THE ASYMMETRIC THERMAL EMISSION OF THE PROTOPLANETARY DISK SURROUNDING HD 142527
SEEN BY SUBARU/COMICS

HIDEAKI FUJIWARA,1 MITSUHIKO HONDA,2 HIROKAZU KATAZA,3 TAKUYA YAMASHITA,2,4 TAKASHI ONAKA,2
MISATO FUKAGAWA,5,6 YOSHIKO K. OKAMOTO,7 TAKASHI MIYATA,4 SHIGEYUKI SAKO,6
TAKUYA FUJYOSHI,4 AND ITSUKI SAKON2

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ABSTRACT

Mid-infrared (MIR) images of the Herbig Ae star HD 142527 were obtained at 18.8 and 24.5 μm with the Subaru/COMICS. Bright extended arclike emission (outer disk) is recognized at r = 0′85 together with a strong central source (inner disk) and a gap around r = 0′67 in both images. The thermal emission on the eastern side is much brighter than that on the western side in the MIR. We estimate the dust size to be a few microns from the observed color of the extended emission and the distance from the star. The dust temperature T and the optical depth τ of the MIR-emitting dust are also derived from the two images as T = 82 ± 1 K, τ = 0.052 ± 0.001 for the eastern side and T = 85 ± 3 K, τ = 0.018 ± 0.001 for the western side. The observed asymmetry in the brightness can be attributed to the difference in the optical depth of the MIR-emitting dust. To account for the present observations, we propose an inclined disk model, in which the outer disk is inclined along the east-west direction with the eastern side being on the far side while the inner rim of the outer disk on the eastern side is directly exposed to us. The proposed model can successfully account for the MIR observations as well as the near-infrared images of the scattering light, in which the asymmetry is seen in the opposite sense and in which the forward scattering light (near-side–western side) is brighter.

Subject headings: circumstellar matter — planetary systems: protoplanetary disks — stars: individual (HD 142527) — stars: pre–main-sequence

1. INTRODUCTION

High angular resolution, multiwavelength imaging of protoplanetary disks can provide us with a unique insight into planet formation processes, since the detailed structure of a disk should bear traces of disk formation history and of young or mature planets. Mid-infrared (MIR) observations especially trace the thermal radiation from warm dust, and these observations allow us to examine the temperature structure and the dust distribution quantitatively. They also allow us to discuss the structure near the central star because the contribution from the photosphere is relatively small and because coronagraphic observations are generally not required for the MIR.

HD 142527 (F7 IIIe) is classified as a Herbig Ae star, as confirmed by its spectrum and photometry, which exhibit the typical characteristics of a pre–main-sequence (PMS) star (Waelkens et al. 1996). Hipparcos measurements suggest its stellar age and mass are 1 Myr and 2.5 ± 0.3 M☉, respectively, derived by comparing the position of HD 142527 in the H–R diagram to theoretical PMS tracks (van Boekel et al. 2005). Malfait et al. (1998) reported that the infrared excess of HD 142527 is comparable to the stellar luminosity, suggesting that a large amount of cold material is present around the star. Radio observations show the disk mass to be Mdisk = 0.15 M☉ (Acke et al. 2004), which is more massive than a typical disk mass by an order of the magnitude. Van Boekel et al. (2004) reported the central concentration of crystalline silicate in the disk.

Fukagawa et al. (2006) resolved an almost face-on disk around HD 142527 in the near-infrared (NIR) scattered light using the Subaru/CIAO. They discovered arclike components facing each other along the east-west direction (“banana-split structure”), with one spiral arm extending to the north from the western arc in the disk. From this unusual morphology, the presence of an unseen eccentric binary and a recent stellar encounter are suggested. However, the coronagraphic mask made it difficult to quantitatively discuss the spatial structure in the vicinity of the central star solely from scattered light observations.

In this Letter, we present high spatial resolution MIR images of HD 142527 obtained with the Subaru Telescope. The obtained images provide us with significant information on the nature of the protoplanetary disk around HD 142527.

2. OBSERVATIONS AND DATA ANALYSIS

We observed the Herbig Ae star HD 142527 with the COoled Mid-Infrared Camera and Spectrometer (COMICS; Kataza et al. 2000; Okamoto et al. 2003; Sako et al. 2003) mounted on the 8.2 m Subaru Telescope on 2004 July 13 and 2005 August 24. Imaging observations with the 18.75 μm (Δλ = 0.9 μm) and 24.56 μm (Δλ = 0.75 μm) bands were carried out. The pixel scale was 0′′13 pixel−1. To cancel out the background radiation, the secondary mirror chopping was used at a frequency of 0.45 Hz for 18.8 μm and 0.46 Hz for 24.5 μm with a 10″ throw. For the Subaru/COMICS, the residual pattern in
the chopping subtraction is very small and negligible compared to the brightness of the target in most cases. We did not apply nodding for the present observations. We selected standard stars (HD 136422 for 18.8 \( \mu m \) and HD 146051 for 24.5 \( \mu m \)) from Cohen et al. (1999) as flux calibrators and reference point-spread functions (PSFs). We observed them before or after the observations of the target in the same manner. The observation parameters are summarized in Table 1.

For the data reduction, we used our own reduction tools and IRAF. The standard chopping pair subtraction and the shift-and-add method were employed. We also corrected for the effect of the different air masses between the object and the standard star by estimating the difference in atmospheric absorption using the ATRAN software (Lord 1992). The derived total absolute fluxes are 14.6 \( \pm \) 0.2 and 19.3 \( \pm \) 0.1 Jy at 18.8 and 24.5 \( \mu m \), respectively, and they were consistent with the flux of the Infrared Space Observatory Short Wavelength Spectrometer spectrum (Sloan et al. 2003).

### 3. RESULTS

The obtained images are shown in Figure 1 (left panels). A prominent extended radiation component is recognized in addition to a central compact component in both the 18.8 and 24.5 \( \mu m \) images. By comparing with the standard stars, the fluxes of the central component of HD 142527 are measured as 10.4 \( \pm \) 0.08 and 6.7 \( \pm \) 0.05 Jy at 18.8 and 24.5 \( \mu m \), respectively. The central component is thought to be the thermal radiation from hot dust within the inner disk close to the star, because the contribution from the photosphere is less than 0.1 Jy and because it is much smaller than the observed emission at these wavelengths. Figure 2 (top panel) shows the profile of the 24.5 \( \mu m \) image along the east-west direction. While the profile of the central component (\( r \leq 0.5 \)) at 18.8 \( \mu m \) is consistent with the PSF (FWHM = 0.52), that at 24.5 \( \mu m \) is broader than the PSF (FWHM = 0.61). The convolved PSF by the Gaussian of FWHM = 0.28 gave the best fit to the profile of the central component at 24.5 \( \mu m \). This suggests that the inner disk may be extended and that its size can be estimated to be \( \geq 80 \) AU from the brightness of the central component at 24.5 \( \mu m \) by simply assuming that the disk is a uniform blackbody. Since N-band spectroscopic observations of HD 142527 by van Boekel et al. (2004) show broad silicate features, micron-sized large grains are dominant in the inner disk. From the fluxes at 18.8 and 24.5 \( \mu m \), the temperature and optical depth of the MIR-emitting dust within the inner disk are derived as \( T = 293 \) K and \( \tau = 4.4 \times 10^{-4} \), respectively, by assuming a single size distribution of silicate for simplicity and by using the emissivity of 2.5 \( \mu m \)-sized astronomical silicate dust (Laor & Draine 1993).

The extended component is thought to be the thermal radiation from the material of relatively low temperatures (\( T < 150 \) K) in the outer region of the protoplanetary disk since it is brighter at 24.5 \( \mu m \) than at 18.8 \( \mu m \). In order to examine the extended emission in detail, we subtracted the central component. For the 18.8 \( \mu m \) data, we subtracted the scaled reference PSF as the central component from the image of HD 142527. For the 24.5 \( \mu m \) data, we subtracted the reference PSF that is convolved by a Gaussian of FWHM = 0.28 as the central component since the central component may be slightly extended (see above). The reference PSFs are very stable, and the uncertainties of the PSF subtractions are estimated as 2.6 mJy arcsec\(^{-2}\) at 24.5 \( \mu m \) around the diffraction ring even in the worst case and less than the background noise level of 6.7 mJy arcsec\(^{-2}\) at 18.8 \( \mu m \). The uncertainties are included in the errors of the following results.

After the subtraction of the central component, asymmetric ring-like structures are clearly seen (Fig. 1, right panels). The eastern side is much brighter than the western side at both 18.8 and 24.5 \( \mu m \). We compare the MIR and NIR images in Figure 3. They were aligned with each other by adjusting the stellar position. The stellar position in the MIR image was determined as the peak position of the central component derived by Gaussian fitting, and its uncertainty is about 0.1 pixel = 0.013. The maximum offset between the positions of the MIR and NIR emission is 0.013. The observed extended emission arcs are also seen in the NIR image as “banana-split structure” (Fukagawa et al. 2006). Gaps in the north and south are also clearly seen in both the MIR and NIR images. However, the contrast of the two arcs is quite different.

### TABLE 1

**Summary of the Observations of HD 142527**

| Object      | Filter | Date (UT)  | Integration (s) | Air Mass | Comments |
|-------------|--------|------------|----------------|----------|----------|
| HD 142527   | Q18.8  | 2004 Jul 13| 502            | 2.1      | ...      |
| HD 136422   | Q18.8  | 2004 Jul 13| 201            | 1.8      | Standard |
| HD 142527   | Q24.5  | 2005 Aug 24| 210            | 2.3–2.4  | ...      |
| HD 146051   | Q24.5  | 2005 Aug 24| 201            | 1.2      | Standard |

### TABLE 2

**Derived Physical Parameters for Each Region**

| Region       | F18.8 (Jy) | F24.5 (Jy) | Position (arcsec) | Width (arcsec) | F18.8/F24.5 | T (K) | \( \tau_{24.5 \mu m} \) |
|--------------|------------|------------|------------------|----------------|-------------|------|---------------------|
| Center       | 10.4 ± 0.08| 6.7 ± 0.05 | ...              | ...            | 1.55 ± 0.02 | 293 ± 8 | 4.4 × 10^{-4} |
| East         | 1.98 ± 0.05| 5.52 ± 0.06| 0.85             | 0.87           | 0.34 ± 0.01 | 82 ± 1 | 0.057 ± 0.001 |
| West         | 0.77 ± 0.05| 2.12 ± 0.06| 0.86             | 0.94           | 0.37 ± 0.03 | 85 ± 3 | 0.018 ± 0.001 |
from the NIR scattered light images, in which the eastern side is brighter than the western side. The spiral arm observed in the NIR is not detected in our MIR images.

To discuss the azimuthal variation in the extended emission, we divided the observed extended emission into two regions as the position angle P.A. = 0°–180° and 180°–360°, which are the eastern and western regions, respectively. The radial profiles of the eastern and western sides are shown in Figure 2. The eastern side is about 3 times brighter than the western side. The radial profiles are almost Gaussian-like, and the peaks are at about r = 0′.85 ( = 170 AU) for both sides. The peak position and profile width (FWHM) in each region derived by Gaussian fitting for the 24.5 μm are listed in Table 2. The widths of both arcs are broader than the beam size.

By integrating the signals within the range of 0′.5 ≤ r ≤ 1′.2, we derived the fluxes of the eastern and western regions at 18.8 and 24.5 μm and the flux ratio of $F_{18.8 \mu m}/F_{24.5 \mu m}$ as a color indicator of the dust emission (Table 2). We calculated the predicted color profiles of the MIR-emitting dust around HD 142527 for the emissivities of various-sized astronomical silicates (Laor & Draine 1993) and compared them with the observed colors (Fig. 4). We assumed $L_∗ = 69 L_⊙$ and $T_{\text{eff}} = 6250 \text{ K}$ for the photospheric spectrum of HD 142527 (van den Ancker et al. 1998). Figure 4 shows that the observed colors of both regions are in agreement with the model calculation for 2.5 μm–sized silicate. Thus, we can suggest the typical size of the MIR-emitting dust within the outer disk of HD 142527 as a few micron when we assume dust species as amorphous silicate. Fukagawa et al. (2006) also argue that the size of the grains responsible for the scattering is ≈1 μm because the color of scattered light from dust around HD 142527 is similar to the color of the star, being in agreement with ours. The dust grains around HD 142527 are larger than the grains in the interstellar medium, suggesting that the dust grains in the disk have already grown to some extent due to coagulation of smaller dust particles. We also derived the temperature and optical depth of the MIR-emitting dust within each region from the fluxes of 18.8 and 24.5 μm, assuming a single size distribution of 2.5 μm–sized silicate (Laor & Draine 1993). We derived the temperatures as $T = 82 \pm 1 \text{ K}$ and $T = 85 \pm 3 \text{ K}$ and the optical depths of the MIR emitting dust as $\tau = 0.057 \pm 0.001$ and $\tau = 0.018 \pm 0.001$ for the eastern and western regions, respectively. While the temperatures of the eastern and western regions are in agreement with each other within the errors, the optical depth of the eastern region is 3 times larger than that of the western region. The asymmetry in the brightness of the extended emission originates from the difference of the optical depth between the eastern and western sides.

While the above results are derived on the assumption of $L_∗ = 69 L_⊙$, van Boekel et al. (2005) proposed $L_∗ \sim 30 L_⊙$. Taking this luminosity, we obtain 1.6 μm as a typical size of grains. The effect of the radiation from the inner disk has also been examined by assuming that the inner disk emits as a blackbody of $T = 1200 \text{ K}$ and $L \sim 0.5L_*$, which is estimated from the spectral energy distribution (SED). The estimated dust size becomes 2 μm. Thus, we conclude that the presence of micron-sized grains in the disk is secure.

4. DISCUSSION

As a global distribution of the material in the disk around HD 142527, we suggest that there are a large amount of cold material in the outer region of $r \approx 170 \text{ AU}$ (outer disk), while there are quite a few materials present in the inner region. Since we can see a drop of radiation at $r = 0′.6$ in the images, a gap in the material density must exist. The existence of the material gap is compatible with the MIR flux gap seen in the SED (Acke et al. 2004). Leinert et al. (2004) suggested the presence of “a nearby very red source” whose temperature is $T \sim 70 \text{ K}$ as the origin of the large far-infrared excess seen in the SED. However, our observations demonstrate that the large far-infrared excess is attributed to the outer disk associated with the star, not to “a nearby very red source.”

As we mentioned in § 3, the asymmetric brightness of the outer disk of HD 142527 can be attributed to the difference in $\tau$ of the MIR-emitting dust. NIR scattered light observations
plotted with the solid lines. Profiles calculated by using the emissivity of astronomical silicate are also shown in Fukagawa et al. (2006). The 850 μm continuum observations by Submillimeter Array (SMA), which is thought to be optically thin to dust emission and a good tracer of the total amount of dust, show an east-west symmetric structure of the extended disk (N. Ohashi et al. 2006, in preparation). To explain these observations, we propose a model in which the disk dust is geometrically thick and inclined as the eastern side is farther to us and the inner rim of the eastern side of the outer disk is exposed to us. Figure 5 shows a schematic view of the model of the HD 142527 system. Since the inner edge and rim are hottest within the outer disk and affect the MIR brightness most strongly, the emitting region of the outer disk appears like a narrow ring. Therefore, the optical depth we mentioned above does not directly correspond to the vertical depth of the MIR-emitting layer of the disk but rather indicates the area size of the MIR-emitting region within the beam. If the disk is inclined as the eastern side is farther to us, the eastern inner rim of the outer disk can be seen directly while the western one cannot because the cooler materials farther out are obscuring the inner hot dust. We suggest that the difference in visibility of the inner rim makes for the strong asymmetric MIR brightness of the outer disk. The model we are proposing here can also explain why the western side is brighter in the NIR scattered light (Fukagawa et al. 2006). In the scattered light, we observe backscattered light on the eastern side and forward-scattered light on the western side. For grains, those sizes are similar to or larger than the wavelength in question, and the forward scattering is much stronger than the back-scattering, resulting in the observed asymmetry in the NIR. An axial symmetric disk inclined to the east-west direction is also consistent with the asymmetric structure of the extended disk traced by 850 μm radiation. It is not necessary to consider an axial asymmetric material distribution such as a circumbinary disk to account for the observations.

Details of the appearance of a protoplanetary disk, including a “peculiar horseshoe-like feature” for models with an inclination of 30°, were predicted in simulations of Kessel et al. (1998). A model 12 μm intensity map in their paper shows a morphology strikingly similar to our images of the outer disk of HD 142527. NIR interferometric observations of LkHα 101 show that an asymmetric arclike radiation component is present in addition to a central compact component (Tuthill et al. 2002). In the case of LkHα 101, the asymmetric arclike structure is thought to be attributed to the hot dust within the inner rim of the inner hole made by dust sublimation. Although the observed spatial scale and wavelength are different, HD 142527 and LkHα 101 agree on the asymmetric arclike morphology of thermal emission. In the case of HD 142527, photoevaporation of dust can be ruled out as the cause of the gap because the position of gap is far from the central star. A secondary object, if any, may be able to create the gap. High spatial resolution radio observations will be required in order to discuss the origin of the gap in detail.

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