emission of several tens of AU. Fedele et al. (2013) add the detection of CH$^+$ in HD97048 based on DIGIT data.

4. DUST EMISSION FROM PROTO-PLANETARY DISKS

The Spectral Energy Distribution of proto-planetary disks is dominated by thermal infrared emission from the dust in the disk. At mid-infrared wavelengths (typically 10 to ~100 μm) the warm dust particles in the disk atmosphere dominate. Apart from a strong continuum, dust grains also produce spectral features (dust bands) as a result of the vibrational resonances in the solid. The wavelength and strength of these dust bands depend on the chemical composition, lattice structure, size and shape of the dust particles. Depending on the thermal history of the grains, the lattice structure can either be amorphous (as is the case for e.g. interstellar silicates), or crystalline. The infrared spectral region is very rich
in strong resonances of the most abundant dust species, and offers an ideal hunting ground for the mineralogy of disks. Below we focus on crystalline silicates and water ice.

The formation of crystalline silicates requires annealing of amorphous silicates to temperatures above the glass temperature of $\sim$1000 K, or gas-phase condensation (typically at temperatures of $\sim$1500 K). Crystalline silicates were found to be abundant in many proto-planetary disks (e.g. Malfait et al. 1998; van Boekel et al. 2005; Juhász et al. 2010; Sicilia-Aguilar et al. 2011; Furlan et al. 2011), and because they are not found in interstellar space they must have been formed in the disk. Tracing the location and abundance of crystalline silicates may thus probe the thermal and mixing history of proto-planetary disks. In addition to crystalline silicates, previous missions have also suggested the presence of hydrosilicates in one Herbig star, HD142527 (Malfait et al. 1999).

So far studies of dust bands using *Herschel*/PACS have been mostly limited to a narrow band of forsterite ($\text{Mg}_2\text{SiO}_4$) near 69 $\mu$m (Sturm et al. 2010; Sturm et al. 2013). Weaker and broader bands (detected with *ISO*-LWS in some objects) were more difficult to study in PACS data because their analysis critically depends on a reliable relative spectral response. However recent improvements in the calibration now make it possible to study other bands. We show in Figure 1 the PACS full scan of HD100546 (Bouwman et al., in preparation). Apart from the 69 $\mu$m forsterite band previously reported by Sturm et al. (2010), the spectrum also shows a weak broad band near 62 $\mu$m which can be attributed to crystalline water ice.

The shape and wavelength of the 69 $\mu$m forsterite band is very sensitive to the presence of Fe in the lattice. Forsterite is the Mg-rich end member of the olivine family, which chemical formula $\text{Mg}_2\text{Fe}_{2-2x}\text{SiO}_4$. Even a small addition of Fe of a few per cent moves the band by several microns, and so this is a very sensitive probe of the chemical composition of crystalline olivine in disks. The width of the band is sensitive to the temperature of the grains. The *Herschel* data show that the amount of Fe is less than 2 per cent (with the notable exception of AB Aur), and fairly warm (100–200 K) (Sturm et al. 2013). In terms of chemistry, Fe has not played a role in the gas-phase condensation of these grains, or it has been removed from the lattice during annealing. The chemical composition of these grains resembles those seen in solar system comets and interplanetary dust grains, and is not consistent with the more Fe-rich olivine found in meteorites that originate from the asteroid belt. Using a detailed radiative transfer model, Mulders et al. (2011) show that the forsterite in HD 100546 is located on the disk surface layers near the inner radius of the outer disk, and probably related to the presence of the disk gap.

Water ice shows strong resonances in the near- and far-infrared. Here we focus on the along wavelength bands near 44 and 60 $\mu$m, probing a cold water ice reservoir in disks. The shape and wavelength of the bands is sensitive to the lattice structure and thermal history of the water ice. The detection of crystalline water ice in disks opens the exciting possibility of studying the snow line in proto-planetary disks. In addition, it allows for a more complete census of water in disks than can be obtained from water vapor measurements. Indeed, prominent crystalline water ice bands at 44 and 60 $\mu$m were already detected by *ISO* in the Herbig star HD 142527 (Malfait et al. 1999). Since the temperature of the water ice in HD 142527 was found to be below the crystallization temperature, substantial thermal processing must have occurred in its outer disk.

Water ice was detected in the PACS spectrum of the T Tau star GQ Lup (McClure et al. 2012), which when confirmed represents the first detection of the 60 $\mu$m water ice band using *Herschel*. The *Herschel*-PACS spectrum of HD 142527 confirms the presence of a large reservoir of water ice in its disk (Min et al., in preparation). However, the broad emission at $\sim$110 $\mu$m reported by Malfait et al. (1999), which was attributed to hydrosilicates, is not found in the PACS data. Bouwman et al. (in preparation) report the detection of crystalline water ice in HD 100546. A preliminary analysis of the water ice shows that it is located slightly beyond the disk wall at $\sim$20 AU and with an abundance of $\sim$1 per cent (Mulders, private communication).

5. THE PROSPECT OF *SPICA*

The tremendous gain in sensitivity that *SPICA* (Nakagawa et al. 2011) will provide opens the possibility to study gas and dust in a large range of objects. In particular full spectral scans using *Herschel* could only be obtained for the brightest,
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most massive disks, with already very rewarding results. Extending the studies of disks to lower mass stars and even brown dwarfs is an important step in quantifying the connection between planet formation and the architecture of mature planetary systems. The wide wavelength range that SPICA will offer allows for a comprehensive inventory of gas and dust from the warm inner disk regions (the region of terrestrial planet formation, tracing e.g. organic chemistry), to the colder outer regions where gas giants and icy planets form. Lastly, SPICA will be the first space observatory since ISO to provide access to the important ∼35 to ∼55 µm wavelength region, which contains a wealth of diagnostic tools.

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Wide Separation Planets and Their Implications for Planet Formation Theory

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ABSTRACT

We discuss significance of direct imaging observations of extrasolar planets from theoretical points of view. Statistical properties of frequency and correlations of mass, semimajor axis and eccentricity for wide separation (≥ 30 AU) gas giants will determine which is the dominant process for formation of gas giant planets, standard core accretion model or disk instability model. We also point out that direct imaging and spectroscopic observation for “habitable” rocky planets is not completely impossible by SPICA SCI, so that it is worth challenging.

1. INTRODUCTION

Since the first discovery of extrasolar planets in 1995, the pace of observational discovery (with radial velocity, transit, microlensing, and direct imaging surveys) has been accelerated. As of 2013, over 1000 extrasolar planets have been confirmed, mostly found by means of precise radial velocity surveys (see e.g., exoplanet.eu). Additionally, there are more than 2700 transiting candidate planets found by the Kepler space telescope. All these detections have revealed that planets are quite common objects and that planetary systems are much more diverse than expected from our own Solar System. The increasing numbers of discovered extrasolar planets provide rich data sets on the statistical properties of extrasolar planets and planetary systems.

To discuss the statistical properties and subtract intrinsic physics of planet formation, “planet population synthesis” is a powerful tool (e.g., Ida & Lin 2004a,b, 2005, 2008a,b, 2010; Ida et al. 2013; Mordasini et al. 2009a,b; Alibert et al. 2011, 2013). Planet formation is composed of multi-step processes such as formation and evolution of a circumstellar disk, dust coagulation to form planetesimals in the disk, planetesimal accretion to form planetary embryos and cores, disk gas accretion onto the cores, orbital migration of planets/cores due to gravitational interactions with the disk, and gravitational scattering between planets. Planet population synthesis is a theoretical model integrating tractable models for the individual processes of planet formation that are based on detailed N-body simulations, fluid dynamical simulations and so on.

Radial velocity and Kepler surveys show that Earths/super-Earths are ubiquitous in extrasolar planetary systems and most of them are members of multiple planets. To calibrate the planet formation theory, it is important to compare theoretical predictions for statistical distributions of overall configurations of planetary systems with observations, rather than individual planets only. While radial velocity and transit observations are biased to close-in planets, direct imaging observations detect wide separation planets.

One possible survey for planetary “systems” is a survey of close-in planets (≪ 0.5 AU) by TESS (the Transiting Exoplanet Survey Satellite) with follow-up by ground-based radial velocity observations for planets with moderate semimajor axes (∼ 0.5–5 AU) and that by direct imaging of wide separation gas giants (≥ 10 AU). TESS will be launched in 2017. It is designed to search for extrasolar planets using the transit method like Kepler. While radial velocity follow-up is difficult for Kepler candidates due to faintness of Kepler target stars, TESS is all-sky survey and target stars for TESS are relatively bright, which makes the follow-up easier. SPICA SCI is one of the most important tools for the direct imaging follow-up.

On the other hand, direct imaging surveys for wide separation gas giants will discriminate between core accretion theory and disk instability theory for formation of gas giants, which we will discuss in section 2. A challenging observation that might be possible for SPICA SCI is direct imaging of “habitable” rocky planets, which will be commented on in section 3.

2. CORE ACCRETION VS. DISK INSTABILITY

Core accretion model is a standard model for formation of gas giants (e.g., Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996; Ikoma et al. 2000), based on planetesimal hypothesis (Safronov 1969; Hayashi et al. 1985). In this model, 1) rocky/icy cores accrete from planetesimals, 2) atmosphere of the core starts quasi-static contraction when the core mass exceeds a critical core mass (∼ 5 − 10M⊕ where M⊕ is Earth mass), and 3) the gas accretion onto the core is accelerated until the planet opens up a gap in the disk or the disk gets depleted.

In disk instability model, gas giants are directly formed by self-gravitational instability of the disk (e.g., Cameron 1978; Boss 1997; Boley 2006). Difficulty of formation of rocky and icy planets was pointed out in this model, while core

1 see e.g., http://www.kepler.nasa.gov/
accretion model reasonably accounts for formation of rocky/icy planets and gas giants in the same planetary system. As a result, core accretion model has been regarded as a “standard” model. However, recently, a tidal downsizing model for the gas clumps formed by the disk instability (e.g., Nayakshin 2010a,b, 2011) was proposed. This model suggests that rocky/icy planets can be formed by tidal stripping of outer gas envelope of inwardly migrating gas clumps, if dust settling into the central part of the clumps occurs quickly.

Because core growth rapidly becomes slower as orbital radius increases, formation of gas giants are limited within ∼ 30 AU (Ida & Lin 2004a) in core accretion model. The discoveries of wide separation (≥ 30 AU) gas giants by direct imaging such as HR 8799 b, c, d and d, GJ 504 b and HD 95086 b raised the possibility of gas giant formation through disk instability model. Scattering between gas giants can send some fraction of gas giant to large orbital radius (e.g., Marzari & Weidenschilling 2002; Nagasawa et al. 2008; Chatterjee et al. 2008). In that case, the orbit of the outwardly scattered planet must be highly eccentric, because the periastron must be preserved in planet forming region at ∼ 30 AU. For example, planets scattered to attain a semimajor axis ≥ 100 AU necessarily have orbits with eccentricity e ≥ 0.7. However, observations suggest that the orbits of the discovered wide separation gas giants are nearly circular.

Ida et al. (2013) showed that their population synthesis model generated a population of relatively massive gas giants in nearly circular orbits with large semimajor axis (a ≥ 30 AU) as shown in Figure 1. In their fiducial model, the fraction of host stars that have these planets is several %. They found that the rapid gas accretion of giants destabilize the orbits of nearby residual planetary embryos (cores) and some cores are scattered to large distance. Because the scattered cores are usually well below the local disk mass, even the relatively low surface density gas damps the core’s eccentricity. A reduction in the planetesimal accretion rate at these distance also lowers the critical core mass. As a result, the core starts gas accretion.

During the course of mass accretion, the planets acquire angular momentum of the disk gas. The scattered core initially has high eccentricity. Since the core spends most of time near the apoapsis for a highly eccentric orbit, the gas the core accretes has higher specific angular momentum than that of the core. Accordingly, as the core evolves into gas giants, its orbit is circularized with a radius close to its apoapsis radius.

The wide separation gas giants in nearly circular orbits formed by this process should have a clear correlation between their mass \( M_p \) and semimajor axis \( a \). The maximum mass of gas giants that is limited by gap opening along their orbits in their natal disks is proportional to their natal disks’ aspect ratio which is generally an increasing function of \( a \) (e.g., Hayashi 1981; Lin & Papaloizou 1985; Ida & Lin 2004a). Whether this trend exists or not is an important target for direct imaging observations.

In this process, multiple cores can be scattered outward to initiate gas accretion. Ida et al. (2013) showed that in their fiducial models, the fraction of systems with two, three, and four giants with low-eccentricity orbits is 0.4%, 0.07%, and 0.04%, respectively.

If a finite disk size is considered, the outwardly scattered cores would not accrete gas beyond the truncation radius. Then, the final semimajor axes of the formed giants would be comparable to the disk size. The observed semimajor axis distribution of gas giant planets could be used to place constraints on the structure and evolution of their natal disks.

Planet population synthesis for disk instability model has been addressed by only one paper (Forgan & Rice 2013). Because the population synthesis for disk instability model has just begun, it has not produced predictions for quantitative probability of wide separation gas giants and correlations in their distributions that can be compared with observations. It is very important to develop the population synthesis for disk instability model in order for direct imaging observation to discriminate between core accretion and disk instability models.

3. DIRECT IMAGING OF HABITABLE PLANETS

While direct imaging surveys of wide separation gas giants are important, it might be possible for \textit{SPICA SCI} to directly image “habitable” rocky planets. The challenging observation, but its impact is very big. Matsuo et al. (2011) showed that SCI can detect planets with a few \( R_{\oplus} \) at ≥ 10 AU, where \( R_{\oplus} \) is Earth physical radius. Such planets can be rocky super-Earths. The location of the ice line beyond which icy grains condense is ∼ 3(\( L_*/L_{\odot} \))^{1/2} AU (Hayashi 1981), where \( L_* \) and \( L_{\odot} \) are stellar and solar luminosities. Around A dwarfs, the ice line can be beyond 10 AU. Around solar-type stars, while the ice line is well inside 10 AU, super-Earths could be scattered outward from the regions inside the ice line.

However, conventional determination of “habitable” zone is located well inside of the ice line. “Habitable” zone is defined by a range of semimajor axis at which liquid water (ocean) can be maintained on planets with thick atmosphere. Kasting et al. (1993) considered stellar irradiation and CO\textsubscript{2} greenhouse effect to determine habitable zone. They determined the outer boundary of habitable zone by condensation of CO\textsubscript{2} (disappearance of greenhouse effect). In that case, the outer boundary is around 1.5(\( L_*/L_{\odot} \))^{1/2} AU. Even around A dwarfs with \( L_* \) ∼ 10\( L_{\odot} \), the outer boundary is ∼ 5 AU. Then, super-Earths at ≥ 10 AU are not likely to be habitable in this framework.

However, if we consider super-Earths or Neptunes, habitable zone could be much broader. It is suggested that some of transiting super-Earths and Neptunes discovered by \textit{Kepler} may have thick H/He atmosphere that may have been acquired from their natal protoplanetary disks. H\textsubscript{2} atmosphere has collision-induced opacity that is important for high density (e.g., Pierrehumbert & Gaidos 2011). Note that the H\textsubscript{2} gas does not condense except for extremely low temperature. Under
the dense H/He atmosphere, long-lived radioactive decay may provide enough heating for maintaining liquid water even without stellar irradiation (Stevenson 1999). Thus, planets with a few $R_\oplus$ at $\gtrsim 10$ AU could be habitable planets.

Figure 1. Distributions of planets of 10000 systems produced by a fiducial model of population synthesis calculations in Ida et al. (2013). Top: Orbital eccentricity $e$ vs. semimajor axis $a$ in AU. Bottom: Planet mass $M_p$ in Earth mass vs. $a$. The planets surrounded by dashed circles are gas giant planets with $a \gtrsim 30$ AU and $e$ (modified from the result in citetIL13)
Ida

A problem is how to identify habitability of such planets. If spectroscopic observation is available, detection of \( \text{H}_2\text{O} \) vapor or measurement of atmospheric mass and pressure to evaluate surface temperature may give information of existence of liquid water. Biomarker is also a problem. So far, detection of \( \text{O}_3 \) line at 10\( \mu \text{m} \) has been proposed to identify existence of photosynthesis life, because the detection implies abundant \( \text{O}_2 \) atmosphere. However, in the dense H/He atmosphere, \( \text{O}_2 \) is quickly depleted by reacting with \( \text{H}_2 \) to form \( \text{H}_2\text{O} \). So, photosynthesis life may not emerge on such planets. Detection of habitable planets is really challenging, but it is not completely impossible. Because just a single detection gives a big impact, it may be worth trying.

4. SUMMARY

We have discussed how direct imaging observations of extrasolar planets constrain planet formation theory. We pointed out that frequency and correlations of wide separation (\( \gtrsim 30 \text{AU} \)) gas giants are important. Planet population synthesis simulations predict that in core accretion model, wide separation gas giants should show a clear correlation that planet mass increases with semimajor axis and the frequency of solar type stars harboring such planets may be several \%. Although similar simulations for disk instability model have not been established yet, statistical distributions of wide separation gas giants that will be revealed by direct imaging surveys can discriminate between standard core accretion model and disk instability model for dominant formation mechanism of gas giants.

We also pointed out theoretical arguments that super-Earths with thick H/He atmosphere can have ocean even at \( \gtrsim 10 \text{AU} \). Direct imaging of such planets is not impossible for SPICA SCI. Although it is highly challenging, its impact is huge. More detailed considerations may be needed for this observation.

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Current Understanding of Young Circumstellar Disks: Observations of Gaseous Protoplanetary Disks

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ABSTRACT

I provide a very brief overview on recent observations of protoplanetary disks, focusing on statistical studies about disk lifetime and mass, high-angular-resolution imaging in scattered light at near-infrared wavelengths and in thermal emission from dust grains in submillimeter. Although the angular resolution of SPICA is not sufficient to resolve detailed structure, SPICA will contribute to investigations of gas content in disks which is a fundamental property to understand planet formation and evolution. In addition, detection of water and organic molecules will be important in the astrobiological context. Combining observations at other wavelengths will allow us to appropriately interpret the observed data and extract the realistic properties of protoplanetary disks.

1. OBSERVATIONS OF PROTOPLANETARY DISKS

It is ubiquitously known that young stars are surrounded by rotating disks consisting of gas and dust particles, resulting primarily from conservation of angular momentum of the parent molecular clouds. Since those disks are believed to be the sites where planets are born, they are called as protoplanetary disks. The longstanding, even growing interest in understanding planet formation process has stimulated enormous observational efforts of protoplanetary disks, but we are still far from establishing their properties. We know few direct evidence of on-going planet formation, and it is even difficult to say whether each disk is capable of yielding planetary bodies. There is no doubt that disks will remain quite important targets for SPICA.

Most observations have been done for disks after the ages of 1 Myr partly because it is easier to detect them without contamination from the surrounding remnant of the molecular cores. The majority of disks at this phase are initially optically thick and gas-rich, meaning that they can still be in the era of formation of gas giant planets. As a typically-observed property, the disk mass is roughly about 1% of the stellar mass and its size is ∼100 AU, corresponding to 1″ in the nearest star-forming regions (Williams & Cieza 2011, for a review). In protoplanetary disks at ∼1–10 Myr, planet formation will occur or is ongoing. It is also possible that formation has recently completed. Thus, what we can learn from them is the initial condition of planet formation, or such as disk-planet interaction, evolution of planetary orbits, and possibility of building another planet that may be triggered by the one which has already formed. In either case, the observational data most likely reflect the combined effect of evolution and intrinsic diversity of disks. As a phenomenon, this can be described by transformation of the interstellar gas and dust, and transport of material in radial and vertical directions within a disk, which is determined by, and can affect the density and temperature structure.

Therefore, the underlying purpose of every observation is simple to say; to measure the actual physical and chemical structure. In practice, however, it is still very challenging. For instance, the density distribution is one of the very basic properties, but it has just started to emerge thanks to the recent submillimeter/millimeter interferometers providing sub-arcsecond angular resolution. In addition, to obtain a comprehensive picture with distinguishing evolution and intrinsic diversity, and to compare the disk properties with the detections of mature exoplanets, the disk property should be investigated at various evolutionary stages, for a wide-range of stellar masses, and under various star-forming environments to consider the influence such as from stellar multiplicity, strength of external radiation field, and metallicity (Harris et al. 2012; Mann & Williams 2010; Yasui et al. 2009).

Disks can be observed in thermal emission from dust grains. At least in the early evolutionary phase, a dust disk is vertically flared coupled with gaseous component where the structure is basically determined by the balance between stellar gravity and thermal pressure. In the upper layer of the disk, the surface is heated mostly by the stellar radiation, and near the mid-plane, grains are warmed up by infrared radiation from the upper surface. Warmer grains near the central star emit at shorter wavelengths, but only from the disk surface if optically thick. On the other hand, cooler grains in the outer region and even near the mid-plane can be detected in submillimeter/millimeter since a disk usually becomes optically thin at radio wavelengths. It is also possible to observe dust grains in scattered light at the wavelengths where the scattering efficiency is high. The outer, cooler region of the disk is thus accessible in optical and near-infrared using scattered light. In the case of an optically thick disk, the scattered light only traces the disk upper layer whereas the radio thermal emission comes from the mid-plane. Observing gaseous component is usually more difficult than detecting dust, but is certainly indispensable since it provides critical information such as on gas kinematics, temperature, and chemical evolution. Various atomic and molecular emission lines are expected from the location at an appropriate density and temperature for individual line transitions like [C II], [O I], water, as well as abundant CO.
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2. DISK LIFETIME AND MASS

Lifetime of a disk provides a strong constraint on the timescale of planet formation. A method commonly-used for estimating the lifetime is to measure the disk frequency in a cluster at a certain age (Hernández et al. 2007; Hillenbrand 2005; Mamajek et al.; Haisch et al. 2001). The age is one of the most difficult quantities to accurately determine (e.g., Bell et al. 2013), but the cluster age is statistically obtained and expected to have less uncertainty than that for each star, except for the potential systematic errors such as in the distance and extinction for the cluster, and in the model isochrones. As an indicator of a disk, infrared excess has widely been used for the dust component whereas gas accretion is often identified with Hz or Bργ (Fedele et al. 2010). The past observations show the decay of disk frequency with the cluster age, which can be expressed by an ad-hoc, exponential decrease with the characteristic timescale of disk dispersal of 2–3 Myr. Until 10 Myr, most stars lose their disks although the frequency is not exactly zero. Therefore, statistically speaking, giant planet formation should finish until then.

If giant planets form in 1–10 Myr, there should remain enough amount of material within a disk. The disk mass has been estimated from dust continuum emission at submillimeter and millimeter wavelengths because the emission is mostly optically thin and suitable for looking into the disk mid-plane where the bulk of mass resides (Lee et al. 2011; Andrews & Williams 2007, 2005; Beckwith et al. 1990). The previous observations show that significant fraction of disks are heavier than that required to produce planetary systems like our Solar System, ∼0.01 $M_\odot$. The dependence on stellar mass has also been investigated and the recent work found the linear relation between disk mass and the stellar mass in the Taurus region, for stars with spectral types earlier than M8.5 (Andrews et al. 2013). At the same time, however, there is a considerable scatter in disk mass (∼0.7 dex; Andrews et al. 2013), which can be attributed to the uncertainty in the conventional prescription of obtaining disk mass. To convert the observed flux density to the mass of dust grains, we need to assume the opacity and temperature. Direct measurement of the opacity is hardly possible and extensive observations with multiple lines are required for determination of the temperature. The gain opacity is expected to change with grain size (relative to the observing wavelength) (Draine 2006), and dust temperature can also change by the evolutionary effect like grain growth and dust settling toward disk mid-plane. In addition, the disk mass is converted to the total mass usually assuming the gas-to-dust mass ratio of 100, which is the value in the interstellar medium and it is not sure at all whether the ratio is preserved in disks at 1–10 Myr. Therefore, it is expected that the evolution of disk material can affect these assumptions significantly. Note also that the mass inferred in this way is for dust grains which are efficient emitters in these wavelengths, and does not show the mass of planetesimals and planets which may have already formed.

3. A FEW NOTABLE EXAMPLES OF SPACE INFRARED OBSERVATIONS

As recently reported, hydrogen deuteride (HD) can be a promising probe to the gas mass. Since the majority of gas is in molecular hydrogen which has no dipole moment, observations often rely on the abundant CO to estimate the gas mass, but always encounter the significant uncertainty in freeze-out effect, temperature, and molecular abundance. HD has a weak dipole moment which yields much stronger line intensity than molecular hydrogen, and less affected by various uncertainties compare to CO. The Herschel data showed the detection of HD at 112 µm with 9 sigma for the disk of TW Hya, providing the estimate of disk mass larger than 0.05 $M_\odot$ (Bergin et al. 2013). TW Hya is about 10 Myr old, and it is surprising that such an old star is still gas-rich. It should also be noted that detecting molecular hydrogen is the sensitivity issue and mid-infrared H$_2$ emission lines can be good target for SPICA.

Herschel has also been successful to detect emission lines of water vapor (Hogerheijde et al. 2011). Water is one of the most abundant molecules in gas phase and icy mantles of dust grains, and found in comets, asteroids, and planets. Although hot water vapor near the central star has been found, the detection of cold water beyond snow line was first brought by Herschel/HIFI for the disk of TW Hya. The emission line is considered to arise from the upper layer of the disk, which suggests the underlying icy solids near the mid-plane. Their modeling work suggests the presence of ice reservoir of at least several thousands of Earth oceans.

4. RECENT HIGH-ANGULAR-RESOLUTION OBSERVATIONS

Detailed structure of protoplanetary disks provides indications of physical process which regulates disk evolution, and possible existence of young planets. Therefore, higher-angular-resolution, as well as higher sensitivity, certainly advances understanding of planet formation. There is one class of objects to which great attention has been paid because they invoke the presence of planets (Strom et al. 1989; Calvet et al. 2002). On the basis of spectral energy distributions associated with the deficits of mid-infrared excess, they are predicted to have dust holes or radial gaps separating inner and outer disks. In fact, the inner cavities were resolved in the dust continuum observations with SMA with the resolution of ∼0′′3 for some of those disks (Andrews et al. 2011). The radii of the resolved cavities are 15–70 AU, and the mechanism to produce such a large cavity is under extensive discussion. One of the possible explanations is the disk clearing by one or multiple planets (Zhu et al. 2012; Dodson-Robinson & Salyk 2011).

A slightly different picture has been obtained for the same class of disks by recent scattered light imaging in near-infrared. At this wavelength regime, the angular resolution of less than 0′′1 (≈10 AU) can be achieved by the combination of large aperture (8–10 m) telescopes and adaptive optics from the ground. It has also been demonstrated that polarization differential imaging (PDI) technique is fairly useful to observe the inner region (∼0″15 ≈20 AU in radius) by suppressing the unpolarized, bright halo of a central star. What is emerging from PDI with adaptive optics is a morphological diversity,
such as gaps, spirals, and sometimes very complex, non-axisymmetric structures (Hashimoto et al. 2011; Mayama et al. 2012; Muto et al. 2012; Grady et al. 2013; Quanz et al. 2013). Comparing the distribution of scattered light with that of submillimeter dust emission, there are notable differences between them. For instance, some show cavities both in submillimeter thermal emission and scattered light while others exhibit submillimeter cavities filled with scattered light (Dong et al. 2012). The difference can be attributed to the different density distribution depending on the grain size (Dong et al. 2012), but in some cases, it may be due to the lower angular resolution in submillimeter.

We need to wait a little more to obtain the comparable (<0.1") resolution with ALMA, but the exciting results have already started to come. As a few examples, ALMA observations toward two disks with known radial gaps revealed the strong asymmetries in the outer disks in azimuthal direction (van der Marel et al. 2013; Casassus et al. 2013; Fukagawa et al. 2013). The azimuthal contrast in flux density reaches to at least 130 at 690 GHz for the disk of Oph IRS 48 (van der Marel et al. 2013), and ~30 at 340 GHz for another case, HD 142527 (Casassus et al. 2013; Fukagawa et al. 2013) (Figure 1). These imply the localized, mass concentration which might accelerate grain growth and subsequent planetesimal growth. We have been attracted by the possible planets within the gap, but the data suggest that the outer, ring-like disk itself can be the forming site of rocky objects or gas giant planets.

Combining with infrared imaging that can mainly probe the (sub)micron-sized grains, it is implied that larger grains are localized in the submillimeter-brighter region for Oph IRS 48. Segregation of dust particle size has been investigated in radial direction (Pérez et al. 2012), but now the azimuthal size segregation is also recognized as an important sign of planet-forming activity. In addition, for some of the brightest disks, we already have the set of spatially-resolved images at multiple wavelengths from optical/near-infrared to radio, which allows us to put constrains on the density and temperature distributions through radiative transfer modeling. The fact is that the real disk structure is very complex as uncovered by recent observations, and an appropriate interpretation (modeling) of the observed data is more and more important these days.

5. ADVANTAGE OF SPICA

The angular resolution that will be obtained with SPICA is not enough to resolve detailed structure of protoplanetary disks (~1") in radius). However, this does not mean that SPICA cannot contribute to this science case at all. The significant merit of using SPICA can be found in its capability of longer IR spectroscopy with the unprecedented sensitivity. For instance, H₂ and HD observations can give us information on gas mass which is fundamental to understand planet formation and evolution. Detection of water and organic molecules, which is difficult from the ground, will be quite important in the astrobiological context. In addition, SPICA and other high-angular-resolution observations are complementary to each other. To interpret the data from gas observations, radiative transfer modeling is normally required with the assumption of temperature and density distributions. For example, the disk mass estimate with HD was obtained through such modeling.
attempts, and the uncertainty remains in temperature structure (Bergin et al. 2013). Additional observations of multiple gas temperature tracers are valuable and ALMA can provide those.

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Evolution of Solid Materials in Planet-Forming Disks
— From AKARI to SPICA

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ABSTRACT

How are planetary systems formed? How is life created? As an approach to these subjects, we propose a study of chemical evolution of solid materials in planet-forming disks based on observations with the SPICA Coronagraph Instrument (SCI). We focus on silicate grains and hydrocarbon molecules including polycyclic aromatic hydrocarbons (PAHs) as origin of rocky-planets and life, respectively.

Our solar system is believed to be made of materials originated in the interstellar space. However, in our solar system, there are many kinds of materials, which are not common in the interstellar space (e.g. crystalline silicates and complex organic molecules). They must be formed at planet-forming stages. Because each material has its own condition for generation, we can obtain clues for events which occur at planet-forming stages, through studies of evolution of these materials.

AKARI performed all-sky surveys in six infrared photometric bands with the wavelengths from 9 to 160 μm. A global picture of life cycle of solid materials in our Galaxy has been revealed from these data. Solid materials are supplied from mass-losing old stars to the interstellar space, and then incorporated into star forming activities. During this cycle, solid materials are processed in local physical environments, changing the infrared spectroscopic features. Based on these scientific results, as a next step, we plan to make detailed analyses of the evolution of the solid materials in star- and planet-forming sites using the SPICA/SCI.

1. INTRODUCTION

In the SPICA era, coronagraph instruments on large telescopes will be working (e.g. MIRI/JWST, MICHI/TMT). They are powerful tools for new detections of exoplanets. Among them, the SPICA Coronagraph Instrument (SCI; Enya et al. 2010) will be the unique instrument. Taking advantages of the space-based coronagraph on the cooled telescope, the SCI can simultaneously realize high contrast, high sensitivity, and mid-IR (4–28 μm) spectroscopic capability.

Thus, one of the unique scientific objectives of the SCI is the study of solid materials in planet-forming disks. High contrast coronagraphic capability is necessary for observations of circum-stellar disks close to bright central stars. High sensitive mid-IR low-resolution (λ/Δλ ~ 200) spectroscopy matches observations of solid matters in space. Silicates show broad features at around 10 and 20 μm. From these features, we can diagnose compositions, temperature, and crystallization degree of them (e.g. Henning 2010). Hydrocarbons (e.g. polycyclic aromatic hydrocarbons; PAHs) also show features and plateaus in this wavelength region (Tielens 2008). We can diagnose size, ionization degree, and aromatic/aliphatic ratio of hydrocarbons from these features. We can also obtain temperatures and size distributions of dust grains from mid-IR continuum (Kuruegel 2003).

We can obtain clues for the planet-forming scenario from the observational results of solid materials in disks. Because each solid material has its own condition of generation (e.g. coagulation temperature of silicates), physical state of solid materials in a part of disks indicates the history of the region as well as current physical state of the region. In this paper, we focus on the chemical evolution of silicates and hydrocarbons, and size evolution of dust grains in planet-forming disks.

2. SCIENTIFIC OBJECTIVES

2.1. Evolution of Silicates

The first topic is on silicates. Figure 1 shows an overview of this subject. Silicates are important materials as main components of rocky planets like the Earth. We believe that stars and planets are made of materials originated in the interstellar medium (ISM). Silicates are mostly amorphous in the interstellar space, which show mid-IR broad absorption
features (Kemper et al. 2004), while many kinds of crystalline silicates are found in our Solar system, which show sharp
and complex mid-IR features. For example, crystalline forsterite and ferrosilite are detected from the ejecta of 9P/Tempel
1 comet (Lisse et al. 2006) by the Spitzer/IRS observation performed as a part of the Deep Impact project (A'Hearn et
al. 2005). Our question is when and where these materials are processed. Crystallization of silicates requires annealing
with temperature higher than 1,000 K (Hallenbeck et al. 2000). If silicates are crystallized at planet-forming stages, there
must be some events, in which solid materials are heated to a temperature higher than 1,000 K.

RESULTS FROM AKARI OBSERVATIONS

One of the most important results from the AKARI all-sky survey is the detection of a new kind of debris disks, which
have various kinds of a large amount of crystalline silicates (Fujisawa et al. 2009, 2010, 2012). These materials are not
familiar in the ISM while they are common in our solar system. Furthermore, they are detected in orbits with lower
equilibrium temperatures, which have not reached the generation temperature of these materials. As a next step, it is
essential to spatially trace the processing of these materials in planet-forming disks.

CLUES FOR PLANET-FORMING SCENARIO

From future observations with the SCI, if concentration of crystalline silicates are found in the inner hot regions in younger
objects, a transportation mechanism of materials from inner orbits to outer orbits will be suggested. If environmental
dependence of crystallization is dominant, shock heating by external sources will be indicated. If crystalline silicates
distribute in a spire-like hydrodynamic pattern in disks at early stages, shock heating by formation and destruction of
massive fragments (Vorobyov 2011) will be indicated. These observational results will be clues for the events which occur
in the planet-forming processes.

2.2. Evolution of Hydrocarbon Molecules

A question remains for hydrocarbons. In the interstellar space, hydrocarbons are dominated by aromatic molecules
(Tielens 2008). However, those in our Solar system are different. For example, hydrocarbons in 81P/Wild 2 comet, which
came from Kaiper-belt and should be filled with pre-solar grains, show features dominated by aliphatic molecules (Keller
et al. 2006). Furthermore, complex organic molecules which may be the origin of life is not found in the interstellar space.
Thus, they must be processed at star and planet-forming stages.

RESULTS FROM AKARI OBSERVATIONS AND ON-GOING ACTIVITIES WITH AKARI DATA

AKARI has revealed the all-sky distribution of the interstellar PAHs (Ishihiara et al. 2010). On a global scale, PAHs
show good spatial correlation with tracers of general ISM, such as CO, HI, and far-IR dust emissions. On a local scale, we
recognize the variation of physical state and compositions of hydrocarbons (e.g. Kaneda et al. 2012). It is reasonable to
presume that PAHs are incorporated into star- and planet- forming sites and processed in the local environment. AKARI
stored near-IR (2–5 \( \mu m \)) spectra for about 10,000 fields, which were taken after exhaustion of liquid helium cryogen.
They cover the 3.3 \( \mu m \) aromatic and 3.4 \( \mu m \) aliphatic features of hydrocarbons. By using these data, we can further make
systematic studies of hydrocarbons in young stellar objects before the launch of SPICA. As a next step, it is important to
trace the processing of hydrocarbons in planet-forming disks with spatially resolved spectroscopic observations.
CLUES FOR PLANET-FORMING SCENARIO

The observational results of hydrocarbons in disks contribute to understandings of the planet formation process. For example, we can investigate the hardness of local radiation fields in disks from observational properties of hydrocarbons (Berne et al. 2009). The number density of hydrocarbons is important for gas thermodynamics in disks, because they contribute to a majority of gas heating. Hydrocarbon molecules also play important roles in the size evolution of dust grains in disks. Dust grains with hydrocarbon mantle grow up faster than bare silicates because their elastic coefficients are smaller than silicates and comparable with that of H2O ice.

2.3. Evolution of Size Distribution

The third topic is on the size evolution of dust grains. We believe that dust grains in debris disks are supplied from collisions of planetesimals. The fate of these dust grains depends on the relative strength of radiation pressure to gravitational force of the central star. This ratio of these forces is described as a function of the dust size and the spectral type of the central star as,

\[ \frac{F_{\text{rad}}}{F_{\text{grav}}} \propto a^{-1} \rho^{-1} \left( \frac{L_*}{M_*} \right), \quad (1) \]

where \( F_{\text{rad}} \) is the force due to the radiation pressure from the central star, \( F_{\text{grav}} \) is the gravitational force, \( a \) is size of the dust grain, \( \rho \) is the density of the dust grain, \( L_* \) is the luminosity of the central star, and \( M_* \) is the mass of the central star. If this ratio is small, the replenished dust grains can stay near the parent orbit. If the radiation pressure is significant, the dust grains are blown out within a Kepler time.

RESULTS FROM AKARI OBSERVATIONS

We could investigate the effect of the parameter \( L_*/M_* \) of eq. (1), based on large samples from the AKARI all-sky survey. We made a systematic survey of debris disks from the data, and reported 24 excess objects (Fujiwara et al. 2013). Furthermore, we are making follow-up observations of accurate \( J, H, K_s \) photometries of the central stars of our excess candidates using the SIRIUS camera (Nagayama et al. 2003) on the IRSF telescope in South Africa. By improving the accuracy of the excess judgments, we obtained 13 additional 18 \( \mu \)m excess objects (Kiriyama et al. 2012). Our sample indicates that the inner radius of disks estimated from dust temperatures is a function of \( L_*/M_* \).

CLUES FOR PLANET-FORMING SCENARIO

We will be able to investigate the effect of the parameter \( a \) of eq. (1) by spatially resolved observations of disks with the SCI. Because the dust temperature \( (T_{\text{dust}}) \) is a function of the size of dust grains \( (a) \), and the distance from the central star \( (R) \) as,

\[ T_{\text{dust}} \propto a^{1/6} R^{-1/3}, \quad (2) \]

we can investigate the dust size \( (a) \) by comparing observed dust temperature with the calculated equilibrium dust temperature in the orbit (Kuruegel 2003). From the size of dust grains, we can investigate currently active planetesimal belts in the system because smaller grains are blown out faster than larger grains (e.g. Okamoto et al. 2004). We can also investigate the formation process of the disk by the spatial variations of size distributions of dust grains : radiation dominated, collision dominated, or Pointing-Robertson (P.-R.) effect dominated. We will also be able to detect the Solar-system type exo-Zodi. It may be difficult to detect 1 Zodi. level extra-solar systems with the SCI. But it is possible to detect solar-system type brighter exo-Zodi. that are dominated by the P.-R. drug effects instead of radiation pressure.

3. TARGETS

Our first strategy is observing spatial distributions of physical state and composition of solid materials in heavy disks, the size of which have been measured in previous studies. Figure 2 left shows the distance versus disk size of proto-planetary disks and debris disks1. There are 71 objects, which have disks larger than the inner working angle (IWA) of the SCI at 6 \( \mu \)m. Our second strategy is new detections and analysis of faint debris disks (exo-Zodi.). The SCI can make effective detections of circum-stellar disks if the IWA for a wavelength band matches the size of the orbit with the equilibrium dust temperature for the band. Figure 2 right compares the IWA of the SCI for 6 and 20 \( \mu \)m with the loci of orbits for equilibrium temperatures of 300 K and 150 K, which show peak intensity at 6 and 20 \( \mu \)m, respectively. A histogram of the number of known dwarf stars as a function of distance (pc) is overlaid on Figure 2 right. At least, for 21 objects, the orbit corresponds to the equilibrium temperature for the SCI bands are spatially resolved by the SCI, though we will possibly be able to detect a larger number of disks due to the high sensitivity of the SCI.

4. SUMMARY

We propose a study on the chemical evolution of solid materials in planet-forming disks with the SCI. We can investigate events which occur at planet-forming stages by observing temporal and spatial variations of physical state and composition

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1 http://circumstellardisks.org/
of silicates and hydrocarbon molecules in disks. From size distributions of dust grains in disks, we can investigate the formation process of debris disks. This study is one of the important approaches for the origin of planetary systems and life. The required specifications for the instrument are the low-resolution ($\lambda/\Delta\lambda \sim 200$) mid-IR (6–28 $\mu$m) spectroscopic capability with the coronagraph.

This study takes advantages of the SPICA/SCI. It will be complementary with the studies performed by the coronagraph instruments on JWST and TMT. It is based on the scientific results from AKARI, previous successful Japanese infrared astronomical mission. It will be also based on the on-going activity for the data reduction of AKARI.

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Debris Discs: From *Herschel* to *SPICA/SAFARI*

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**ABSTRACT**

The *Herschel Space Observatory* has been used to further our understanding of debris discs around nearby stars. Three ‘key programmes’ were performed, whose primary aim was the characterisation of the population as a whole and, in doing so, to better understand our Solar-System in the wider context.

In this article the parameter space probed by these surveys is assessed with respect to previous work performed, at similar wavelengths, with *Spitzer* and *IRAS*. This is then further developed, quantifying the potential improvement that could be achieved, for similar surveys, using the SAFARI instrument on-board the forthcoming *SPICA* space observatory.

1. INTRODUCTION

Debris discs are belts of dusty circumstellar material created by collisions within a parent belt of planetesimals (*Wyatt 2008*). The dust observed cannot be attributed to residual primordial material from which the star formed as it would have been removed from the system, either by drag forces causing the dust to fall onto the star or blown out by radiation pressure, on time scales far shorter than the typical ages of these stars (*Backman & Paresce 1993*).

The prerequisite of planetesimals for a debris disc makes the detection of debris around a star a clear indicator that the planet formation process reached the stage of gravity-dominated bodies. Consequently, debris discs are a key component in the study of extra-Solar planetary systems. By studying the incidence, properties and evolution of debris discs it is possible to obtain a greater understanding of their underlying planetary systems.

Since the discovery of the first debris disc by *Aumann et al. (1984)* using *IRAS* (*Neugebauer et al. 1984*), a wealth of new discs have been discovered (e.g. *Oudmaijer et al. 1992; Holland et al. 1998; Carpenter et al. 2009*). The infrared and submillimetre wavelength range has proved particularly valuable, with a significant contribution coming from the MIPS instrument (*Rieke et al. 2004*) on-board *Spitzer* (*Werner et al. 2004*), whose sensitivity made it possible to discover discs with lower fractional luminosities than ever before.

The aim of this article is to review the progress made by the *Herschel Space Observatory* (*Pilbratt et al. 2010*) in probing the parameter space associated with the search for, and characterisation of, debris discs, and thereby place into context the capabilities of the SAFARI instrument (*Roelfsema et al. 2012*), on-board *SPICA* (*Nakagawa et al. 2011*), in this field of study.

SAFARI is a three band Fourier transform spectrometer, providing continuous spectra from 34–210 µm at spectral resolutions up to R = 2000. The instrument can also operate in a photometric mode, providing simultaneous images at 47, 85 and 160 µm. The primary mirror of the *SPICA* telescope is ~3 m in diameter, and is cooled to ~6 K. The cold *SPICA* telescope provides a very low background environment, making it possible for instruments on-board to reach unprecedented sensitivities in the far infrared.

A review of the surveys carried out by *Herschel* is given in Section 2, including the sensitivity limits from these data. Section 3 presents example *SPICA/SAFARI* surveys, based on current system performance estimates, and discusses the potential such surveys could have to push the limits of our current debris disc knowledge.

2. THE HERSHEYEL LEGACY

*Herschel* performed a large number of observing programmes dedicated to the study of debris discs. For simplicity this article will consider only data from the three large ‘key programmes’: the two open time programmes DEBRIS (PI Matthews) and DUNES (PI Eiroa), and the Stellar Disk Evolution guaranteed time programme (PI Olofsson).

2.1. Photometry

The DEBRIS (Matthews et al. in prep) and DUNES (Eiroa et al. 2013) programmes both performed photometric imaging surveys using the PACS (*Poglitsch et al. 2010*) and SPIRE (*Griffin et al. 2010*) cameras. Data at 100 and 160 µm lead the surveys, with interesting disc detections being followed-up at 70 µm with PACS, and 250, 350 and 500 µm with SPIRE, as appropriate. DEBRIS performed a flux limited unbiased survey of 446 nearby stars of spectral types A–M, whilst DUNES focused on observations of Sun-like stars, i.e. spectral types F, G and K. There was significant overlap between the target lists of these two surveys, leading to a co-operative data sharing arrangement.

One of the key aspects of these surveys was to understand the statistical properties of these sources as a population. The sensitivity limits achieved by *Herschel* are thus best assessed in this context. Figure 1 shows the 30% detection limits for
Figure 1. Detection limits for a confusion limited photometric SAFARI survey of the F, G and K spectral-type stars in the DEBRIS sample. The shading shows the fraction of the total sample that could be detected at the ≥ 3σ level, with white representing a complete sample, and back representing an incomplete sample. The shading uses linear scaling. The uncertainties used to calculate these limits are a 2% uncertainty on the stellar photospheric flux density estimate, 3% absolute flux calibration uncertainty, and confusion noise levels of 0.015, 0.5 and 5 mJy in the 47, 85 and 160 μm bands respectively. Additional contours are also plotted to show the 30% sample completeness for existing IRAS, Spitzer/MIPS and Herschel/PACS data, as well as for the simulated SAFARI survey. In all cases the limiting sensitivity is based on the combination of data from all bands for a given system. The location of the Kuiper (KB) and Asteroid (AB) belts are also plotted for reference.

the PACS observations of DEBRIS and DUNES F, G and K spectral type stars. This line shows the limiting fractional luminosity for which a disc would be detected, at ≥ 3σ significance, in 30% of the target sample, as a function of radius. The fraction of the sample in which a disc would be detected increases above this line up to 100%, and decreases to 0% below the line. The 30% level is shown as it represents the lower limit, below which the sample can no longer be regarded as sufficient to be representative of the wider population. The equivalent detection limits are shown for the same sample for IRAS and MIPS. A limit is also shown for SAFARI (see Section 3 for details).

Eiroa et al. (2013) find several discs, within the DUNES sample, with fractional luminosities a few times larger than that of the Kuiper belt, and upper limits for 19 sources of $L_{\text{disc}}/L_\star \leq 10^{-7}$. This represents an order of magnitude improvement in sensitivity, albeit only for a small number of the nearest stars.

The high angular resolution of Herschel also meant that a large number of discs could be spatially resolved (e.g. Lestrade et al. 2012; Wyatt et al. 2012; Broekhoven-Fiene et al. 2013). It was this high angular resolution that drove the photometric component of the Stellar Disk Evolution programme. Here deep imaging observations were made of six well known and resolved debris discs: β Pic (Vandenbussche et al. 2010), ε Eri (Greaves et al. in prep), Fomalhaut (Acke et al. 2012), AU Mic (Matthews et al. in prep.), Vega (Sibthorpe et al. 2010) and τ Ceti (Di Francesco et al. in prep.).

By close study of the morphology of these resolved discs it is possible to gain insights into the underlying planetary systems. The physical location of the dust can also provide data on the dust grain size distributions and composition. These data can then be extrapolated to the wider unresolved disc population to assist in interpretation of the full dataset. The large number of resolved sources seen by Herschel provides better statistics with which to characterise these properties in a way which is more representative of the debris disc population as a whole (Booth et al. 2013).

2.2. Spectroscopy

Debris discs are traditionally thought of as gas poor. This, coupled with the extremely low brightness of these sources, means that very few have been detected and/or characterised spectroscopically. As part of the Stellar Disk Evolution programme, however, spectroscopic observations were performed for their sample of six well known discs. A particular
Figure 2. Top: Forsterite mineral feature detected in the beta Pic debris disc by de Vries et al. (2012). Bottom: Predicted number of debris discs for which a 3-σ detection of a similar feature could be detected in other known debris discs as a function of the total on-source survey integration time. A detection is characterised in this case as a 3-σ detection of the peak of the spectral feature above the continuum.

The highlight from this work was the discovery and characterisation of the 69 μm forsterite feature in the β Pic debris disc (de Vries et al. 2012).

The forsterite detection of de Vries et al. (2012) is shown in Figure 2a. The width and peak wavelength of this feature are sensitive to both dust grain temperature and composition, making it extremely useful for the characterisation of the debris dust. The dust in this case was found to be very similar to that found in the most primitive comets in the Solar-System.

The β Pic debris disc is unusually bright, and whilst similar observations of other debris discs would be useful, calculations showed that despite Herschel’s sensitivity, these were not feasible.

3. THE ROLE OF SPICA/SAFARI

Characterisation of the debris disc population as a whole has been significantly improved using Herschel data. The longer wavelength bands, with respect to the previous large samples obtained with Spitzer, has allowed the peak of the spectral energy distributions to be constrained for a larger sample than ever before. In addition, the completion of the large unbiased survey, DEBRIS, makes it possible to study the nature of these sources in an unbiased way. However, the sensitivity limits imposed by the warm telescope optics of Herschel mean that it is not possible to reach the noise levels required to detect and study true Kuiper belt analogues, with similar fractional luminosities and radii. The active cooling of SPICA’s telescope will overcome this problem, however, thereby providing unprecedented sensitivity in this wavelength range.
3.1. Photometry

SAFARI will be confusion limited with approximately 2 minutes of observing time in all three photometric bands. This should, in principle, provide sufficient sensitivity to detect true Kuiper belt analogues around nearby stars \( \frac{L_{\text{disc}}}{L_*} \approx 10^{-7} \). In practice, however, uncertainties in the absolute calibration of these data and estimates of the stellar photosphere will ultimately limit the true photometric capabilities of SAFARI. Figure 1 shows the sensitivity limits that could be reached for a confusion limited survey of the DEBRIS sample F, G and K spectral type stars. Whilst an improvement on the Herschel results is achieved, it is not substantial.

This simulation, however, is for unresolved sources. In cases where the source is resolved, uncertainties in absolute calibration and stellar photospheric flux density estimates are unimportant, as the disc can be observed directly. Using the 3-m SPICA telescope, it should be possible to resolve discs with a radius equivalent to that of the Kuiper belt out to approximately 10 pc, equivalent to 400 stars within the DEBRIS sample. In this situation SAFARI will make it possible to detect a large number of true Kuiper belt analogues for the first time.

3.2. Spectroscopy

The primary function of SAFARI is as a spectrometer, and it is in this capacity that it has the potential to make the greatest contribution. The high sensitivity of SAFARI makes it uniquely equipped to execute the first large spectroscopic survey of debris discs in the far infrared. A survey of this type could perform detailed studies of the mineral features within the SAFARI 34–210 μm wavelength range, and thereby characterise not only the dust in these systems, but also the larger planetesimals from which it is generated.

Results from a SAFARI spectroscopic survey of debris discs could then be compared with data from a similar study of bodies within the Solar-System, and thereby assess how representative the Solar-System is.

Using the results of de Vries et al. (2012) as a starting point, it is possible to estimate the size of survey that could be performed using SAFARI. If it is assumed that the forsterite feature detected in de Vries et al. (2012) is common to all debris discs, and scales linearly with the continuum flux density, then it is possible to calculate the number of discs for which the peak of the forsterite feature could be detected at the 3σ level. The results for this calculation are given in Figure 2b. The time in this figure relates to raw on-source observing time.

A survey of 40 discs would require ~100 hours of observing time. This estimate is based on the conservative criterion, based on detection of the peak of the forsterite feature. The use of matched filtering and model fitting techniques would likely improve the signal to noise ratio, making the number of discs which could be detected in this time at significantly higher.

This is a simple example to illustrate the number of sources that could be detected. In practice, a survey of this type would look for many different spectral features, and require a range of different observation depths.

4. SUMMARY

The sensitivity and wavelength coverage of the data obtained with Herschel has made it possible to characterise the debris disc population to a higher degree than ever before. The large surveys performed, described in Section 2, along with the numerous additional small programmes, will provide a legacy which will be exploited for many years to come. However, the study of debris discs with Herschel was ultimately limited by the warm telescope background.

The SPICA/SAFARI system has the capability to pick up where Herschel left off. The high sensitivity of SAFARI relative to the Herschel, will make it possible to directly detect true Kuiper belt analogues around nearby stars. Moreover, it will be able to perform the first large spectroscopic survey of these sources in the far infrared. Comparing these data with similar observations of targets within the Solar-System will make it possible understand the diversity of extra-Solar Kuiper belts, and better understand where our own Solar-System lies within the wider galactic context.

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Debris discs: From Herschel to SPICA/SAFARI

Warm Debris Disks with SPICA

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ABSTRACT

Recent space infrared observations with Spitzer and AKARI have discovered excess emission in the mid-infrared around main-sequence stars, which suggests the presence of warm (> 150 K) debris dust. These warm debris objects constitute a new class of debris disks distinct from those found in the far-infrared. A significant fraction of them show too high a fractional luminosity (a ratio of the excess to the stellar flux) to be accounted for by the steady-state collisional cascade model and often show solid features in the mid-infrared, some of which are attributed to silica, species rarely seen in other celestial objects. These facts suggest that they are formed by recent violent events, such as giant impacts or late heavy bombardments, the former of which have a direct link to the formation of terrestrial planets. While a variability of the features is predicted since they must originate in submicron-sized particles that will be blown out in a short time scale by the radiation from the central star, no systematic variation has so far been detected over 20–30 years except for a few cases, suggesting continuous replenishment of debris possibly from outer regions. Observations in the far-infrared are thus indispensable for the understanding of the origin and spatial distribution of the debris in these objects. Unprecedented sensitivities and wide field-of-views of MCS and SAFARI onboard SPICA enable us to make efficient imaging and spectroscopic surveys of warm debris disks from mid- to far-infrared and revolutionizes our understanding of the terrestrial plant formation for the first time. We discuss possible observations of warm debris disks with SPICA to study the formation process of the warm debris and their relation to the formation of terrestrial planets.

1. INTRODUCTION

IRAS discovered a number of debris disks in main-sequence stars as excess emission at 60 μm (Backman & Paresce 1993; Rhee et al. 2007) following the first detection in Vega (Aumann et al. 1984). The excess emission originates in small dust particles whose lifetime is much shorter than the age of the central star, suggesting that they are replenished by cascade collisions of large bodies (Wyatt et al. 2007; Wyatt 2008). The estimated temperatures (T < 100 K) suggest that those dust grains are located at distances further than 10 AU from the central star.

Recently AKARI and Spitzer discovered debris disks that show large excess emission at 18 or 24 μm (Olofsson et al. 2012; Meng et al. 2012; Fujiwara et al. 2013). Excess at the mid-infrared indicates the presence of warm (> 150 K) dust, which must be located at terrestrial planet forming regions (< 2 AU). They often show characteristics distinct from the original debris objects detected in the far-infrared, suggesting that they may constitute a new class of debris disks. Here we discuss possible observations of warm debris disks with SPICA that can revolutionize our understanding of the planet formation process.

2. WARM DEBRIS DISKS

Fujiwara et al. (2013) made a survey of excess emission at 18 μm around main-sequence stars based on the all-sky survey with the Infrared Camera (IRC; Onaka et al. 2007) on board AKARI (Ishihara et al. 2010). With the conservative criteria for the detection, they found 24 debris disk candidates, 8 of which were new. They further showed that debris disks around stars later than F0 tend to have higher debris temperatures (≥ 170 K) and quite large fractional luminosities (> 10⁻³), which are defined as the ratio of the infrared excess luminosity to the stellar luminosity. The steady-state cascade collision model has an upper limit of the fractional luminosity as a function of the stellar age (Wyatt et al. 2007). The observed large fractional luminosities for some of the warm debris disks discovered suggests that the steady-state model cannot account for them and that transient events must be taking place in these objects.

Follow-up observations of one of the warm debris disk objects, HD 15407A, show that its mid-infrared spectrum has unusual features, which can be attributed to silica (SiO₂) dust (Figure 1, Fujiwara et al. 2012a). Silica is one of the most abundant minerals in the Earth’s crust, but are rarely seen in celestial objects. Silica-rich granite in the Earth surface results from a rare combination of the plate tectonics, the subduction of the basaltic component, and the presence of water (Campbell & Taylor 1983), which suggests that an Earth-like object might already be present around HD 15407A, while giant hyper-velocity impacts of rocky bodies can also produce silica dust (Lisse et al. 2009). In the latter process, SiO gas is expected to be produced. Detection of vibration bands of SiO gas at the mid-infrared is reported for one of the silica
disk objects HD 172555 (Lisse et al. 2009). In HD 15407A, no vibration modes of SiO gas have so far been detected clearly. Search for SiO gas at radio frequencies would also be interesting.

The large fractional luminosity of HD 15407A (~0.005) further suggests that violent transients, such as giant impacts, which led to the formation of the Moon, or late heavy bombardments (LHBs) (e.g., Lisse et al. 2012), are taking place around the star (Fujiwara et al. 2012a). HD 15407A is not only an object that shows the silica feature (e.g., Lisse et al. 2009). A large fraction of the warm debris disks in fact show distinct dust features in the mid-infrared (Olofsson et al. 2012). These facts suggest that some fraction of warm debris disk objects already have large bodies in their system. The debris is located around terrestrial planet forming regions (~1–2 AU) and they may be in a last stage of the terrestrial planet formation if a giant impact is occurring. Further investigations would thus provide valuable information on the formation process of terrestrial planets.

The large fractional luminosity also suggests that the excess emission in the mid-infrared is short-lived. In particular, the spectral features in the 10 µm region must come from dust grains smaller than a few µm, which will be blown out by the stellar radiation in a time scale as short as years (e.g., Johnson et al. 2012). Olofsson et al. (2012) show that several warm debris disks that show mid-infrared features do not indicate systematic time variations in the wide-band photometry over ~30 years (Figure 2), whereas Meng et al. (2012) report variations in the infrared flux for two warm debris disks on a timescale of a few years. The photometric flux is dominated by emission from large dust grains and may not vary appreciably in a very short time scale. Observations of the time variability of mid-infrared spectra are quite important to understand the origin and evolution of dust grains responsible for the mid-infrared features. Also note that the variabilities shown in Figure 2 are estimated from various instruments. While the filter response of each instrument is taken into account using IRS spectra, possible differences in the absolute calibration preclude us from making detailed investigations.

Figure 2a shows that HD 15407A does not show a systematic variation in the last 30 years. Little variability suggests the replenishment of small grains from outer regions or the resonance trapping of small grains. Fujiwara et al. (2012b), however, show that there is no appreciable amount of grains in the outer region of HD 15407A, which favors giant impacts rather than late heavy bombardments as the origin of transient warm debris. The absence of cold debris does not support the dust replenishment from outer regions. The relatively large upper limit on the far-infrared flux, however, prevents from making a definite conclusion. Further observations with higher sensitivity in the far-infrared together with spectroscopic monitoring observations in the mid-infrared are definitely needed to understand the origin of warm debris and the formation process of large bodies in these systems.

3. WARM DEBRIS WITH SPICA

As described above, some fraction of the warm debris disk objects may be in a last stage of terrestrial planet formation and thus further investigations could bring new information on the planetary formation process. However, the number of warm debris disk candidates is still small and it would be highly desired to increase the size of the sample for the detailed study. Spectroscopy and the variability observations in the mid-infrared spectrum are crucial for the understanding of the origin of warm debris. Far-infrared observations will also be important for the study of the dust replenishment process. In this regard, collaborative observations of the MCS and the SAFARI on board SPICA will offer an unparalleled observation opportunity.
As described above, some fraction of the warm debris disk objects may be in a last stage of terrestrial planet formation if a giant impact is occurring. Further investigations would thus provide valuable information on the formation process of large bodies in these systems.

Monitoring observations in the mid-infrared are definitely needed to understand the origin of warm debris and the formation mechanism. Further observations with higher sensitivity in the far-infrared together with spectroscopic studies of the replenishment of small grains from outer regions or the resonance trapping of small grains. Fujiwara et al. (2012b), shown in Figure 2 are estimated from various instruments. While the filter response of each instrument is taken into account, the large fractional luminosity of HD 15407A (∼0.005) further suggests that violent transients, such as giant impacts, are major players in the evolution of the debris disk. Search for SiO gas at radio frequencies would also be interesting.

The large fractional luminosity of HD 15407A (∼0.005) further suggests that violent transients, such as giant impacts, are major players in the evolution of the debris disk. Search for SiO gas at radio frequencies would also be interesting.

Figure 2. Time variation in the infrared flux for three warm debris disks. The black open circles indicate the fluxes in 8–12 µm, while the red filled circles show those in 18–25 µm. The data are taken from Olofsson et al. (2012) and normalized by the IRS data.

Figure 3. Detectability of the photosphere of main-sequence stars of a function of the distance with SPICA at various wavelengths based on the 1hr 5σ sensitivities.

Figure 3 plots the estimated sensitivity for the detection of the photosphere of a main-sequence star of the various spectral types as a function of the distance. It clearly demonstrates the power of the MCS and the SAFARI. The MCS slit-less mode can reach photosphere of a M0 star at 1 kpc and that of a G0 star at 2 kpc at 10 µm. K0 stars with significant excess can also be easily detected even at 2 kpc.

Taking an advantage of the large field-of-view of the MCS (∼5′), we propose to make an efficient slit-less grism survey of open clusters of a similar size. According to Dias et al. (2002), there are more than 300 open clusters that have the size less than 5′ within 2 kpc. Spectroscopy at 10 and 20 µm can characterize the debris dust around stars. Assuming...
that we observe 30–40 stars per cluster with the detection rate of excess emission of 1 %, observing 300 clusters will provide a sample of \( \sim 100 \) warm debris disk candidates with mid-infrared spectral information, which will increase the sample size by more than an order of magnitude. The new spectral sample will certainly renew our understanding of the terrestrial planet formation drastically. Follow-up observations with the SAFARI and variability observations should also be executed within the lifetime of SPICA. Monitoring observations with the same instrument allow us to make reliable and accurate investigations on the spectroscopic variability.

It should be noted that the AKARI slit-less survey of the Large Magellanic Cloud demonstrates that slit-less spectroscopy is an efficient mode for a wide field survey, but also has a problem of spectrum overlap (Shimonishi et al. 2013). To make an efficient and effective slit-less spectroscopic survey, a special observation sequence is proposed, in which a photometric image is taken first and then the position angle of the slit-less image will be adjusted to avoid spectrum overlap as much as possible within the allowed range. A simulator for the slit-less spectroscopy is also very useful in the planning phase of the observations. Good absolute calibration is required to detect faint excess emission.

4. SUMMARY

Warm debris disks, which have been discovered by recent AKARI and Spitzer observations at 18 or 24 \( \mu \)m, possess characteristics distinct from original debris disks detected at the far-infrared in the points that a significant fraction of them show too high a fractional luminosity to be accounted for by the steady-state collisional cascade model and that some of them have clear dust features in the mid-infrared, both of which suggest that some fraction of warm debris disks objects are in a last stage of terrestrial planet formation.

Owing to its high sensitivity and large field-of-view, slit-less spectroscopy with the MCS offers an unparalleled opportunity to increase the size of the spectral sample, which enables us to make a statistical investigation and study the true origin of warm debris. To have an efficient slit-less survey, a special observation sequence is proposed. The accuracy of the absolute calibration is also important for the detection of weak excess emission. With coordinated surveys with the SAFARI, SPICA will provide us revolutionary information on our understanding of the formation process of terrestrial planets.

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\textbf{ABSTRACT}

\textit{SPICA Coronagraph Instrument} (SCI) is an instrument dedicated for direct detection and characterization of exoplanets and also for other science that needs a high-contrast imaging and spectroscopic capability in the near to mid-infrared wavelengths. We will present the major science cases for exoplanets from the instrument proposal of SCI. Thanks to the high-contrast imaging and spectroscopic capability, we will be able to tackle the various problems on the exoplanet science. SCI will give us the unique opportunity to observationally understand the formation process of jovian planets, which is still poorly understood, by measuring temperatures of young jovian planets. Spectroscopy of planet atmospheres will enable us to reveal the chemical compositions by measuring the abundances of various important molecules such as CO, CH$_4$, H$_2$O, H$_2$ etc. We will also access to the structure of jovian atmosphere, for example the existence of thermal inversion which is known for our Solar system planets. Furthermore, the direct detection of icy giants around early-type stars with SCI will open a new window to investigate these enigmatic planets.

\section{INTRODUCTION}

One of the most important uniqueness of \textit{SPICA} is continuous wavelength coverage from the mid- to far-IR spectral region with a very cold (6 K) telescope. The spectral range of 4–28 μm, which is the core wavelength range continuously covered by \textit{SPICA Coronagraph Instrument} (SCI, Kotani et al. 2012), includes many of the fundamental vibration modes of minerals, organic matter, and ices as well as many rotational modes of important molecular gases such as H$_2$. Space-based observations have a great advantage over ground-based observations in terms of the continuous spectral coverage not hampered by the atmospheric absorption, which is essential to unambiguously identify relatively broad spectral features inherent to solid particles. SCI is designed to have not only imaging (1 arcmin × 1 arcmin area) but also slit-spectroscopic ($R = 200$) capability, and coronagraph is applicable to both imaging and spectroscopic modes.

The primary scientific cases with the SCI are the characterization of the exoplanets with molecular gases and dust specific to the mid-IR region, and the discovery of icy giant planets which can be detected only at longer IR wavelengths. It is a
perfect complement to studies on exo-planetary science which are performed or to be performed by many other dedicated programs at shorter wavelengths. In particular, the mid-IR characterization would enable us to accurately determine temperatures of young planets at cooling phases, which are crucial to examine planetary formation theory: core-accretion model or disk instability model. The studies of solid materials around planet-forming stars will lead us to understanding raw materials of planets and even the origin of life on planets.

2. PLANET FORMATION PROCESS REVEALED BY THERMAL HISTORY

The key parameter to reveal planet formation process is the temperature of the planetary atmosphere soon after the planet is formed. The atmospheric temperature imposes constraint on the amount of the gas accretion onto the planet, which takes place at the final stage of the gas giant formation. Recent theoretical models (e.g. Spiegel & Burrows 2012) indicated that the initial conditions of the planet depend on the formation process, i.e. core accretion or disk instability, although their conclusions are still in debate. The planets formed through the two processes are different in the atmospheric temperature. The planets are expected to retain their initial conditions for 1 Gyr after the gas accretion onto the core is completed. Thus the planet temperature in the gas accretion stage is very important for understanding both the planet and the satellite formations. With the SCI, it will be possible to estimate the initial condition of the planet through measuring the planet temperature as a function of the age of a planet.

The spectral features of atmospheric molecules are crucial indicators of the planet temperature. Since there are several important molecular absorption lines in the wavelength coverage of the SCI, the atmospheric temperature can be determined through spectroscopy of the planet atmosphere. CO and N$_2$ are stable at temperatures higher than 1500 K. As the temperature decreases, they react with H$_2$ to form CH$_4$ and NH$_3$. As a result, they become the dominant carbon- and nitrogen-bearing species at low temperatures, respectively. At a total gas pressure of 1 atmosphere, CH$_4$ and NH$_3$ mainly form at temperatures below 1000 K and 700 K, respectively. In addition, the mixing fraction of H$_2$O increases by releasing the oxygen tied up in CO. Thus, while CO is an indicator of high-temperature objects, CH$_4$, NH$_3$ and H$_2$O are indicators of low-temperature objects. Therefore the planetary atmospheric temperature can be measured through observing the molecular absorption.

In order to observationally restrict the planetary formation process through the atmospheric temperature at the final stage of the gas accretion, both the age and the dynamical mass of the planetary system have to be known in advance. Therefore nearby young moving groups and open clusters, whose ages are determined by the H-R diagram, are observational targets for the SCI. Future precise astrometric observations with ground-based or space telescopes such as LBTI, VLTI, and GAIA, would discover planetary-mass objects even around young systems to determine those dynamical masses. Figure 1 compares the planet-search regions with the SCI and the future astrometric observations. The spectroscopic follow-up observations with the SCI will be able to determine the atmospheric temperatures of the planets whose ages and masses are already determined.

This study requires spectral resolution $R \sim 200$ and wavelength coverage from 4 to 12 $\mu$m to resolve the molecular absorption features due to CO (4.7 $\mu$m), CH$_4$ (6.5 $\mu$m, 7.7 $\mu$m), NH$_3$ (6.1 $\mu$m, 10.5 $\mu$m), and H$_2$O (6.2 $\mu$m). High contrast ($10^{-6}$ level) is needed because the planet formed by the core-accretion process is already faint even at the final stage of the
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gas accretion. Therefore the SCI provides a unique opportunity for revealing the planet formation process from a point of view of the atmospheric temperatures.

3. H$_2$ AND HE IN THE ATMOSPHERE OF JOVIAN EXOPLANETS

H$_2$ is the major component in the atmosphere of Jovian planets and it is a main factor in determining the opacity. Investigation of the H$_2$ spectral feature is important in determining the cooling process and the heat balance in the Jovian atmosphere. For example, Jupiter and Saturn are two gas-giant planets in our solar system and similar in many characteristics, but the atmospheric He abundance of Saturn significantly differs from that of Jupiter; the He mass fraction of Saturn is much less than those of Jupiter (Conrath et al. 1987). The atmospheric abundance of He in the planets of evolved systems can be significantly reduced from the initial value due to the differentiation process of He in the atmosphere during the planet evolution (e.g. Gautier et al. 1981; Stevenson & Salpeter 1977). It is believed that the He differentiation process has not, or at least only recently, started in the atmosphere of Jupiter, while it has already proceeded in that of Saturn. Since we only know the cases of Saturn and Jupiter, we do not know which case is more typical in gas-giant planets. The effective approach to this issue is a systematic measurement of the atmospheric He abundances of gas-giant exoplanets with the SCI.

Mid-IR spectroscopy of Jupiter by Voyager revealed that the broad collision-induced S(0) and S(1) transitions of H$_2$ are seen in the wavelengths of 13–20 $\mu$m, and > 20 $\mu$m, respectively (Hanel et al. 1979). The SCI aims to obtain similar spectra for exoplanets in the coronagraphic spectroscopy mode. The opacity determined by measuring the H$_2$ features will contribute to understanding of the cooling process and the heat balance. It would be possible to obtain the abundance ratio of H$_2$ to He by fitting the spectra with the appropriate models considering the temperature dependence, as demonstrated by the Voyager 1/IRIS observation (Gautier et al. 1981). It requires the continuous spectral coverage from 10 to 28 $\mu$m with the spectral resolution of $R \sim 50$ to cover the entire S(1) feature and part of the S(0) feature.

4. ATMOSPHERIC STRUCTURE OF JOVIAN EXOPLANETS

4.1. Thermal Inversion

It is a controversial issue whether the thermal inversion, i.e., the turn-over of the pressure-temperature profile, is common or not in the atmosphere of planets. The thermal inversion would imply a thermal input from outside of the atmosphere. Mid-IR spectroscopy by Voyager contributed much to obtaining such information for outer planets in our solar system. In the case of extra-solar systems, infrared SEDs were recently obtained for transiting exoplanets (i.e. inner planets) and the temperature profiles were derived (Madhusudhan & Seager 2009), however the thermal structure of the atmosphere is yet to be understood well, especially for outer planets. The thermal environment of inner planets is expected to be quite different from that of outer planets, although the thermal inversion in the atmosphere of outer planets is currently studied only for our solar planets. SCI will provide the infrared spectra of outer exoplanets, which enable us to make a systematic study of the thermal inversion for outer exoplanets. Spectroscopy with $R \sim 200$ and continuous coverage between 4–20 $\mu$m is important for this study.

4.2. Photo-Chemistry in the Upper Atmosphere

In our solar system, strong C$_2$H$_6$ feature (12.2 $\mu$m) is detected in the mid-IR spectra of Uranus and Neptune (Conrath et al. 1989). It is believed that the photolysis of CH$_4$ under 1 $\mu$bar produces C$_2$H$_6$ found in Uranus and Neptune. The material produced by photo-chemistry is potentially of small particle origin, which can affect thermal phenomena via radiation cooling and the green-house effect. It is known that the ratio of C$_2$H$_6$ to CH$_4$ is 1.99 % in Uranus, but only 0.0006 % in Jupiter. The SCI has a capability to measure the intensity of the C$_2$H$_6$ feature. Spectroscopy with $R \sim 50$ and spectral coverage between 10–14 $\mu$m is important for the measurement of this feature.

4.3. Haze in the Atmosphere of Exoplanet

Haze, non-gas small particles floating in the atmosphere, which are also known as dust or cloud, is likely to play an important role in the atmosphere, affecting the thermal phenomena via radiation cooling and the green-house effect. In the case of brown dwarfs, dust is considered to be an important component in their photospheres (e.g., Tsuji et al. 1996). When the photosphere is cooled below the condensation temperature, dust forms in the photosphere, changing the thermal structure and chemical composition of the photosphere. However the haze in the atmosphere of exoplanets has not been studied well, especially that in outer exoplanets. One of possible studies on the haze with the SCI is to search for major dust features such as those due to hydrocarbon grains.

4.4. 4 $\mu$m Excess in the Spectra of Jovian Exoplanets

The clear evidence that exoplanets have the Jupiter-like atmosphere can be obtained by detecting an SED excess at wavelengths of 4–5 $\mu$m, which is caused by looking at inner warm regions through the opacity window of the Jovian thick atmosphere. The amplitude of the SED excess can also be an alternative indicator of the age of an exoplanet. Spectroscopy with $R \sim 50$ covering 4–5 $\mu$m and longer wavelengths can detect this SED excess, as well as the baseline of the SED.
5. FONSTRAINING HEAVY ELEMENT ABUNDANCE

The temperature of the atmosphere of exoplanets is the key to understanding planetary formation process with the SCI. Another key is the abundances of heavy elements. The abundances of heavy elements in the envelope of a gas giant planet can be an indicator to determine whether the planet was formed via the core accretion model or the disk instability model. Gas giant planets formed via the core accretion model tend to have metal-rich envelopes through capture of planetesimals during runaway accretion of the envelopes (e.g., Shiraishi & Ida 2008). In contrast, the capture of planetesimals by fragmented clumps formed by disk instability is difficult especially in the case of distant gas giant planets like ones orbiting HR 8799 (Helled & Bodenheimer 2010). Therefore measurement of heavy elements for exoplanets can distinguish the planet formation models independently from that of the temperature of their atmosphere.

The SCI will perform systematic observations to obtain the infrared spectra of the outer exoplanets in order to give constraints on the abundances of heavy elements by comparing observed infrared spectra with model spectra, including the molecular features of CH$_4$, CO$_2$, CO, H$_2$O, and NH$_3$, etc. Such an approach is already applied to determine the abundances for transiting exoplanets (Madhusudhan et al. 2011). The coronagraphic spectroscopy with the SCI requires the wavelength coverage of 4–20 µm with R ~ 200 so that we can compare observed spectra with model spectra directly. Only the SCI provides the capability of such coronagraphic spectroscopy in the mid-IR, which will be unique even in the SPICA era.

6. DIRECT DETECTION AND CHARACTERIZATION OF ICY GIANTS

Icy giants, consisting of Neptune-mass bodies, are mostly composed of mixtures of water, ammonia, and methane ices, whereas the helium and the hydrogen gas only exist in the outer envelopes of these planets, in contrast to Jovian planets. Mid-IR direct imaging observations of extra-solar icy giants with the SCI will enable us to better understand inner structures and the formation and evolution scenarios of these types of planets. The high sensitivity and the high contrast of the SCI at wavelengths longer than 10 µm will enable us to detect extra-solar icy giants orbiting around early-type stars, because the thermal emission from a planet relaxes the required contrast ratio to a host star. Early-type host stars are especially suited well for this study as they are typically younger than 1 Gyr and there exist enough samples (38 stars within 25 pc). Future near-IR high contrast experiments including JWST and ELTs cannot reach these icy giants due to their limited contrast, hence the SCI is a unique instrument for the study of extra-solar icy giants.

7. CONCLUSION

SCI is a high-contrast imaging spectrometer for SPICA and the primary scientific cases are the characterization of the exoplanets with molecular gases and dust specific to the mid-IR region, and the discovery of icy giant planets. High-contrast imaging / spectroscopy would enable us to accurately determine temperatures of young planets at cooling phases, which are crucial to examine planetary formation theory. The studies of solid materials around planet-forming stars will lead us to understanding raw materials of planets and even the origin of life on planets.

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Zodiacal and Kuiper Belt Dust around Solar Type Stars

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ABSTRACT

The SEDs of solar-type main sequence stars in the far infrared are examined. Like the Sun, the majority of these DUNES stars exhibit evidence for temperature inversions in their atmospheres. However, a third of them does not follow this trend, which could imply that their temperature minima are masked by the FIR emission of cool circumstellar dust. Levels of a few times that of the Edgeworth-Kuiper Belt could accomplish this, potentially pointing toward old planetary systems. Likewise, for future investigations of planetary atmospheres, the presence of zodiacal-like dust clouds in the habitable zones need to be assessed. SPICA instruments will have the necessary sensitivity to achieve these goals.

1. INTRODUCTION

The rapid expansion of the exo-planet field in astronomy has contributed to the acceptance of the not-any-longer-so-ridiculous idea to search for extraterrestrial life. There is also general agreement that this would require spectroscopic observations of rocky planets in the temperate belt around other stars, where planetary surface water can be expected to be mostly liquid, and that such observations will need to be carried out from space. However, the first generation of such missions will likely have a limited collecting area, with the risk of severe flooding by the local zodiacal light. Its source is a flattened cloud of dust particles in the inner solar system that scatter sunlight in the optical and emit thermal radiation in the mid-infrared (MIR).

External planetary systems can be expected to possess their own zodi-clouds. These will add to the noise budget and might, for very dusty and/or inhomogenous sources, lead to unfeasible integration times. The exact level for this will depend on the observing waveband, the observing mode and configuration, and the total aperture size, but several tens of Zodies would appear very uncomfortable (Absil et al. 2010; Defrère et al. 2010). That level, about 30 Zodies say, is what new ground-based facilities under development and/or in the planning will be able to do.

A true exo-zodi has as yet to be discovered, as the intensity would be far below current detection levels (Millan-Gabet et al. 2011; Roberge et al. 2012, and references therein). On the other hand, dust at distances further out in the stellar systems has been discovered with space borne facilities in the far infrared (FIR). There, the dust is considerably cooler than in the habitable zones and provides enhanced contrast between the stellar photospheres and the dust excess emission. According to the census by the DUNES programme (Eiroa et al. 2013), about a quarter of all observed F, G and K stars in the solar neighbourhood ($D \leq 20\, \text{pc}$) show Kuiper Belt like dust emission.

In these debris systems, shapes and sizes seem to indicate the presence of unseen planets and, by analogy with the solar case, one might ask, how common it is that a warm zodi disc (ZD) accompanies a cool Kuiper Belt (KB)? In addition, for the solar system, $(f_{\text{ZD}}/f_{\text{KB}})_{\sigma} = O(1)$, where the fractional dust luminosity $f_{\text{dust}} \equiv L_{\text{dust}}/L_{\text{star}} \sim 10^{-7}$ (Vitense et al. 2012) and also called here 1 EKB (Edgeworth-Kuiper Belt unit). What are the corresponding relations for the exo-systems? To answer these and similar questions, new facilities in space are needed. SPICA will be uniquely and excellently suited to address these issues.

2. RECENT HERSCHEL RESULTS

From the photometric observation of over a hundred nearby solar type stars in the far infrared, Eiroa et al. (2013) found that almost a quarter of them is associated with cool dust. This dust is seen as excess emission over the photospheres of the stars. This was quantified as detected when $\chi^2 > 3$, where for a given waveband $\chi^2 \equiv (S_{\text{obs}} - S_{\text{mod}})/\sigma_{\text{obs}}$. Here, $S_{\text{obs}}$ and $\sigma_{\text{obs}}$ are the observed flux density and its rms uncertainty at $\lambda$, respectively, and $S_{\text{mod}}$ is the ditto flux density of the proper theoretical model of the stellar photosphere (see Eiroa et al. 2013, for details).

The DUNES observations were most sensitive at 100 $\mu$m and in the left-hand panel of Figure 1, $\chi_{100}$-histograms are presented for stars that were classified as non-excess sources, i.e. for which $\chi_{100} \leq 3$. This figure is similar to Figure 6 of Eiroa et al. (2013), but here we also show the relative distribution among the stellar spectral classes. The histograms for the F, G and K stars do not show any significant differences. Instead, they all reveal a large number of negative $\chi_{100}$-values. Actually, $\chi_{100} < 0$ for more than 80% of the non-excess sources. Similar results are obtained at 160 $\mu$m, the other observed waveband.

41 The DUNES near NEarby Stars are within 25 pc and of spectral type F, G and K, see Eiroa et al. (2013).

1 For various definitions of the Zodi unit (e.g., 1 Z), see Roberge et al. (2012). Here, as an equivalent observable, the dust fractional luminosity of $10^{-7}$ is used, the details of the spectrum however undefined.
Liseau

Figure 1. Left: Histograms of $\chi_{100}$ for the non-excess F, G and K stars. The lack of values larger than three is artificial ($\chi_{100} \leq 3$) and offsets of $N = 10$ and $N = 25$ are introduced for clarity. Right: The observed flux density at 100 $\mu$m as a function of $\chi_{100}$ for the DUNES non-excess stars. The $\alpha$ Cen AB binary accounts for the two outliers in this plot. The 100 $\mu$m confusion noise level is at about 1.5–2 mJy (Berta et al. 2011; Eiroa et al. 2013), below the swarm of data points.

Figure 2. FIR and submm observations of $\alpha$ Cen A (Liseau et al. 2013) are depicted by filled squares and, for comparison, dito of the quiet Sun by open circles. The curvy long dashes show an empirical model for the solar temperature minimum and its chromosphere (Vernazza et al. 1981). The straight line of long dashes shows the RJ-extrapolation of the PHOENIX-model beyond 40 $\mu$m, whereas the solid line shows the identical physical model, but computed up to 200 $\mu$m with the MARCS code (private communication K. Eriksson, and Gustafsson et al. 2008).

The theoretical flux densities $S_{\text{mod}}$ are based on the PHOENIX-Gaia grid by Brott & Hauschildt (2005). These stellar model atmospheres have been computed for wavelengths up to about 40 $\mu$m. Thus, theoretical flux densities $S_{\text{mod}}$ at longer wavelengths were actually not available, but were estimated from Rayleigh-Jeans (RJ) extrapolations. For solar-type stars with chromospheres, this might not really work, as is demonstrated by the solar twin $\alpha$ Cen A (G2 V) in Figure 2. There, the radiation temperature is shown in Kelvin as a function of the wavelength, viz. $T_{\text{B}}(\nu) = h\nu/k\left[\ln(2\pi R_{\odot}^2 D^2 c^2 S_{\nu} + 1)\right]^{-1}$ with obvious notations (see Liseau et al. 2013).

For both the Sun and $\alpha$ Cen A, $T_{\text{min}}/T_{\text{eff}} < 1$, and that appears to be the case also for many other stars of the DUNES sample (Figure 1). Toward longer wavelengths, this ratio increases to values above unity and the explaining physics are often presented in terms of magnetic heating of the chromosphere. The theory has been worked out only in some approximate detail and that only for one case, i.e. the Sun, and several questions remain open in general (e.g., de la
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Figure 3. The sensitivity curves for the SPICA imaging instruments (SAFARI: B. Sibthorpe, private communication) are compared to those of other observing facilities. Nominally, SPICA will reach even sub-Z⊙ and sub-EKB levels, but in practice, very careful calibrations will be required.

Rodríguez et al. 2013. The energy transport in stellar atmospheres is an important astrophysical problem and the detailed study of also other stars may help to solve some of the remaining mysteries.

However, for a number of the DUNES F, G, K stars “without excess”, χ100 is slightly positive, i.e. 0 < χ100 < 3. If proven significant in the future, then one possibility could be that some of these stars, if not all, have their temperature minima concealed by feeble emission from circumstellar dust. To estimate the potential magnitude of this effect for unresolved non-excess sources, we used the high-S/N SED of α Cen A, “filled the pit with sand”, and determined the resulting fractional luminosity, fKB (Wiegert et al. 2013). The physical basis for this was dynamical disc modelling for the density structure, in conjunction with the solving of the energy equation to derive the proper temperature profile of the disc, resulting in fKB ∼ 2 × 10⁻². This is about twice the value that has been estimated for the solar Kuiper Belt, viz. 1 EKB ∼ 10⁻⁷ (Vitense et al. 2012), and is beyond the limit of what is believed would be possible with Herschel (see Roberge et al. 2012; Eiroa et al. 2013).

Wiegert et al. (2013) made a similar exercise also for a putative zodi cloud or disc around α Cen A, for which Spitzer obtained at 24 µm a value of χ24 = +2.5. The resulting 3σ upper limit of fZD ∼ 2 × 10⁻³ is more than two orders of magnitude higher than the corresponding solar value, 1 Z⊙ ∼ 10⁻⁷ (Fixsen & Dwek 2002; Nesvorný et al. 2010). For future spectroscopic work on Earth-like planets, this is an interestingly high upper limit and will need to come down by at least one order of magnitude by future observations.

3. MEASURING FZD AND FKBY FOR EXTRA-SOLAR SYSTEMS

Like the solar zodi cloud, external zodi dust around solar-type stars can be expected to radiate also predominantly in the mid-infrared (MIR). Grain temperatures will be roughly 100-300 K, with typical blackbody maxima in the 10–30 µm region. At 24 µm, the MCS-WFC point source sensitivity is about 6 µJy (5σ in 1 hour). That corresponds to the solar system zodi (Izod ∼ 100 MJy sr⁻¹) seen at 10 pc with the instrument PSF (≥ 2 arcsec). Similarly, at that distance, the peak flux from the solar Kuiper Belt (1 EKB) would be about 500 µJy in the 40 – 50 µm region (Vitense et al. 2012), which would compare very favourably with the sensitivity of SAFARI at 47 µm (about 50 µJy, 5 σ in 1 hour, Figure 3). It would thus appear entirely feasible to observe the 384 F, G, K stars of the Darwin² catalogue (D ≤ 25 pc, V ≤ 12 mag, Cockell et al. 2009) at both MIR and FIR wavelengths. In the foreseeable future, only SPICA will be able to do this.

3.1. CHALLENGES

Even if the instrumental sensitivities are high enough, such observations are not without difficulties. A few of them are mentioned here.

² Darwin is a mission proposal for the spectroscopic observation of Earth-like planets in the habitable zones of their host stars.
Stellar model photospheres: The required stability and photometric accuracy of the observations will also need considerably better stellar model atmospheres than what is currently available, where estimated uncertainties of the LTE-models are about 1–5 % (e.g., Gustafsson et al. 2008). This contrasts with the level of, e.g. 1 EKB, i.e. 0.5 % of the photospheric flux at peak (Vitense et al. 2012).

Stellar model chromospheres: Here models can diverge widely, due to non-LTE effects that determine the opacities (Figure 4). In addition, solar/stellar activity can add to the large dispersion in both observations and models.

Confusion noise: At the longer wavelengths of Kuiper-Belt observations, one could expect that, for the 3 m telescope of SPICA, background confusion might become an issue, especially for weak sources. Current estimates for the background limited flux are 15 µJy at 47 µm, 500 µJy at 85 µm, 5000 µJy at 160 µm (SAFARI Fact sheet V0.1 – 31January 2013). For F, G, K stars selected for future spectroscopy of Earth-like planets, this should not present a major problem (c.f. right panel of Figure 1).

Source brightness levels: Contrast, and detector saturation for the brightest stars, may become a problem, in particular in the mid-IR. Also, coronagraphy will not be an option for most zodi observations, as $n \lambda / D = n$ arcsec at 10 µm, whereas a typical zodi size of 5 AU subtends 0.5 arcsec at 10 pc.

4. CONCLUSIONS

- Based on Herschel observations, the minimum temperature in the SED of $\alpha$ Cen A (G2 V) was measured on another star for the first time. Like in the Sun, this occurs near 150 µm, but $T_{\text{min}}$ of $\alpha$ Cen A appears marginally lower than in the Sun.
- This seems not to be an isolated phenomenon, as 2/3 of about 100 “non-detections” in the DUNES sample also show the $T_{\text{min}}$ effect. Confirmation would require data at much better S/N and with SPICA, astrophysics could contribute to unravel the mysteries of chromospheric heating.
- If temperature inversions ($T_{\text{min}} / T_{\text{eff}} < 1$) are universal for F, G, K stars, then for the remaining 1/3 of the DUNES non-excess stars, the non-detections may mask true Kuiper Belt analogues ($L_{\text{dust}} / L_{\text{star}} = \text{afew} \times 10^{-7}$), potentially also hinting at the high incidence of unseen planetesimals and/or planets.
- Observations with the SPICA instruments will reach sub-$Z_{\odot}$ and sub-EKB levels and will connect Solar Physics/Astrophysics with Planetary System Physics.

The very interesting discussions with members of the DUNES team are very much appreciated. The continued support by the Swedish National Space Board (SNSB) is acknowledged.

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ZODIACAL AND KUIPER BELT DUST AROUND SOLAR TYPE STARS

Results of the Chromatic Differential Astrometry Demonstration Bench and Application to the SPICA Mission

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ABSTRACT
We present experimental results from the Color Differential Astrometry (CDA) test bench. The CDA is expected to enable direct characterization (astrometry and spectra) of Giant Extra-Solar planets very close to their parent star, thus complementing the direct imaging instruments (aimed at outer planets). The goal of this experiment is to validate high precision spectro-astrometric measurements at the level of a few $10^{-4}$ pixels through a comparison between a numerical model of the method and a “real-world” setup. Once validated, these results can be extrapolated to several spectrometric instruments onboard SPICA, provided the noise sources of the instrument are sufficiently well known, as they are in our experiment. The CDA observing mode can be used with the SCI (SPICA Coronagraphic Imager) without any additional hardware device. The SCI benefits from a tip-tilt stabilization of the optical beam with a moderate accuracy (< 0.1 pixel 0–peak), possibly enough to reach ~ $10^{-4}$ pixels differential astrometric accuracy. We show that theoretical predictions are consistent with experimental results in our experiment and how it can be extrapolated to the SPICA mission.

1. SCIENTIFIC OBJECTIVES
The goal of the proposed method is to be able to spectrally and astrometrically characterize close-in, highly irradiated extrasolar planets. Planetary atmosphere models predict that such planets orbiting beyond 0.1 AU exhibit more or less contrasted spectral features. The case studies in that framework are G and M-type stars. The CDA allows the direct recovery of the stellar spectral types, the planetary orbital separation, and the distance of the system. The closest separations favor the signal at short wavelength (where the higher temperature of the planet compensates the smaller angular separation in the photocenter displacement — see below), whereas the largely separated planets are better measured towards longer wavelength. Also, planets with not-so-short separations show significantly larger variations of the signal over the spectrum, which might offer interpretation in terms of atmospheric composition and physical characteristics.

2. CDA AND APPLICATION TO SPICA
Constraints on the instrumental stability and on the required precision in general are very much relaxed thanks to the colour-differential aspect of CDA, i.e. the fact it measures photocenters relatively between some spectral channel and a reference channel chosen appropriately. The possibility to measure the relative position of an image with a precision much higher than its equivalent size was first shown by (Beckers (1981)). As a reminder, the photocenter is the angular vector $\vec{e}(\lambda)$ measured at time t and wavelength $\lambda$, which can be written as:

$$\vec{e}(t, \lambda) = \frac{\int o(\vec{r}, \lambda)dr}{\int o(\vec{r}, \lambda)dr} + I(t, \lambda) + b(t, \lambda)$$

(1)

where $o(\vec{r}, \lambda)$ represents the angular brightness distribution of the source observed by the telescope in the spectral channel of wavelength $\lambda$, $I(t, \lambda)$ represents the global effects and biases from the instrument, and $b(t, \lambda)$ the fundamental noises. By measuring the photocenter difference $e(\lambda) - e(\lambda_{ref})$, and since any channels $\lambda$ and $\lambda_{ref}$ are measured simultaneously, their biases and variable effects, mostly achromatic, are largely suppressed. In order to correct also for the chromatic effects, a calibration using an reference star is also required, and repeated at a period corresponding to the timescale where variations of chromatic effects become critical in the noise budget.

3. THE CDA LABORATORY DEMONSTRATION
We developed a numerical model of the CDA including a number of noise sources that are affecting the performance of the method. In parallel we set-up a laboratory experiment in order to validate this model.
3.1. Methodology

The methodology of this work is therefore to thoroughly study and characterize the individual components of the experiment (optics, opto-mechanical mounts, detectors...) and derive parameters that serve as inputs for the numerical model. Our goal is then to be able to provide realistic estimations of the mode based on numerical simulations with an actual real-world experiment. Thus this experiment is not to be considered as a simulator of the mode onboard SPICA. The outputs of this work is to provide a numerical model that can be used to simulate the performance of the CDA on SPICA.

3.2. Numerical Simulator

Our estimates for the potential, feasibility and limits of the observing mode presently proposed were computed using a front-to-end simulation software (written in Yorick), which allows to compute:

- the theoretical astrophysical signal. In the present case we considered either the case of an extrasolar planets (for some given orbital separation, albedo, temperature and host star type parameters) for estimating the detection potential, or the simpler case of a laboratory white light source, in order to allow the comparison with the experiment.
- The “fundamental noises” associated with the observations. These noises include the photon, thermal and read-out noises, for a number of basic observational and detector parameters.
- The instrumental effects, which are principally: the non-homogeneity and variation of detector gain table, the tip-tilt of the beam (and its variations, possibly introduced as a power spectrum) during the acquisition, and the beam pointing/re-pointing accuracy.

The precision and accuracy on the calibrated measurement are derived by comparing, over a statistically significant number of events, the simulated measurements on a science and a calibration source. Other effects considered by the detector include the possible use of a coronagraphic mask, the detector non-linearity as a function of flux, the intra-pixel effects and the binning of pixels along spatial or spectral directions. All these effects are defined within some given instrumental parameters set-up (e.g. SCI/SPICA or our experimental bench) but are individually adaptable, either for updating technical characteristics or for exploring a range of values.

3.3. Experiment Implementation

The optical bench is shown on Figure 3 of Abe et al. (2012). It shows the optical layout of our bench and the actual realized implementation. The light is emitted by a so-called super-continuum pulsed white laser from Leukos. it is connected to an off-axis reflective collimator. The beam is then going through two parabolic mirrors used in a symmetric “W” configuration. At the two parabola focal points (where pupil images are formed) a tip-tilt mirror and a linear 50 gr/mm grating sit. The final dispersed image is directed to a SBIG ST-10XME camera and to a tip-tilt monitoring Prosilica camera.

When possible each element of the bench was characterized by individual, independent experiments. We evidenced (and understood) differential mechanical drifts between the tip-tilt and the SBIG cameras that were beyond our requirements.

The measured flat-field and dark-field data were first analyzed to estimate the roughness (i.e. spatial variation) and time variation of the detector gain. Within a time scale of about an hour, the standard deviation of the table gain happens to be $\approx 2 \times 10^{-3}$ both spatially and temporally, associated with a power spectrum very similar to a white noise. The slower (and larger) variations were removed by the differential process. Also, the measurement of the beam tip-tilt was approximately 0.1 pixel RMS over the same time length.

At the present, we obtain an RMS precision of about 0.02 pixel per short frame on the differential photocenter, i.e. about $2 \times 10^{-4}$ pixel for the cumulated 1.25 hours of integration period on the science source, with the same amount of time spent on calibration frames.

4. RESULTS

4.1. Experimental Precision of CDA

The measured flat-field and dark-field data were first analyzed to estimate the roughness (i.e. spatial variation) and time variation of the detector gain. Within a time scale of about an hour, the standard deviation of the table gain happens to be $\approx 2 \times 10^{-3}$ both spatially and temporally, associated with a power spectrum very similar to a white noise. The slower (and larger) variations were removed by the differential process. Also, the measurement of the beam tip-tilt was approximately 0.1 pixel RMS over the same time length.

At the present, we obtain an RMS precision of about 0.02 pixel per short frame on the differential photocenter, i.e. about $2 \times 10^{-4}$ pixel for the cumulated 1.25 hours of integration period on the science source, with the same amount of time spent on calibration frames.

4.2. Comparison between Simulation and Experiment

With the measured table gain roughness and stability parameters introduced in the simulator along with the tip-tilt statistics, we obtain from the a Monte-Carlo simulation a precision of about $1.5 \times 10^{-4}$. The ratio between the measured and simulated CDA precisions is therefore 1.3, which represents a good agreement considering a number of unknown values among the secondary effects. This difference would translate quadratically by a factor 1.7 on the required observation time for reaching a given precision, with respect to our simulated estimations.

4.3. Application and Extrapolation to SCI/SPICA and Conclusions

Applying this to SCI/SPICA is a more tricky task, since actual table gain and tip-tilt stability, as well as the pointing accuracies or the possible calibration cycle period of the instrument are not yet known. We assumed in Figure 1 four
different cases combining the following parameters: either 5 or 15 calibration cycles, tip-tilt stability of 20 or 60 mas, pointing accuracy between science and calibration source of either 10 or 60 mas, detector gain table roughness of 1 %, and detector gain table relative stability of 0.25 %. The plain black curve is the noiseless photocenter signal, and the dotted one corresponds to the noisy signal with photon, readout and thermal noises only.

The fair agreement found between our test bench measurements and the simulator in the visible range gives us confidence that our simulations for SPICA are not unrealistic, with these parameters. In order to fully realize the experiment’s objectives (better image stabilization in the science detector), we realized that we were limited by several instability issues. These are currently being studied so that an improved version of our bench is envisaged.

REFERENCES
Markov Chain Monte Carlo Simulations and Binary Orbital Elements

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ABSTRACT

Recent simulations and observational data have been used to investigate the possibility of planet–planet scattering or Kozai oscillations to explain the formation of certain non-solar-like planetary systems. Markov Chain Monte Carlo (MCMC) simulations have benefits compared to standard Monte Carlo ones. With these advantages in mind, an advanced three-dimensional MCMC simulator has been written to investigate the orbital solutions to the τ Boo system in order to better understand its possible formation history.

Over 890 extrasolar planets (or exoplanets) have been confirmed so far, with nearly 2000 more candidates awaiting ground-based follow-up, (Schneider et al. 2011; Batalha et al. 2013). Thanks to the large number of known planets, we are beginning to understand how planetary systems form and how abundant solar-like systems are. The first formation models assumed that planets formed on approximately coplanar and circular orbits, as we observe in our solar system today. However, as more planets were observed, it became clear that many (∼17%) are in close-in orbits, while others are eccentric or misaligned, (Nagasawa & Ida 2011). For these planets, new mechanisms were proposed to explain their existence. The two leading mechanisms are planet–planet scattering and Kozai oscillations, both of which involve a distant or ejected companion object.

In planet–planet scattering, the planetary system contains two planets with the larger one being slightly further out. Due to orbital interactions between these two, the outer planet is launched into a more distant and eccentric orbit where it then experiences dynamical friction with the planetary disk. This friction adds energy and angular momentum causing its pericenter to rise, (Chatterjee et al. 2011). Meanwhile, the inner planet will move inward and also see a raised eccentricity for some time until it is dissipated by tidal forces from the parent star. In the case of the 51 Pegasus system, if the tidal dissipation has not had the chance to fully circularize its orbit, the eccentric solution to the radial velocity curve can be explained using planet–planet scattering. The second body could possibly still be bound in a distant (a > 20 AU) and eccentric orbit outside the range to be easily detected, (Rasio & Ford 1996). Recent high-contrast efforts have found a class of planets matching this category with high-mass, distant and eccentric orbits from the parent star, providing further support to this mechanism, (Kalas et al. 2008; Marois et al. 2008).

For those systems where a planet hosting primary star also has a stellar mass companion, Kozai oscillations can play an important role in the system’s evolution. Exchanges of energy and angular momentum between the stellar companion and planet induce an oscillation of their eccentricities and inclinations. When excited to a higher eccentricity, the planet would consequently also have closer periapsis passages where tidal dissipation could damp the planet onto a short-period, nearly circular orbit, (Beust et al. 2012). This process is commonly referred to as Kozai migration. Now knowing that most stars form in multi-star systems, suggestions of the Kozai migration’s possible role in evolution histories have become more common. This effect could possibly explain the orbit of τ Boo Ab, caused by the interactions with the very distant and eccentric companion star, τ Boo B. The orbit of τ Boo Ab is only ∼3.3 days and has an eccentricity that is compatible with zero (Brogi et al. 2012; Rodler et al. 2012; Donati et al. 2008). With strongly constrained orbital parameters the equations of Ford et al. (2000) can be applied to compare the period of the Kozai oscillations to the ∼2 Gyr age of τ Boo A, allowing for investigation if they could have played a role in the planet’s formation.

Three previous investigations of τ Boo B’s orbit estimated it to have a 390–2000 year period and an eccentricity of 0.42–0.91 (Hale 1994; Popović & Pavlović 1996; Roberts et al. 2011), see Figure 1. Even with 163 years of observations, τ Boo B has traversed less than half of the shortest proposed orbit. Investigations of such long-period systems require careful analyses, preferably with explicit priors and well-characterized posterior probability distributions. We therefore re-analyze the τ Boo system using Markov Chain Monte Carlo (MCMC).

One of the benefits of MCMC is that, in the limit of a long chain, its samples are drawn directly from the posterior probability distribution. A standard Monte Carlo simulation, by contrast, will draw many points in regions of parameter space with exceptionally low likelihood. MCMC can therefore be significantly more efficient at exploring the parameter space in spite of the fact that its samples are not independent. Because MCMC directly probes the posterior probability distribution, calculating 68% and 95% confidence intervals for each parameter also becomes trivial.
Figure 1. Three previously proposed orbits for \( \tau \) Boo B (Hale 1994; Popović & Pavlović 1996; Roberts et al. 2011), together with our best-fit. The locations of \( \tau \) Boo B are shown as the small stars, with their associated errors, and \( \tau \) Boo A at the origin. The proposed orbits have not converged to a consensus solution, which is needed for a complete assessment of the Kozai formation scenario.

Figure 2. The posterior distribution of the eccentricity parameter from \( \tau \) Boo Ab orbital fitting using our MCMC simulator. The black lines mark the median value, dashed line the best fit, dark grey bars are within the 68.3\% confidence region and light grey are within the 95\%.

A further advantage of well developed posterior distributions for the model parameters is to allow the investigation of values very close to the parameter’s limits. For short period planets \((P \sim 1–20\ \text{days})\), the close proximity to the parent star causes strong tidal forces that will likely dampen any perturbations due to an eccentric orbit, (Husnoo et al. 2012). Owing to the hard minimum limit of zero on the eccentricity, \( e \), it is impossible to prove that an orbit is circular, but rejection of any orbit over \( e > 0.1 \) to a 95\% degree of confidence is sufficient to show compatibility. In the case of \( \tau \) Boo Ab, one of the most recent investigations into this planet’s orbit demonstrated that it had an eccentricity compatible with zero by showing the parameter’s posterior distribution had a strong trend towards zero (Brogi et al. 2012), compared to a previous solution of \( e \sim 0.02 \) by Butler et al. (2006). During the verification process of our own MCMC simulator, the \( \tau \) Boo Ab orbit was found to contain 95\% of the solutions to \( e < 0.022 \) and a maximum value of 0.055, shown in Figure 2. We thereby also conclude that its orbit is circular and provide a plot of our fit in Figure 3.

Previous investigations of \( \tau \) Boo B’s orbit used only the positions measured from direct imaging data. However, radial velocity measurements of \( \tau \) Boo A show a trend from \( \tau \) Boo B superimposed on \( \tau \) Boo Ab’s 3.3 day orbit. We are taking advantage of these new data, along with more recent astrometry, in a full three-dimensional simulator. This analysis will improve our understanding of \( \tau \) Boo B’s orbit, and constrain models suggesting Kozai oscillations as the origin of the “hot
Figure 3. The radial velocity curve plot for our best fit circular solution for τ Boo Ab along with the post-1995 data from Butler et al. (2006) and Donati et al. (2008).

Jupiter” τ Boo Ab. Our initial results show a more eccentric orbit for τ Boo B than the most recent investigation, Roberts et al. (2011), with $e = 0.79 \pm 0.01$.

Our new constraints on the orbit of τ Boo B will allow dynamical calculations of plausible orbital histories of the system over its 2 Gyr life, and will confirm or reject the possibility of a Kozai origin.

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Direct Observation of Icy Grain Distribution and the Snow Line in Circumstellar Disks Using SPICA

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ABSTRACT

Icy grains are supposed to play various important and critical roles on planet formation, though observational understanding of the ice distribution is quite limited so far. With the SPICA observations of ice and its distribution in the various disks, we can make a significant progress on our understanding of the icy grain distribution in the disk. In instruments proposed for SPICA, especially the SCI has big potential for tracing the distribution of the icy grain directly thanks to the function of the coroangraphic spectroscopy. The aims of the direct observations with the SCI are (1) to establish the existence of the water ice in the debris disk, (2) to measure spatial distribution of ice grain, and (3) to challenge to trace the “snow line”, for the first time. Combined observations of SAFARI (aiming for 44 \(\mu\)m water ice feature) and SCI (aiming for 3, 6.2 \(\mu\)m water ice feature) will be especially effective for establishing the presence/non-presence of water ice grain in the debris disks.

1. IMPORTANCE OF ICE IN THE DISK FOR THE PLANET FORMATION

Ices, mostly consist of water ice, are supposed to play various important and critical roles on planet formation. Volatiles such as icy dust are not supposed to exist at the inner warm region of the disk where they immediately evaporate. While icy dust can indeed present at the outer cold region of the disk, thus there should be an ice condensation/sublimation front called “snow line” in the disk which are schematically shown in Figure 1. Following Hayashi et al. (1985), surface density of solid matter increases beyond the snow line due to the increase of the icy dust mass, which enables to form a massive 10 earth-mass solid core of the gas giant. This is the popular theory to explain why the rocky planets orbit at the inner region of the Solar system, while the gas-giants exist at the further out. To confirm this theory, it is strongly desired to observe the distribution of icy dust in the disk and location of “snow line”.

Furthermore, to understand the origin of the water/ocean in the Earth, our understanding of the water ice distribution in the disk is the fundamental information, because there is a scenario that icy planetesimals or comets bring the water to Earth (Morbidelli et al. 2000; Raymond et al. 2004), of which depend on the assumption of water ice distribution of the disk. In addition, Yurimoto & Kuramoto (2004) suggested that water ice evaporation at the inner region of the disk brought the oxygen isotope anomaly seen in the meteorites. Thus our robust understanding of the water ice distribution in the disk is critical for various scenario and theories.

However, as will be stated later, our observational understanding of the ice distribution is quite limited so far, thus observations of the ice distribution in the disk are of great importance for various research fields and topics. With the SPICA observations of ice and its distribution in the various disks, we can make a significant progress on our understanding of ice grain distribution in the disk, which also enables us to verify the assumption of above scenario and theories, universality/diversity of ice distribution, and unique/common nature of our Solar system.

2. PREVIOUS OBSERVATIONS

Although a lot of theoretical studies on ice in the disk have been done so far, observations of the ice in the disk is limited. For example, the spatial distribution of the ice in the disk is not well constrained and no one directly resolved the “snow line” so far. We only know that ice grain can be present toward line of sight to the edge-on protoplanetary disks using the 3 \(\mu\)m water ice absorption feature (Terada et al. 2007; Aikawa et al. 2012), which indicate there is ice in some area (probably cold region) of the disk. The 44 \(\mu\)m and 62 \(\mu\)m emission features from the water ice grains are detected toward a few sources (Malfait et al. 1999), but the number of the detection is quite limited. Recently, using near-infrared multiband imaging of the scattered light from the protoplanetary disks from the ground-based telescope, the radial distribution of ice grains has been investigated (see Figure 2; Inoue et al. 2008; Honda et al. 2009). However, due to the lower spectral resolution, such multi-band imaging approach is difficult to distinguish water ice (~3.1 \(\mu\)m) and hydrated minerals (~2.7 \(\mu\)m), thus spatially and spectrally high resolution 2.5–5 \(\mu\)m observation of the disk is strongly desired. As for the debris disks, even the presence of ice grains is not clearly established observationally. A tentative detection of the 62 \(\mu\)m water ice emission feature is claimed (Chen et al. 2008), however, the significance is not high and there is little observational evidence for the water ice in the debris disks. With the SPICA, we can make a breakthrough...
Honda, Inoue and Enya

Figure 1. Schematic figure of the distribution of silicate and ice in the disk. Water ice sublimation front is called snow line (adopted from Chiang et al. (2001).)

to our understanding of the water ice in the disk. SPICA/SCI can make a spatially-resolved coronagraphic spectroscopic observations of the disk (Enya et al. 2011; Kotani et al. 2012), and SPICA/SAFARI will enable us to make observations of 44 $\mu$m water ice emission features from the disk. Such observations will bring us the first systematic studies on ice in the disk, which enables us to understand the evolution of the ice from the young protoplanetary disks ($\sim$ a few Myrs) to the old debris disks (more than 10 Myrs).

Figure 2. Ground-based trial for water ice grain detection from the scattered light from the disk (Honda et al. 2009).

3. WATER ICE DISTRIBUTION AS REVEALED BY SPICA/SCI

The aim of the SPICA/SCI observations in the context discussed here will be (1) the establishment of the existence of the water ice in the debris disk and (2) the detection of the water ice “snow line” directly for the first time. As already stated, it is not clear whether water ice grains exist in the debris disk. This is because the scattered light from the debris disk is relatively faint, thus it is hard to get a high S/N ratio imaging/spectroscopy data of 3 $\mu$m absorption in the thermal infrared wavelengths (2.5–5 $\mu$m) from the ground. Furthermore, the behavior of the “3 $\mu$m absorption” is expected to show a bit complex profile due to the optically thin dust scattering (Inoue et al. 2008), therefore it will require the spectroscopic observations to trace the water ice feature. Such capability is only provided by SPICA/SCI. To establish the existence or non-existence of the water ice grains in the debris disk is important from the view of the origin of the debris dust. When we confirm the water ice grains in the debris disk, it naturally indicates that this dust comes from the collision of ice-bearing planetesimals (cometesimals). On the other hand, when we find that the debris dust does not contain water ice, it is a surprising result that the debris dust originates non-ice-bearing planetesimals such as rocky asteroids even though its temperature is low enough. The radial distribution of the ice and detection of snow line are also of great interest. The
ICE AND SNOW LINE IN THE DISK

The radial position of the snow line is a function of the stellar luminosity and is predicted to be 10–30 AU assuming the stellar luminosity of 1–10 L☉ (Oka et al. 2012). Since SCI will provide the coronagraphic spectroscopy (IWA is 0′′4–0′′8 at 3.5 μm) between 2.5–5 μm with a resolving power R~100, we can resolve the snow line of the debris disk within ~30 pc from the earth. The possible targets will be the nearby Vega-like stars. We estimated the required contrast to be ~10^−5 for detecting β Pic disk at 1′′5 from the central star (Mouillet et al. 1997). It is apparent that the observational confirmation of the snow line in the disk is fundamentally important to our understanding of planet formation and disk evolution. On the other hand, due to the limited spatial resolution, it would be difficult to resolve the snow line of the protoplanetary disks. However, thanks to the unique SPICA/SCI capability of coronagraphic spectroscopy, we will be able to obtain the scattered light spectroscopy from the outer region of the protoplanetary disks. With such spectra, we can clearly distinguish the water ice and hydrated minerals. Furthermore, we can trace not only water ice but also less abundant ices such as CO, CO₂, and so on. Therefore, we can investigate the evolution of ice in the disk systematically for the first time.

4. SYNERGY WITH SAFARI ICE OBSERVATIONS

SPICA/SAFARI far-infrared spectroscopy will also contribute to our understanding of the ice grains in the disk. Although one of the strongest feature of the water ice is the 4.5 μm feature, this wavelength is not accessed since ISO (SST and Hershel did not). Thus the systematic observations of 44 μm feature by SPICA/SAFARI will bring important information on ice in the disk. Clearly, we can expect a synergy with SPICA/SCI observations of water ices. In general, features of solid matter is relatively broad compared to the sharp lines of gases which leads to contamination/blending from other dust features, thus single feature identification is hazardous and multiple identification of the feature is required for reliable identification. Combined observations of SAFARI (aiming for 44 μm water ice feature) and SCI (aiming for 3 μm water ice feature) will be especially effective for establishing the presence/non-presence of water ice grains in the debris disks.

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First Census of Habitable Zone of Protoplanetary Disks in the Galactic Scale

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ABSTRACT

Circumstellar disks have been thoroughly studied with MIR wavelengths because MIR traces the critical components of disks, such as life habitable zone of protoplanetary disks and debris disk. As a result, many characteristics of the disk evolution have been revealed, e.g., disk lifetime, dust growth, transitional disk. However, previous studies are only in the solar neighborhood ($D \lesssim 2$ kpc). Whether protoplanetary disks throughout the Galaxy evolve similarly to those in the solar neighborhood is of great interest.

As the next step, I propose studies of circumstellar disks in the Galactic scale. Due to low sensitivities of previous MIR instruments, studies beyond the solar neighborhood have not been possible. With the high sensitivity of SPICA MCS, $\sim 1 \mu$Jy at 10 and 20 $\mu$m, excess of circumstellar disks can be fully characterized and disk lifetime can be precisely estimated. Very wide field of view ($\sim 5^\prime \times 5^\prime$) is also a great advantage compared to the other future instruments, such as JWST MIRI and TMT MICHI. Protoplanetary disks of sub-solar mass stars and even debris disks of intermediate-mass stars can be detected. Eventually, these kind of studies will be connected to the search of life throughout the Galaxy.

1. INTRODUCTION

Circumstellar disks are not only essential objects to understand the star formation process, but are also critical objects to understand planet formation (e.g., Lada & Lada 2003). Disk lifetime is one of the most fundamental parameters of a circumstellar disk because it directly constrains the time for planet formation (e.g., Williams & Cieza 2011). Many estimations of disk lifetime are now available. For protoplanetary disks, which are directly connected to Jupiter-mass planet formation, disk lifetime is generally estimated to be 5–10 Myr (Williams & Cieza 2011). For the inner disk ($\lesssim 0.1–5$ AU), dust disk evolution is observed with NIR/MIR (e.g., Lada 1999; Haisch et al. 2001; Sicilia-Aguilar et al. 2006), while gas disk evolution is observed with Hα (Fedele et al. 2010). For the outer disk ($\gtrsim 50$ AU), dust and gas disk evolution are observed with submm (e.g., Andrews & Williams 2005) and FIR [O I] 63 $\mu$m (Meeus et al. 2012), respectively. As a result, the entire disk ($\lesssim 0.1–100$ AU / gas+dust) are thought to disperse almost simultaneously with $\Delta t \lesssim 0.5$ Myr (Williams & Cieza 2011). For debris disks, which is directly connected to terrestrial planet formation, disk lifetime is estimated to be $t \sim 100$ Myr from 24 $\mu$m observation (e.g., Wyatt 2008; Gáspár et al. 2009). However, previous studies are only for the solar neighborhood (see Figure 1). Next interest is how about in other environments.

We are extending the lifetime study to the whole Galaxy to see if there is any dependence on e.g., metallicity dependence. As the first step, we studied lifetime of protoplanetary disks in low-metallicity environments ([M/H] $\sim -1$ dex) by observing star forming regions located in the outer Galaxy at $R_G \gtrsim 15$ kpc. As a result, disk fractions there are found to be systematically low (Yasui et al. 2009), suggesting quite short disk lifetime compared to that in the solar metallicity (Yasui et al. 2010, Figure 2). Because these previous studies are only with NIR, new sensitive MIR observation is necessary for investigating “habitable zones” of protoplanetary disks and debris disks.

2. PROPOSED STUDY

2.1. Target

The locations of target star-forming clusters are assumed from the inner Galaxy ($R_G \sim 3$ kpc) to the outer Galaxy ($R_G \sim 15$ kpc), thus the distance is $D \gtrsim 5$ kpc (Figure 1).

2.2. Method

For protoplanetary disks MIR SED slope between $\lambda \sim 5–10$ $\mu$m is used to pick up disk-harboring stars in star-forming clusters (Hernández et al. 2007), while $\sim 20$ $\mu$m excess is used (Hernández et al. 2009) for debris disks. The procedures of disk lifetime estimation are: i) derive disk fraction, which is the ratio of the number of stars with IR excess to the total number of stars, in various star forming regions in wide age range, ii) then estimate disk lifetime from disk fraction vs. age plot (Figure 2).
Yasui

Figure 1. Target regions on the artistic illustration of the face-on Galaxy (R. Hurt, NASA/JPL-CalTech/SSC). On the Galaxy scale the solar neighborhood (yellow), which has been previously studied, is quite limited, while the outer Galaxy (blue) and inner Galaxy (red) are left widely unexplored.

Figure 2. Disk fraction as a function of cluster age. JHK disk fractions of the young clusters with low metallicity are shown by red filled circles, while those of young clusters with solar metallicity are shown by black filled circles. The black line shows the disk fraction evolution under solar metallicity, while the red arrow shows the proposed JHK disk fraction evolution in low-metallicity environments. From Yasui et al. (2010).

2.3. Sensitivity

I estimated required sensitivities for protoplanetary and debris disk observations assuming the target distance of 5 kpc. For protoplanetary disks, the flux densities are estimated as $F_{5 \mu m} \gtrsim 200 \text{ mJy}$ for intermediate-mass stars and $F_{16 \mu m} \gtrsim 5 \text{ mJy}$ for low-mass stars from the previous study of IC 348 star forming region with the distance of 320 pc (Lada et al. 2006). For debris disks, $F_{24 \mu m} \gtrsim 10 \text{ mJy}$ for intermediate-mass stars from λ Orionis with $D = 450 \text{ pc}$ (Hernández et al. 2009) and $F_{24 \mu m} \gtrsim 0.4 \text{ mJy}$ for low-mass stars from IC 2391 with $D = 150 \text{ pc}$ (Siegler et al. 2007) are estimated to be necessary. From the above flux densities and distances of star forming regions, the required sensitivities for the target distance are summarized in Table 1. Considering the sensitivities of SPICA MCS (see Table 2), protoplanetary disks can be photometrically detected both for low-mass and intermediate-mass stars. Even debris disks can be detected for intermediate-mass stars.
Protoplanetary Disks in the Galactic Scale

Table 1. Required sensitivities for protoplanetary/debris disk observations of intermediate-/low-mass stars at $D = 5$ kpc.

<table>
<thead>
<tr>
<th></th>
<th>Intermediate-mass</th>
<th>Low-mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protoplanetary disk</td>
<td>$2 , \text{mJy} @ 10 , \mu m$</td>
<td>$50 , \mu Jy @ 10 , \mu m$</td>
</tr>
<tr>
<td>Debris disk</td>
<td>$0.1 , \text{mJy} @ 10 , \mu m$</td>
<td>$0.3 , \mu Jy @ 20 , \mu m$</td>
</tr>
</tbody>
</table>

Table 2. Comparison of imaging specifications for the coming MIR instruments.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>SPICA</th>
<th>TMT</th>
<th>JWST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [m]</td>
<td>3.2</td>
<td>30</td>
<td>6.5</td>
</tr>
<tr>
<td>MIR Instruments</td>
<td>MCS</td>
<td>MICHI (w/AO)</td>
<td>MIRI</td>
</tr>
<tr>
<td>Wavelength [$\mu m$]</td>
<td>5–38</td>
<td>N. Q-band</td>
<td>5–28</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>$0.8'' @ 10 , \mu m$</td>
<td>$0.08'' @ 10 , \mu m$</td>
<td>$0.4'' @ 10 , \mu m$</td>
</tr>
<tr>
<td>Sensitivity (5$\sigma$, 1hr)</td>
<td>$1 , \mu Jy @ 5–25 , \mu m$</td>
<td>$0.1 , \mu Jy @ N$-band</td>
<td>$0.4 , \mu Jy @ 10 , \mu m$</td>
</tr>
<tr>
<td>FoV (imager)</td>
<td>$5' \times 5'$</td>
<td>$\sim 30'' \times 30''$</td>
<td>$\sim 1' \times 2'$</td>
</tr>
</tbody>
</table>

2.4. Advantages of SPICA

I summarized specifications of the coming MIR instruments, SPICA MCS, TMT MICHI and JWST MIRI in Table 2. Because the extent of star forming regions at 5 kpc is about 1 pc, subtraction of contamination by foreground and background stars using control field with sufficient area is necessary. For this purpose, SPICA MCS has a great advantage because images of both target cluster and control fields can be obtained simultaneously in the wide FoV of $5' \times 5'$. In addition, the relatively high sensitivities are also an advantage. Although the spatial resolution is not very high among three MIR instruments, spatially-resolved photometry with reasonable accuracy should be achieved with the expected typical separation of stars in target star-forming clusters ($\sim 1''$; Allen et al. 2007).

REFERENCES

SPICA’s Capability for Studying Transiting Super-Earths

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ABSTRACT

Super-Earths are potentially important targets for the SPICA mission, which has a great capability to reveal the nature of super-Earths via transit observations. Measurements of atmospheric transmission spectra during planetary transits enable us to infer compositions of atmospheres and thereby internal structures of super-Earths. Dozens of good targets of transiting super-Earths are expected to be discovered by TESS (Transiting Exoplanets Survey Satellite) by the launch of the SPICA. We propose to reveal the diversity of natures of super-Earths with the SPICA in the 2020s.

1. SUPER-EARTHS AND IMPORTANCE OF TRANSMISSION SPECTROSCOPY

Super-Earths are an emerging population of extrasolar planets whose masses and radii lie between those of the Earth and the Uranus or Neptune. Although there is currently no official definition for super-Earths, we regard such planets with 1–4 R⊕ or 1–15 M⊕ as super-Earths in this manuscript. As super-earths do not exist in our Solar System, uncovering the nature of super-earths is one of the most important studies in both planetary and exoplanetary science in terms of comparative planetology.

Transiting super-earths are thus the most fascinating targets, because one can learn the true mass, radius, and density for transiting planets. However, it is still difficult to determine a unique solution for the planetary structure, since some different solutions of planetary structures are degenerated at the same mass and radius. Figure 1 shows a current summary of the mass and radius of super-Earths and indicate the degeneracy of planetary structures. To solve this degeneracy and find a unique solution, one need to determine planetary atmospheric compositions via an independent way.

During a planetary transit, a part of starlight transmits through the planetary upper atmosphere (optically thin region). For this reason, transit depths depend on wavelength according to planetary atmospheric compositions. Thus measurements of atmospheric transmission spectra during planetary transits enable us to infer compositions of planetary atmospheres. This methodology is referred to as transmission spectroscopy.

It is thus quite important to conduct transmission spectroscopy for super-Earths to uncover not only the atmospheric compositions but also infer the internal structures of this type of planets.

2. POTENTIAL CAPABILITY OF SPICA

Figure 2 shows transmission spectra of two representative atmospheric models for super-Earths. The figure assumes parameters of GJ 1214b, which is one of the well-known super-Earths at this point.

The differences of the two atmospheric models are whether the planet has a low molecular weight (hydrogen dominated) atmosphere or a high molecular weight atmosphere (e.g., H2O, CH4, CO2, etc). The molecular weight determines a scale height of a planetary atmosphere. The high molecular weight atmosphere has small wavelength dependence in transit depths, while the low molecular weight atmosphere shows large dependence. The difference can be easily differentiated by transmission spectroscopy with a good precision and wide wavelength coverage in near-to-mid infrared wavelength.

Among the SPICA’s planned instruments, the MCS (Mid-infrared Camera and Spectrometer) and the SCI (SPICA coronagraphic instrument: Enya et al. 2011) are potentially useful for transmission spectroscopy of transiting super-Earths. Both instruments have low-to-medium resolution spectroscopic capability in mid-infrared wavelength. Thus the instruments can determine a likely atmosphere model for super-Earths with a single transit observation with SPICA.

3. CURRENT PROBLEMS

As of September 2013, only two transiting super-Earths (GJ 1214b and GJ 3470b) have been discovered around bright host stars. The brightness is important because host stars need to be very bright to do transmission spectroscopy with a good precision, which is important to discriminate atmospheric models at a high confidence level.

For the case of GJ 1214b, various observations for transmission spectroscopy were conducted with ground-based telescopes and the two space-based telescopes (Hubble and Spitzer). At this point, a unique atmospheric model has not yet been determined, mainly due to uncertainties of the transit depths and lack of wide wavelength coverage up to mid-infrared wavelength. From the previous observations, we have learned that not only optical and near-infrared region but also mid-infrared region are important. The warm Spitzer is still useful, but very weak for determining a likely atmosphere model. Thus one needs a space-based telescope which can observe mid-infrared wavelength with a high precision for transmission spectroscopy of transiting super-Earths.
Figure 1. The mass (horizontal) – radius (vertical) relation of known super-Earths as of September 2013. The masses have large uncertainties because of the facts that most of the super-Earths are discovered by the *Kepler* satellite and that the masses are poorly constrained by radial velocities or transit timing variations due to the faintness of host stars. The red solid lines indicate mass-radius relations for hydrogen-dominated (low molecular weight) atmospheres, while the blue dashed lines show relations for water-dominated (high molecular weight) atmospheres. The black dotted line represents relation for rocky planets without atmosphere. Courtesy of Masahiro Ikoma.

4. POTENTIAL TARGETS FOR SPICA

In April 2013, *TESS* (Transiting Exoplanet Survey Satellite: Ricker et al. 2010) led by MIT is approved by NASA as an Explorer program. *TESS* is going to be launched in 2017, and is expected to discover hundreds of super-Earths around nearby stars, including dozens of super-Earths orbiting around M dwarfs, which are suitable for transmission spectroscopy.

For such super-Earths, *SPICA*’s SCI and MCS can measure transit depths covering wide wavelength regions (from near-infrared to mid-infrared) by spectro-photometry, with likely higher precision than *Spitzer*. The wide wavelength coverage allow us to pin down a likely atmospheric model.

We note that similar transmission spectroscopy studies can be done by ground-based telescopes. But potential targets for ground-based telescopes are very limited to transiting super-Earths around very bright late-M dwarfs. Thus one indeed needs a space-based telescope to extend potential targets for transmission spectroscopy and to reveal the diversity of super-Earths’ atmospheres statistically.

5. SYNERGY WITH SCI’S CORONAGRAPHIC STUDY

*SPICA*’s SCI can take spectra of direct imaged outer planets. This capability provide us very unique opportunities to investigate spectra of both inner transiting planets and outer direct imaged planets. Such a capability is very unique and one can study compositions of a whole planetary system. Thus *SPICA* can reveal “the whole recipe of planetary systems” with SCI.
**Figure 2.** Two representative theoretical transmission spectra of GJ 1214b. The red line shows a case for a solar abundance (hydrogen-dominated) atmosphere, and the blue line does a case for a high molecular weight (water and nitrogen dominated) atmosphere. The major compositions determine the scale height of the planetary atmosphere. The largest differences are located in 2–4 μm and 6–8 μm. Courtesy of Yui Kawashima.

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A Comprehensive Study of Brown Dwarf and Exoplanet Atmospheres

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ABSTRACT

We present an analysis of brown dwarf spectra taken by AKARI, a Japanese infrared astronomical satellite. We observed 27 brown dwarfs, and for the first time obtained good continuous spectra between 2.5 and 5.0 μm for 16 sources. We investigate the appearance of the CH₄ (3.3 μm), CO₂ (4.2 μm) and CO (4.6 μm) molecular absorption bands in this new wavelength range along their spectral types, and attempt to interpret these results with the Unified Cloudy Model (UCM), a theoretical brown dwarf atmosphere model.

We find that the physical and chemical structures in the brown dwarf atmospheres deviate from theoretical predictions for local thermodynamic equilibrium (LTE) with solar metallicity. As our first trial for improving UCM, we focus on “elemental abundances”. We find that the CO₂ band is better reproduced by a model with revised C & O abundances than the solar elemental abundance model, except for very late-T dwarfs.

There are two types of brown dwarfs: isolated objects, the targets of our current study, and objects orbiting around a primary star (extra gas planets). We are also interested in the atmospheres of such extra gas planets, especially, those having relatively longer orbital radii and masses and temperatures similar to those of brown dwarfs. To understand their atmospheres, we should compare these two types of objects through the analysis of infrared spectra. This study may also inform us about the origin of gas planet formation. We will observe such extra gas planets with SPICA/SCI, and gain a comprehensive understanding of atmospheres from brown dwarfs to gas planets.

1. INTRODUCTION

Brown dwarfs are objects with mass intermediate between stars and planets. Heavier brown dwarfs maintain deuterium burning when they are young (10⁶ yr) instead of hydrogen fusion in their core. Hence, they simply cool after deuterium burning ends (Burrows et al. 2001). Their effective temperatures are very low (2200–600 K). They are classified into spectral types L and T (Geballe et al. 2002); L dwarfs are warmer than T dwarfs. Since they are very faint, the first observation was only made in 1995 (Nakajima et al. 1995).

The atmospheres of brown dwarfs are dominated by molecules and dust. Infrared spectra of brown dwarfs are the most important tools for understanding their physical and chemical structures, because there are many molecular absorption bands. The effects of dust are observed in the near-infrared spectra of L dwarfs (Tsuji et al. 2004), particularly in the J- and H-bands, whereas the spectra of T dwarfs show little sign of dust (Tsuji & Nakajima 2003). Current brown dwarf atmosphere models include dust effects empirically through a model parameter (Tsuji 2002, 2005; Allard et al. 2001, 2003; Ackerman & Marley 2001; Woitke & Helling 2003; Helling et al. 2008). For example, the Unified Cloudy Model (UCM), a brown dwarf atmosphere model constructed by Tsuji (2002, 2005), considers dust formation and sublimation/sedimentation. This model can explain the observed SEDs more or less satisfactorily, however the models still have problems explaining some molecular absorption band strengths, for example, the 4.6 μm CO band (Geballe et al. 2009).

2. SPECTRA OF 16 AKARI OBJECTS

We observed 27 brown dwarfs with AKARI, a Japanese infrared astronomical satellite launched in February 2006 (Murakami et al. 2007). The InfraRed Camera (IRC) on-board AKARI is capable of obtaining moderate-resolution (R~120) spectra devoid of any degradation due to telluric features (Onaka et al. 2007). We use the IRC to obtain continuous spectra of brown dwarfs in the wavelength range 2.5–5.0 μm. We obtained 16 good quality spectra (11 L dwarfs and 5 T dwarfs) with a signal-to-noise ratio (S/N) averaged over the spectra higher than or about 3.0. Known binaries are excluded. Figure 1 shows the spectra of the brown dwarfs as a sequence of their spectral types from L1 (bottom) to T8 (top). We investigate the appearance of three molecular absorption bands (CH₄ at 3.3 μm, CO₂ at 4.2 μm and CO at 4.6 μm) in the brown dwarf spectra along their spectral types (Sorahana & Yamamura 2012).

2.1. CO Fundamental Absorption Band at 4.6 μm

The CO 4.6 μm band appears in all spectral types including late-T dwarfs. This result confirms that CO generally exists in the atmospheres of all spectral types, contrary to the prediction by UCM. However, we have not yet succeeded in understanding these phenomena and will investigate these CO excesses in future work.
Figure 1. *AKARI* spectra of brown dwarfs with errors shown in black. Eleven L dwarfs and 5 T dwarfs are successfully observed. The $3.3 \mu m$ CH$_4$, $4.2 \mu m$ CO$_2$ and $4.6 \mu m$ CO absorption bands are shown in red, green and blue, respectively in the left panel. We also enlarge the CO$_2$ absorption band region and show a comparison between the observations and models with varying elemental abundances. We pick up 9 sources of our sample. They show the $4.2 \mu m$ CO$_2$ band, except for 2MASS J1523+3014. Three objects are better explained by the model with increased C and O elemental abundances (green), one object is well reproduced by the model with decreased abundances (blue), and the spectra of the other three sources are best explained by the solar abundance model (red). We are not yet able to explain the other two T8 sources.
A Comprehensive Study of Brown Dwarf and Exoplanet Atmospheres

2.2. CH₄ Fundamental Absorption Band at 3.3 μm
The CH₄ 3.3 μm band appears in spectra later than L5. This result indicates that CH₄ already exists and plays a role in the photosphere of mid-L dwarfs. The band is seen in only two of our four L5 dwarfs. We confirm that the appearance of the CH₄ band in two L5 dwarfs is associated with the presence of dust by model fitting with UCM.

2.3. CO₂ Absorption Band at 4.2 μm
We have made the first detection of the CO₂ 4.2 μm absorption band in the spectra of late-L and T type dwarfs. We find that the CO₂ molecule is generally observed in the atmosphere of T dwarfs. We also find that the observed CO₂ bands in some spectra are stronger or weaker than the prediction of UCM.

3. ELEMENTAL ABUNDANCES OF BROWN DWARFS
We discuss possible elemental abundance variations among brown dwarfs using model atmospheres and AKARI data to explain the deviations. We construct a set of models with various elemental abundances as a first trial, and investigate the variation of the molecular composition and atmospheric structure. From the results, we suggest that a possible reason for the CO₂ 4.2 μm absorption feature in the late-L and T type spectra is the C and O elemental abundances being higher or lower than the solar values used in previous studies (Figure 1; see also Tsuji et al. 2011, Sorahana et al. 2013, in preparation).

4. FROM BROWN DWARFS TO EXOPLANETS WITH SPICA
We now understand that the physical and chemical structures of brown dwarf atmospheres are complicated, and do not simply follow a radiative equilibrium state under LTE. We are also interested in whether the atmospheric structures of extra gas planets can also not be explained by a simple radiative equilibrium model. To test this, we extend our analysis of brown dwarfs to extra gas planets, especially those having relatively longer orbital radii and masses and temperatures similar to those of brown dwarfs. We derive their atmospheric structure by model fitting and compare the atmospheres of the two types of objects. Since we can derive the elemental abundances of extra gas planets, we will also gain insight into the origin of gas planet formation. We will observe such extra gas planets with SPICA/SCI (Nakagawa et al. 2011), and gain a comprehensive understanding of the atmospheres from brown dwarfs to gas planets.

This research is based on observations with AKARI, a JAXA project with the participation of ESA. We thank Prof. Takashi Tsuji for his kind permission to access the UCM and helpful suggestions. SS aknowledges JSPS Research Fellowship for Young Scientists. This work is supported by JSPS/KAKENHI(c) No. 22540260 (PI: I. Yamamura).

REFERENCES
Search for Disks in Binary Systems with White Dwarf

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ABSTRACT

Circumstellar disks seem to be present at every stage of stellar evolution, beginning from proto-stellar cores, through evolutionary advanced stages, like first-ascent, asymptotic giant branch (AGB) stars, post-AGB objects, and ending on isolated white dwarfs (WDs). WDs are relatively recent addition to this track. The nature of disks around evolutionary advanced objects is still a matter of debate. Disks around pre-main sequence stars are very likely to be sites of planets formation. We do not know yet whether protoplanets can be formed in disks around evolutionary advanced stars. Therefore, understanding the creation, evolution and survival of such disks is a matter of primary importance. We propose a study of known disks around isolated white dwarfs and of possible disks around binary systems that contain WD component with the SAFARI instrument on board of the SPICA satellite.

1. INTRODUCTION

The first white dwarf, G29-38, exhibiting near-infrared (NIR) excess that was not associated with a stellar companion has been discovered by Zucker & Becklin (1987). The crucial argument that this NIR excess is not related to the emission from a brown dwarf companion follows the discovery of additional excess at 10 micrometres (Tokunaga et al. 1990). Moreover, an additional constraint came from a detection of many metals in the atmosphere of G29-38, which has been interpreted as the evidence of the current accretion of the material from the flat dusty debris disk (Jura 2003) by the white dwarf (Koester et al. 1997).

At the end of 2010, about 20 isolated white dwarfs with circumstellar disks were known (Farihi 2011, Table 5.1). However, no binary systems with WD are known so far to have circumstellar disk. We do not know any isolated WD with planets neither, except GJ 3483 that hosts a Y type brown dwarf. However, more than 10 eclipsing binary systems containing WD with planet candidates inferred from the interpretation of O-C diagrams are known. An example of such

Figure 1. SEDs of: isolated WD without a disk (top-left), binary system with WD and a disk (top-right) and binary system with WD and a disk candidate (bottom-right). Photometric measurements were obtained from GALEX (FUV and NUV), SDSS (u, g, r, i and z), 2MASS (J, H and K) and WISE (W1, W2, W3 and W4) surveys. In the case of G29–38 (top-right panel) the infrared excess due to disk presence is clearly visible. The SED’s Rayleigh-Jeans extrapolation for SAFARI detection range is also shown. Estimated flux values are as follows: 30 μm – 1360 μJy, 100 μm – 130 μJy, 150 μm – 70 μJy and 210 μm – 40 μJy. Therefore, this source will be detected with S/N > 5 σ within one hour of observations even at the wavelengths longer than 150 microns.
Figure 2. $J - H$ vs. $J - W_1$ (top panel) and $J - H$ vs. $J - W_2$ (bottom panel) colour-colour diagrams for non-binary WDs (red dots) and binary systems with WD (yellow dots). Black filled circles mark known isolated WDs with dusty debris disks (Farihi 2011, Table 5.1). Blue circles and squares mark non-binary WDs and binary systems with WD disk candidates, respectively. Cooling track was modelled as in Renedo et al. (2010) for the final white dwarf mass of $M_f = 0.6 \, M_\odot$ and metallicity of $Z = 0.01$, using the black-body atmosphere model. For WDs with temperatures lower than 5,000 K there is a strong evidence for the departure of isolated WDs from the cooling track towards the higher values of $J - H$. This is caused by the so called collision induced absorption (CIA, Borysow et al. 1997) which depends on the H/He ratio in the WD atmospheres, $T_{\text{eff}}$ and $g$. Special symbols that denote four individual objects: blue square is for WD 1242–105 — an isolated WD without disk, blue rhombus is for SDSS J130558.92+2514598 — a binary system with WD without disk, while blue filled circle and blue triangle are for G29–38 (an isolated WD) and WD 1422+095 (binary system with WD) with disk or disk candidate, respectively. SEDs of these four objects are presented in Figure 1.

A system is HU Aqr that likely hosts a planet of 7 Jupiter masses on the circumbinary orbit with the orbital period of 10 years (Goździewski et al. 2012; Słowińska et al.). Therefore, we propose a study of known and candidate disks around isolated and especially binary systems with the SAFARI instrument. We aim to understand a possibility of planet formation in circumstellar/circumbinary disks.

2. SAMPLE SELECTION AND DISK CANDIDATES

We have selected a sample of white dwarfs from following three catalogues: The White Dwarf Catalogue of Villanova University (McCook & Sion 1999), SDSS DR7 White Dwarf Catalog (Kleinman et al. 2013), Post-common envelope binaries from SDSS - XIV. The DR7 white dwarf-main-sequence binary catalogue (Rebassa-Mansergas et al. 2012).

We gathered 22,756 objects from the above catalogues, among which 2,972 are classified, mostly based on the analysis of the SDSS spectra, as binaries. It turns out that the optical spectra (e.g. SDSS) are not always available, so the classification may not be adequate. While preparing our WD database we took into account proper motion since some close WDs have very high angular change in position over time. Examples of typical spectral energy distribution (SED) of an isolated WD and binary system with WD without (left panels) and with a disk or a disk candidate (right panels), are shown in Figure 1.

From our database (Rybińska et al. 2013) we selected a sample that obeys the following conditions: 2MASS $J$ and $H$, as well as WISE $W_1$ and $W_2$ photometry is available for all 4 filters and for all of them it has a quality flag “A”. There are 413 non-binary WDs and 990 WDs in binary systems which sum up to 1,403 objects that fulfil the applied criteria. Obtained sample was extended with objects from the Farihi’s list (Farihi 2011, Table 5.1). We tried to include all 20
Search for Disks in Binary Systems with White Dwarf

objects, however for some of them the photometric \((J, H, W_1, W_2)\) data were missing. Figure 2 illustrates two kinds of colour-colour diagrams, i.e. \(J - H\) vs. \(J - W_1\) (upper panel) and \(J - H\) vs. \(J - W_2\) (bottom panel) for non-binary and binary WDs. In addition to objects with colours similar to the known isolated WDs with disks, we marked by blue circles and squares disk candidates that have \(J - W_1 > 1.5\) for non-binary WDs and binary systems with WD, respectively. These objects are also shown on \(J - W_2\) diagram.

3. CONCLUSIONS

A detection of circumbinary disks around binary systems with WD is a matter of great importance, as yet no such disks are found. Discovery of a disk around close binary could establish a missing link in the binary system evolution that leads to circumbinary planet creation. It would be especially interesting in a case of close binaries that are suspected of hosting planets on circumbinary orbits. Our broadband photometric analysis allowed us to select promising candidates that might have disks. There are several non-binary WDs as well as binary systems with WD in our sample that meet our selection criteria and are bright enough to be detected with SAFARI.

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Mid-Infrared Asteroid Survey: From AKARI to SPICA

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ABSTRACT

The physical properties of asteroids, including Main-belt asteroids (MBAs), Near-Earth asteroids (NEAs), Jovian Trojans (JTs), irregular satellites, are fundamental to understanding the formation of our solar system, since they are remnant of planetesimals and seem to preserve clues of the initial conditions of our solar nebula 4.6 Gyr ago. The size distribution of these small bodies is the most basic and useful tool to obtain an insight into their original mass and collisional history of our solar system. The radiometric method with the infrared space telescopes (e.g., IRAS, MSX, ISO, Spitzer, AKARI, WISE, and Herschel) can determine the size and albedo of asteroids. The sensitivity of SPICA is much higher than those of previous observations, especially in 20 μm or longer wavelength, and it can detect faint asteroids, for example, down to ∼50 m MBAs. It is important to comprehend the population of such small asteroids also from standpoint of the “spaceguard”. Observations at far-infrared wavelengths will allow us to study Trans-Neptunian objects (TNOs) and Centaurs in the outer regions beyond the giant planets. Their size distribution, as well as bulk densities of binary systems, become as important key elements for the history of our solar system.

1. SIZE OF ASTEROIDS MEASURED BY THERMAL INFRARED OBSERVATIONS

Size is one of the most basic physical quantities of asteroids. However, little is still known about the size distribution of asteroids, because there are millions of asteroids, ranging widely in size from >1000 km across to <10 m (more than five order of magnitude). Size distribution can help us to understand the current mass distribution in the asteroid belt, the collisional evolution of asteroids and asteroidal families, the production ratio of interplanetary dusts, all of which are linked to planet formation in our solar system. Based on size information, it is enabled to study correlation between size, albedo, thermal inertia, color, surface material, and orbital element of asteroids. This will also contribute to future Rendezvous / sample return missions of small objects.

One of the most effective methods for determining the size of asteroids is through combining radiometric measurements at visible and thermal infrared wavelengths. The radiometric measurements from space allow a large number of objects to be observed in a short period of time. The first systematic survey of asteroids using a space telescope was made by IRAS (Tedesco et al. 2002). AKARI made the next generation asteroid survey based on the 16-month infrared all-sky survey observation (Usui et al. 2011). WISE also completed an all-sky survey with high sensitivity detectors and its database includes more than 130,000 asteroids (Mainzer et al. 2011, and subsequent papers).

2. OBJECTIVES

2.1. Asteroid Survey

The sensitivity of SPICA is much higher than those of previous observations. With SPICA/MCS, much fainter asteroids in the range of undiscovered size can be detected (see Figure 1). It is a new frontier for asteroid study.

Expected number of known/unknown asteroids detected by systematic survey with SPICA/MCS is 6.5 / FOV for MBAs, 0.5 / FOV for JTs, and 0.1 / FOV for TNOs, which corresponds d > 0.1 km, > 0.5 km, and > 100 km, respectively (Yoshida & Nakamura 2007, 2008; Fuentes et al. 2009, also see Figure 2), where d means the diameter of asteroid. To complete this survey program, we will observe the selected sky at the ecliptic latitude of 0°, ±5°, ±10°, ±15°, and ±20° during 10 months (avoiding the galactic plane), which require the total observation time of

\[ (1 \text{ hr} \times 2 \text{ times}) \times 9 \text{ positions} \times 10 \text{ months} = 180 \text{ hrs} . \]

It should be noted that we may share imaging data with the zodiacal light observations (Ootsubo et al., this volume) to increase the observational efficiency.
**Figure 1.** Estimated detection limit of size of objects with *SPICA* ($5\sigma$, 100 sec exposure) against the heliocentric distance.

**Figure 2.** Cumulative size frequency distribution of MBAs and detectability with *IRAS* (Tedesco et al. 2002), *AKARI* (Usui et al. 2011), *WISE* (Mainzer et al. 2011), and *SPICA*. 
2.2. TNOs Study

TNOs represent the primitive remnants of the planetesimal disk from which the planets formed. \textit{Herschel} made observations of TNOs/Centraurs of \~{}130 objects within 373 hrs (Müller et al. 2009). \textit{SPICA} will detect most discovered TNOs (and TNOs to be discovered by HSC/Subaru, Pan-STARRS, and LSST in the future) by photometric-mode of SAFARI, at far-infrared wavelengths. Spectroscopic observation with SAFARI is also essential for studying surface material of TNOs. With \textit{SPICA}, we will make pointed observations for selected targets of the known TNOs with 

\[(1 \text{ hr} \times 2 \text{ times}) \times (250 \text{ ~} 500) \text{ objects} = (500 \text{ ~} 1000) \text{ hrs (at maximum)} .\]

2.3. Spectroscopic Observations of JTs

JTs are mostly D-type asteroids, which have close relation with the comet nuclei. For some JTs, 10 $\mu$m emission feature was detected with \textit{Spitzer} (Emery et al. 2006), while no 1 $\mu$m absorption was detected with IRTF/Spex (Yang & Jewitt 2011). These results suggest that some JTs have iron-poor (Mg-rich) material and have a thin layer of fine silicate grain, which may be related to past/on-going cometary activity.

With \textit{SPICA}, observations of 10 $\mu$m emission feature of comets have been proposed (Kawakita et al., this volume; Furusho et al., this volume). It is worth extending the same procedure to JTs for investigating the surface property of JTs. $d \sim 1$ km for JTs can be detected in grism mode (SG2) with $5\sigma$, 100 sec. Since there is a plan for sample return mission from JTs by the Solar Power Sail spacecraft in 2020s, it is important to have knowledge of JT’s surface before the mission.

2.4. Natural Satellites in Orbit around Giant Planets

Regular/irregular satellites of giant planets are also interesting for considering planetary formation and evolution. As the same way of size determination of asteroids described in Section 2.1, we will survey physical information for known natural satellites. The number of \textit{SPICA}’s detectable satellites is \~{}70 of Jupiter, \~{}60 of Saturn, \~{}30 of Uranus, and \~{}15 of Neptune, which correspond $d > 1$ km, > (several) km, > 10 km, and > (several $\times$ 10) km, respectively. Also satellites of Pluto can be detected. It should be noted that detailed feasibility study of these observations is needed to avoid stray light from the planets.

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Disentanglement of Small-Scale Structures from the Zodiacal Dust Cloud

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ABSTRACT

The zodiacal light (ZL) is the dominant diffuse radiation in the mid-infrared wavelengths from the interplanetary dust. Although the zodiacal dust cloud has a relatively smooth distribution, it has many small-scale structures, such as asteroidal dust bands and a circumsolar resonance ring. A number of models for the zodiacal dust cloud have been developed, in particular, using the infrared satellite data, such as IRAS and COBE/DIRBE, thus far. Although the DIRBE ZL model reproduces the observed infrared sky well, there are still uncertainties in the model parameters. Since IRAS, COBE/DIRBE, and AKARI were the sun-synchronous orbit satellites, they observed the infrared sky through the circumsolar ring in the Earth’s orbit. SPICA will be launched onto a halo orbit around L2 point, which is 0.01 AU away from the Earth. In this orbit, we may be able to observe the small-scale structures more clearly. The asteroidal dust bands contribute to the ZL brightness most in the 25–100 µm region. SPICA can cover this wavelength region, whereas JWST can observe shorter than 28 µm.

1. BACKGROUND AND MOTIVATION

The zodiacal light (ZL) is the dominant diffuse radiation in the mid-infrared wavelengths due to thermal emission from the interplanetary dust. The interplanetary dust originates mainly from comets and asteroids, and it spreads over the solar system. This “zodiacal dust cloud” has a relatively smooth distribution as a whole. It has, however, many small-scale structures, such as asteroidal dust bands and a circumsolar resonance ring, generated by interactions and resonances with the large bodies in the Solar System (Low et al. 1984; Dermott et al. 1984, 1994; Reach et al. 1995). Many efforts have been devoted to describing the structure of the zodiacal dust cloud so far. A number of models have been developed, in particular, using the infrared satellite data, such as IRAS and COBE/DIRBE. The ZL model most commonly used to date is the one based on the DIRBE data (e.g. Kelsall et al. 1998; Wright 1998). Since ZL is the nearest and forefront diffuse source to the earth, it is extremely important to understand the nature of the zodiacal dust cloud not only for the solar system and extra-solar system sciences but also for the study of the Galactic/extragalactic objects and cosmology.

Although the DIRBE ZL model reproduces the observed infrared sky well, there are still uncertainties in the model parameters. Based on the AKARI data, Pyo et al. (2010) found that the DIRBE ZL model underestimates the Earth’s resonant ring component. The DIRBE model also cannot reproduce the real fine structure of the asteroidal dust band component, because the DIRBE had the large 42′ × 42′ beam. Based on the IRAS observation, Nesvorný et al. (2010) present a zodiacal cloud model based on the orbital properties and lifetimes of comets and asteroids, and on the dynamical evolution of dust after ejection. They found that 85%–95% of the observed mid-infrared emission is produced by particles from Jupiter-family comets and < 10% by dust from long-period comets. Asteroidal dust is found to be present at < 10%. Since IRAS, COBE/DIRBE, and AKARI were the sun-synchronous orbit satellites, they observed the infrared sky through the circumsolar resonance ring in the orbit of the Earth. It is difficult to evaluate the contribution of these dust components in the model precisely, if the model is based on the data of these satellites.

SPICA will be launched onto a halo orbit around L2 point, which is about 0.01 AU away from the Earth in the direction opposite to the Sun (Nakagawa et al. 2011). In this orbit, the contribution from the Earth’s circumsolar ring will decrease and we may be able to observe the small-scale structures in the zodiacal cloud more clearly. The comparison of the results with AKARI and COBE/DIRBE is expected to give us a new insight into the structure of the zodiacal dust cloud.

2. SCIENTIFIC GOALS

Main scientific goals and objectives of the SPICA observations regarding the zodiacal dust cloud are as follows:

• Observe the ZL cloud less contaminated with the Earth’s resonant ring. Estimate the contribution of the circumsolar ring and the Earth trailing blob component more precisely.
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• Compare the spectrum of the asteroidal dust band, which is not contaminated with the circumsolar ring component, with smooth cloud component. Clarify the contribution of cometary and asteroidal dust to the total ZL more precisely.

• Discover faint small-scale structures originate from distant objects, such as Centaurs and trans-Neptunian objects (TNOs).

3. OBJECTIVES OF ZL OBSERVATIONS

3.1. Observations of the ZL Cloud from Different Angles

*SPICA* will observe the zodiacal dust cloud from the different position from *IRAS*, *COBE/DIRBE*, and *AKARI*, which is 0.01 AU away from the Earth in the direction opposite to the Sun. In this orbit, the contribution from the circumsolar ring will slightly decrease and the observational data will not be affected by the moon and the South Atlantic Anomaly (SAA). The change of the detector response due to the moon and SAA passage is significant, and it makes the precise observation of faint diffuse emission very difficult, especially near the ecliptic plane (*Kondo et al. 2013, this volume*). We may be able to observe the small-scale structures in the zodiacal cloud more clearly with *SPICA*. Since the asteroidal dust bands originate from the collision in the main asteroid belt, the dust grains in the dust bands show the lower temperature than the circumsolar ring at 1 AU, and contribute to the ZL brightness most in the 25–100 $\mu$m region (*Kelsall et al. 1998*). Thus, mid-infrared observations at longer than 25 $\mu$m are very important for the precise construction of the zodiacal dust cloud model. *SPICA* can cover this wavelength region with MCS/WFC and SAFARI, although *JWST* can only observe shorter than 28 $\mu$m.

3.2. Comparison of the Spectrum of the Asteroidal Dust Band with the Smooth Cloud

Based on the *IRAS* observation, *Nesvorný et al. (2010)* found that 85%–95% of the observed mid-infrared emission is produced by particles from Jupiter-family comets. Mid-infrared spectroscopic observations with *AKARI* suggest that spectra of the major mineral phases in collected anhydrous chondritic porous interplanetary dust particles, which are of probable cometary origin, have features at the same wavelengths as the ZL spectrum (*Ootsubo et al. 2009*). However, there may be the difference in the spectral features between near ecliptic plane and high ecliptic latitude regions (*Figure 1 in Ootsubo et al. 2009*). *SPICA* can obtain the observational evidence for the supply source of the interplanetary dust cloud.

3.3. Discover Faint Small-scale Structures Originate from Distant Objects

There is a possibility that *SPICA* can detect the small-scale structures which originate from the Edgeworth-Kuiper Belt (EKB). *Yamamoto & Mukai (1998)* examine the thermal emission from the EKB dust cloud produced by the mutual collisions of TNOs within the EKB and by the interstellar dust impacts on TNOs. The EKB dust cloud farther than the main asteroid belt is expected to have lower temperatures than the dust in the asteroidal dust bands. The maximum case of thermal emission from the EKB dust cloud becomes to be comparable to that of foreground zodiacal emission at the wavelength of about tens of $\mu$m to hundreds of $\mu$m (*Yamamoto & Mukai 1998*). When the EKB dust cloud has a narrow spatial band structure with a thickness of about 10 degree around the ecliptic, the detailed observations with *SPICA* may reveal the contribution of the EKB dust to the foreground zodiacal dust cloud.

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Chemical Evolution of Cometary Molecules Revealed through Mid-IR High-Dispersion Spectroscopy by SPICA

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ABSTRACT
Comets are thought to be remnants of the planetesimals in the proto-planetary disk so that cometary ices provide us with precious clues of physical and chemical conditions in the early solar system. The mid-IR region is a very fruitful window to study the cometary volatiles since numerous ro-vibronic bands of molecules are observed simultaneously, and symmetric molecules can be accessed. However, because of the strong atmospheric extinction and the capability of previous instruments, there are only a few studies of cometary molecules in mid-IR regions with discontinuous limited wavelength regions or with low-dispersion spectroscopy. The mid-IR high-dispersion spectroscopy with SPICA could make a breakthrough discovery in the cometary volatiles like aliphatic hydrocarbons (e.g., C2H2, C2H4, C2H6), PAHs as well as the pre-biotic molecules (e.g., PH3). In this study, we discuss the feasibility to find new molecular species and to identify previously unidentified emission lines and the composition of those new species.

1. INTRODUCTION
Comets are thought to be aggregates of planetesimals that were remnants of the early solar system. The volatiles incorporated into the comets are precious clue to the physical and chemical evolution of molecules. Parent volatiles that are directly released from the cometary nucleus such as H2O, CO2, and CO are usually studied in near-IR region or radio domain. However, those observations are severely affected by telluric absorption. The space telescopes like AKARI and SPICA are powerful tools to study such volatiles. In particular, although there are transitions of C-H, N-H, C-O bending modes of many molecules, the mid-IR region could not be fully accessed from ground based observatories. Moreover, the high-dispersion spectroscopy provides us the rotational temperature of volatiles. Chemical compositions of cometary organic volatiles are particularly important to study the chemical evolution of our solar system.

2. FLUORESCENCE EXCITATION MODELS
In order to determine the chemical composition of cometary coma, we need the g-factors for the molecular species. Here, we introduce the fluorescence excitation models of the volatiles that could be observed in mid-IR region. Cometary volatiles are assumed to be excited by the solar radiation field in the model. We also assumed that the rotational population distribution follows the Boltzmann distribution that is maintained by inter-molecular collisions in the inner coma. Downward transitions into vibrational states from highly excited states are neglected in this study. Only direct pumping from the ground state is considered (see Figure 1 as an example). The balance equations for each energy level are solved numerically to determine the population in each level. Then the g-factor is calculated as a product of the population and the relevant Einstein A coefficient. Einstein A coefficients necessary to build the equations are basically taken from the HITRAN database (Rothman et al. 2008). High-resolution solar spectrum is taken from Kurucz (2005) and the results based on his stellar model.

3. RESULTS
We constructed fluorescence excitation models of the aliphatic hydrocarbons (C2H2, C2H4, and C2H6), PH3 and NH3. Here we show a case when we assumed a rotational temperature of 100 K and the comet at 1 AU from the Sun in Figure 2–4 and give some description of each molecule below.

3.1. Aliphatic Hydrocarbons (C2H2, C2H4, and C2H6)
In the case of aliphatic hydrocarbons, emission lines appear around 10 to 14 μm region. In particular, cometary C2H2 is one of key species for the chemical reactions related to the formation of C2H6. Moreover, C2H4 has never been detected in comets by previous studies. It will be a candidate of the species newly detected in comets. Although CH4 is another aliphatic hydrocarbon, the emission lines appear in 7 μm region. The abundances of CH4 and C2H6 are important for comparisons with ISM. The near-IR observations are also needed to investigate the CH4. Thus, the 10 μm region is so important.
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Figure 1. Fluorescence excitation model of NH$_3$ as an example. The fluorescence excitation model of each molecular species includes its fundamental transition. The solar radiation field is considered as the main energy source for pumping from the ground state.

Figure 2. The synthesized spectra of the hydrocarbon molecules that have fundamental vibrational transitions around 10 $\mu$m region. We expect strong fluorescence emission lines of C$_2$H$_2$, C$_2$H$_4$ and C$_2$H$_6$ in this wavelength region. C$_2$H$_4$ has especially strong emission bands while this molecule has never been detected in comets in the near-infrared wavelength region.

3.2. PH$_3$

Phosphorus “P” is one of the important species for biology and PH$_3$ has never been found in cometary coma or ices. Recently, 103P/Hartley 2 showed the D/H ratio in H$_2$O similar to that of VSMOW (Hartogh et al. 2011). This result indicates that the pre-biotic molecules are possibly brought by the comets to the early Earth. Our calculation show the strongest line is found at 10 $\mu$m if the molecule exists. However, SPICA/MCS (high-dispersion spectrograph) cannot cover around the 10 $\mu$m regions. We propose the 10 $\mu$m region high-dispersion spectrograph with SPICA. Also, we need the laboratory measurements of PH$_3$ and chemical evolutionary models including phosphorus atoms.

3.3. NH$_3$

Ammonia has been previously well studied in both near-IR regions and radio domain. However, in the near-IR region, the line intensity is relatively weaker than in the mid-IR region. The nuclear spin isomers ratio of ammonia is one of the important metrics to investigate the formation temperature of the species. In a previous study, Shinnaka et al. (2011) reported the nuclear spin temperature of ammonia as $\sim$30 K, higher than the typical dark molecular cloud ($\sim$10 K). If we try to observe NH$_3$ in the mid-IR region, the 10 $\mu$m region is also important.
From Exoplanets to Distant Galaxies: SPICA's New Window

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Mid-IR High-Dispersion Spectroscopy of Cometary Molecules with SPICA

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Figure 3. Same as Figure 2 but for PH$_3$. The strong Q-branch for the vibrational band at $\sim$10 $\mu$m is the candidate for the detection in comets.

Figure 4. Same as Figure 2 but for NH$_3$. The spectrum of NH$_3$ shows the inversion doublet for each rotational line.

4. SUMMARY

SPICA will provide us with the precious opportunities to investigate comets in the mid-infrared wavelength region. The success of the high-dispersion spectroscopic observations for the molecules proposed here will shed light on the origin of the solar system and it also makes clear view on the delivery of organic molecules into the early Earth as the origin of life. As far as molecules we studied in this paper, the capability for spectroscopy down to 10 $\mu$m region (at least) is desired.

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**SPICA Spectroscopy of Cometary Refractory and Icy Dust Grains**

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**ABSTRACT**

We propose mid/far-infrared spectroscopy of comets to study (1) precise astromineralogy of cometary refractory dust and, (2) environment of H$_2$O ice formation (temperature and gas density) in the early solar nebula. The mid/far-infrared spectroscopy is a powerful diagnostic tool to investigate the size, shape, and chemical composition of cometary dust, so that it will enable us to reveal the process of refractory grain growth and radial transportation of dust grains in the early solar nebula. However, it is not easy to disentangle constituent minerals clearly only with the 10 µm-band of ground-based observations. The crystalline silicate bands at 33, 49, and 69 µm are a clue to investigate the dust size and chemical composition. Whether cometary H$_2$O icy dust grain is amorphous or crystalline reflects its formation environment (temperature and gas density). The H$_2$O ice bands are at 6, 12, 44 and 65 µm. Since the reason why crystalline H$_2$O icy grains were detected in a few comets is still unclear, statistical study on the abundance of the cometary crystalline H$_2$O ice dust is important to reveal the history of formation and evolution of the comets.

**1. BACKGROUND AND MOTIVATION**

1.1. Astromineralogy of Cometary Refractory Dust

The mid/far-infrared spectroscopy is a powerful diagnostic tool to investigate the size, shape, and chemical composition of cometary dust, so that it will enable us to reveal the process of refractory grain growth and radial transportation of dust grains in the early solar nebula. However, it is not easy to disentangle constituent minerals clearly only with the 10 µm-band of ground-based observations. Comets are generally thought to be the icy remnants body of the early solar nebula. They are divided into two different groups according to its orbital characteristics which reflect its formation region. One group is Oort Comets (OCs) which are thought to be formed in Jupiter-Uranus region, and ejected out to the Oort cloud (Morbidelli 2007). The other is Ecliptic Comets (ECs) which are thought to be formed in trans-Neptunian region (Duncan & Levison 1997). Thus these two groups are expected to have different physical or chemical properties.

1.2. Cometary H$_2$O Icy Dust

The H$_2$O ice bands are at 6, 12, 44 and 65 µm. Whether cometary H$_2$O icy dust grain is amorphous or crystalline reflects its formation environment (temperature and gas density). In addition, energy of transition of H$_2$O ice from amorphous to crystalline is considered to be one of possible drivers of the outburst activity (e.g., Meech & Svoren 2004). However, the detection of cometary H$_2$O icy grains is so rare that the reason why crystalline H$_2$O icy grains were detected in a few comets is still unclear. Therefore, statistical study on the abundance of the cometary crystalline H$_2$O ice dust is important to reveal the history of formation and evolution of the comets. Especially, it is important to detect H$_2$O icy grains on the Centaurs/distant comets and the main-belt comets and, to perform statistical comparison of whether it is crystalline or amorphous.

1.3. Goal

The goal of our proposal is as follows:

1. Reveal the process of grain growth and radial transportation of dust grains in the early solar nebula by the investigation of the size, shape, and chemical compositions of cometary dust.

2. Reveal the history of formation and evolution of the comets by the statistical investigation of the crystallinity of H$_2$O icy dust grains of comets.
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Table 1. Observation strategy.

<table>
<thead>
<tr>
<th>Instruments &amp; Mode</th>
<th>MCS MRS-S/L + Safari</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>cometary refractory/icy dust grains</td>
</tr>
<tr>
<td>Line Features</td>
<td>10, 20, 33, 49, and 69 ( \mu m ) for silicate dust</td>
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<tr>
<td></td>
<td>6, 12, 44 and 65 ( \mu m ) for ( \text{H}_2\text{O} ) icy dust</td>
</tr>
<tr>
<td>Number of targets</td>
<td>( \sim ) 30 comets (Ecliptic/Oort comets, Centaurs, Main-belt comets)</td>
</tr>
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2. OBJECTIVE AND OBSERVATION STRATEGY

2.1. Astromineralogy of Cometary Refractory Dust

One of our objectives is to observe mid-IR + far-IR crystalline silicate features at 33, 49, and 69 \( \mu m \) of dozens of comets (for Ecliptic comets, Oort cloud comets, and Halley-type comets), and:

1. Estimate the Fe/Mg ratio and pyroxene/olivine ratio of silicate grains. Based on the result, study the temperature and chemical environment in the early solar system disk.
2. Investigate the dust grain size evolution and the formation mechanisms of cometary nuclei.

2.2. Cometary \( \text{H}_2\text{O} \) Icy Dust

Another is to observe mid-IR + far-IR \( \text{H}_2\text{O} \) ice bands at 6, 12, 44 and 65 \( \mu m \) of dozens of comets (for Centaurs and Main-belt comets, as well as Ecliptic comets, Oort cloud comets, and Halley-type comets). In addition, our objectives are also to detect \( \text{H}_2\text{O} \) icy grains and, to study the correlation between crystallinity of \( \text{H}_2\text{O} \) ice and distance, activity, or orbital character of the comet statistically.

2.3. Observation Strategy

Observation strategy is summarized in Table 1. We would like to note that simultaneous spectroscopic observations of 33 and 69 \( \mu m \) crystalline silicate features can be carried out only with \textit{SPICA}/MCS+Safari.

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The trans-Neptunian Objects after \textit{Herschel}: What Could \textit{SPICA} Add to the Understanding of the Kuiper Belt?

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ABSTRACT

About 400 hours of the \textit{Herschel Space Observatory}'s time has been used by the Open Time Key Programme “TNOs are Cool: A survey of the trans-Neptunian region” to obtain PACS (70, 100 and 160 µm) and SPIRE (250, 350 and 500 µm) photometry of 132 objects representing different dynamical classes (resonant, classical, scattered disk and detached TNOs as well as Centaurs), including 25 binary systems. As leftovers of the formation of the Solar System TNOs and their physical properties provide constraints to the models of formation and evolution of the various dynamical classes. \textit{SPICA} is going to be a main leap forward on the way that \textit{Herschel} started in the characterization of TNOs by determining size, albedo and other surface properties. \textit{SPICA} is going to cover the mid- to far-IR wavelengths where TNO SEDs peaks (currently covered with \textit{Herschel}/PACS and \textit{Spitzer}/MIPS together). While \textit{Herschel} could observe about 10\% of the known TNOs, with its increased sensitivity \textit{SPICA} would be able to detect most (probably all) currently known TNOs. The observing strategy we used in our key program will also be relevant for \textit{SPICA} observations to beat the confusion noise.

1. INTRODUCTION

Transneptunian Objects (TNOs) are believed to represent one of the most primordial populations in the Solar System. TNOs, as any other small bodies, are part of the ancient and today very tenuous debris disk of our Solar System. This population — that includes various subpopulations with different orbital characteristics — is particularly interesting since similar “Kuiper-belt-like” debris disk are often found around other stars, although usually at a different age and brightness than in our Solar System. The major difference between these disks and our Kuiper belt is that in the case of exosolar systems we are just able to observe the smallest sizes, the thermal emission from microscopic dust grains. In our Solar System, however, we are unable to detect this dust component (mostly due to the strong foreground, the Zodiacal emission), but we can study a significant fraction of larger bodies — this cannot be done in other planetary systems. As the surface temperatures of Kuiper-belt objects are in the order of 40–50 K, their thermal emission peaks in the far-infrared. This made the PACS and SPIRE cameras of the \textit{Herschel Space Observatory} (Pilbratt et al. 2010) especially suitable to survey the trans-Neptunian region. In the “TNOs are Cool!” Open Time Key Program (Muller et al. 2009) we aimed to obtain sizes, albedos, surface thermal properties, etc. of a large sample of trans-Neptunian objects and characterizing our debris disk for the first time and these kind of information cannot be derived from visual range measurements only.

2. \textit{HERSCHEL} OBSERVATION DESIGN AND DATA REDUCTION STRATEGIES

Confusion noise is a major limiting factor for the observations of faint targets in the far-infrared (see e.g. Kiss et al. 2005). Despite its large primary mirror compared to previous space infrared telescopes like the \textit{Infrared Space Observatory} and the \textit{Spitzer Space Telescope}, even the measurements with the \textit{Herschel Space Observatory} were limited by confusion noise, especially at the longer photometric wavelengths (160 µm and above). Confusion noise due to the extragalactic background and Galactic cirrus will be very similar in the case of \textit{SPICA} to that seen by the \textit{Herschel Space Observatory} due to the similar primary mirror size and resolution power of the two telescopes.

In the “TNOs are Cool!” OTKP we paid a special attention to confusion noise. First, we selected those observation dates for our TNOs are Centaurs when the expected confusion noise due to the background was the possible smallest during their motion in the sky (Kiss et al. 2005; Kiss 2007). In addition, we used multiple epoch observations — the way these observations were combined was very effective in eliminating the background and hence the confusion noise. All our observations were processed with a dedicated pipeline, optimized for these faint targets. Special techniques were used
Kiss et al.

Figure 1. Size distribution of hot (red) and cold (blue) classical trans-Neptunian objects (Vilenius et al. 2013).

to correct for errors originated from pointing differences of the telescope as well as for relative positional uncertainties. All observation design and data reduction techniques are discussed in detail in our dedicated paper (Kiss et al. 2013).

A good majority of our targets (>90%) are detected in at least one band (in the blue band in almost all cases), about 50% of them are detected in all the three PACS bands. With our techniques we managed to reach 0.6, 0.9 and 1.6 mJy flux uncertainties using the combined products of 5-repetition single maps in the 70, 100 and 160 µm PACS bands, respectively, with a total integration time of ~90 min at the shorter PACS wavelengths and ~180 min in the 160 µm band.

As the confusion noise could be very effectively eliminated with our techniques, the final limitation is the instrument noise in our OTKP. Using our observation and data reduction strategies, a similar survey with SPICA would be able fully exploit the superior capabilities of the detectors planned (Nakagawa et al. 2011).

3. MAIN HERSCHEL SCIENCE RESULTS AND THE PERSPECTIVES FOR SPICA

3.1. Thermal Properties

The investigation of the thermal properties of TNOs are Centaurs (Lellouch et al., 2013) revealed that beaming factors (\(\eta\)) range from values of <1 to ~2.5, but we are lacking large values at small heliocentric distances. The mean thermal inertia in the population is found to be \(\Gamma = (2.5 \pm 0.5) \, \text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}\), and there is a strong suggestion that the thermal inertia decreases with heliocentric distance The observed thermal inertias are 2–3 orders lower than expected for compact ices and are generally smaller than on Saturn’s satellites or in the Pluto/Charon system. Objects with high albedos (>20%) have lower beaming factors than the rest of the population, i.e. they have unusually low thermal inertias. This possibly results from smaller grain size. An exception is Makemake. The ensemble of our results suggests strongly porous surfaces, in which the heat transfer is affected by radiative conductivity within pores and increases with depth in the subsurface.

To obtain thermal properties from infrared measurements in the sample above, the target has to be clearly detected at several wavelengths. As was mentioned, this was not the case with our Herschel/PACS sample that limited the number of objects that such a study could be performed for. The higher sensitivity of SPICA at these wavelengths will allow the determination of thermal properties for a larger number of targets and will certainly probe the small end of the size distribution. These smaller targets may have thermal properties significantly different from those in our current sample, revealing different formation and evolution scenarios.

3.2. Size Distribution

One of the most important global characteristics of a debris disk is its size distribution. In our OTKP we sampled all major populations of the trans-Neptunian region: Classical, Plutinos, Scattered disk and detached objects, resonant TNOs, and Centaurs, too. We could derive the main characteristics of these populations, like the slope parameter of the size distribution. E.g. Plutinos at \(D = 120–400\) km have a slope parameter of 2, and at larger sizes of 3 (Mommert et al. 2012). Hot classical at \(D = 100–600\) km have a slope parameter of 1.4, based on a smaller sample (Vilenius et al. 2012).
TNOs are Cool!

In the extended sample (Vilenius et al. 2013) hot Classicals have a larger maximum size and therefore a wider part of the distribution is observed. The difference in the distributions is compatible with the hypothesis that hot Classicals were formed in a region where the surface mass density was higher than in the case of cold Classicals.

3.3. Surface Characteristics of Scattered Disk and Detached Objects

Our sample of Scattered disk and detached objects shows two interesting correlations. More reflective objects are larger, probably because large objects can retain bright ices more easily than small objects. However, we do not see this in other dynamical classes; The other interesting feature is that brighter and larger SDOs have larger perihelia. This correlation has been explained by increased ice sublimation and/or space weathering at low heliocentric distances (Santos-Sanz et al. 2012).

4. CONCLUSIONS

The “TNOs are Cool!” Open Time Key Program was very effective in measuring the thermal emission of Centaurs and TNOs that revealed many important individual characteristics of specific targets, and also allowed us to derive such properties of the Kuiper belt populations that were not known before. However, Herschel could just observe a rather limited sample and it could only be SPICA (with the capability of observe almost 100% of the presently known TNOs) in the relatively near future that would be able to extend the limits of our OTKP in order to better understand the evolution of our own Solar System as well as that of exo-solar debris systems.

The work of Cs.K. has been supported by the PECS 98073 contract of the European Space Agency and the Hungarian Space Office, the #104607 grant of the Hungarian Research Fund (OTKA) and by the Bolyai Research Fellowship of the Hungarian Academy of Sciences.

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The AKARI Mid-IR All-Sky Diffuse Maps: Lessons Learned for SPICA

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ABSTRACT
We are creating all-sky diffuse maps from the AKARI 9 and 18 \( \mu m \) band survey data. In particular, the 9 \( \mu m \) map is a unique resource as an all-sky tracer of polycyclic aromatic hydrocarbons. Original data include artifacts, such as the scattered light from the moon. In addition, the zodiacal light is a dominant component in the mid-IR. In order to correct these artifacts and remove the zodiacal light, we have carried out special analyses. As a result, we have obtained accurately-calibrated all-sky maps and learned technical lessons for SPICA.

1. INTRODUCTION
AKARI carried out mid-IR all-sky surveys in the 9 and 18 \( \mu m \) bands. The 9 \( \mu m \) map is crucial to investigate the all-sky distribution of polycyclic aromatic hydrocarbons (PAHs), while the 18 \( \mu m \) map is useful to trace hot dust grains. However, original data include artifacts, such as the scattered light from the moon. Figure 1 Top shows an example of the AKARI 9 \( \mu m \) map around the Galactic center affected by these artifacts. In addition to these artifacts, the zodiacal light is a dominant component in the mid-IR. We have to remove the zodiacal light from the maps to obtain the Galactic diffuse maps. It has been physically modeled in past studies (e.g., Kelsall et al. 1998), however, there remains discrepancy between the observational result and model prediction, which is still larger than Galactic cirrus emission at high galactic latitudes (Kondo 2013). In order to obtain accurate mid-IR Galactic diffuse maps, we have carried out special analyses.

2. DATA REDUCTION AND RESULTS
2.1. Removal of the Scattered Light from the Moon
We found that the observational data are strongly affected by the scattered light from the moon, even if the moon is about 40 degrees away from the field of view (Mouri 2012). We therefore evaluated the pattern of the scattered light from the moon in the detector array coordinates with the moon in the center (Figure 2). As a result, we obtain the pattern which is asymmetrical with respect to the moon position with spider-like structures. Thus, the intensity of the scattered light cannot be estimated as a function of the moon avoidance. We also find that the scattered light is distributed over 40 degrees away from the moon. Because this pattern is stable from season to season, we establish the method to remove the scattered light component from the maps. Figure 1 Bottom shows the 9 \( \mu m \) map around the Galactic center after removing the scattered light from the moon.

2.2. Removal of the Zodiacal Light
We have obtained the maps in which we corrected the artifacts, as shown in Figure 1 Bottom. Yet, the zodiacal light is a dominant foreground emission compared to the Galactic diffuse emission as shown in Figure 3 Left. In the standard zodiacal light model, the interplanetary dust cloud is composed of three components: the smooth cloud, the dust bands, and the mean-motion-resonance (MMR) component (Kelsall et al. 1998). In past studies, the emissivities of these three components were determined by the zodiacal light model fitting using the data of seasonal variations of the zodiacal light (Kelsall et al. 1998; Pyo et al. 2010).

On the other hand, we divide the MMR component into the circumsolar ring and the trailing blob, and carry out the model fitting simultaneously using all the seasonal data. As a result, we obtain the emissivity of each component shown in Table 1, where we also show the emissivity determined by the COBE/DIRBE 12 \( \mu m \) band (Kelsall et al. 1998) for comparison. We find that the emissivities of the MMR component (especially the trailing blob component) in the 9 \( \mu m \) band are higher than those in the 12 \( \mu m \) band, while the emissivity of the smooth cloud is similar in both bands. On the contrary, the emissivity of the dust bands in the 9 \( \mu m \) band is considerably lower than that in the 12 \( \mu m \) band. After these modifications of the emissivity parameters, we successfully reduce the intensity of the residual component down to 2% of the zodiacal light component at the ecliptic plane, which is compared with 6% in the past study (Kelsall et al. 1998). Figure 3 Right shows the result of the removal of the zodiacal light in the 9 \( \mu m \) band.
Figure 1.  
Top: AKARI 9 $\mu$m map around the Galactic center of an area of about 30 deg x 10 deg. The white box and the white arrow indicate the scattered light from the moon and the scan direction, respectively. The stripes parallel to the scan direction are ionizing radiation effects (The detail appears in Mouri et al. (2011)). Bottom: Same data as the top panel, but after removing the scattered light from the moon and the ionizing radiation effects.

Figure 2.  Pattern of the scattered light from the moon in the 9 $\mu$m band in the detector array coordinates. The moon is located in the center.

3. LESSONS LEARNED FOR SPICA

We have learned technical lessons for SPICA through the correction of the scattered light from the moon and the removal of the zodiacal light. SPICA will suffer stray light of objects fainter than the moon (e.g., asteroids, bright stars) because the sensitivity of SPICA is higher than that of AKARI. We have identified critical paths of the scattered light from the moon into the telescope, investigating the structure of the telescope baffle and the pattern of the scattered light shown in
THE AKARI MID-IR ALL-SKY DIFFUSE MAPS

Figure 3. The 9 µm all-sky maps in the ecliptic coordinates before (left) and after (right) removing the zodiacal light. The units of the color scales are given in MJy sr⁻¹.

Table 1. Emissivity modification factors.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Smooth cloud</th>
<th>Dust bands</th>
<th>Ring</th>
<th>Blob</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 µm (present study)</td>
<td>1.084 ± 0.002</td>
<td>0.31 ± 0.04</td>
<td>1.55 ± 0.04</td>
<td>2.80 ± 0.02</td>
</tr>
<tr>
<td>12 µm (Kelsall et al. 1998)</td>
<td>0.958 ± 0.003</td>
<td>1.0 ± 0.2</td>
<td>1.06 ± 0.09</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. We feed back the information to the optical design of the baffle of SPICA. For the zodiacal light, we improve the model parameters to explain the AKARI data. The new zodiacal light model will be useful for observation planning and data reduction of SPICA.

4. SUMMARY

The AKARI 9 µm map is a unique resource as an all-sky PAH tracer. In order to create accurately calibrated maps, we have carried out special data analyses, such as correction of the scattered light from the moon and removal of the zodiacal light. As a result, we have learned technical lessons for SPICA through these analyses.

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SESSION 4:

INSTRUMENTATION / OTHERS
An Experimental Study of Stitching Interferometry for the SPICA Telescope

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ABSTRACT

For optical testing of the SPICA telescope, we require sub-aperture stitching interferometry, because an accurate autocollimating flat mirror (ACF) with a size comparable to the telescope (3.2 m) is hardly available. Therefore we use small ACFs which rotate with respect to the optical axis of the telescope to cover the full pupil of the telescope. We verified the feasibility of the sub-aperture stitching interferometry by performing real optical measurement. At cryogenic temperatures, in particular, ACFs can be deformed due to thermal contraction. Since surface figure errors of ACFs can make errors in the sub-aperture stitching result, we propose a new method to mitigate the effects of the ACF errors. We evaluated the feasibility of this method by performing an experimental study utilizing the 800-mm telescope and a 300-mm ACF with a designed large deformation. As a result, we find that this method is applicable for the optical test of the telescope, although it needs to be further developed.

1. INTRODUCTION

The SPICA telescope has a diameter of 3.2 m, mirrors of which are made of silicon carbide (SiC) or its related material. The telescope has requirements for its total weight to be lighter than 700 kg and imaging performance to be diffraction-limited at 5 μm at the operating temperature of 6 K. The design of the telescope system has been studied by Europe-Japan telescope working group led by ESA with European industries (Castel et al. 2012). According to the current plan, optical testing of the telescope at temperatures below 100 K and acoustic and vibration tests will be performed in Europe. Then the telescope will be delivered to Japan for the final optical testing of the telescope assembly at temperatures below 10 K.

The total wave-front error (WFE) of the telescope is required to be smaller than 350 nm rms for high-resolution observations. Thus we need to evaluate the surface shape of the telescope precisely. Since an accurate autocollimating flat mirror (ACF) with a size comparable to the telescope (3.2 m) is hardly available, it is difficult to measure the full aperture of the telescope at one time. Instead we adopt sub-aperture stitching interferometry for the optical test of the telescope; small ACFs which rotate with respect to the optical axis of the telescope are used to measure sub-aperture WFEs, and then sub-aperture datasets thus derived are stitched to the full-aperture WFE of the telescope. It should be noted, however, that ACFs can be deformed by thermal contraction at cryogenic temperatures. Surface figure errors (SFEs) of ACFs can make errors in the sub-aperture stitching result and they are difficult to be measured directly in the test.

(a) Configuration for the sub-aperture stitching measurement. The telescope and interferometer are set on the left-hand side, while the 300-mm ACF is set on the right-hand side. (b) The 300-mm ACF used in the sub-aperture stitching measurement. The ACF is rotated by a step angle of 22.5 degrees in a counterclockwise direction. (c) Configuration for the full-aperture measurement. The 900-mm flat mirror is placed on the right-hand side.

Figure 1.
In this paper, we report an initial result of our experimental study for the sub-aperture stitching interferometry, and then we discuss how to mitigate the effects of ACF errors by proposing a new method.

2. MEASUREMENTS

We have verified that the sub-aperture stitching interferometry is applicable to the optical test of the telescope by performing the real optical measurement of the telescope (Kaneda et al. 2012). Figure 1 shows the configurations for our measurement. We utilize the 800-mm lightweight telescope all made of the C/SiC called HBCesic, which is a candidate mirror material for the SPICA telescope (Suganuma et al. 2010). For the ACF, we use the 300-mm glass mirror which has a high-precision flat surface (0.016 \( \lambda \) rms). Here and hereafter, \( \lambda \) is the He-Ne laser wavelength of 632.8 nm. An optical interferometer is used to measure the WFEs of the telescope. The ACF is rotated by a step angle of 22.5 degrees with respect to the optical axis of the telescope to perform sub-aperture stitching measurement as described above. In order to evaluate the sub-aperture stitching result, we also utilize the 900-mm glass flat mirror, which can cover the full aperture of the telescope at one time, to compare the results obtained by the sub-aperture stitching and full-aperture measurement.

Figure 2a shows sub-aperture WFE maps of the telescope. The WFE maps of the telescope obtained by the sub-aperture stitching and the full-aperture measurement are shown in Figures 2b and 2c, respectively. As can be seen in the figures, the results show an excellent agreement with each other.

Figure 3. (a) SFE map of the ACF with a designed large deformation. (b) The WEF map of the telescope obtained by the sub-aperture stitching measurement using the deformed ACF, shown together with the positions and directions of the small movements of the ACF. (c) The SFE map of the ACF reproduced by our method. (d) The resultant WFE map of the telescope obtained by the sub-aperture stitching measurement after the correction of the ACF errors.
**Stitching Interferometry for the SPICA Telescope**

As described above, ACFs can be deformed at cryogenic temperatures, causing additional stitching errors by propagation of their SFEs. Therefore, prior to the sub-aperture stitching, we need to estimate the SFEs of the ACFs and subtract them from the sub-aperture WFEs. We estimate the SFE of the ACF independently of the WFE of the telescope by small movements of the ACF in the \(x\)- and \(y\)-axis directions (i.e., analogous to a shearing method). According to our current test plan, each ACF has one degree of freedom for rotation with respect to its center, and thus we can fix the orientation of the ACFs in the inertial frame while rotating. In this configuration, small rotations at 0 and 90 degrees are equivalent to small movements in the \(x\)- and \(y\)-axis directions, respectively. We calculate the difference, between the WFE maps before and after the movement of the ACF for each direction to estimate the SFE of the ACF. Details of our algorithm will be reported in a separate paper.

3. **RESULTS**

In order to check the validity of our new method, we fabricated an ACF with a designed large deformation as shown in Figure 3a. Figure 3b shows the sub-aperture stitching result obtained by using this ACF, where we can see that the SFE of the ACF seriously affects the sub-aperture stitching result, and therefore we cannot evaluate the WFE of the telescope correctly.

According to the new method mentioned above, we extract the SFE map of the ACF as shown in Figure 3c. As compared with Figure 3a, our result reproduces the original SFE map of the ACF fairly well. Then we subtract this SFE from each sub-aperture dataset prior to the sub-aperture stitching, and Figure 3d shows the sub-aperture stitching result thus derived. As can be seen in the figure, the WFE map of the telescope after the correction of the ACF errors is qualitatively similar to the original one (Figure 2b). Quantitatively, however, we find that there are still residual errors caused by the ACF errors. Checking carefully Figure 3c with Figure 3a, it is seen that the SFE map of the ACF obtained from our method does not reproduce a power component of the original one. This discrepancy may cause such residual errors. Thus we need to develop the algorithm of our method or measurement configurations to remove them.

4. **FUTURE PLAN**

In order to reproduce the power component of the deformed ACF, we will introduce additional systems to monitor an unwanted tilt of the ACF which can be generated during the small movement. In addition, the above measurement has been performed at an ambient pressure, not at a vacuum pressure. Therefore we will start our experiments at a vacuum pressure and then proceed to measurement at cryogenic temperatures.

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Study on the Specification of Filters and Grisms for the Wide Field Camera: A Progress Report from the MCS Filter Working Group

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6Service d’Astrophysique, CEA Saclay, France

ABSTRACT

We have started the study on the specification of filters and grisms for SPICA Mid-Infrared Camera and Spectrometer (MCS; Kataza et al. 2012) Wide Field Camera (WFC) within the framework of MCS Filter Working Group (FWG). The FWG activity aims to obtain the baseline specification of imaging filters and grisms optimized for the maximum science output in any scientific fields of “extragalactic science”, “ISM science” and “planetary science” by taking account of the technical constraints. The resultant baseline specifications will be opened to wider science members of SPICA project and FWG will get a more effective baseline set of filters and grisms for WFC by reflecting the feedback received. In this article, the latest progress report on the specification of filters and grisms for WFC studied by the MCS FWG is given.

1. THE VERY BASIC SPECIFICATION FOR WFC FILTERS REQUESTED FROM THE EXTRAGALACTIC SCIENCE, ISM SCIENCE AND PLANETARY SCIENCE

In order to carry out the SED analyses of any galaxies at different redshift evenly, the extragalactic science cases request that the WFC filters shall have constant spectral resolution power ($R \sim 5$ for WFC-S and $R \sim 10$ for WFC-L) and continuous spectral coverage (4–26$\mu$m for WFC-S and 18–38$\mu$m for WFC-L). Thus, the center wavelength of $n^{th}$ photometric band, $\lambda_c(n)$, is defined as

$$\lambda_c(n) = \lambda_c(1) \left\{ \left( 1 + \frac{1}{2} R^{-1} \right) \left( 1 - \frac{1}{2} R^{-1} \right)^{-1} \right\}^{n-1},$$

where $R$ is the spectral resolution power and $\lambda_c(1)$ is the center wavelength of the initial photometric band.

On the other hand, many ISM and planetary science cases focus on emission and/or absorption features arising from various dust species in different physical condition in the spectral range of MCS. While the spectroscopy is required for the detailed identification and physical/chemical diagnoses of those spectral features, multi-band photometry with WFC shall aim to efficiently find objects that have unusual SED in the mid-infrared.

2. THE CANDIDATE SET OF WFC-S PHOTOMETRIC FILTERS

Table 1 shows the candidate set of WFC-S photometric filters selected to measure the emission and/or absorption strengths of astronomical silicate and the UIR bands effectively. $\lambda_c(1) = 4.39 \mu$m and $R = 4.5$ are adopted for this selection. We confirmed that S5.4, S9.8 and S14.6 bands are almost free from major UIR bands and those bands are used to measure the strength of silicate absorption and to define the hot dust continuum underlying the UIR features. Based on our simulation analyses using ISO SWS spectra of various types of Galactic objects (Hony et al. 2001; Sloan et al. 2003), we confirmed that S6.6 and S8.0 bands will efficiently measure the strengths of UIR 6.2$\mu$m and 7.7$\mu$m features, respectively, after subtracting the hot dust continuum emission contribution estimated by S5.4, S9.8 and S14.6 bands. However, we found that the strength of UIR 11.2$\mu$m feature cannot be correctly measured by S12.0 band. Additional U11.2 photometric band with $\lambda_c = 11.20 \mu$m and $\Delta \lambda = 0.40 \mu$m is, therefore, strongly requested to discriminate UIR 11.2$\mu$m feature out from the hot dust continuum emission.

3. THE CANDIDATE SET OF WFC-L PHOTOMETRIC FILTERS

Because of the difficulty in measuring the strengths of faint dust features on strong hot dust continuum emission in the spectral range of WFC-L, it is hard to find a superior set of WFC-L photometric filters based on our knowledges.
Sakon et al.

on wavelength positions of certain dust species. While the extragalactic science cases generally requires multi-band photometric capability with \( R \sim 10 \), ISM science cases requires efficient mapping capability using smaller number of imaging filters with \( R < 5 \). In Table 2 the candidate sets of WFC-L photometric filters are shown. Plan A assumes \( \lambda_c(1) = 18.9 \mu m \) and \( R = 10.0 \) for narrow band filters and \( \lambda_c(1) = 27.0 \mu m \) and \( R = 4.5 \) for wide band filters, while Plan B assumes \( \lambda_c(1) = 20.5 \mu m \) and \( R = 8.0 \) for narrow band filters and \( \lambda_c(1) = 23.0 \mu m \) and \( R = 4.5 \) for wide band filters.

4. GRISMS FOR WFC

WFC plans to have low-resolution slit-less spectroscopic capability using 293’’ \( \times \) 300’’ FOV and short slit spectroscopic capability using 7’’ length slit at FOV edge (Kataza et al. 2012). Table 3 summarizes the list of grisms requested to achieve the extragalactic, ISM and planetary science cases proposed in the SPICA mission requirement documents.

SG1, SG2, LG3 and LG4 will provide us successive spectroscopic capability from 5–39 \( \mu m \) with \( R = 50 \) and are requested, in particular, by extragalactic science cases. Slit-less spectroscopic capability with SG1H and SG2H will have advantages over JWST/MIRI for some science cases such as the investigations of infrared absorption spectra of foreground molecular clouds using background stars. Moreover, some science cases targeting time varying phenomena (e.g., SNe, LVBs, WRs) require wide spectral coverage in 4–38 \( \mu m \) with relatively high spectral resolution. For such purpose, simultaneous data acquisition between WFC-S/SG1H, SG2H (4–13 \( \mu m \), \( R = 200 \)) and MRS (12.2–37.5 \( \mu m \), \( R = 1100–3000 \); see Sakon et al. 2012) are crucial to investigate the signatures of interaction between stellar wind and circumstellar medium and to demonstrate the physical phase transition of matters including gas ejection, formation of molecules and condensation of dust in circumstellar environment.

Table 1. Candidate set of WFC-S photometric filters

<table>
<thead>
<tr>
<th>Band</th>
<th>( \lambda_c ) (( \mu m ))</th>
<th>( \Delta \lambda ) (( \mu m ))</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>S4.4</td>
<td>4.39</td>
<td>0.88</td>
<td>Continuum (stellar/hot dust), CO</td>
</tr>
<tr>
<td>S5.4</td>
<td>5.36</td>
<td>1.07</td>
<td>Continuum (stellar/hot dust)</td>
</tr>
<tr>
<td>S6.6</td>
<td>6.56</td>
<td>1.31</td>
<td>PAH C-C stretch (UIR 6.2 ( \mu m ))</td>
</tr>
<tr>
<td>S8.0</td>
<td>8.01</td>
<td>1.60</td>
<td>PAH C-C stretch (UIR 7.7 ( \mu m ) complex, UIR 8.6 ( \mu m ))</td>
</tr>
<tr>
<td>S9.8</td>
<td>9.79</td>
<td>1.96</td>
<td>Silicate abs./emi.</td>
</tr>
<tr>
<td>S12.0</td>
<td>11.97</td>
<td>2.39</td>
<td>PAH C-H oop bending (UIR 11.2 ( \mu m ), 12.7 ( \mu m )), [Ne II]</td>
</tr>
<tr>
<td>S14.6</td>
<td>14.63</td>
<td>2.93</td>
<td>Hot Dust Continuum, [Ar II]</td>
</tr>
<tr>
<td>S17.9</td>
<td>17.88</td>
<td>3.58</td>
<td>Silicate abs./emi., PAH C-C-C wagging, C60, [S III]</td>
</tr>
<tr>
<td>S21.8</td>
<td>21.85</td>
<td>4.37</td>
<td>Hot Dust Continuum, Crystalline Silicate</td>
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</table>

Table 2. Candidate sets of WFC-L photometric filters

<table>
<thead>
<tr>
<th>Band</th>
<th>Plan A</th>
<th>Plan B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_c ) (( \mu m ))</td>
<td>( \Delta \lambda ) (( \mu m ))</td>
<td>( \lambda_c ) (( \mu m ))</td>
</tr>
<tr>
<td>L18.9</td>
<td>18.92</td>
<td>1.89</td>
</tr>
<tr>
<td>L20.8</td>
<td>20.81</td>
<td>2.08</td>
</tr>
<tr>
<td>L22.9</td>
<td>22.89</td>
<td>2.29</td>
</tr>
<tr>
<td>L25.2</td>
<td>25.18</td>
<td>2.52</td>
</tr>
<tr>
<td>L27.7</td>
<td>27.70</td>
<td>2.77</td>
</tr>
<tr>
<td>L30.5</td>
<td>30.47</td>
<td>3.05</td>
</tr>
<tr>
<td>L33.5</td>
<td>33.52</td>
<td>3.35</td>
</tr>
<tr>
<td>L36.9</td>
<td>36.87</td>
<td>3.69</td>
</tr>
<tr>
<td>L27W</td>
<td>27.00</td>
<td>6.0</td>
</tr>
<tr>
<td>L34W</td>
<td>33.75</td>
<td>7.5</td>
</tr>
</tbody>
</table>
A Progress Report from the MCS Filter Working Group

Table 3. Candidate sets of grisms for WFC

<table>
<thead>
<tr>
<th>channel</th>
<th>disperser</th>
<th>wavelength (µm)</th>
<th>spectral resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>WFC-S</td>
<td>SG1H</td>
<td>4–7.5</td>
<td>R = 200</td>
</tr>
<tr>
<td></td>
<td>SG2H</td>
<td>7–13.0</td>
<td>R = 200</td>
</tr>
<tr>
<td></td>
<td>SG1</td>
<td>5–9</td>
<td>R = 50</td>
</tr>
<tr>
<td></td>
<td>SG2</td>
<td>8–15</td>
<td>R = 50</td>
</tr>
<tr>
<td>WFC-L</td>
<td>LG3</td>
<td>14–26</td>
<td>R = 50</td>
</tr>
<tr>
<td></td>
<td>LG4</td>
<td>24–39</td>
<td>R = 50</td>
</tr>
</tbody>
</table>

Figure 1. Available slots for filters and grisms for WFC-S and WFC-L.

5. TECHNICAL CONSTRAINTS FOR THE CHOICE OF FILTERS AND GRISMS FOR WFC

Each channel of WFC plans to employ double filter wheels. The number of slots in each filter wheel should be smaller than 10 for WFC-S and 8 for WFC-L from the technical reason. Each filter wheel must have "hole" position and either one of the filter wheel must have a "blind" position. Therefore, at most 17 slots are available for the imaging filters and grisms for WFC-S and 13 slots for WFC-L. Figure 1 shows the available slots for filters and grisms for WFC-S and WFC-L. Besides the baseline filter set discussed in Sections 2–4, 3 slots in WFC-S and 1–2 slots in WFC-L are available for additional narrow band filters and/or wide band filters. Further discussion is still needed to get the even more useful baseline set of filters and grisms for WFC-S and WFC-L.

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Development of Far-Infrared Germanium Photoconductors with Surface Activated Wafer Bonding Technology

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ABSTRACT

We present our recent activities on the development of new Ge photoconductors for far-infrared (far-IR) astronomy. Using the surface-activated wafer bonding (SAB) method provided by Mitsubishi Heavy Industries, we fabricated a Ge

$$p^+\cdot i\cdot p^-$$

junction device with clean abrupt junction, which basically possesses a Blocked-Impurity-Band-type (BIB-type) structure. We measured the far-IR sensitivity of the device at 1.7 K using a blackbody source and spectral response curves at 2.8 K using a Fourier transform spectrometer. The device shows considerably higher sensitivity and wider spectral coverage than a conventional bulk Ge:Ga device, demonstrating promising applicability of SAB Ge

$$p^+\cdot i$$

junction devices to BIB-type Ge detectors.

1. INTRODUCTION

For future far-IR astronomy in the SPICA era, improvements in the detector technology are crucial. There are two main streams for the development of detectors covering the far-IR region (50–200 μm): photoconductor and bolometer. Ge:Ga photoconductors have been widely used for instruments carried on major IR astronomical satellites ever launched. For SPICA, superconducting bolometer technology is being developed to be adopted for the far-IR instrument, SAFARI. Although the superconducting bolometer is expected to possess unprecedentedly high sensitivity, a photoconductor is still advantageous in achieving a wide dynamic range of signal detection, reducing the size of a pixel of an array, and most importantly not requiring sub-Kelvin coolers.

We are developing new Ge photoconductors which possess a Blocked-Impurity-Band-type structure. BIB-type Ge detectors are known to mitigate problems, such as cosmic-ray-induced fluctuations of detector sensitivity and non-linear slow transient responses, which are notorious problems for conventional Ge:Ga photoconductors. They can also cover a relatively wide spectral range with a longer cutoff wavelength because of shallow energy levels of heavily-doped impurities. We are developing layered extrinsic photoconductors using the room-temperature, surface-activated wafer bonding (SAB) technology provided by Mitsubishi Heavy Industries (Takagi et al. 1996; Takagi & Maeda 2006). In the SAB method, two wafers are attached in a high vacuum chamber at a room temperature after activation of their contact surface by an Ar ion beam. Since the SAB method is a non-thermal process, the layered photoconductors obtain clean abrupt junction with almost no thermal contamination by impurities from a heavily-doped layer to an intrinsic layer. Recently, Watanabe et al. (2011) tested SAB-processed Ge:Ga devices at temperatures of 300 and 77 K; they bonded two Ge:Ga layers, both with the same Ga concentration of \(2 \times 10^{16} \text{cm}^{-3}\). They demonstrated that there was no degradation in electrical properties at the bonded interface, although there was a crystallographic discontinuity.

Using the same process as described in Watanabe et al. (2011), we have fabricated SAB Ge

$$p^+\cdot i$$

junction devices consisting of a heavily-doped Ge:Ga layer (\(p^+\) layer) and a non-doped intrinsic Ge layer (\(i\) layer). The initial results of evaluating the electric and photoconductive properties of the devices under dark conditions were reported in Kaneda et al. (2011), where the derived properties were found to be physically reasonable for BIB-type devices. In this paper, we report further results of the evaluation to demonstrate applicability of the device to BIB-type Ge detectors.

2. MEASUREMENTS

Using the SAB method, we have fabricated a Ge

$$p^+\cdot i$$

junction device with the size of \(1 \times 1 \times 0.55 \text{mm}^3\). The device consists of two layers; a heavily-doped Ge:Ga layer of thickness 0.5 mm with a Ga concentration of \(1 \times 10^{16} \text{cm}^{-3}\) and a non-doped intrinsic Ge layer of thickness 0.05 mm. In order to evaluate the properties of each layer independently, we fabricated a non-doped bulk Ge device and a heavily-doped bulk Ge:Ga device with a Ga concentration of \(1 \times 10^{16} \text{cm}^{-3}\). The former basically has the same properties as the \(i\) layer, and the latter has the same properties as the \(p^+\) layer. As a reference sample, we also fabricated a conventional bulk Ge:Ga device with a Ga concentration of \(2 \times 10^{14} \text{cm}^{-3}\).

We measured the electric and photoconductive properties of the devices at temperatures of 1.7–77 K. Figure 1 Left shows a measurement system on a cold stage which consists of a blackbody source with a cold shutter and a housing where
Figure 1.  Left: Configuration for measurement of sensitivity and thermal current under dark condition. Right: Configuration for measurement of spectral response curves using an external FT-IR spectrometer.

Table 1. Responsivity of the $p^+\text{-}i$ junction device and the bulk Ge:Ga device, both measured at 1.7 K with $V_{\text{bias}} = 100$ mV.

<table>
<thead>
<tr>
<th>Device</th>
<th>$R$ (A/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bulk Ge:Ga</td>
<td>0.37</td>
</tr>
<tr>
<td>$p^+\text{-}i$ type</td>
<td>13</td>
</tr>
</tbody>
</table>

the test device is installed. This system provides dark conditions, so that we can precisely measure the far-IR sensitivity of the test device. To evaluate the sensitivity, we measured the output photo current of the device against the illumination of far-IR photons by the 40 K internal blackbody source. Additionally, we evaluated the temperature dependence of the thermal current of the device at a fixed voltage bias; we controlled the operational temperature of the device by changing the internal pressure of the liquid-He tank of the cryostat.

Figure 1 Right shows a measurement system for spectral response, which consists of a device housing and optical filters on a cryostat wall and cold shrouds. Illuminating far-IR light from an external Fourier transform infrared (FT-IR) spectrometer to the device through the filters, we obtained spectral response curves of each device. For the curves, we removed the wavelength dependences of the emission of the light source and the transmission of the optical filters.

3. RESULTS

Table 1 shows the responsivity of the Ge $p^+\text{-}i$ junction device and the conventional bulk Ge:Ga device with a Ga concentration of $2 \times 10^{14}$ cm$^{-3}$. Both devices are measured at temperature of 1.7 K with a bias voltage of 100 mV. From Table 1, we find that the Ge $p^+\text{-}i$ junction device has sensitivity much higher than the conventional Ge:Ga bulk device.

Figure 2 Left shows spectral response curves of the Ge $p^+\text{-}i$ junction device and the conventional bulk Ge:Ga device at temperature of 2.8 K with bias voltages of 1 V and 25 mV, respectively. The peak sensitivity of each device is normalized to a unity. From Figure 2 Left, we find that the cutoff wavelength of the Ge $p^+\text{-}i$ junction device is extended to 160 µm, significantly longer than that of the bulk Ge:Ga device without mechanical stress.

Figure 2 Right shows the output current plotted against the reciprocal of the operating temperature for the heavily-doped bulk Ge:Ga device with a Ga concentration of $1 \times 10^{16}$ cm$^{-3}$, measured under dark conditions. The current is measured with a bias voltage of 100 mV. At low temperatures, output current is dominated by the thermal excitation of carriers, and hence the current is almost proportional to the Boltzmann factor, $\exp(-E_A/kT)$, where $E_A$ is the depth of the Ga energy level. By fitting the temperature dependence of the current at $20 \leq T \leq 40$ K while avoiding the influence of the hopping current, we obtain $E_A = 7.2$ meV, which corresponds to the cutoff wavelength of 165 µm. This result is consistent with the cutoff wavelength derived from the measurement of the spectral response curve.

4. SUMMARY

We have fabricated the Ge $p^+\text{-}i$ junction device consisting of a heavily-doped Ge:Ga layer and a non-doped Ge layer, using the SAB method. We evaluated the sensitivity and spectral response curves of the device and compared them with those of the conventional bulk Ge:Ga device at temperatures of 1.7–77 K. As a result, we find that the Ge $p^+\text{-}i$ junction device has sensitivity considerably higher than that of the Ge:Ga bulk device. We also find that spectral response curves of the Ge $p^+\text{-}i$ junction device are extended to the cutoff wavelength of $\sim 160$ µm, significantly longer than that of the Ge:Ga bulk device without mechanical stress. Our overall results suggest promising applicability of SAB Ge $p^+\text{-}i$ junction
Figure 2. Left: Spectral response curves. The blue solid line is the spectral response curve of the Ge $p^+\!-\!i$ junction device while the red dashed line is that of the conventional bulk Ge:Ga device without mechanical stress. The vertical axis shows the responsivity, the peak of which is normalized to a unity for each device. Right: Output thermal current plotted against the reciprocal of the operating temperature for the heavily-doped bulk Ge:Ga device, measured under dark conditions. The green dashed line is the result of fitting to the data in a range of 20 K to 40 K.

In a future work, the Ga concentration of the $p^+$ layer will be further increased to extend the cutoff wavelength up to 200 $\mu$m.

REFERENCES

ABSTRACT

We are currently involved in the development of stellar coronagraphs, with which the contrast between a star and a planet orbiting it can be improved, with the primary aim of the direct observation of exoplanets. We have carried out demonstrations of our mask design ideas for the pupil of SPICA and developed new free-standing masks (Mask-B and Mask-C) using thin sheets of nickel. Mask-B is intended to be used with a small inner working angle (IWA), and therefore, would be useful for direct observations of young Jovian planets very close to stars. With Mask-C a wide-field coronagraphic image is realized, so would be useful for efficient surveys of unknown exoplanets far from their stars and observations of diffuse targets such as circumstellar disks related to planetary formation. These mask have the general advantages of a binary pupil mask, i.e., (1) they are robust against pointing errors, and (2) they can, in principle, make observations over a wide range of wavelengths. Furthermore, the design of these masks gives them the following very important asset in that (3) they are applicable to the pupil of the SPICA telescope, which is partially obscured by a secondary mirror and support spiders. We obtained the first results of our laboratory experiments using Mask-B and Mask-C. The contrast of Mask-B close to the center was $\sim 10^{-4}$ and that of Mask-C over an extended field of view (6–23 $\lambda/D$) was $\sim 10^{-5}$–$10^{-6}$.

1. INTRODUCTION

It is important to directly observe exoplanets in order to understand the processes by which they were formed, evolved, and their diversity. However, the enormous contrast in flux between a star and a planet associated with it is the primary difficulty in making direct observations (Traub & Jucks 2002). Thus, the development of stellar coronagraphs, which can improve the contrast between the star and the planet, is needed. We are studying binary-shaped pupil mask coronagraphs, with the intention of applying them to the SPICA coronagraphic instrument (Enya et al. 2011). Space-borne telescopes have advantages as platforms for high contrast coronagraphs, because they are free from air turbulence and atmospheric infrared absorption. Working in the mid-infrared (mid-IR) region has the great advantage that the contrast between the sun and the planet is $10^{-6}$, compared with visible wavelengths where it is $10^{-10}$.

To demonstrate the principle, we have developed a checkerboard mask on a substrate, which is a type of binary-shaped pupil mask, and a large vacuum experimental platform, the High-dynamic range Optical Coronagraph Testbed (HOCT),
2. NEW MASK DESIGNS (MASK-B AND MASK-C)

We have started demonstrating our mask design ideas for the pupil of SPICA. Figures 1 and 2 show the designs of Mask-B and Mask-C, respectively. The central brightest region of the PSF is called the “core”, and the regions near to the core, in which diffracted light is reduced, are called the “Dark Regions (DRs)”. Mask-B is intended to be used with a small inner working angle (IWA). The contrast for this is $10^{-4}$ at an IWA = 1.7 $\lambda/D$, where $\lambda$ is the wavelength and $D$ is the pupil diameter. The mask is useful for direct observation of young Jovian planets very close to the star. With Mask-C a wide-field coronagraphic image is obtained. The contrast for this is $10^{-4.5}$ at 4 $\lambda/D$ and $10^{-7}$ between 12 $\lambda/D$ and 25 $\lambda/D$. This mask is useful for efficiently surveying unknown exoplanets far from the stars they orbit and for observations of diffuse targets such as a circumstellar disks related to planetary formation. These masks have the general advantages of binary pupil masks: (1) They are robust against pointing errors. (2) They can, in principle, make observations over a wide range of wavelengths. These particular masks have a particular important asset: (3) The design makes them applicable to the pupil of the SPICA telescope, which is partially obscured by a secondary mirror and support spiders.

3. EXPERIMENTS AND RESULTS

We developed these new free-standing masks using thin sheets of nickel. The effective area of the masks is contained within an area of 10 mm $\times$ 10 mm. The thicknesses of Mask-B are 5 and 20 $\mu$m and the thickness of Mask-C is 25 $\mu$m.
LABORATORY EXPERIMENTS USING BINARY PUPIL MASKS FOR THE SCI

Figure 4. Left: Mask-B formed of nickel laminate. The effective region is within a 10 mm × 10 mm area. Middle: Observed PSF of Mask-B. Right: Close-up image and observed PSF profile of Mask-B.

Figure 5. Left: The Mask-C formed of nickel laminate. The effective region is within a 10 mm × 10 mm area. Middle: Observed PSF profile of Mask-C. Right: Observed PSF profile of Mask-C. We used a focal plane mask which limited the coverage of the DRs.

In the production of Mask-C, it was difficult to form long accurate structures, but we succeeded in making free-standing masks by modifying the parameters. These masks were made with HOWA SANGYO, CO., LTD and Photo Precision Co., Ltd.

Figure 3 shows the experimental platform (HOCT) used for this work. A coronagraphic optical system was set up on an optical bench in HOCT. A Super luminescent Light Emitting Diode (SLED) with a center wavelength at 650 nm was used as the light source. The core was observed with 0.3 s exposure using neutral density filters with an optical density of 4. The dark region was observed with 200 s exposure.

We obtained the first experimental results with Mask-B and Mask-C, as shown in Figures 4 and 5. These obtained shapes of the PSF cores and DRs are quite consistent with the expectations from theory, as shown in Figures 1 and 2. The contrast obtained with Mask-B was around 4 orders of magnitude. The patterns near the IWA were not seen, because of light scattered from the core. Thus a focal plane mask suitable for the PSF of Mask-B is needed. The contrast obtained with Mask-C was ~ 10^{-5}–10^{-6} over an extended field of view (6–23 λ/D), which is less than the theoretical value. Speckles are the major limiting factor. The results show that the contrast obtained with these masks is significantly better than that obtained using non-coronagraphic optics. In order to improve the contrast by PSF subtraction, it is beneficial to have a highly stable environment. For this purpose, we have completed the fabrication of a super-invar optical bench for HOCT.

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Laboratory Experiments of an Infrared Detector and Metal Mirrors for the SCI Development

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ABSTRACT

We present our recent activities on laboratory experiments of an infrared detector and metal mirrors for the SPICA/SCI. We plan to adopt a Si:As detector array for the SCI to cover the wavelength region from 4 to 28 $\mu$m. We have evaluated a bias dependence of the cutoff wavelength of the Si:As detector. Our results suggest a possible extension of the cutoff wavelength through efficient increase in the sensitivity at longer wavelengths. We have also measured the wavelength dependence of reflectance on the detector surface to verify that the detector receives the light of wavelengths longer than the designed cutoff wavelength. We also fabricated prototype metal mirrors and evaluated their surface roughness and surface figure errors. The roughness satisfies the SCI requirement, while the figure errors do not. We have identified a problem in each of the fabrication and evaluation processes, which will lead to the improvements of the surface figure errors and the measurement accuracies.

1. INTRODUCTION

The SCI (SPICA Coronagraph Instrument) is one of the focal-plane instruments proposed for SPICA. At wavelengths from 4 to 28 $\mu$m, the SCI will observe objects close to bright sources such as exoplanetary systems, debris disks and galactic nuclei (Enya et al. 2011). To achieve the coronagraphic capability of the wide wavelength coverage, a Si:As array detector and high-accuracy optics are needed. We report our recent activities on laboratory experiments of the detector and metal mirrors.

2. LABORATORY TESTS OF A SI:AS INFRARED DETECTOR FOR DEVELOPMENT OF THE SCI

The extension of the cutoff wavelength of a Si:As detector beyond $\sim$28 $\mu$m is desirable, because molecular hydrogen gas emits the pure rotational fundamental line at a wavelength of $\sim$28 $\mu$m. Therefore, we have investigated the bias dependence of the cutoff wavelength. We have also measured the reflectance on the detector surface. For these investigations we utilized a Si:As detector, a backup detector for the AKARI/IRC (Wada et al. 2008).

We have evaluated the photo-response of the Si:As detector with two broadband filters. Figure 1 Left shows the spectral transmission curves of the filters. For both filter bands, the relative photo-response increases with bias voltages. This increase is larger for filter1 than for filter2. The result suggests an elongation of the cutoff wavelength of the detector sensitivity with higher bias voltage (Mori et al. 2012).

![Figure 1](image1.png)

Figure 1. Left: Transmission curves of filters 1 and 2. Right: Bias dependence of the relative photo-response of the detector with filters 1 and 2. The responses at a bias voltage 0.6 V are normalized to a unity.
We have measured the reflectance of the detector surface using a Fourier transform infrared spectrometer (FT-IR). The Si:As array detector is installed in the optical path of the FT-IR (Figure 2 Left) and the gold-coated mirror is used as a reference. We find that the surface reflectance of the detector is less than 20% for a wavelength range of 2–40 \( \mu \text{m} \) at a room temperature (Figure 2 Right). Thus we confirm that the detector receives infrared light at wavelengths longer than the designed cutoff wavelength of the Si:As detector.

3. FABRICATION AND EVALUATION OF METAL MIRRORS

To achieve high coronagraphic performance, the SCI requires high precision optics. To minimize thermal deformation of optical elements and misalignment of the optics at cryogenic temperatures, all the mirrors and support structures are made of aluminum alloy, the same material with the whole structure of the SCI assembly. The fabrication of the mirrors needs ultra-precision machining to meet the SCI requirements.

We fabricated four prototypes of aluminum alloy mirrors with different parameters of the machining. Two mirrors are flat and the two others are off-axis paraboloidal. The aperture sizes of the flat mirrors and the off-axis paraboloidal mirrors are 20 mm and 50 mm, respectively. Figure 3 shows photos of our sample mirrors. Table 1 summarizes the machining parameters. We have evaluated the surface figure errors and the surface roughness of the sample mirrors by a Fizeau interferometer. A He-Ne laser is used as a light source. For the measured surface figure errors of the mirrors, we calculated the power spectral densities (PSDs), which are plotted in Figure 4.

From the measurement of all the mirrors, we find that the surface roughness is <10 nm (RMS) which satisfies the SCI requirement. However, the surface figure errors do not satisfy the requirements as can be seen in Figure 4; we find that the surface figure errors are dominated by low-frequency components, which is probably attributed to thermal deformation of the machining table. For the off-axis paraboloidal mirrors, the measurement of the surface figure errors is likely to be affected by misalignment of the optics during tests. In order to mitigate the deformation of the machining table, we will control the temperature of the table more precisely. In order to improve the optical alignment, we prepare the Shack-Hartmann sensor optics, which is used simultaneously in measuring the mirrors by the Fizeau interferometer.

Table 1. Machining parameters for mirror fabrication.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>A1</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror type</td>
<td>flat</td>
<td>paraboloidal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Num. of screw holes for fixation</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Table rotation speed [rpm]</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>900</td>
</tr>
<tr>
<td>Radius of bite edge [mm]</td>
<td>0.4</td>
<td>0.4</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Feed per revolution [( \mu \text{m/rev} )]</td>
<td>5.0</td>
<td>3.0</td>
<td>4.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>
4. SUMMARY

We have evaluated a bias dependence of the cutoff wavelength of the Si:As detector. Our results suggest an elongation of the cutoff wavelength of the detector sensitivity with higher bias voltage. The surface reflectance of the detector is measured to be lower than 20% at 2–40 \( \mu \)m. Thus we confirm that the detector receives infrared light at wavelengths longer than 28 \( \mu \)m. We have also fabricated and evaluated the prototype metal mirrors for the SCI. The surface roughness of <10 nm (RMS) satisfies the SCI requirement, while the surface figure errors do not. As for the latter, we have two issues to be addressed; one is temperature control during the machining, and the other is optical alignment during the measurement.

REFERENCES

Key Science Drivers for MICHI: A MIR Instrument Concept for the TMT

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3Faculty of Science, Ibaraki University, Japan

ABSTRACT

We discuss the key science drivers for a mid-IR instrument for the 30 m TMT, taking advantage of the spatial and spectral resolution afforded by the large aperture of the TMT.

1. INTRODUCTION

The Thirty Meter Telescope (TMT) is a next-generation ground-based telescope with a 30 m aperture constructed from 492 mirror segments. The chosen site is Mauna Kea, offering exceptional infrared (IR) qualities and enabling synergy with the many observatories operational at that location. The TMT will enable a revolution in light-gathering power and very sensitive diffraction-limited spatial resolutions with suitable adaptive optics (AO) systems. In the mid-infrared (MIR, 7.5–26 µm) region, the TMT will afford ~15 times higher sensitivity than ground-based 8 m class telescopes and a spatial resolution of ~55 milli-arcseconds (mas) at 8 m with a MIR AO system. Both SPICA and the James Webb Space Telescope (JWST) will feature outstanding sensitivity, but at a spatial resolution >4.6 times inferior to the TMT. Where broadband sensitivity is critical, SPICA and/or JWST will be clearly the instruments of choice, but where spatial resolution is key, a MIR instrument on the TMT will be crucial. In the Spitzer and 8 m era, we have already witnessed the synergy of those observatories at MIR wavelengths, where Spitzer’s sensitivity is used in tandem with 8 m spatial resolution.

Additional to high spatial resolution, the TMT’s huge light gathering capacity opens a new window of very high-dispersion \((R\sim10^3)\) spectroscopy, which has thus far rarely been used at MIR wavelengths. The 10 µm optimized high spectral resolution instrument TEXES \((R\sim10^5)\) has been used for three science campaigns on Gemini, producing results as varied as a spatially resolved study of Neptune stratospheric heating and cooling (Greathouse et al. 2011), demonstrating a new technique for establishing the effective temperature in low mass dwarf stars (Viti et al. 2008), and spectrally resolved C_2H_2 absorption toward the nucleus of a ULIRG (Lahuis et al. 2007). The bulk of the TEXES/Gemini work deals with star formation regions: disc gas emission (e.g. Najita et al. 2009), molecular absorption from gas along the line of sight (Knez et al. 2009), and tracing dynamics of ionized gas near embedded, massive star forming regions (Lacy et al. 2007). TEXES was offered on Gemini in 2013B, and was oversubscribed by ~3. These papers tantalizingly demonstrate the promise of such high spectral resolution combined with high spatial resolution, which will be greatly enhanced on a 30 m-class telescope.

Recently, we, a collaborating group of MIR astronomers based predominantly in the USA and Japan have further studied MIR science drivers in varied astronomical fields. We find that a MIR capability on the TMT is essential to make progress in several fields, and especially those of disc and planet formation/evolution, solar system objects, lifecycle of materials in the universe, extragalactic super massive black holes, star formation and activity in galaxies, and cosmology (Okamoto et al. 2010). Based on these studies, we modified the design of MIRES (Elias et al. 2006), a planned MIR instrument for the first decade of TMT operation to address these science cases. We call this instrument MICHI, the MIR Camera, High-dispersion spectrometer, and IFU, where a feasibility level design is described by Tokunaga et al. (2010).

2. MICHI SCIENCE CASES

We investigated the (a) transformative and (b) broad science cases enabled through MIR on the TMT. Science requirements were flowed to instrument requirements, later addressed by our feasibility-level design. Below we highlight MICHI transformative science ‘threads’ in the areas of disc and planetary formation/evolution, exoplanet, and extragalactic astronomy. Additional cases of lifecycle of materials and formation/evolution of dust grains are omitted for space reasons. The science is leveraged from the huge increases in spatial resolution and light gathering capacity pushing ground-based MIR astronomy past a tipping point in target numbers, leading to order(s) of magnitude increase in available targets.

2.1. High Spectral Resolution Science Drivers

TMT will advance MIR high-resolution spectroscopic studies from the current level, where most studies concentrate on the brightest 5–10 objects of a given class, to where a comparative study of ~100 objects with good signal-to-noise ratio (SNR) is entirely practical. This arises from the raw sensitivity gain that scales as \(D^2\) and the improvement in the time to reach a given SNR for an object that scales as \(D^4\). For example, a typical solar mass T Tauri star can be studied in a
volume that extends past Orion as opposed to only reaching Taurus with 8 m telescopes — this permits study of cluster star formation, not just formation in small aggregates. With the TMT, objects ~3 magnitudes fainter become accessible; 8 m surveys requiring 10 hours of integration time per target will require 3 minutes to reach the same SNR.

The larger aperture, when coupled with a high-Strehl AO system, translates into a radically improved spatial resolution and smaller enclosed energy radius. With the TMT, the 10 $\mu$m spatial resolution of 70 mas corresponds to ~10 AU at 140 pc, the distance of nearby star forming regions. With the high SNR enabled by TMT, spectroastrometry becomes feasible for atomic, ionic, and molecular features from disk gas. Spectroastrometry of 4.7 $\mu$m CO lines with the VLT has provided sub-mas precision (Pontoppidan et al. 2011). Scaling by the aperture of TMT, this suggests spectroastrometry could provide information down to ~0.03 AU in nearby star forming regions close to the star where dust evaporates. MIR high spectral resolution has many significant benefits, including:

- Providing access to the line profile which enables the study of dynamics.
- Maximal sensitivity to intrinsically narrow features, such as those in quiescent gas.
- Separation of neighboring features enables study of weak features close to strong ones, and enables study of scientifically interesting features lying close to obscuring lines from Earth’s atmosphere; with high-resolution and a good site, such as Mauna Kea, Earth’s orbital velocity often Doppler shifts telluric lines off of the desired target lines.

### 2.2. Discs and Exoplanet Science Drivers

Exoplanets observations have rapidly advanced, revealing surprisingly diverse exoplanetary systems. Observations of planet forming regions, protoplanetary and debris discs, have revealed astonishing pictures of planet forming discs such as spirals, gaps, holes, and dips, strongly implying that planets are forming there. Dust evolution, the key ingredient of planets, through grain growth and crystallization, has been observed. An ideal wavelength to characterize dust and planets is the MIR, because it has many key spectral features. However, such studies are limited from 8 m class observatories by the combination of limited (a) spatial resolution and (b) sensitivity. Both limitations will be greatly reduced by observations from the TMT. Thus studies of discs and exoplanets are promising science drivers for TMT/MICHI.

### 2.3. Extragalactic Science Drivers

A full understanding of the relationship between the SMBH and host galaxy, as well as any activity, will help to address two crucial questions in cosmology: (1) which formed first, the SMBH or the galaxy, and (2) how did SMBHs form so shortly after the big bang?

### THE AGN TORUS

AGN are largely explained in the context of a unified theory, by which a geometrically and optically thick torus of gas and dust can obscure the AGN central engine from some lines of sight. The exact properties of the torus remain uncertain, and there are still several open questions: (a) What is the nature of the torus material and its connection with the ISM of the host galaxy, (b) How do the properties, such as, geometry and optical depth, of the torus depend on the AGN luminosity and/or activity class, (c) Do the dust properties change with the AGN luminosity/type, (d) What is the role of nuclear ($\leq 100$ pc) starbursts in feeding and/or obscuring AGNs, and (e) How is the fueling of AGN achieved? Observations at MIR wavelengths are essential to these investigations as the torus intercepts and re-radiates a substantial amount of flux from the central engine, peaking in the MIR, and the level of contamination from stellar emission is greatly reduced compared to optical/near-IR observations.

The torus is compact (few pc) in moderate activity AGN (i.e. Packham et al. 2005; Mason et al. 2006), and perhaps absent in low activity AGN. The torus structure was revealed to be best described by a ‘clumpy’ distribution of gas (Nenkova et al. 2002), rather than a homogeneous distribution of dust. Tentative new results seem to show the precise torus structure and perhaps presence is strongly affected by the level of activity in the AGN, which in turn is related to the fueling of the central engine. A systematic survey of AGN tori is in progress using 8 m class telescopes (Alonso-Herrero & Packham 2013), but this is confined to the local universe due to the combination of (a) flux and (b) spatial resolution limitations. Through the ~3.75 times increase in the diffraction limit (and at a much higher Strehl ratio when using a MIR AO system on the TMT, as compared to the tip/tilt correction often used on existing 8 m class observatories), observations of fainter and/or more distant objects can be performed. At $z=0.5$, the spatial resolution of JWST/MIRI is 1.5 kpc and is hence heavily contaminated by galactic star forming rings, etc., whereas the TMT spatial resolution is 330 pc and is nuclear dominated. Through careful imaging and spectral observations of the torus in $z\leq 0.5$ objects, templates can be produced that will be of crucial importance to calibrating and interpreting observations from JWST and SPICA. Only through combined results will an accurate examination of the torus properties, effect of radio loudness, and the host galaxy versus both the level of AGN activity and redshift be probed. Further, the WISE all-sky survey will use colors of the sources to search for and characterize type 2 QSOs, for which MICHI will be ideal to perform the detailed follow-up examinations, with the aim of modeling and parameterizing the torus of these objects, allowing a thorough comparison to other AGN classes.
KEY SCIENCE DRIVERS FOR MICHI

REFERENCES

Alonso-Herrero, A., & Packham, C. 2013, RMxAC, 42, 41
AKARI's Legacy to SPICA

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1Institute of Space and Astronautical Science (ISAS), JAXA, Japan

ABSTRACT

AKARI is the first Japanese satellite mission dedicated to the infrared astronomy. AKARI was launched in February 2006 and carried out an all-sky survey as well as twenty thousands of pointed observations from near- to far-IR wavelengths over four-years mission. AKARI operation was terminated in November, 2011. The All-Sky far- and mid-IR Point Source Catalogues, Asteroid catalogue, as well as point source catalogues from the Large Magellanic Cloud and the North Ecliptic Pole region have been published. Science targets of AKARI range from the solar system objects to cosmology. Science highlights from the AKARI data are briefly summarized. The AKARI project has been reconfigured in April 2013 to focus on data reduction and archiving. Revision of far-IR All-Sky Survey point source catalogue, mid- and far-IR faint source catalogues, All-Sky image maps are planned to be produced. Imaging and spectroscopic data taken in the pointed observation mode will also be archived as “science-ready” data products AKARI data and our experience through the mission are a legacy to promote the SPICA mission.

1. THE AKARI MISSION

The first Japanese infrared astronomical satellite AKARI (Murakami et al. 2007) was launched on February 22, 2006 (JST) by the 8th M-V rocket from the Uchinoura Space Center. AKARI was equipped with a 68.5 cm telescope cooled down to the cryogenic temperature (below 7 K) and two scientific instruments, the Far-Infrared Surveyor (FIS; Kawada et al. 2007) and the Infrared Camera (IRC; Onaka et al. 2007). The FIS covered the wavelength range between 50–180 μm by two broad and two narrow bands. The Fourier Transform Spectrometer (FTS) enabled us to carry out imaging-spectroscopic observations in the same wavelength range. The IRC observed with three cameras, namely the NIR (1.8–5.3 μm), the MIR-S (5.4–13.1 μm) and the MIR-L (12.4–26.5 μm). Each camera had three filter bands and grism/prism for low-resolution spectroscopy.

Observations were carried out in two attitude control modes; the survey mode and the pointing mode. The former was used for the All-Sky Survey. The FIS and IRC MIR-S&L were operated and scanned the sky with a speed of ~3.6 arcmin/sec. The pointing mode was used for deep imaging and spectroscopic observations of particular targets. A pointing enabled about 12 minute exposure with a cost of total 30 minutes including maneuver etc.

The scientific operation officially started on May 7, 2006. The first half year was defined as Phase 1, which was dedicated to the All-Sky Survey and only a small number of pointed observations were carried out in the high-visibility (i.e., high ecliptic latitude) regions. In Phase 2, started from November 2006, supplemental observations to complete the All-Sky Survey and thousands of pointed observations were carried out. It lasted until the liquid helium boiled off on August 26, 2007. Phase 3 started in June 2008 with only the NIR channel of the IRC, cooled with the cryocoolers. Thirteen thousands imaging and spectroscopic observations were carried out until February 2010, when the scientific observations were suspended due to the degradation of the cryocoolers.

The AKARI observations were classified into several categories. The Large Area Survey (LS) included the All-Sky Survey, the Large Magellanic Cloud (LMC) Survey, and the North-Ecliptic Pole (NEP) Survey. They were conducted under responsibility of the project team. The latter two surveys were carried out in the pointing mode. Mission Programmes (MP) were proposed by the working groups consisted of the project team members. Relatively large number of pointing opportunities were allocated per programme, and the programmes were designed to produce comprehensive data-set to be the legacy to the future researches. About 30 per cent of the total number of pointed observations were opened to the astronomical communities in Japan-Korea, and the ESA supported countries. Beside them about 7 per cent of the orbits were allocated to calibration and director’s discretionary time (DDT).

2. AKARI DATA PROCESSING AND ARCHIVING ACTIVITY

A huge amount of data taken by the AKARI is a legacy to the future astronomical researches and must be archived so that world-wide astronomical communities can easily access the data. Table 1 summarizes the data products so far released to the public.

The first products from the AKARI All-Sky Survey were the point source catalogues. The IRC Point Source Catalogue ver.1 (Ishihara et al. 2010) and the FIS Bright Source Catalogue ver.1 (Yamamura et al. 2010) were released in March 2010. Because of large differences in spatial resolution and wavelength coverage, two catalogues were provided in two separate files. The IRC catalogue contains 870,973 sources, and the FIS catalogue nominates 427,071 objects. Interestingly, we find...
Table 1. Published AKARI Processed Data Products

<table>
<thead>
<tr>
<th>Product Name</th>
<th># of Sources</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIS Bright Source Catalogue Ver. 1</td>
<td>427,071</td>
<td>Mar. 2010</td>
</tr>
<tr>
<td>IRC Point Source Catalogue Ver. 1</td>
<td>870,973</td>
<td>Mar. 2010</td>
</tr>
<tr>
<td>Asteroid Catalogue Ver. 1</td>
<td>5,120</td>
<td>Oct. 2011</td>
</tr>
<tr>
<td>LMC Point Source Catalogue Ver. 1</td>
<td>660,286</td>
<td>Nov. 2012</td>
</tr>
<tr>
<td>LMC Near-IR Spectral Catalogue Ver. 1</td>
<td>1,757</td>
<td>Jan. 2013</td>
</tr>
<tr>
<td>NEP-Wide Field Point Source Catalogue Ver. 1</td>
<td>114,793</td>
<td>Mar. 2013</td>
</tr>
<tr>
<td>NEP-Deep Field Point Source Catalogue Ver. 1</td>
<td>27,770</td>
<td>Oct. 2013</td>
</tr>
<tr>
<td>NEP-Deep Field Point Source Catalogue Ver. 2</td>
<td>7,284</td>
<td>Mar. 2013</td>
</tr>
</tbody>
</table>

Table 1. Published AKARI Processed Data Products

the fact that only 20,000–30,000 sources (depending on search radius) matches between two catalogues within positional errors. This emphasizes the difference in population in the catalogues. The catalogues have been and will be broadly used in many astronomical researches.

Usui et al. (2011) searched for signals from the asteroids in the mid-IR All-Sky Survey data by matching the scanned timestamps and positions with those predicted from the orbital elements. They succeeded to identify 5120 asteroids and catalogued their size and albedo calculated from the AKARI fluxes using standard thermal model of the asteroids. The catalogue is the most complete one among those has been publically used, and enables us to make more precise statistical study of the asteroids.

Catalogues from other two Large Area Surveys have also been published. The North Ecliptic Pole region survey resulted in the point source catalogues (Takagi et al. 2012; Kim et al. 2013; Murata et al. 2013). The catalogues are extensively used for the extragalactic science, for instance studies of the galaxy evolution (see Goto et al, this volume). Thanks to the continuous wavelength coverage of the AKARI/IRC filters precise SED analysis becomes possible.

Two products have been published from the Large Magellanic Cloud (LMC) survey. The AKARI-LMC point source catalogue (Kato et al. 2012) nominates 660 thousands of point sources detected in the near- and mid-IR. They are commonly observed by the Spitzer-SAGE survey (Meixner et al. 2006). Shimonishi et al. (2013) published near-IR spectra of 1757 sources observed in the LMC survey. These catalogues shall be useful for classification of the objects as well as the gas and solid state features of the young and evolved stars.

In addition to the data listed in Table 1, raw data of the pointed observations except for special observing modes are distributed from the ISAS data archive, DARTS1 so that users can reduce the data with the provided toolkits. Interested users are welcome to visit the AKARI user support web page. 2

Following the termination of the satellite operation, the AKARI project team was reconfigured in April 2013. The new team is dedicated to the data processing and archiving. The activity will continue in the next five years; the first three years for the data processing and construction of “science-ready” datasets, and the following two years for completion of data archiving and maintenance of the products. Table 2 describes the products we plan to provide. The products are prioritized by their potential impact to the researches and technical difficulties. See also Makiuti et al. and Kondo et al. (in this volume).

3. SCIENCE HIGHLIGHTS

In this section we introduce selected science highlights from the AKARI observations. They are only a part of the many important AKARI results. We draw your attention to the articles by Kaneda et al., Yano et al., Shirahata et al., Pollo et al., Malek et al., and Murata et al. in this volume.

3.1. Cosmic Star Formation History

Goto et al. (2010, see also Goto et al., this volume) measured infrared luminosity of the galaxies with the AKARRI All-Sky Catalogues and the North Ecliptic Pole (NEP) survey catalogue, and presented the star formation history from $z = 0$ to 2.2. Thanks to the continuous wavelength coverage the accuracy of the luminosity estimate is much better than the previous works. They found that star formation rate increases toward the past, and that the contribution of (Ultra) Luminous Infrared Galaxies (LIRGs and ULIRGs) increases more prominently.

1 http://darts.isas.jaxa.jp/ir/akari/
2 http://www.ir.isas.jaxa.jp/AKARI/Observation/
AKARI’s Legacy to SPICA

Table 2. Planned AKARI Processed Data Products

<table>
<thead>
<tr>
<th>Product name</th>
<th>Description</th>
<th>Priority</th>
<th>Public Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIS Bright Source Catalogue Ver.2</td>
<td>Revision of the FIS BSC. Accuracy and reliability will be improved. Single-scan photometric database and scan density data will also be available.</td>
<td>1</td>
<td>Mar. 2015</td>
</tr>
<tr>
<td>FIS Faint Source Catalogue Ver.1</td>
<td>The catalogue improves detection limit in the high-visibility regions.</td>
<td>1</td>
<td>June 2015</td>
</tr>
<tr>
<td>FIS All-SKY image maps</td>
<td>All-Sky image maps in the four FIS bands (65, 90, 140, 160 ( \mu \text{m} ))</td>
<td>2</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>IRC Faint Source Catalogue</td>
<td>The catalogue improves detection limit in the high-visibility regions.</td>
<td>1</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>IRC All-SKY Image Maps</td>
<td>All-Sky image maps in the two IRC bands (9 &amp; 18 ( \mu \text{m} ))</td>
<td>2</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>Asteroid Catalogue ver.2</td>
<td>Additional 1000 asteroids supplemental to the Ver.1 are expected.</td>
<td>5</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>FIS Slow-scan Atlas</td>
<td>Processed image data of individual FIS Slow-scan mapping observations.</td>
<td>4</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>FIS FTS data</td>
<td>Processed imaging-spectroscopic dataset observed with the Fourier Transform Spectrometer (FTS) of the FIS.</td>
<td>5</td>
<td>Sep. 2015</td>
</tr>
<tr>
<td>IRC Pointed Observation Images</td>
<td>Processed imaging (photometric) observation data of the IRC. Individual observation data will be processed separately. No mosaicing will be applied.</td>
<td>4</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>FIS Slow-scan Atlas</td>
<td>Processed image data of individual FIS Slow-scan mapping observations.</td>
<td>4</td>
<td>Sep. 2015</td>
</tr>
<tr>
<td>IRC Slit spectroscopy Data</td>
<td>Spectra taken with the IRC spectroscopic mode with slit (and point source aperture mask).</td>
<td>4</td>
<td>Mar. 2016</td>
</tr>
<tr>
<td>IRC Slitless spectroscopy Data</td>
<td>Spectra taken with the IRC spectroscopic mode on the imaging field with the objective grism/prism.</td>
<td>5</td>
<td>Mar. 2016</td>
</tr>
</tbody>
</table>

3.2. Cosmic Infrared Background

Matsumoto et al. (2011) analysed the near-IR imaging data of AKARI’s most frequently observed area (in the NEP survey region). They added-up the available data to produce the best sensitivity and quality image, then remove the all known point sources and smoothed the remaining “background” light. The images at 2, 3, and 4 \( \mu \text{m} \) data show similar structures, which the authors argued the light from the first generation stars. Matsuura et al. (2011) measured the absolute sky brightness at the far-IR wavelengths, and found that the background radiation at these wavelengths is twice as bright as the theoretically predicted values. The source of this excess is not yet known, but they argue possibilities such as radiation from black-holes in the early universe. Future follow-up observations with SPICA will tell us hints to further understanding of this problem.

3.3. Dust Shell around Evolved Stars

Izumiura et al. (2011) reported the results of far-IR mapping of dust shell around an red-giant star U Hydræa. Model analysis indicated that the star experienced a short-period, extreme mass loss (ejected dust mass was of the order of 10^{-5} \( \text{M}_\odot \)) in the past. Ueta et al. (2008) detected a bow-shock around Betelgeuse (\( \alpha \) Ori), which was formed by interaction between stellar mass-loss wind and interstellar matter. The stream of the interstellar matter was measured from the analysis of the bow-shock shape, which was a new tool to investigate how the matter ejected from stars mix in the interstellar media. More than 100 stars were observed in the same programme and wait for detailed analysis (Tomasino et al., this volume).
3.4. Debris Disks

High sensitivity AKARI All-Sky catalogues enable us to search for stars with debris disks. Fujiwara et al. (2013) surveyed stars with infrared excess at AKARI 18 µm band using the IRC Point Source Catalogue and found 24 such stars in which 8 are newly detected by AKARI. These mid-IR excess stars have warm dust located in a terrestrial planet region, i.e., they may have information of terrestrial planet formation. Fujiwara et al. (2012a,b) found that HD 15407A possesses extremely large amount of µm-size silica dust, which requires unidentified mechanism of dust trapping or continuous dust production. See also Fujiwara et al. and Onaka et al. (this volume).

3.5. Brown Dwarfs

One of the AKARI’s unique capability is the high-sensitivity spectroscopy in the near-IR region (2–5 µm). For the first time we could take spectra of brown dwarfs continuously covering 2.5–5 µm where ro-vibrational transitions of major molecules such as CO, H$_2$O, CH$_4$, and CO$_2$ present. Series of papers (Yamamura et al. 2010; Tsuji et al. 2011; Sorahana & Yamamura 2012; Sorahana et al. 2013) reported that: (1) detection of CO$_2$ and possible variation of C & O abundance in the brown dwarfs, (2) CO abundance enhancement in the coolest dwarfs, and (3) variation of radius along the brown dwarf evolution. See also Sorahana (this volume).

4. SUMMARY

AKARI has completed the 2nd generation All-Sky Survey in mid- and far-IR wavelength and produced the All-Sky Point Source Catalogues containing in total 1.3 million sources. The most of the sources in the catalogue have not ever been investigated in detail, and can possibly be critical objects that will open a new door of the astronomical research. Image maps and pointed observation data are also waiting for follow-up by the future facilities, such as SPICA. In addition, our experiences in the instruments and spacecraft development as well as operation through the AKARI mission will be a valuable treasure for making the SPICA project as successful as possible.

AKARI is a JAXA project with the participation of ESA.

REFERENCES

Usui, F., Kuroda, D., Müller, T. G., et al. 2011, PASJ, 63, 1117
AKARI All-Sky Point Source Catalogues — Characteristics, Improvements, and Prospects —

Sin’itirou Makiuti,1 Issei Yamamura,1 Tatsuya Koga,1 Daisuke Ishihara,2 and AKARI team

1Institute of Space and Astronautical Science, JAXA, Japan
2Graduate School of Science, Nagoya University, Japan

ABSTRACT

AKARI carried out an all-sky survey with two onboard instruments; the Infrared Camera (IRC) and the Far-Infrared Surveyor (FIS). The first version of the catalogues, the FIS Bright Source Catalogue (FIS-BSC) and the IRC Point Source Catalogue (IRC-PSC) were released publicly in March 2010. The AKARI All-Sky catalogues are superior to the previous all-sky infrared catalogues by IRAS significantly in spatial resolution, sensitivity, and wavelength coverage. We present the specifications of the AKARI catalogues and their characteristics by comparing with other infrared source catalogues. We continue efforts to improve the AKARI catalogues in reliability and completeness as well as accuracy of flux and position measurements. FIS Faint Source Catalogue, which provides fainter sources than the BSC at the high-visibility regions, is also planned to be produced. We report the current status of improvement works and prospects for the future.

1. THE AKARI SATELLITE: MISSION AND OBSERVATIONS

AKARI (ASTRO-F) is the second Japanese space mission for infrared astronomy with the participation of ESA (Murakami et al. 2007). AKARI satellite was launched by a M-V rocket on February 22, 2006 (JST). The satellite has a 68.5 cm telescope cooled down to 6 K by liquid helium and mechanical coolers, and two scientific instruments, namely the Infrared Camera (IRC; 1.8–26.5 μm; Onaka et al. 2007) and the Far-Infrared Surveyor (FIS; 50–180 μm; Kawada et al. 2007). AKARI had two observational modes; pointed observations and all-sky survey. One of the key objectives of the AKARI mission is to carry out an all-sky survey in the mid- and far-infrared wavelengths. IRAS (Infrared Astronomical Satellite, launched in 1983 by USA, UK, and the Netherlands; Neugebauer et al. 1984) carried out the first all-sky survey at four infrared wavelengths and provided catalogs of infrared sources. The AKARI All-Sky Survey is expected to surpass the IRAS survey with the higher spatial resolution, better sensitivity, and broader wavelength coverage. During the 16-months operation period with the liquid helium, AKARI scanned more than 96 per cent of the entire sky.

2. THE AKARI ALL-SKY POINT SOURCE CATALOGUES

The first version of the AKARI All-Sky point source catalogues have been in public since March 2010 and been widely used in the various fields of astronomy and astrophysics.

Figure 1 shows an all-sky distribution of the point sources in the catalogues. The IRC Point Source Catalogue (IRC-PSC) version 1 provides positions and fluxes for 870,973 sources measured at mid-infrared wavelengths centered at 9 and 18 μm (Ishihara et al. 2010). The detection limit for point sources are 50 mJy for the 9 μm and 130 mJy for the 18 μm band, respectively. The FIS Bright Source Catalogue (FIS-BSC) version 1 contains data of 427,071 sources measured at four far-infrared wavelength bands centered at 65, 90, 140, and 160 μm (Yamamura et al. 2011).

Specification of the catalogues is summarized in Table 1. FITS and text format catalogue data file and the release note can be downloaded from the AKARI site1. They are also available from AKARI Catalogue Archive Server (CAS2; Yamauchi et al. 2011) with various data search services including matching with other databases.

3. CATALOGUE CHARACTERISTICS

The AKARI point source catalogues detected much more sources than the IRAS point source catalog in any wavelength bands (Figure 2).

The distribution of the sources is different at different band. In 9 and 18 μm, the extra sources that AKARI newly detected are mostly below the IRAS’s detection limit, while at 90 μm AKARI detected more sources in any flux range. It is explained that higher spatial resolution of AKARI resolves sources in the crowded areas, such as the Galactic plain and molecular clouds. It is also true for nearby galaxies. AKARI extracted more sources from the spiral arms.

Table 2 shows the result of cross-match between IRAS and AKARI catalogues. Almost 90 per cent of the AKARI sources have counterpart in the IRAS catalogue. The matching rate decreases in the high and low flux ranges, due to saturation in the AKARI measurement or non-detection in the IRAS catalog, respectively.

References

1 http://www.ir.isas.jaxa.jp/AKARI/Observation/
2 http://darts.isas.jaxa.jp/astro/akari/
Figure 1. All-Sky distribution of the infrared sources based on the AKARI catalogues. Mid- and Far-infrared objects are shown together in the Galactic coordinates.

Table 1. AKARI All-Sky Point Source Catalogues

<table>
<thead>
<tr>
<th></th>
<th>IRC PSC ver.1</th>
<th>FIS BSC ver.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band [µm]</td>
<td>9, 18</td>
<td>65, 90, 140, 160</td>
</tr>
<tr>
<td>Num. of sources</td>
<td>844,649, 194,551</td>
<td>29,336, 373,819, 117,994, 36,646</td>
</tr>
<tr>
<td>(total)</td>
<td>(870,973)</td>
<td>(427,071)</td>
</tr>
<tr>
<td>Detect. Lim. [mJy]</td>
<td>50, 130</td>
<td>3200, 550, 3800, 7500</td>
</tr>
<tr>
<td>Photo. Accur. [%]</td>
<td>5, ~20</td>
<td>7, ~20, ~20</td>
</tr>
<tr>
<td>Spatial Res. [arcsec]</td>
<td>~7</td>
<td>40, ~70</td>
</tr>
<tr>
<td>Pos. Uncertainty [arcsec]</td>
<td>1, ~3</td>
<td>~6</td>
</tr>
</tbody>
</table>

Figure 2. Comparison of flux number count plot between AKARI and IRAS. AKARI detected fainter source and increased the number of detected sources.

Care should be taken for the flux comparison between AKARI and IRAS. The ratios of the AKARI 90 µm flux to the IRAS 100 µm flux of cross-identified sources seem to be divided into two groups. This pattern is not obvious in the comparison of AKARI 90 µm to the IRAS 60 µm (Figure 3). The IRAS Point Source Catalog contains flags for the information of background radiation. A certain correlation between the background levels and the flux ratios of \( F_{90}/F_{100} \) is found. Interstellar dust emission (cirrus component) is typically peaked around 100 µm, so it contributes to the FIR
**AKARI All-Sky Point Source Catalogues**

Table 2. *AKARI* vs. IRAS; FIR sources number and cross-matched rate.

<table>
<thead>
<tr>
<th>Flux (AKARI90) [Jy]</th>
<th>IRAS(60) Identified</th>
<th>Rate (%)</th>
<th>IRAS(100) Identified</th>
<th>Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 ≤ F &lt; 1</td>
<td>18890</td>
<td>63.9</td>
<td>1315</td>
<td>15.8</td>
</tr>
<tr>
<td>1 ≤ F &lt; 10</td>
<td>9176</td>
<td>87.2</td>
<td>33743</td>
<td>37.5</td>
</tr>
<tr>
<td>10 ≤ F &lt; 100</td>
<td>594</td>
<td>92.1</td>
<td>1278</td>
<td>83.1</td>
</tr>
<tr>
<td>100 ≤ F &lt; 1000</td>
<td>56</td>
<td>44.6</td>
<td>62</td>
<td>61.3</td>
</tr>
<tr>
<td>1000 ≤ F</td>
<td>7</td>
<td>14.3</td>
<td>11</td>
<td>9.1</td>
</tr>
<tr>
<td>Total</td>
<td>28723</td>
<td>71.9</td>
<td>36409</td>
<td>38.3</td>
</tr>
</tbody>
</table>

Figure 3. Flux correlation between *AKARI* 90 µm and IRAS 100 µm.

100 µm band flux significantly, especially near the Galactic plane. Since the beam sizes of the *AKARI* and IRAS detectors are significantly different, it is possible that IRAS grabbed more background radiation together with a point source and caused higher flux. This conspicuous discrepancy between the catalogues is needed to be examined in detail in the future.

4. FUTURE PLAN

As described in detail in Yamamura et al. (this volume), *AKARI* Far-infrared Bright Source Catalogue (BSC) is planned to be updated. Software development and data verification works continue. The revised version is expected to have better completeness, reliability, and accuracy compared to the current version. For this purpose, data reduction processes such as detector responsivity correction and dark subtraction have been re-investigated and applied to the scan data. Also, a problem of the current version, which very bright sources are removed out due to misidentification as cosmic-ray hits, will be fixed. In the source extraction process, optimization of operation parameters will improve the reliability of the detection. More accurate measurements of position and flux measurements will be implemented. Moreover, background information will be considered in the flux measurement.

Faint Source Catalogue (FSC) is also planned to be produced. In the FSC production process, data redundancy is used to improve the detection limit instead of detection reliability by confirmation. Great increase of source numbers has been obtained in the high-visibility regions near the ecliptic poles, in a test processing. Data verification and evaluation work is undergoing.

*AKARI* is a JAXA project with the participation of ESA.

REFERENCES


This document is provided by JAXA.
Makiuti et al.

Yamamura, I., et al. 2011, AKARI/FIS All-Sky Survey Bright Source Catalogue Version 1.0 Release Note
SPICA Conference Summary

THIJS DE GRAAUW

ALMA Observatory, Chile

The objectives of the 2013 SPICA Science Conference were to present to the astronomical community the planned SPICA observatory with its science capabilities and to present and discuss the science cases in order to optimize the future use of this new facility.

The preparation of the SPICA mission has advanced considerably. We were informed that some months ago, following an international review, a final decision was made on the ensemble of the focal plane instruments. The risk mitigation exercise, addressing the most critical components of the mission and satellite resources, was reported to progress well and the project had already received a positive recommendation by the astronomy and astrophysics subcommittee. The moment for final approval by the Science Council of Japan is getting closer.

The organizers summarized the science goals for SPICA into three major categories: a) resolution of the birth and evolution of galaxies, b) “transmigration” and evolution of the ISM, c) thorough understanding of planetary system formation. They asked the conference participants whether a key scientific question was missing that could affect the suit of focal plane instrumentation. In other words, can the current focal plane instrumentation address all the key sciences which should be undertaken with SPICA?

The present SPICA science capabilities are impressive. One of the key features is that the 3.2 m telescope will be operating at 6 K thus providing SPICA a superior sensitivity with respect to Herschel, at an almost equivalent angular resolution. Furthermore, there will be a complete coverage of the mid- and far infrared spectral range, thus continuing the trend set by ISO and Spitzer. The core wavelength range (5 μm–210 μm) is covered by a mid infrared instrument (MCS), including cameras and spectrometers, together with a far-infrared Instrument, the imaging spectrometer SAFARI. These instruments include state-of-the-art detectors and together with the dramatically reduced background from the cooled telescope, the overall sensitivity is estimated to improve by a factor hundred or more as compared to Herschel. It is therefore no surprise that interest in the SPICA mission is coming from all traditional areas in infrared and sub-millimeter astronomy. There were a few studies proposed coming from different fields like high energy astrophysics.

In the presentations the SPICA science goals were amply considered in view of the achievements of the Herschel and Spitzer missions. Not so much attention was given to the latest results from the ground-based sub-millimeter observatories like ALMA, the South Pole Telescope and the future mid-infrared capabilities of the JWST-MIRI mission and the ELT’s.

It was shown that Herschel could only reveal the tip of the iceberg as limitations in sensitivity and mission life time constrained the number of sources that could be investigated. For example, although Herschel excelled in large-scale FIR photometric imaging and revealed the filamentary structure of star-forming clouds, SPICAâĂŹs spectroscopy and sensitivity, allows for each pixel of these maps to determine the physical conditions and chemical composition. One can also investigate large, unbiased samples of individual sources covering pre-stellar cores and proto-stars to planetary disks and exo-planets. Note however, that although Herschel covered only the far-infrared range, it had the capability of a very high spectral resolution observations from 150–600 μm, a feature that is not available in SPICA. In addressing the origin of cosmic infrared background, Herschel with a passively cooled telescope, never reached the 70 μm confusion limit and could not follow up its typical survey detections with spectroscopy. In comparison SAFARI can do full 34–210 μm spectra in 900 hours for 1 deg × 1 deg field down to a noise level of 5 × 10⁻¹⁹ W/m² (5σ) while for Herschel-PACS it would have taken 1800 hrs for the same sensitivity for a 60–210 μm spectrum on a single pointing. With SPICA-SAFARI unique spectroscopic cosmological surveys can be made, with characterization of the infrared sources out to at least z = 3 over wavelength ranges up to 210 μm. Suggestions were made to have the photometry bands extended to 400 μm to have some overlap with the ALMA bands.

The Mid- and Far-IR are the spectral ranges that include fine structure atomic and ionic lines, molecular lines, including hydrides, spectral features of PAHs, ices, silicates and crystalline materials, etc.. The unique capability of these “Great Diagnostic Spectroscopy Tools” for studies of galaxy evolution and the role of the central black hole versus star formation was presented and highlighted in the different sessions dedicated to galaxy formation and evolution. For an overview see amongst others presentations by Luigi Spinoglio, a long time advocate of the unique diagnostic powers of the mid- and far-infrared fine structure lines toolbox, and overviews by Eckhard Sturm, Dieter Lutz, Lee Armus and Tomotsugu Goto, etc. A challenging and interesting example was presented by Phil Appleton who presented Spitzer observations showing a population of galaxies with extreme warm H₂/PAH emission. The H₂ and PAH values may indicate shock or turbulently heated H₂. SPICA-SAFARI Spectral surveys can uncover these rare “extreme H₂” emitters in the 0–0 S(0) and 0–0 S(1) lines of H₂ out to z < 5.

It was shown that these spectroscopic tools are also extremely important for diagnosis of the heating and cooling of the interstellar matter (ISM) and circumstellar matter in the various evolutionary stages of star and planet formation. SPICA will have the required sensitivity to carry out a full spectral characterization of low-mass to high-mass protostars (energetics and chemistry) and of protoplanetary disks (water). Reviews by Javier Goicoechea, Xander Tielen, Csica Kemper, Young-Chol Minh and Hidehiro Kaneda showed where we are in understanding the processes of cycling matter.
between ISM, stars, galaxies and IGM since Herschel and what SPICA, with its superior sensitivity will add. It was in this area where concern was expressed about the low spectral resolution in wavelength range from 4 to 12 µm.

There was considerable interest presented to use SPICA for studies of planet formation and detection of exo-planets, making a strong case for the “optional” SPICA Coronagraph Instrument. A wealth of gasses and solid materials (ices, minerals) are out there for further characterization of planet forming environments, circum-stellar disks and the solar system. Comparisons with other facilities aiming similar studies were made and the strength of the science case for SPICA is depending on the performance of the SCI instrument.

A maverick proposal was put forward by Poshak Gandhi to make high timing resolutions (sub-second) observations of relativistic jets with SPICA. Simultaneous observations in broadband low-resolution mode and with accurate relative and absolute timing calibration capabilities with an X-ray facility, would allow to catch jet formation in a stellar-mass black hole. It is really worthwhile to investigate how far the time resolution can be pushed and one can implement sub-second sampling.

Finally new science cases will appear, coming from JWST, ALMA or other facilities. During the conference it was reported that ESO’s Very Large Telescope Interferometer had gathered the most detailed observations ever of the dust around the huge black hole at the centre of an active galaxy. Rather than finding all of the glowing dust in a doughnut-shaped torus around the black hole as expected it appeared that much of the dust is located above and below the torus. These observations show that dust is being pushed away from the black hole.

A space observatory like SPICA is crucial to carry out the necessary characterization!
Notes

Among the papers submitted to the conference, five papers were devoted to presenting the status of the SPICA project or its instrumentation at the time of the conference in 2013. However, the mission configuration and the international collaboration framework were revisited and changed significantly in the years after the conference. At the time of publication of the proceedings, SPICA is being proposed as an ESA-led, M-class mission in the ESA Cosmic Vision program with a significant contribution from JAXA. Since contents of the mission and the instrument papers are very much outdated and inapplicable to SPICA as we currently envisage, we decided not to include these papers for now and we are looking for an alternative to publish them.

Editors