Observing 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; $L_{\rm IR} > 10^{11}\,{\rm L}_{\odot}$). *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 II], [Ne V], [Ne III], [S III] 18.7 μm, [O IV], [Fe II], [S III] 33.5 μm, 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 μm 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 μm PAH EQW $\leq$ 0.3 μm *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).

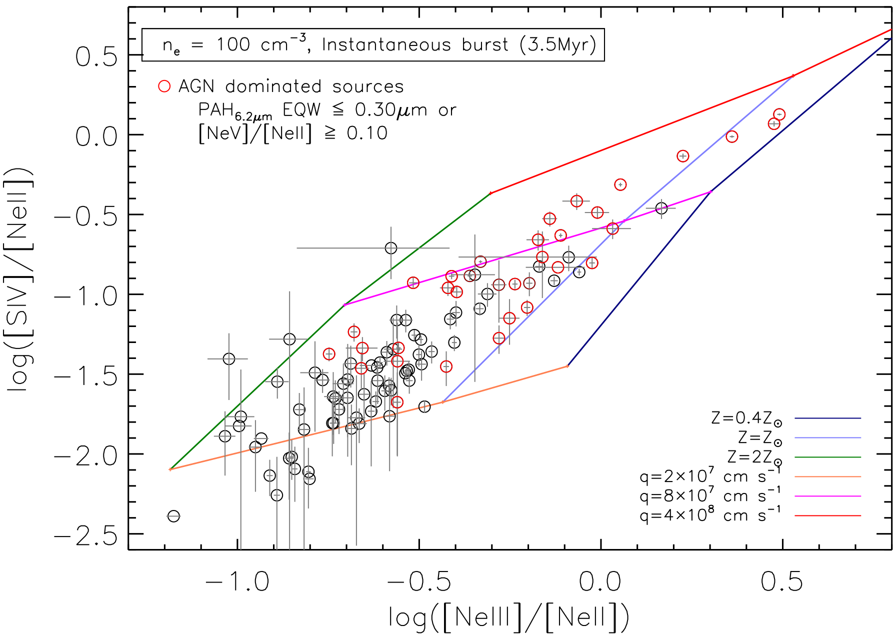

Figure 1. [S IV]/[Ne II] vs. [Ne III]/[Ne II] line flux ratio plots for the GOALS sample compared with the instantaneous starburst models at a starburst age of 3.5 Myr (Inami et al. 2013). The models assume an electron density of $n_e = 10^2\,\mathrm{cm}^{-3}$. The other model parameters shown in the figure are metallicity (dark blue: $Z = 0.4Z_\odot$, *light blue*: $Z = Z_\odot$, *green*: $Z = 2Z_\odot$) and ionization parameter (*orange*: $q = 2 \times 10^7\,\mathrm{cm\,s}^{-1}$, *magenta*: $q = 8 \times 10^7\,\mathrm{cm\,s}^{-1}$, *red*: $q = 4 \times 10^8\,\mathrm{cm\,s}^{-1}$). The red circles represent the AGN dominated sources with 6.2 μm PAH EQW $\leq 0.3\,\mu$m or [Ne V]/[Ne II] ≥ 0.1.

The [S III] 33.5 μm/[S III] 18.7μm 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 $\sim 300\,\mathrm{cm}^{-3}$, 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 $100\,\mathrm{cm}^{-3}$, 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×$10^7\,\mathrm{cm\,s}^{-1}$ and metallicities between 1–2 $Z_\odot$.

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 $\mathrm{km\,s}^{-1}$ and magnetic field strengths of 1–100 μG. Five of them also show resolved neon emission line profiles (FWHM $\geq 600\,\mathrm{km\,s}^{-1}$). 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 $\gtrsim 100\,\mathrm{km\,s}^{-1}$. One of its high sensitivity detectors, MCS, will facilitate detections of [Ne II] in ULIRGs ($\log(L_{\mathrm{IR}}/\mathrm{L}_\odot) > 12$) 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

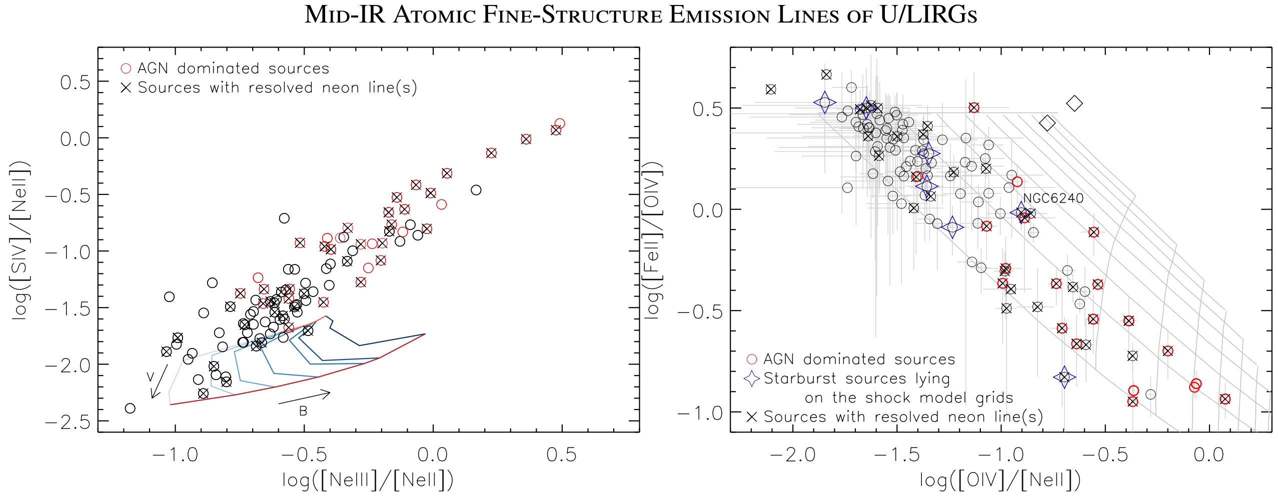

Figure 2. *Left:* The same line ratio diagram as Figure 1, but with the shock model grids (Allen et al. 2008) superposed. The AGN dominated sources are indicated with the red circles. The black crosses (×) denote the sources with at least one of the neon lines having a line width (FWHM) of > 600 km s^{-1}. The parameters of shock velocities V and the magnetic fields B increase with the directions of the arrows, in steps of 100, 200 km s^{-1} (the pink and red lines, respectively) and 1, 5, 10, 20, 40, 50, 100 μG (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 %, ...).

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
($6 \lesssim \log(M_{\rm BH}/{\rm M}_\odot) \lesssim 7$), 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 $\log(L_{\rm IR}/{\rm L}_\odot) = 11$ ($\log(L_{\rm IR}/{\rm L}_\odot) = 12$) 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 μm, [Ne III], [Ne II], and [S III] 18.7 μm can be detected up to $z \sim 0.4$ ($z \sim 0.5$, or $z \sim 1.0$ without taking [Ne V] 14.3 μm 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_*) 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 μm 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 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 intersteller 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 $\sim 100\,\mathrm{km\,s^{-1}}$. 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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