Publications of the Korean Astronomical Society
32: 067 ∼ 071, 2017 March

pISSN 1225-1534
eISSN 2287-6936
https://doi.org/10.5303/PKAS.2017.32.1.067

DEBRIS DISKS AND THE ZODIACAL LIGHT EXPLORED BY THE AKARI MID-INFRARED ALL-SKY SURVEY

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(Received October 3, 2014; Revised October 20, 2016; Accepted October 20, 2016)

ABSTRACT

Debris disks are circumstellar dust disks around main-sequence stars. They are important observational clues to understanding the planetary system formation. The zodiacal light is the thermal emission from the dust disk in our Solar system. For a comprehensive understanding of the nature and the evolution of dust disks around main-sequence stars, we try a comparative study of debris disks and the zodiacal light. We search for debris disks using the AKARI mid-infrared all-sky point source catalog. By applying accurate flux estimate of the photospheric emission based on the follow-up near-infrared observations with IRSF, we have improved the detection rate of debris disks. For a detailed study of the structure and grain properties in the zodiacal dust cloud, as an example of dust disks around main-sequence stars, we analyze the AKARI mid-infrared all-sky diffuse maps. As a result of the debris disks search, we found old (>1 Gyr) debris disks which have large excess emission compared to their age, which cannot be explained simply by the conventional steady-state evolution model. From the zodiacal light analysis, we find the possibility that the dust grains trapped in the Earth's resonance orbits have increased by a factor of ∼3 in the past ∼20 years. Combining these results, we discuss the non-steady processes in debris disks and the zodiacal light.

Key words: circumstellar matter; zodiacal dust; infrared: stars

1. INTRODUCTION

Debris disks are circumstellar dust disks around main-sequence stars. Dust grains in these gas-less systems must be supplied recently or continuously because they can not survive for longer than a few years due to the radiation pressure of the central stars. The most plausible explanation is the dust supply by the collisions of planetesimals or growing proto-planets (e.g. Kobayashi & Tanaka, 2010; Wyatt, 2008). Therefore, these objects are important for studies of the planetary system formation. Since the first detection by the IRAS infrared survey (Aumann et al., 1984), samples have been increased based on space-based infrared observations (e.g. Beichman et al., 2005; Bryden et al., 2006; Chen et al., 2005; Fujiwara et al., 2013). Their evolution is now conventionally explained by the steady state collisional cascade model (Wyatt, 2008). However, there still remain many mysteries on their evolution. For example, a statistical correlation is not found yet between the current samples of exoplanets and debris disks.

Our Solar system also has a dust disk named the zodiacal dust cloud. It is first modeled by Kelsall et al. (1989) based on the COBE/Diffuse Infrared Background Experiment (DIRBE) experiments. Through the observations from inner side of the disk, we can study the detailed structure and the physical properties of constituent dust grains. Therefore we can investigate the dust supplying and holding processes in a planetary system which is also applicable for debris disks, though a simple comparison is difficult because the zodiacal light emission is 10^{3-4} times fainter than the current samples of debris disks.

Figure 1 shows the spatial distribution of the point source catalogue (PSC) sources and the diffuse emission in the AKARI 9 μm and 18 μm mid-infrared (IR) all-sky survey data. In this paper, we try a comparative study of debris disks and the zodiacal light by exploring debris disks in the AKARI mid-IR PSC and by modeling the zodiacal light emission in the AKARI mid-IR diffuse maps.

2. DATA ANALYSIS

2.1. Search for debris disks

We search for debris disks with 18 μm excess emission. We first select 1735 main-sequence candidates with the AKARI 18 μm fluxes from the Tycho-2 spectral type catalogue (Wright et al., 2003), and on the Hertzsprung-Russell diagram based on the Hipparcos catalogue (Perryman et al., 1997). Then, we cross-check our samples using the SIMBAD database and exclude suspected ones. Double stars and multiple stars are also removed to make a purified list of 754 single main-sequence stars. Then, we estimate the 18 μm photospheric emission of them based on the B-, V-, J-, H-, and Ks-band fluxes of the central stars using the Kurucz photospheric model (Kurucz, 1992) and the extinction model (Fitzpatrick & Massa, 2009). By comparing the estimated photospheric fluxes and the observed fluxes, we identify excess emission around the central stars.

In this process, the near-IR flux accuracy is important as well as the accuracy of the 18 μm fluxes. For nearby bright stars saturated in the 2MASS catalogue, we have made the near-IR follow-up observations using the IRSF telescope by applying neutral density filters (Nagayama et al., 2003). Figure 2 compares the estimate of excess emission based on the 2MASS and IRSF photometry. In this case, the signal-to-noise ratio for the excess emission is improved by using IRSF photometry. Takeuchi et al. (2014) present the details on the search for debris disks by AKARI and IRSF.

2.2. Modeling of the zodiacal light

We investigate the cloud structures and the grain properties of the dust disk in our Solar system, using the AKARI mid-IR all-sky diffuse maps. The AKARI mid-IR maps have been recently improved by applying additional data analyses (Amatsutsu et al., 2014). We use the Kelsall model (Kelsall et al., 1989) for modeling the zodiacal light component mixed with the Galactic emission in the maps. This model explain the zodiacal cloud by three components: a smooth cloud, dust bands, and a resonance component. The resonance component is the cloud of dust trapped in the Earth's resonance orbits and consists of two sub-components: the circum solar ring along the Earth's orbit and the blob trailing the Earth. Figure 3 demonstrates the separation of the zodiacal light and Galactic emission components from the AKARI 9 μm maps. Through the model fitting of the AKARI data, we obtain the geometrical parameters of these cloud components and the temperature distribution of dust grains. Details are described in Kondo et al. (2014).

3. RESULTS

3.1. Debris disks

As a result of the debris disks search, we have identified 57 objects out of 754 main-sequence stars. Figure 4 shows distance versus spectral type for our samples. The distribution of all the main-sequence samples are reasonable considering the survey volume estimated form the detection limit of the AKARI mid-IR all-sky survey. The relatively distant samples are identified by using 2MASS photometry, while nearby samples are identified by using the IRSF photometry. Among them, 13 debris disks are identified by applying the IRSF photometry instead of the saturated 2MASS photometry. The debris disk frequency for the 2MASS based samples and the IRSF based samples are ∼8 % and ∼7 %, respectively. By applying the IRSF photometry for bright stars, we obtain the samples with uniform quality. Based on our new samples, we discuss the evolution of debris disks in Section 4

3.2. Zodiacal dust cloud

We have successfully separate the zodiacal light component from the maps. The residual component level is evaluated as ∼1 % of the original data (Figure 3c). Through the model fitting of the AKARI 9 and 18 μm data, we obtain different model parameters from those based on the COBE/DIRBE data (Kelsall et al., 1989). The details will be reported in the future work. In this paper, we focus on the important parameter which significantly changes the property of the zodiacal cloud: the number density of dust grains in the Earth's reso-

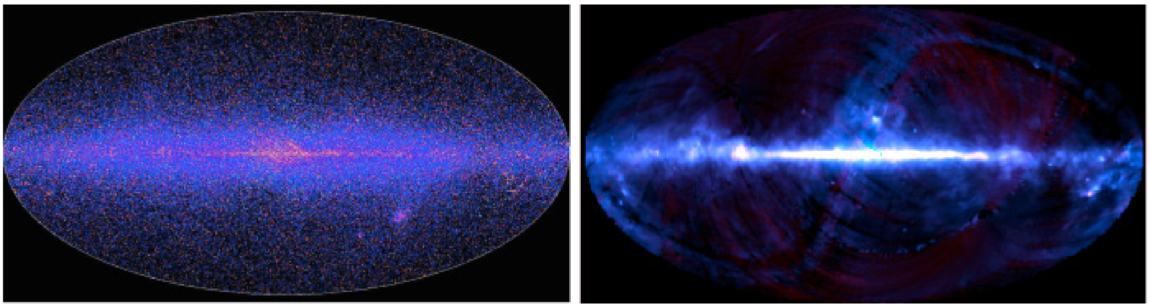

Figure 1. (a) Spatial distributions of the AKARI mid-IR all-sky PSC sources in the Galactic coordinates (Ishihara et al., 2010). The color figure is in the online version. Blue dots indicate 9 μm sources, while red dots indicate 18 μm sources. (b) AKARI mid-IR all-sky diffuse maps in the Galactic coordinates. The zodiacal light emission is subtracted from both bands. The color figure is in the online version. Blue and green indicate 9 μm emission, while indicates red 18 μm emission.

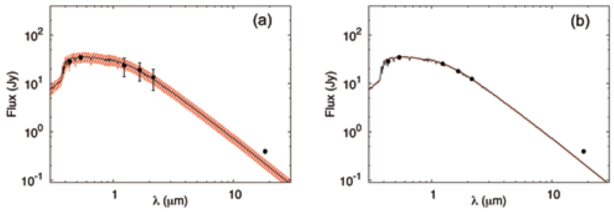

Figure 2. Photospheric emission of a star, HD 62952 predicted by using (a) 2MASS photometry, and (b) IRSF photometry. The points with error bars, solid curve, and hatched area indicate the measured fluxes, the predicted SED, and its error, respectively.

nance components. It has been possibly increased by ~3 times in the past ~20 years between the epochs of the COBE and AKARI observations (Kondo et al., 2014).

4. DISCUSSION

We discuss the evolution of debris disks using our new samples. According to the conventional steady-state evolution model (Wyatt, 2008), the excess ratio ($F_{\rm disk}/F_*$), which is the indicative of the dust mass in the disks, decreases along the age with a time scale of t_0. The variation of t_0 indicates the variation of disk properties such as total dust mass, typical size of planetesimals, radius and the eccentricity of the planetesimal belt.

Figure 5 plots the excess ratio as a function of stellar age for F- and G-type debris disks samples taken from this work and the previous works (Beichman et al., 2005, 2006; Bryden et al., 2006; Chen et al., 2005; Hillenbrand et al., 2008; Trilling et al., 2008). Most of young and old debris disk samples are commonly explained by timescales of $t_0 < 0.5$ Gyr. However, ~10 old our debris disk samples show time scales of t_0 >2 Gyr. These old large excess samples can not be explained by the conventional steady state evolution model by which most of younger debris disks are explained. Therefore, we have to consider non-steady state processes such as dynamical events or resonance traps in planets' resonance orbits.

Through the analysis of the zodiacal light described in Section 3.2, we find the possibility of the temporal increase of the dust grains in the Earth's resonance orbits. The large excess old ($t_0 > 2$ Gyr) debris disk samples might undergo similar processes, if they have planets. However, they require a temporal brightening with more than one order of magnitude compared to the disk fluxes of most of the samples ($t_0 < 0.5$ Gyr). It is difficult to explain these large excess objects by the dust trapping mechanism in the resonance orbits of the planets. Therefore, we have to consider dynamical events like a giant impact or a late heavy bombardment (LHB) which can make temporal brightening with 1–2 orders of magnitude (Booth et al., 2009).

For the progress of this study, it is essential to investigate time variations of these excess emission or enlarge the number of old debris disk samples by the next infrared space mission, SPICA. It is also important to search for Jovian planets in these systems which invoke dynamical events.

5. SUMMARY

For a comprehensive understanding of the evolution of planetary systems, we make a comparative study of debris disks and the zodiacal light based on the AKARI 9 and 18 μm mid-IR all-sky data. We searched for debris disks with 18 μm excess emission based on the PSC. We also modeled the zodiacal light component in the diffuse maps by modifying the Kelsall model (Kelsall et al., 1989).

As a result of debris disks search, we have identified 57 objects from 754 main-sequence stars. Debris disks

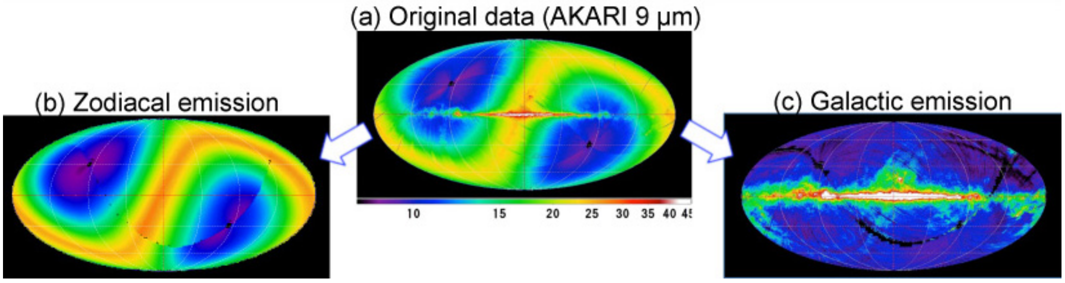

Figure 3. Separation of the zodiacal light emission and Galactic emission from the AKARI 9 μm all-sky data. (a) Original map. (b) The zodiacal light component obtained by the model fitting of the data with the Kelsall model (Kelsall et al., 1989). (c) Galactic emission component. All the maps are shown in the galactic coordinates.

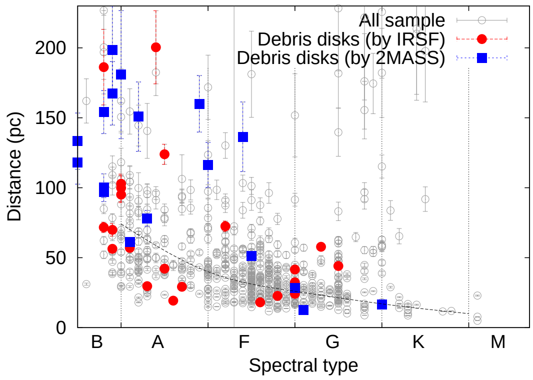

Figure 4. Distance of our samples plotted as a function of spectral type. Open circles indicate all the main-sequence samples. Filled squares and filled circles indicate debris disk candidates detected by using 2MASS and IRSF photometry, respectively.

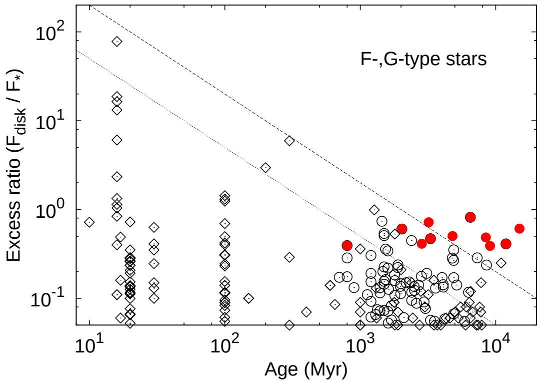

Figure 5. Excess ratio versus age for debris disk samples of F- and G-type stars. Filled circles, open circles, and open diamonds indicate our debris disk samples, all our main-sequence samples, and the debris disk samples from the previous works (Beichman et al., 2005, 2006; Bryden et al., 2006; Chen et al., 2005; Hillenbrand et al., 2008; Trilling et al., 2008), respectively. The dotted and dashed lines indicate the evolutionary tracks for objects with t_0=0.5 Gyr and t_0=2 Gyr, respectively.

around nearby bright stars are identified by the accurate estimate of the photospheric emission based on the near-IR follow-up observations with IRSF. Our modeling of the zodiacal light imply that the dust grains in the Earth's resonance component might have increased by a factor of ~3 in the past ~20 years.

In our debris disk samples, large excess emission is detected even around old main-sequence stars, which can not be explained by the conventional steady-state evolution model. They must undergo non-steady processes, which temporarily brighten the disk fluxes by more than one order of magnitude. The resonance trap effect observed in our Solar system can not make such drastic changes. Thus, we have to consider another scenario, dynamical events like a giant impact or a LHB. For the progress of this study, we expect future infrared space missions for studies of time variation and detailed characterization of older debris disks.

ACKNOWLEDGMENTS

This research is based on observations with AKARI, a JAXA project with the participation of ESA. This work is supported by JSPS KAKENHI Grant Numbers No. 24740122, 26707008, and 50377925.

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