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 plant 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 ($\gtrsim$ 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 (SiO_2) 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

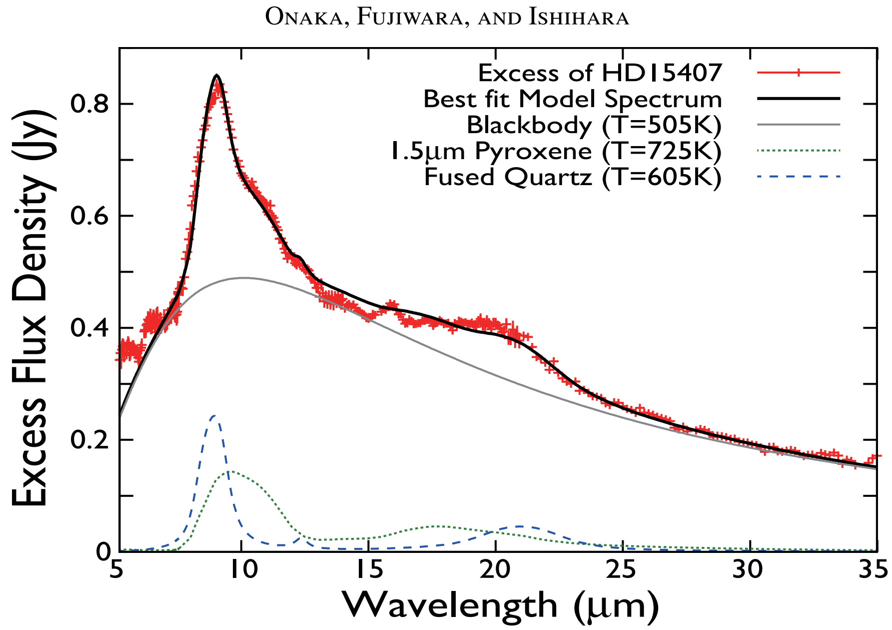

Figure 1. *Spitzer* IRS spectrum of HD 15407 after subtraction of the stellar continuum (red line) and the model fit including silica dust (thick black line, Fujiwara et al. 2012a).

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 onboard *SPICA* will offer an unparalleled observation opportunity.

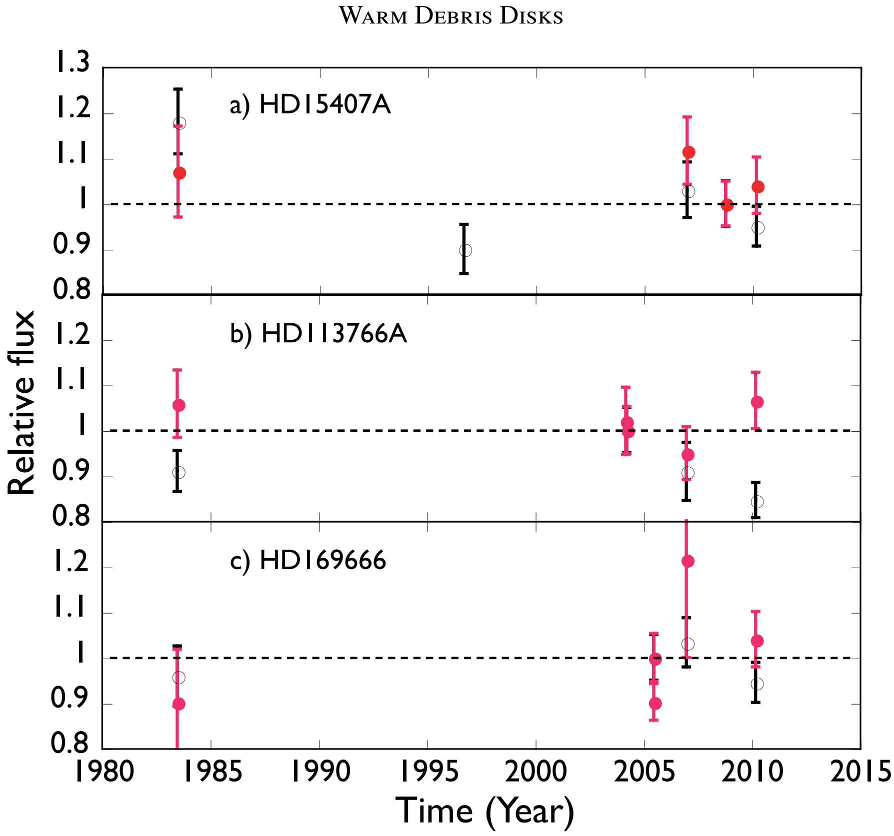

Figure 2. Time variation in the infrared flux for three warm debris disks. The black open circles indicate the fluxes in 8–12 μm, while the red filled circles show those in 18–25 μm. The data are taken from Olofsson et al. (2012) and normalized by the IRS data.

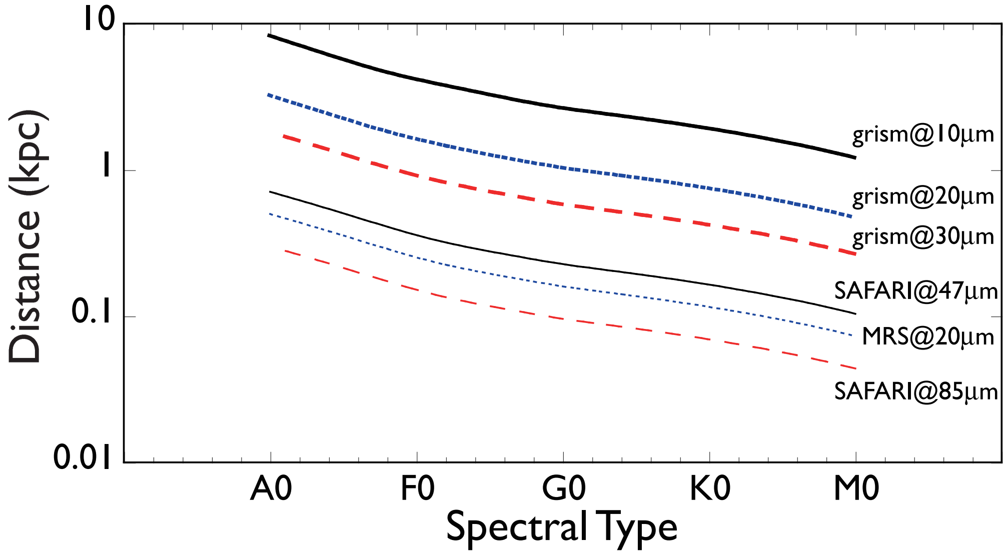

Figure 3. Detectability of the photosphere of main-sequence stars of a function of the distance with *SPICA* at various wavelengths based on the 1hr 5σ sensitivities.

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 ($\sim 5'$), 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 ~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 μm, 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 plant 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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REFERENCES

Aumann, H. H., et al. 1984, ApJL, 278, L17
Backman, D. E., & Paresce, F. 1993, in in Protostars and Planets III, edited by E. H. Levy, & J. I. Lunine (Arizona: University of Arizona.), p1253
Campbell, T. H., & Taylor, S. R. 1983, GRL, 10, 1061
Dias, W. S., et al. 2002, A&A, 389, 871
Fujiwara, H., et al. 2012a, ApJL, 749, L29
— 2012b, ApJL, 759, L18
— 2013, A&A, 550, A45
Ishihara, D., et al. 2010, A&A, 514, A1
Johnson, B. C., et al. 2012, ApJ, 761, 45
Lisse, C. M., et al. 2009, ApJ, 701, 2019
— 2012, ApJ, 747, 93
Meng, H. Y. A., et al. 2012, ApJL, 751, L17
Olofsson, J., et al. 2012, A&A, 542, A90
Onaka, T., et al. 2007, PASJ, S59, 401
Rhee, et al. 2007, ApJ, 660, 1556
Shimonishi, T., et al. 2013, AJ, 145, 32
Wyatt, M. C. 2008, ARA&A, 46, 339
Wyatt, M. C., et al. 2007, ApJ, 663, 365