THE ABSENCE OF COLD DUST AROUND WARM DEBRIS DISK STAR HD 15407A

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ABSTRACT

We report Herschel and AKARI photometric observations at far-infrared (FIR) wavelengths of the debris disk around the F3V star HD 15407A, in which the presence of an extremely large amount of warm dust (∼500–600 K) has been suggested by mid-infrared (MIR) photometry and spectroscopy. The observed flux densities of the debris disk at 60–100 μm are clearly above the photospheric level of the star, suggesting excess emission at FIR as well as at MIR wavelengths previously reported. The observed FIR excess emission is consistent with the continuum level extrapolated from the MIR excess, suggesting that it originates in the inner warm debris disk and cold dust (∼50–130 K) is absent in the outer region of the disk. The absence of cold dust does not support a late-heavy-bombardment-like event as the origin of the large amount of warm debris dust around HD 15047A.

Key words: circumstellar matter – infrared: stars – stars: individual (HD 15407A) – zodiacal dust

1. INTRODUCTION

Debris disks are considered to be dusty disks replenished by the formation of second generation dust during the main-sequence star phase, not as direct leftovers of protoplanetary disks (e.g., Backman & Paresce 1993). Therefore debris disks hold hints of circumstellar rocky materials such as planets or their building blocks. Recent mid-infrared (MIR) observations by Spitzer and AKARI of high sensitivity have revealed the presence of warm debris disks that show MIR excess emission over the photosphere (e.g., Fujiwara et al. 2010). Some warm debris disks possess a large amount of dust and cannot be explained by steady-state evolution of the disks by planetesimal collisions. They may be formed by transient events (Wyatt et al. 2007). As transient events that generate bright warm debris disks, two major mechanisms are suggested. One is akin to the late heavy bombardment (LHB), which has been suggested to account for the debris disk around η Corvi (Lisse et al. 2012). The other is a two-body impact, which is akin to the giant impact that created the Moon, and has been suggested to account for the debris disk around BD +20 307 (Weinberger et al. 2011). The examination of transient events relevant to debris disks is important not only for understanding dynamical evolution and the presence of small bodies in the planetary system, but also for understanding the history of our solar system.

HD 15407A is an F3V main-sequence star at a distance of 55 pc from the Sun (van Leeuwen 2007), which possesses one of the most extreme warm debris disks. Large excess over the expected stellar photospheric emission at λ > 5 μm has been reported by IRAS, AKARI, and Spitzer observations (Oudmaijer et al. 1992; Fujiwara et al. 2012a). The fractional luminosity (fraction of excess luminosity over stellar luminosity) of the MIR excess emission is estimated to be L_{dust}/L∗ ~ 0.005. Fine dust of silica (SiO2) and amorphous silicate are detected toward the star (Fujiwara et al. 2012a). The effective temperature and the metallicity of the star have been estimated to be 6350 K and [Fe/H] = +0.08, respectively, by the Geneva–Copenhagen Survey (Holmberg et al. 2009) and high-dispersion spectra obtained with Okayama Astrophysical Observatory/HIDES (Fujiwara et al. 2012a). As for the stellar age, two values, 80±20 Myr (Melis et al. 2010) and 2.1 ± 0.3 Gyr (Holmberg et al. 2009), have been suggested.

In this Letter, we report new far-infrared (FIR) photometry of HD 15407A obtained with Herschel and AKARI, which constrains the amount of low-temperature dust around the star. We report the detection of FIR excess emission toward the star, which is accounted for solely by the MIR-emitting warm dust, suggesting the absence of cold dust around the star. We discuss the possible formation mechanism of the warm debris disk around HD 15407A.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Herschel/PACS Observations

HD 15407A was observed on 2011 July 15 (UT) with the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) on board Herschel (Pilbratt et al. 2010) using the photometer (scan map) mode (Observation ID: 134224222–134224225, PI: Ben Zuckerman) with three channels: 70 μm (blue), 100 μm (green), and 160 μm (red). We use the pipeline-processed Level-2 data products taken from the Herschel Science Archive. The star is seen clearly in the blue and green channel images and marginally in the red channel images. A very red source is also seen at the separation of 30′′ north of HD 15407A in the green and red images.

Aperture photometry is conducted for all individual images using IRAF apphot task. The aperture radius and sky annulus dimensions are chosen to be 5′′ and 50′′–70′′, respectively, to obtain the best signal-to-noise ratios and the minimum contamination by the nearby source. Aperture correction is applied to the measured flux density using the aperture correction factors for a 5′′ aperture shown in the PACS Observer’s Manual (2011). We calculate the weighted mean of the flux density of individual observations for each band. We take the 3σ of scatter of individual measurements to be the photometric uncertainty for each band. The derived flux densities are shown in Table 1. Color
correction is not applied. The color-correction factors for sources of \( \geq 50 \text{K} \) are 0.98–1.07 (Poglitsch et al. 2010) and are much less than the photometric errors.

### 2.2. AKARI/FIS Slow-scan Observations

HD 15407A was observed on 2007 August 18 (UT) with the Far-Infrared Surveyor (FIS; Kawada et al. 2007) on board AKARI using the FIS01 observation mode as part of the director’s time (Observation ID: 5110122-001). The FIS was operated in the photometry mode with the four bands: N60 (65 \( \mu \text{m} \)), WIDE-S (90 \( \mu \text{m} \)), WIDE-L (140 \( \mu \text{m} \)), and N116 (160 \( \mu \text{m} \)). The FIS data were processed with the FAST reduction toolkit for FIS slow-scan observation data, which is distributed within the AKARI internal team at present. Basic reduction procedure is the same as the FIS Slow-Scan Toolkit Version 20070914 officially provided. Among the four-band images, a source is seen at the position of HD 15407A only in the N60 and WIDE-S images. The detected source is significantly affected by the dead pixel in the N60 image and reliable photometry of the source is difficult to obtain for this band.

Aperture photometry is conducted only for the WIDE-S images using the IRAF apphot task. The aperture radius and sky annulus dimensions are chosen as 40\(\arcsec\) and 120\(\arcsec\)–200\(\arcsec\), respectively. Aperture correction and flux calibration for point source are applied to the measured flux density as described in Shirahata et al. (2009). Due to the large beam size of AKARI/FIS (30\(\arcsec\) for WIDE-S), the nearby source detected by Herschel/PACS contaminates the signal. Since Herschel/PACS observations suggest that the signal count of the nearby source is about half of HD 15407A at \( \sim 100 \mu \text{m} \), the measured flux density in the WIDE-S band is divided by 1.5 to estimate the flux density of HD 15407A. The final estimated flux density of HD 15407A in the WIDE-S band of AKARI/FIS is shown in Table 1.

### 3. RESULTS

#### 3.1. Spectral Energy Distribution and FIR Excess—Absence of Cold Dust

The obtained spectral energy distribution (SED) of HD 15407A compiled with all of the measured and collected photometric data in the NIR–FIR is shown in Figure 1. We also plot the Spitzer/IRS spectrum at 5–35 \( \mu \text{m} \) and the photospheric emission of HD 15407A estimated from the Kurucz model (Kurucz 1992) with the effective temperature of 6500 K and surface gravity of \( \log g = +4.0 \) fitted to the 2MASS \( K_s \)-band photometry (Fujimura et al. 2012a). Significant excess emission over the photosphere in the FIR is clearly shown by the Herschel/PACS and AKARI/FIS photometry, in addition to the large MIR excess previously reported. The detected flux densities at 70–160 \( \mu \text{m} \) are \( \lesssim 10 \) times larger than the photospheric emission.

In Figure 1, we plot the continuum level of the excess emission (a blackbody of the temperature \( T = 505 \text{K} \) with the fractional luminosity \( L_{\text{dust}}/L_\ast = 0.005 \)) estimated from the dust model fitted to the Spitzer/IRS spectrum at 5–35 \( \mu \text{m} \) (Fujimura et al. 2012a). The Herschel/PACS flux densities at 70 and 100 \( \mu \text{m} \) are consistent with the extrapolation of the estimated continuum level of the MIR excess within a 1\(\sigma\) photometric uncertainty, suggesting that the excess at 70 and 100 \( \mu \text{m} \) originates in the inner warm debris dust. AKARI/FIS photometry at 90 \( \mu \text{m} \) is also consistent with the estimated continuum level within a 1\(\sigma\) uncertainty. The consistency between the continuum estimated from the Spitzer/IRS spectrum (5–35 \( \mu \text{m} \)) and the FIR photometry (70–100 \( \mu \text{m} \)) suggests the absence of cold materials of \( \sim 130–50 \text{K} \) in the outer region \( (R_{\text{dust}} = 10–60 \text{AU}) \) of the HD 15407A system since such cold materials should show additional emission peaking at 35–100 \( \mu \text{m} \) over the continuum, which is not seen in the SED. A conservative upper limit on the fractional luminosity of cold dust around HD 15407A is set as \( L_{\text{dust}}/L_\ast \lesssim 2 \times 10^{-6} \), from a maximum thermal emission of additional blackbody of 50 K over the MIR excess emission allowed within the uncertainties of Herschel/PACS photometries. Although the 160 \( \mu \text{m} \) photometry of Herschel/PACS lies slightly above the estimated continuum level, the uncertainty is large, and thus the presence of very cold dust (\( \lesssim 30 \text{K} \)) is not confirmed at present.
3.2. Mass of Warm Debris around HD 15047A

Fujiwara et al. (2012a) estimated the mass of fine warm dust around HD 15047A to be $7 \times 10^{17}$ kg $\sim 10^{-7} M_\odot$ from the dust model fitted to the band features seen in the Spitzer/IRS spectrum at 5–35 μm. This value does not include the mass of the blackbody dust, which consists of large ($\gtrsim 10 \mu$m in size) grains and rubble.

Assuming that the continuum component of the observed excess emission at MIR and FIR wavelengths is attributable to blackbody grains of 505 K at $R_{\text{dust}} = 0.6$ AU, as suggested by Fujiwara et al. (2012a) and this work, and that its flux density is proportional to the sum of geometrical cross sections of the dust with the grain size distribution of $n(a) \propto a^{-3.5}$, we could estimate the total mass of large debris dust as

$$\frac{M_{\text{total}}}{M_\odot} = 2.7 \times 10^{-4} \left( \frac{L_{\text{dust}}}{L_\odot} \right) \left( \frac{\rho}{2.5 \text{ g cm}^{-3}} \right) \left( \frac{a_{\text{min}}}{\mu\text{m}} \right)^{\frac{1}{3}} \times \left( \frac{a_{\text{max}}}{\mu\text{m}} \right)^{\frac{1}{3}} \left( \frac{R_{\text{dust}}}{\text{AU}} \right)^{2},$$

(Hillenbrand et al. 2008), where $\rho$, $a_{\text{min}}$, and $a_{\text{max}}$ are the specific density and the minimum and maximum grain size of dust, respectively. Adopting $L_{\text{dust}}/L_\odot = 0.005$ for the continuum excess emission from warm dust around HD 15047A, $\rho = 2.5$ g cm$^{-3}$ of silicate, $a_{\text{min}} = 10 \mu$m as the smallest size of grain with a featureless spectrum in the MIR, and $R_{\text{dust}} = 0.6$ AU, the total mass is calculated as

$$\frac{M_{\text{total}}}{M_\odot} = 1.5 \times 10^{-6} \left( \frac{a_{\text{max}}}{\mu\text{m}} \right)^{\frac{1}{3}}.$$

The maximum size $a_{\text{max}}$ is not known, however. The total mass of the warm debris dust around HD 15047A is estimated to be $\sim 5 \times 10^{-5} M_\odot \sim 3 \times 10^{20}$ kg assuming $a_{\text{max}} = 1$ mm. Assuming $a_{\text{max}} = 1$ km, the total mass is estimated to be $\sim 0.05 M_\odot \sim 3 \times 10^{23}$ kg, corresponding to a few lunar masses or about half of Mars’ mass.

An upper limit on the mass of cold dust ($\sim 50$ K at $R_{\text{dust}} = 60$ AU) around HD 15047A could also be estimated in the same manner from the upper limit on the fractional luminosity $L_{\text{dust}}/L_\odot \lesssim 2 \times 10^{-6}$ set by the present work. Assuming the same grain size distribution ($n(a)$, $a_{\text{min}}$, $a_{\text{max}}$) as that of warm dust, an upper limit on the mass of cold dust is given as just a few times of the mass of warm dust as estimated above.

3.3. NIR Excess

As mentioned in the previous subsection, no debris material colder than $\sim 500$ K is suggested by the MIR–FIR SED of HD 15047A. On the other hand, photometry at 4.6 μm in the WISE W2 band shows excess over the estimated continuum component of blackbody (Figure 1), suggesting the presence of another component in addition to the warm dust component of blackbody (Figure 1), suggesting the presence of another component in addition to the warm dust component examined by Fujiwara et al. (2012a). Spitzer/IRS observations of HD 15047A show that the residual spectrum subtracted by the best-fit model of the 5–35 μm excess increases toward $\lambda \lesssim 5$ μm. Weak excess emission at 3.4 μm over the continuum component is also seen in the WISE W1-band data. Figure 2 plots the residual flux densities of excess emission at 3–7 μm subtracted by the warm (500–600 K) dust components derived in Fujiwara et al. (2012a). Although the residual flux densities seen around 3–6 μm might be attributable to hotter dust ($\gtrsim 1000$ K) in the vicinity of the star, the rise of the residual toward $\sim 4.6$ μm from both of its sides seems too steep, suggesting the possible presence of a band feature attributable to circumstellar gas. A possible carrier of the NIR...
Section 4).

Figure 2. NIR–MIR residual flux densities of HD 15407A subtracted by the model fitted to the Spitzer/IRS spectrum at 5–35 μm. The crosses and filled circles indicate data from Spitzer/IRS and WISE, respectively. The vertical and horizontal bars of the photometric data show the flux density errors and the bandwidths, respectively.

excess is the first overtone mode of SiO gas around 4 μm, which might be related to a collisional event of rocky bodies (see Section 4).

4. DISCUSSION

MIR observations of HD 15407A by AKARI/IRC and Spitzer/IRS revealed the presence of a large amount of warm dust (500–600 K) at the distance of ≲1 AU from the central star. FIR observations of the star by Herschel/PACS and AKARI/FIS in this work suggest remarkable results—cold dust at ≳10 AU is absent and all of the measured 60–100 μm emission comes from the same population of dust grains that produce the bright MIR emission seen by AKARI/IRC and Spitzer/IRS. The results are contrary to a previous prediction by Olofsson et al. (2012) who suggested the presence of a population of cool dust around the star based on a MIR spectral model. NIR–MIR observations by WISE also suggest the possible presence of hotter dust or gas component. In summary, the HD 15407A system possesses abundant warm dust at ≲1 AU and no cold dust at ≳10 AU, which suggests that the system is quite different from most of the known debris disks with cold dust mainly discovered by IRAS (Rhee et al. 2007). So far about 10 bright warm debris disks around solar-type stars are known. Among those, HD 15407A seems similar to the G-star BD+20 307, which possesses dust within 1 AU and no cold dust in the further region (Weinberger et al. 2011).

An interesting issue of the debris disk around HD 15407A is its large fractional luminosity, which is estimated to be ~0.005 solely from MIR observations by Fujiwara et al. (2012a). This value is still secure even if the flux densities in the FIR are taken into account. Although the estimated age ranges from 80 Myr to 2 Gyr, the fractional luminosity of the disk is exceptionally (~10^4–10^5) larger than those predicted by steady-state models of planetesimal collisions for the suggested age range (10^{-6}–10^{-8}; Wyatt et al. 2007). Transient events are thus suggested to be responsible for the large amount of debris dust around HD 15407A.

As the formation mechanism of warm debris disk around the ∼1 Gyr old main-sequence star ε Corvi, an LHB-like event is suggested by Lisse et al. (2012). Submillimeter observations by the James Clerk Maxwell Telescope detect a cold debris belt at ∼150 AU around the star (Wyatt et al. 2005), which might form from planetesimals in the outer region (analog of Kuiper Belt objects). The MIR spectrum of the star suggests the presence of a large amount of warm debris dust, which might be produced at a few AU through collision(s) of an icy Kuiper Belt body or bodies falling from the outer region of the system (Lisse et al. 2012). In the scheme of an LHB event, the presence of a large amount of planetesimals in the outer region is required as impactors in the inner region. Self-grinding of the planetesimals should produce abundant small dust grains with low temperatures, which produce thermal emission at FIR wavelengths, as seen toward ε Corvi. N-body simulations of the LHB in the solar system by Booth et al. (2009) based on the Nice model (Gomes et al. 2005) suggest that the mass surface density of debris at ∼20–30 AU from the Sun would be ~10 times larger than that at a few AU during the LHB. Therefore, the absence of cold dust around HD 15407A does not support an LHB-like event as a source of the warm dust around HD 15407A.

Catastrophic collisions of two rocky, planetary-scale bodies in the terrestrial zone, which are an analog of the giant impact in the solar system, is suggested as a most likely source of warm debris around BD+20 307 (Weinberger et al. 2011). This giant-impact-like event might be applicable to the origin of the disk with warm debris and no cold material around HD 15407A, since a giant-impact-like event does not require a reservoir of planetesimals in the outer region. Lisse et al. (2009) conclude that the detection of silica dust and SiO gas features toward HD 172555 suggests a hypervelocity impact as the origin of the debris disk. Detection of abundant silica dust around HD 15407A would be harmonic with the possible mechanism of debris akin to that of HD 172555, but the presence of SiO gas around HD 15407A is not confirmed in its Spitzer/IRS spectrum (Fujiwara et al. 2012a). Spectroscopic observations at 3–5 μm are needed to search for a hint of the first overtone feature of SiO gas.

A giant impact is a probable hypothesis for the Moon formation around the Earth (Canup 2004) and is predicted to have been common during the final stage of terrestrial planet formation in extra-solar systems (Kenyon & Bromley 2006). A large amount of debris should be ejected in a giant impact. A recent theoretical study of the evocation of debris created in the Moon-forming giant impact (Jackson & Wyatt 2012) suggests that a giant impact generates a debris ring around the Earth orbit and that the fractional luminosity of the debris ring depends on the size of the largest fragment as well as the time after the impact. According to Jackson & Wyatt (2012), a fractional luminosity larger than 0.005 would be achieved until 100 yr after the impact when the size of the largest fragment is 1–10^3 m and would not be achieved when the size of the largest fragment is >10 km. Assuming 100 yr as the lifetime of a giant-impact-generated bright debris disk, the probability of detecting such an event is ~10^{-6} and ~10^{-7} for a star with an age of 100 Myr and 1 Gyr, respectively. Even if we consider that the formation of an Earth-like planet requires around 10 giant impacts (e.g., Kenyon & Bromley 2006), the probability increases only by one order of magnitude. HD 15407A is found as a possible giant-impact star among ~600 FGK dwarf stars in the AKARI survey (Fujiwara et al. 2012b) and the apparent probability is ~10^{-3}, which is much larger than the value estimated above.
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The discrepancy might be due to an observational bias since MIR-luminous sources are easily found from the survey. A complete census of debris disks in a larger volume space by WISE may fill the gap.

It should be noted that HD 15407A is in a possible binary system with the K2V star HD 15407B with a separation of 21′′2 (projected distance of 1170 AU) and HD 15407B might disturb the circumstellar material around HD 15407A dynamically. The study of the stability zone in a binary system by Holman & Wiegert (1999) suggests that materials at <400 and <150 AU from HD 15407A are dynamically stable when the eccentricity of the system is 0.0 and 0.5, respectively. Thus the absence of cold materials at ∼10–60 AU around the star is not due to the dynamical effect in the binary system.

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