Debris Disks and the Zodiacal Light - from *AKARI* to *SPICA*

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ABSTRACT

For the studies of the late stages of the planetary-system formation, the dust-supply and trapping processes observed in exosolar debris disks and the zodiacal dust cloud of our solar system are important clues. The debris-disk sample explored by *AKARI* includes 24 objects whose *AKARI* (2006–2007) and *WISE* (2009–2010) fluxes cannot be explained by the same blackbody radiation and suggests temporal variation in 2–4 years. Through the follow-up λ 8–13 μm spectroscopy of them using Subaru/COMICS in 2015–2017, two of them turn out to be mysterious objects; although they have a large amount of small grains whose dissipation timescales are shorter than the observation intervals, most of the grains have been kept during the observed epochs. They cannot be simply explained by neither the conventional steady-state collisional cascade process nor transient events such as Giant Impact with rapid dust dissipation. Through the analyses of the *AKARI* mid-IR all-sky survey data, various non-steady dust-supply and trapping processes are indicated for the zodiacal dust cloud: temporal variation of the dust component trapped in the Earth's resonant orbits, catastrophic events in the dust-bands formation, and transportation of small grains by a coronal mass ejection, etc. We should carefully investigate the processes in the exosolar debris disks referring the phenomena in our zodiacal dust cloud and extend discussions to the statistical studies of the zodiacal dust cloud analogous by *SPICA*.

Keywords: Solar system and planetary formation, zodiacal dust, protoplanetary disks

1. INTRODUCTION

Debris disks are dust disks around main-sequence stars. The disk emission is observed as infrared excess emission compared to the photospheric emission. They are thought to be objects at late stages of the planetary-system formation after the dissipation of their primordial gas (e.g., Wyatt 2008). Small grains in gas-less interplanetary space should dissipate in a short time scale by the radiation pressure of the central star. Especially grains smaller than "blow-out limit" size of the system are dissipated in a Kepler time, which is much shorter than the time scale of the planetary-system formation. Thus, dust grains and their properties in these systems are crucial clues for understanding the recent events that happened in them, i.e., events in the late stages of planetary-system formation. Our solar system also has a gas-less dust disk called the zodiacal dust cloud. Although the total dust mass is too small to be compared with the current debris disk samples we can study details of dust supply and dissipation processes from the inner side of the disk, which can be applicable to the observed extra-solar debris disks.

AKARI performed mid-IR all-sky survey observations in 9 and 18 μm bands (Ishihara et al. 2006) with the on-board Infrared Camera (IRC; Onaka et al. 2007). The point source catalogue is publicly available (Ishihara et al. 2010) and the all-sky diffuse map is under preparation for the publication. In this study, we explore extra-solar debris disks and make statistical discussions on their evolution using the mid-IR point source catalogue. In addition, we analyze detailed dust supply processes in our solar system through the development of the mid-IR all-sky maps.

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2. DATA AND ANALYSIS

2.1. Debris disks exploration

In the debris disks exploration, first, we have made optical-to-near-IR spectral energy distributions (SEDs) of main-sequence stars which have *AKARI* 18 μm measurements. Debris disks are detected as mid-IR excess emission on top of the photospheric emission predicted from the optical or near-IR photometry of the central stars. The threshold of the mid-IR excess detection depends on the accuracy of the prediction of the mid-IR emission of the photosphere in addition to the accuracy mid-IR photometry of the object. Details are given in Ishihara et al. (2017). For bright our sample ($Ks < 6$), because the 2MASS J, H, Ks photometry show large uncertainties due to the saturation, we have performed accurate near-IR photometry by using neutral density (ND) filters on SIRIUS/IRSF telescope (Sato et al. 2001; Nagayama et al. 2003). By replacing the near-IR photometry with our new results, we have successfully improved the photometric accuracy in the predicted photospheric flux of our sample stars from ~20% to ~2% on average. Using these near-IR photometories and 18 μm fluxes from the *AKARI* mid-IR PSC, we have explored infrared excess emission for main-sequence stars.

2.2. Zodiacal light analysis

In separating the galactic and extra-galactic emission from the foreground emission of the zodiacal light in the *AKARI* 9 and 18 μm all-sky survey data, we have used and optimized the standard model of the zodiacal light emission (Kelsall et al. 1989). Details are given in Kondo et al. (2016). As a result of this study, the model parameters were changed from those in Kelsall et al. (1989), which provide improvements in the fitting of the overall spatial distribution and temporal variation of the zodiacal light observed with *COBE* and *AKARI* (See Section 3.2).

3. RESULTS

3.1. Evolution of debris disks

As a result of debris disks exploration using *AKARI* and IRSF, we have successfully detected 53 debris disks with 18 μm excess out of 708 main-sequence stars. Using this sample, we investigate the evolution of debris disks. Details are described in Ishihara et al. (2017). Figure 1 plots the relative disk flux (fractional luminosity) at *AKARI* 18 μm as a function of stellar age for our FG-type sample along with previous samples from the *Spitzer*/MIPS 24 μm observations (Beichman et al. 2005, 2006; Bryden et al. 2006; Chen et al. 2005a,b; Hillenbrand et al. 2008; Trilling et al. 2008). The fractional luminosity decreases along the stellar age. A large fraction of these objects is explained by the standard steady-state collisional cascade model (Kobayashi & Tanaka 2010). However, some objects show large fractional luminosity even at old ages which cannot be explained simply by the standard model. The non-steady processes such as Giant Impact (Genda et al. 2015) or Late Heavy Bombardment might be indicated for these objects.

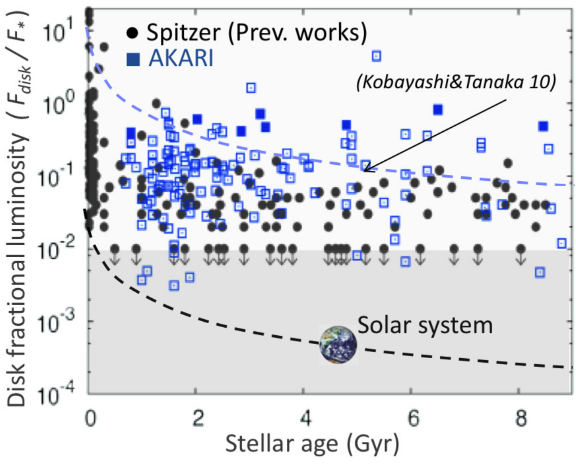

Figure 1. Evolution of debris disks. The disk fractional luminosity ($F_{\rm disk}/F_*$) is plotted as a function of the stellar age for FG-stars. Squares indicate our sample with *AKARI* 18 μm measurements, while circles indicate samples from previous works based on *Spitzer*/MIPS 24 μm observations (Beichman et al. 2005, 2006; Bryden et al. 2006; Chen et al. 2005a,b; Hillenbrand et al. 2008; Trilling et al. 2008). The dotted curves indicate the tracks predicted by the model (Kobayashi & Tanaka 2010). The location of the zodiacal light of our solar system in this plot is indicated with Earth's mark.

3.2. Dust supply processes in the zodiacal cloud

Figure 2 compares the zodiacal light subtracted residual maps: both of our new model (Kondo et al. 2016) and the Kelsall's model (Kelsall et al. 1989) applied for both of the *AKARI* 9 μm map and *COBE* 12 μm maps. The rms levels of these residual maps indicate that our new model better explains both of the *AKARI* and *COBE* data except for the Earth trailing blob. The spatial distribution of the Earth trailing blob component has been changed between the *COBE* (1995–94) and *AKARI* (2006–2007) eras: the weighted center of the blob component has been shifted to the north by 0.001 au. Changes in other parameters provide a better fit in the overall spatial distribution. The density distribution indicates that the dust grains are more concentrated toward the inner region than that expected simply by Poynting-Robertson effect. It indicates active dust supply in the inner region by comets or other processes. This indication is qualitatively consistent with the results by Rowan-Robinson & May (2013). The temperature distribution indicates that the dust grains are warmer than that expected simply by thermal equilibrium of BlackBody dust. It indicates that dust grains are smaller or darker than previously thought. Non-continuous supply of dust grains from the minor planet families is indicated through the analysis of the dust band components of the zodiacal light emission (Takaba et al. in this volume). The zodiacal dust cloud of our solar system shows clues on various kinds of non-steady episodic dust supply to the interplanetary space.

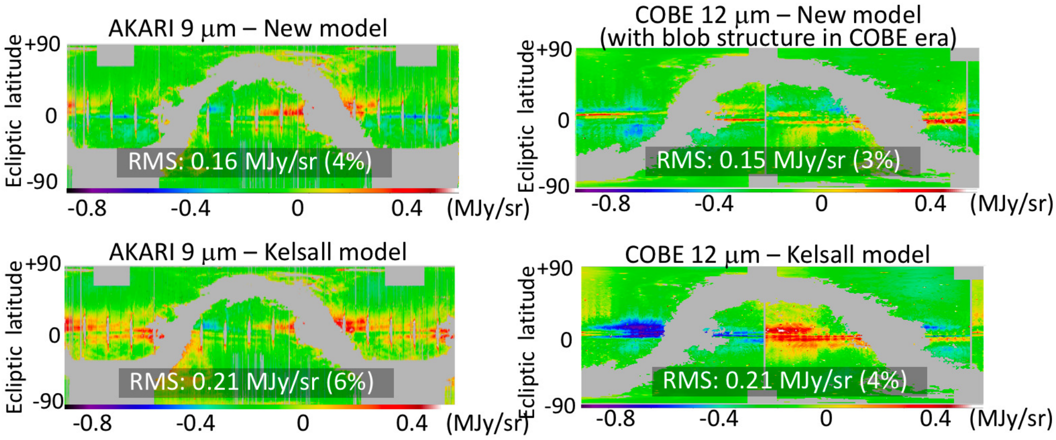

Figure 2. The residual all-sky maps after subtraction of the zodiacal light. The vertical axis indicates ecliptic longitude while the horizontal axis indicates time (which is proportional to the ecliptic latitude). The Galactic plane is masked in all the images. (a) *AKARI* 9 μm data - our new model (Kondo et al. 2016), (b) *AKARI* 9 μm data - Kelsall's model (Kelsall et al. 1989), (c) *COBE* 12 μm data - our new model (with the Earth trailing blob at *COBE* era), and (d) *COBE* 12 μm data - Kelsall's model. The rms levels of the residual component are overlaid in the right bottom of each panel.

4. DISCUSSION

4.1. Follow-up observations of debris disks sample by Subaru/COMICS

To investigate the properties of the disks in our sample, we have made mid-IR SEDs combining the *AKARI* 9 and 18 μm fluxes with the *WISE* 12 and 22 μm fluxes. About half of the disk SEDs of our sample can be explained by blackbody radiation, while 24 objects cannot, which indicate that these disks might show temporal flux variation between the observed epochs by *AKARI* (2006–2007) and *WISE* (2009–2010) and/or mid-IR dust spectral features such as silicates. We have made follow-up mid-IR (λ 8–13 μm) spectroscopy using Subaru/COMICS (Kataza et al. 2000) to investigate their nature. Details will be reported in Ishihara et al. in prep. We investigate the temporal variation of disk fluxes from the *AKARI* era, as well as the physical properties of dust grains in disks by modeling the obtained spectra. The shape of the mid-IR spectra indicates compositions of dust grains in disks while the sharpness of the spectral peaks indicates the size of grains, because Si–O stretching modes of silicates appear in the observed wavelength range. As a result, the slight temporal variation of disk flux is detected from 4 objects while the silicate dust features are detected from 4 objects. Three of the objects with silicate features show the temporal variation. Most astonishing is that some stars sustain large amount of grains much smaller than the blow-out size of the systems for more than 10 years, which cannot be explained simply by the non-steady dust supply processes such as Giant Impact or Late Heavy Bombardment. The objects which cannot be simply explained by the steady state evolution cannot be explained only by simple non-steady processes neither.

4.2. Future works with *SPICA*

We have made the statistical study on the evolution of relatively bright (>1000 zodi., where 1 zodi. is $1\times10^{-7}\,L_{\odot}$) extra-solar debris disks, and the detailed studies on dust supply processes in the zodiacal dust cloud (1 zodi.). The luminosity of the zodiacal emission of our solar system is still two orders of magnitude fainter than the current extra-solar debris disks samples. In Figure 1, the parameters of our solar system are indicated by the mark of the Earth. To study the zodiacal dust cloud in the framework of debris disk evolution, it is expected to fill the hatched parameter space in Figure 1. Using the high sensitive mid-IR spectrometer (SMI/LR; λ 18–36 μm) on-board *SPICA*, we can get close to the disk luminosity range comparable to our solar system, by detecting the spectral shape of the disk emission instead of detecting faint infrared excess emission. It is expected that about 1,800–2,600 debris disks samples down to the luminosity range of 5–10 $L_{\odot}$ will be provided at least by the planned *SPICA* 10-deg^2 cosmological survey. Details are given in Kaneda et al. (2017).

5. SUMMARY

By using the *AKARI* 9 and 18 μm mid-IR all-sky survey data, we made a statistical study on the evolution of extra-solar debris disks and detailed studies on the dust supply processes in the dust disk of our solar system. Most of the debris disks sample follow the evolution track predicted by the standard model of the steady state evolution. Some disks show large IR excess emission even at old ages, which cannot be explained by the simple model without non-steady processes. In our solar system, various clues for non-steady dust supply processes other than the Giant Impact or Late Heavy Bombardment were found through detailed analyses. The follow-up mid-IR spectroscopy of our debris disks sample by Subaru/COMICS indicates that small grains survive through an unexpectedly long period in some systems, which cannot be explained by the conventional steady state model nor transient non-steady dust supply processes. We should carefully investigate the processes in the exosolar debris disks referring the phenomena in our zodiacal dust cloud and extend discussions to statistical studies of zodiacal dust cloud analogues to be discovered by *SPICA*.

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