HIGH-RESOLUTION 25 μM IMAGING OF THE DISKS AROUND HERBIG AE/BE STARS*

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ABSTRACT

We imaged circumstellar disks around 22 Herbig Ae/Be stars at 25 μm using Subaru/COMICS and Gemini/T-ReCS. Our sample consists of an equal number of objects from each of the two categories defined by Meeus et al.; 11 group I (flaring disk) and II (flat disk) sources. We find that group I sources tend to show more extended emission than group II sources. Previous studies have shown that the continuous disk is difficult to resolve with 8 m class telescopes in the Q band due to the strong emission from the unresolved innermost region of the disk. This indicates that the resolved Q-band sources require a hole or gap in the disk material distribution to suppress the contribution from the innermost region of the disk. As many group I sources are resolved at 25 μm, we suggest that many, but not all, group I Herbig Ae/Be disks have a hole or gap and are (pre-)transitional disks. On the other hand, the unresolved nature of many group II sources at 25 μm supports the idea that group II disks have a continuous flat disk geometry. It has been inferred that group I disks may evolve into group II through the settling of dust grains into the mid-plane of the protoplanetary disk. However, considering the growing evidence for the presence of a hole or gap in the disk of group I sources, such an evolutionary scenario is unlikely. The difference between groups I and II may reflect different evolutionary pathways of protoplanetary disks.

Key words: circumstellar matter – protoplanetary disks – stars: pre-main sequence

1. INTRODUCTION

Recent discoveries of numerous exoplanets have revealed the diversity of planetary systems (e.g., Marois et al. 2008). However, the origin of such variety is still uncertain. Planets should have formed in protoplanetary disks and it is essential to understand their evolution in order to resolve why such differences exist. In studies of lower-mass young stars such as T Tauri stars, transitional disks have received attention from the planet formation point of view. Transitional or pre-transitional disks are protoplanetary disks with an inner hole and/or gaps indicated by the weak near-infrared/NIR/mid-infrared/MIR excess in their spectral energy distribution (SED; Strom et al. 1989; Espaillat et al. 2007). Since a primordial protoplanetary disk must have a continuous distribution of dust/gas without gaps, and since the disk structure will be affected by planet formation, those disks with an inner hole and/or gaps must be in a transitional phase moving from a primordial to an evolved planetary-system stage.

Disks around nearby Herbig Ae/Be stars have also been studied extensively in the context of disk evolution and planet formation, but using a different classification approach. Based on an analysis of SEDs, Meeus et al. (2001) classified Herbig Ae/Be stars into two groups: group I sources, which show both power-law and blackbody components up to far-infrared (FIR) wavelengths in their SEDs, and group II sources, whose SEDs can be well modeled with only a single power law from MIR to FIR wavelengths. They suggested that group I has a flaring disk while the disk around group II is geometrically flat.

There have been several proposed scenarios for an evolutionary link between groups I and II sources. Dullemond & Dominik (2004) showed that SEDs of group I sources can be interpreted as hydrostatic disks with flaring geometry, while group II sources are an evolved version of group I sources that have undergone grain growth and grain settling onto the mid-plane of the disk. Such a settled disk would become a self-shadowed disk by a puffed-up inner rim that accounts for weak FIR emission (Dullemond & Dominik 2004). Marúšas et al. (2011) performed a MIR imaging survey of Herbig Ae/Be disks at 12 and 18 μm. They found that group I disks show more extended emission than those of group II and suggested that the trend can be naturally understood in terms of the difference in disk geometry.

Recent high spatial resolution observations at various wavelengths have revealed a more complex structure, including a hole or gaps in disks. In particular, there is growing evidence for the presence of a hole and/or gaps toward group I sources, such as AB Aur (Lin et al. 2006; Honda et al. 2010), HD 142527 (Fujiwara, et al. 2006; Fukagawa et al. 2006; Verheoff et al. 2011), HD 135344 B (Brown et al. 2009; Grady, et al. 2009), HD 36112 (Isella et al. 2010), HD 169142 (Grady et al. 2007;...
Table 1  
Summary of Subaru/COMICS and Gemini/T-ReCS Observations

| Object     | Subaru/COMICS Q24.5 Imaging | Gemini/T-ReCS Qb Imaging |
|------------|----------------------------|--------------------------|
|            | Date | $t^{\prime}$ | PSF | Date | $t^{\prime}$ | PSF |
| Elias3-1   | 2004 Jul 11, 12 | 399 | βAnd | ... | ... | ... |
| HD 100546  | ... | ... | ... | ... | ... | ... |
| HD135344B  | 2004 Jul 11 | 101 | δOph | ... | ... | ... |
| HD 139614  | ... | ... | ... | 2011 Jul 27 | 1369 | αCen A |
| HD 169142  | ... | ... | ... | ... | ... | ... |
| HD179218   | 2004 Jul 11 | 99 | αHer | ... | ... | ... |
| HD 36112   | 2005 Dec 14, 2011 Jan 26 | 3297 | αTau | 2011 Jan 26 | 438 | αTau |
| HD97048    | ... | ... | ... | 2011 Jun 28 | 638 | γSgr |
| RCtA       | 2004 Jul 11 | 100 | δOph | 2004 Jul 12 | 40 | αHer |
| TCtA       | 2004 Jul 11 | 312 | αHer | 2004 Jul 12 | 175 | αHer |
| 51 Oph     | 2004 Jul 11 | 237 | δOph | ... | ... | ... |
| AK Sco      | ... | ... | ... | ... | ... | ... |
| CQ Tau     | 2005 Dec 15 | 553 | αTau | 2005 Dec 15 | 541 | αTau |
| HD142666   | 2004 Jul 11 | 148 | δOph | ... | ... | ... |
| HD144432   | 2004 Jul 11 | 193 | δOph | ... | ... | ... |
| HD150193   | 2004 Jul 12 | 168 | αHer | ... | ... | ... |
| HD163296   | 2004 Jul 11, 12 | 557 | δOph | ... | ... | ... |
| HD31648    | 2005 Dec 14 | 1510 | αTau | 2005 Dec 15 | 578 | αTau |
| HD35187    | 2005 Dec 14, 16 | 1580 | αTau | ... | ... | ... |
| HR5999     | ... | ... | ... | ... | ... | ... |
| KK Oph     | ... | ... | ... | 2011 Jul 24 | 638 | αTra |

* Total integration time in seconds used in this study.

Honda et al. (2012), Oph IRS 48 (Geers et al. 2007), HD 100546 (Bouwman et al. 2003; Benisty et al. 2010), HD 139614 (Matter et al. 2014), and HD 97048 (Maaskant et al. 2013). Recently, Honda et al. (2012) and Maaskant et al. (2013) proposed that group I sources possess a disk with a strongly depleted inner region (i.e., a transitional disk). Such a discontinuous structure is different from that originally proposed for group I disks. As little or no evidence for a hole and/or gaps has been reported from group II to group III needs to be reconsidered.

In this paper, we present the results of an imaging survey of nearby (roughly within 200 pc) Herbig Ae/Be stars at 24.5 μm using the 8.2 m Subaru Telescope and 8.1 m Gemini Telescope. At 24.5 μm, the point-spread function (PSF) is relatively stable compared to those at shorter wavelengths because of a larger Fried length, which enables us to discuss small extended structures with high reliability. In addition, it allows us to investigate the cooler outer part of the disk at a dust temperature ~100 K. Early examples of our imaging survey have been published previously (Fujiiwara, et al. 2006; Honda et al. 2010, 2012; Maaskant et al. 2013). This paper provides a summary of the survey.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Subaru/COMICS Data

We performed imaging observations of Herbig Ae/Be stars using the Cooled MIR Camera and Spectrometer (COMICS; Kataza et al. 2000; Okamoto et al. 2003; Sako, et al. 2003) on the 8.2 m Subaru Telescope with the Q24.5 filter ($\lambda_c = 24.5$ μm, $\Delta \lambda = 0.8$ μm). We also observed a portion of the targets with the Q18.8 filter ($\lambda_c = 18.8$ μm, $\Delta \lambda = 0.8$ μm). The chopping throw was 10″ and the chopping frequency was 0.45 Hz. The pixel scale is 0″/30/pix. Immediately before and/or after observations of the target, we performed observations of PSF reference stars. A summary of the observations is provided in Table 1.

For data reduction, we employed a shift-and-add method to rectify the blurring caused by tracking and/or registration errors. The imaging data consist of 0.983 s on-source integration frames of coadded exposures at each beam position. First, the fluctuation of the thermal background and the dark current signals were removed through differentiation of the chopped pair frames. The object is bright enough to be recognized even in 0.983 s integration chop-subtracted frames. We estimated the peak position of the source without difficulty using a Gaussian fit. Then, we shifted the frames to align the peak position and summed the frames. We excluded those frames whose Gaussian FWHMs deviate by more than 1σ from the mean value.

2.2. Gemini/T-ReCS Data

Observations were performed using T-ReCS (Telesco et al. 1998) on the 8.1 m Gemini South telescope. T-ReCS uses a Raytheon 320 x 240 pixel Si:As IBC array with a pixel scale of 0.08633 ± 0′00013 pixel−1, providing a field of view (FOV) of 27′6 × 20′7. The Q_b (λ_c = 24.56 μm, $\Delta \lambda = 0.94$ μm, 50% cut-on/off) filter was used in the present observations. A summary of the observations is also shown in Table 1. Observations were performed using a standard chop-nod technique to remove time-variable sky background and telescope thermal emission, and to reduce the effect of 1/f noise from the array-electronics. In all of our observations, the chop-throw was 15″, the chop-angle was 45° E of N, and the telescope was nodded approximately every 40 s. Standard stars were observed immediately before and/or after each object observation using the same instrumental configuration (Cohen et al. 1999).

The data were reduced using the Gemini IRAF package. The difference for each chopped pair was calculated and a pair of...
the nod sets were then differentiated and combined to create a single image. All of the nodding data were examined if they had high background due either to the presence of terrestrial clouds or temporarily high water vapor precipitation. No data were found to be severely affected by these problems.

Although there is slight differences in the characteristics of the filters used by COMICS and T-ReCS, we will refer to $Q_{24.5}$ and $Q_{b}$ as 25 $\mu$m throughout this paper.

3. RESULTS

Since the observed images show circularly symmetric shapes and the azimuthal variation is not significant, we focus on the radial profile of the targets and do not discuss their azimuthal structures in this study. First, we created azimuthally averaged radial profiles of the targets and relevant PSF stars at 25 $\mu$m as shown in Figure 1. We then measured their FWHMs from the
profiles directly; we call these “direct FWHMs” ($\Phi_{d,\text{target}}$ and $\Phi_{d,\text{PSF}}$, for the targets and PSFs, respectively). These FWHMs are the real extensions of the sources convolved with the instrumental FWHM. These measurements are summarized in Table 2, accompanied by those of the corresponding PSF stars.

The radial brightness profiles of most targets are comparable to or slightly wider compared to those of the PSF stars. As a quantitative measure of the intrinsic size of the MIR emission from the disk, we employ a quadrature-subtraction of the FWHM of the PSF star from that of the target following Mariñas et al. (2011). We refer to this as the “intrinsic FWHM” ($\Phi_i$), which is derived from

$$\Phi_i = \sqrt{\Phi_{d,\text{target}}^2 - \Phi_{d,\text{PSF}}^2}.$$ 

Although this method provides a correct size only when the intrinsic radial profiles of both the target and the PSF star are given by a Gaussian, we adopt this method to semi-quantitatively discuss the extension of the sources with the same measure for the sake of simplicity. Eight sources are observed by both COMICS and T-ReCS, and the results were consistent with each other within the measurement errors. To be conservative, we adopt the smaller and more stringent value of the intrinsic FWHM in these cases. The derived values are summarized in Table 3.

### 4. DISCUSSION

#### 4.1. Trends in Extended Emission

To investigate possible trends in the 25 μm extension of the Herbig Ae/Be stars with other parameters, we collected the distance, stellar luminosity, classification of the group proposed by Meeus et al. (2001), and the MIR spectral index given by the flux density ratio at 13.5 and 30 μm (Acke et al. 2004, 2010; Acke & van den Ancker 2006; Meeus et al. 2012). The flux densities at 13.5 and 30 μm reflect the underlying continuum shape and are chosen to avoid MIR dust features such as silicates and polycyclic aromatic hydrocarbons (PAHs). For those objects whose spectral index is not available, we calculated it ourselves using the Infrared Space Observatory or Spitzer archive spectra. We also converted the diameter in arcseconds to AU using the distance to the objects given in Table 3. We added AB Aur, which was part of our survey but with results published earlier in Honda et al. (2010), to Table 3.

We note that group I sources tend to show more extended MIR emission than group II sources. Nine out of 11 group I sources are resolved (i.e., >82%) with a signal-to-noise ratio larger than three, as are 4 out of 11 group II sources, which, however, is only 36%. This trend is similar to the results of the study by Mariñas et al. (2011) at 12 and 18 μm. The present results also confirm the trend at 25 μm.

In Figure 2, we plot the intrinsic FWHM ($\Phi_i$) against the stellar luminosity ($L*$). One may expect that luminous sources show more extended emission, however, we could not find a clear trend in the plot. Some sources in our sample are not resolved even though they are luminous ($L* > 40L_\odot$).

On the other hand, when we plot the intrinsic FWHM against the MIR spectral index (Figure 3), we find that significantly extended (FWHM > 40 AU) sources all belong to the “red” group I. Such objects exhibit MIR spectral indices [30/13.5] larger than 4.2, while moderately extended or unresolved sources all appear below that value, even among group I. It is also interesting to note that the MIR spectral indices of well-resolved MIR disk sources such as HD 142527 (Fujiiwara, et al. 2006), Oph IRS48 (Geers et al. 2007), and HD141569 (Fisher et al. 2000; Marsh et al. 2002) are 5, 10.4, and 6.8, respectively, in agreement with the present finding. We therefore suggest that the redder Herbig Ae/Be stars with MIR spectral index larger than 4.2 exhibit more extended MIR emission. In general, group

### Table 2

FWHM Measurements of COMICS and T-ReCS Observations

| Object   | Subaru/COMICS Q24.5 Imaging | Subaru/COMICS Q18.8 Imaging | Gemini/T-ReCS Qb Imaging |
|----------|-----------------------------|-----------------------------|--------------------------|
|          | $\Phi_{d,\text{target}}$ (μ) | $\Phi_{d,\text{PSF}}$ (μ) | $\Phi_{d,\text{target}}$ (μ) | $\Phi_{d,\text{PSF}}$ (μ) |
| Elias3-1 | 0.672 ± 0.012                | 0.634 ± 0.003               | ...                       | ...                        |
| HD 100546 | ...                         | ...                         | ...                       | ...                        |
| HD13534B | ...                         | ...                         | ...                       | ...                        |
| HD 139614 | 0.643 ± 0.031                | 0.633 ± 0.011               | ...                       | ...                        |
| HD 169142 | ...                         | ...                         | ...                       | ...                        |
| HD179218 | 0.637 ± 0.009                | 0.645 ± 0.004               | ...                       | ...                        |
| HD 36112 | 0.751 ± 0.009                | 0.649 ± 0.003               | ...                       | ...                        |
| HD97048  | ...                         | ...                         | ...                       | ...                        |
| RC Tra   | 0.687 ± 0.016                | 0.629 ± 0.020               | ...                       | ...                        |
| TC Tra   | 0.748 ± 0.013                | 0.634 ± 0.002               | ...                       | ...                        |
| SL Oph   | 0.663 ± 0.037                | 0.626 ± 0.006               | ...                       | ...                        |
| AK Sco   | ...                         | ...                         | ...                       | ...                        |
| CQ Tau   | 0.687 ± 0.023                | 0.627 ± 0.004               | ...                       | ...                        |
| HD142666 | 0.710 ± 0.063                | 0.637 ± 0.008               | ...                       | ...                        |
| HD144432 | 0.652 ± 0.031                | 0.639 ± 0.006               | ...                       | ...                        |
| HD150193 | 0.728 ± 0.001                | 0.641 ± 0.002               | ...                       | ...                        |
| HD163296 | 0.649 ± 0.011                | 0.632 ± 0.003               | ...                       | ...                        |
| HD31648  | 0.677 ± 0.013                | 0.646 ± 0.006               | 0.503 ± 0.007             | 0.493 ± 0.007             |
| HD35187  | 0.689 ± 0.010                | 0.649 ± 0.002               | ...                       | ...                        |
| HD141569 | ...                         | ...                         | ...                       | ...                        |
| HD142527 | ...                         | ...                         | ...                       | ...                        |

* Resolved(Y) or not(N).
sources tend to show MIR continuum emission redder than for
source in group II. Thus, the present
findings are consistent with
the trend wherein group I sources are likely to exhibit more
extended emission than group II sources.

4.2. Origin of Extended Emission of MIR Red Source

The origin of the Q-band (16–25 μm) extended emission in
group I Herbig Ae/Be stars or red MIR sources has been
discussed previously by several groups. Honda et al. (2010, 2012)
and Maaskant et al. (2013) demonstrated the
difficulty in explaining the extended Q-band emission of group
I sources with a continuous disk. The Q-band emission from a
continuous disk mostly originates from dust grains located in
the inner ⩽ 10 AU, which corresponds to ~0″07, if located at a
typical distance of ~150 pc from our targets. Considering the
PSF size (~0″07) at 25 μm, this is too small to be resolved with
8 m class telescopes. This situation may apply to most of the
unresolved targets in our sample. In contrast, we have de
finitely resolved many group I sources, indicating that the continuous
disk interpretation is not valid for these objects.
The shape of the SEDs for group I sources can be interpreted
as having an MIR dip because of the rising FIR emission. The
dip indicates that hot/warm dust grains responsible for the MIR
radiation are depleted in the inner region of the protoplanetary
disk. An inner hole and/or gaps in the disk can naturally explain
both the MIR dip in the SED and the extended emission in the
Q band. The presence of an inner hole, for example, causes the
inner edge of the disk to be directly illuminated by the central
star. This edge, being relatively further away due to the inner
hole, produces the red MIR index (i.e., a large [30/13.5] ratio)

| Object   | Distance (pc) | $L_\odot$ | Ref. | $\phi_i$ (°) | $\phi_i$ (AU) | Group | Ref. | $[30/13.5]$ | Ref. |
|----------|---------------|----------|------|-------------|--------------|-------|------|-------------|------|
| AB Aur   | 139.3         | 33.0     | b    | 0.50±0.05   | 70.2±6.91    | I     | a    | 4.5         | a    |
| Elias3-1 | 160           | 0.7      | d    | 0.22±0.04   | 35.5±6.1     | I     | c    | 2.3         | e    |
| HD 100546| 96.9          | 22.7     | b    | 0.33±0.02   | 31.7±2.3     | I     | a    | 3.5         | a    |
| HD135344B| 142           | 8.1      | b    | 0.36±0.02   | 50.6±2.7     | I     | a    | 10.9        | a    |
| HD 139614| 140           | 7.6      | b    | 0.04±0.17   | 5.3±24.0     | I     | a    | 4.2         | a    |
| HD 169142| 145           | 9.4      | b    | 0.31±0.04   | 45.1±5.4     | I     | a    | 7.8         | a    |
| HD179218 | 240           | 100.0    | d    | <0.12       | <28.81       | I     | a    | 2.4         | a    |
| HD 36112 | 279.3         | 33.7     | b    | 0.38±0.02   | 105.6±5.5    | I     | a    | 4.1         | a    |
| HD97048  | 158.5         | 30.7     | b    | 0.33±0.03   | 52.8±5.5     | I     | a    | 5.9         | a    |
| RCrA     | 130           | 0.6      | d    | 0.31±0.07   | 40.9±9.5     | I     | c    | 2.1         | e    |
| TCrA     | 130           | 0.7      | d    | 0.34±0.06   | 43.8±7.2     | I     | a    | 5           | a    |
| 51 Oph   | 124.4         | 285.0    | b    | 0.11±0.09   | 13.7±11.4    | II    | a    | 0.59        | a    |
| AK Sco   | 150           | 8.9      | d    | 0.06±0.27   | 9.6±40.1     | II    | a    | 3.3         | a    |
| CQTau    | 113           | 3.4      | b    | 0.28±0.06   | 31.5±6.4     | II    | b    | 4.1         | e    |
| HD142666 | 145           | 13.5     | b    | 0.20±0.04   | 28.7±5.3     | II    | a    | 1.53        | a    |
| HD144432 | 145           | 10.2     | d    | 0.05±0.23   | 6.6±33.5     | II    | a    | 1.82        | a    |
| HD150193 | 216.5         | 48.7     | b    | <0.17       | <37.3        | II    | a    | 1.42        | a    |
| HD163296 | 118.6         | 33.1     | b    | <0.16       | <19.2        | II    | a    | 2           | a    |
| HD31648  | 137           | 13.7     | b    | 0.20±0.05   | 27.3±6.3     | II    | a    | 1.19        | a    |
| HD35187  | 114.2         | 17.4     | b    | 0.23±0.03   | 26.5±5.4     | II    | a    | 2.1         | a    |
| HR5999   | 210           | 87.1     | d    | <0.11       | <23.6        | II    | a    | 0.96        | a    |
| KK Oph   | 260           | 13.7     | b    | <0.23       | <58.9        | II    | a    | 1.04        | a    |

References. (a) Acke et al. (2010), (b) Meeus et al. (2012), (c) Acke & van den Ancker (2006), (d) Acke et al. (2004), (e) derived from the archival spectra.
and the strong FIR radiation as reflected in the SED, as well as the extended Q-band emission. In fact, significantly extended sources (intrinsic FWHM > 40 AU) in our sample exhibit MIR spectral indices [30/13.5] larger than 4.2, indicating that the dust temperature of the inner edge of the outer disk is ~155 K assuming a blackbody. If the luminosity of the central star were 30 $L_\odot$ (a typical value for well-extended group I sources), then the distance to the 155 K blackbody would be about 18 AU, indicating an inner hole diameter of 36 AU, which corresponds to approximately 0″24 if located at a typical distance of 150 pc. An emission region of this size, when convolved with the PSF of the telescope, can be (marginally) resolved with 8 m class telescopes in the Q band. We suggest that this applies to our resolved sample.

This interpretation is supported by an increasing number of detections of inner holes and gaps in group I protoplanetary disks by high-spatial resolution observations in the NIR and at radio wavelengths, as described in Section 1. On the other hand, little evidence has been reported for inner holes and/or gaps toward group II sources, which is also consistent with the present results of unresolved or limited extended emission. Continuous disks seem to be rather difficult to resolve in the Q band with 8 m class telescopes.

In general, group I sources tend to show redder MIR continuum emission than group II sources. In our sample, most group I sources show an MIR spectral index higher than 2, while most group II objects show an index below 2. This is consistent with a recent classification criterion put forward by S. Khalefinejad (2015, in preparation) that the MIR index [30/13.5] of group I sources is greater than 2.1. A blackbody at $T \sim 195$ K would yield an MIR index of 2. Thus, the dust temperature of the inner edge of the outer disk around group I objects must be below 195 K, which puts the inner edge at some distance from the central star, producing extended Q-band emission. Both the high MIR index and the extended Q-band emission can naturally be accounted for by the presence of the inner edge of the outer disk located at some distance.

As mentioned earlier, there is now growing evidence that an inner hole and/or gaps exist in the protoplanetary disk of group I sources. Our finding above (the general trend between the extended Q-band emission and the MIR color for group I objects) also appears to reconfirm this view.

### 4.3. Comparison with Models

To demonstrate the effect of a gap in the disk on Q-band image size, we constructed disk models and derived FWHM of the disk image at 25 $\mu$m for comparison with observations. We follow the model used in Maaskant et al. (2013), who employed the radiative transfer tool MCMax (Min et al. 2009). The parameters used in this model are summarized in Table 4. We focus on the model with these typical Herbig Ae parameters as an example only, and we are not going to construct models that best predict individual imaging results.

First, we constructed a continuous disk model (no gap) whose SED has a rising FIR flux density similar to the group I objects. The model image at 25 $\mu$m is displayed in the top panel.
of Figure 4, and the SED is shown in Figure 5. Then, we introduced a radial gap into the model. The gap inner radius is fixed at 1 AU, and the gap outer radius increased from 10 to 50 AU in steps of 10 AU. Images and SEDs for these models are shown in Figures 4 and 5, respectively. The morphology of the gapped disk images is dominated by ring-like emission arising from the inner edge of the outer disk (see top panels of Figure 4). As the size of the gap is increased, more thermal radiation from the increasingly larger gapped area is removed from the SED, resulting in a weakened MIR emission and an enhanced FIR flux (see Figure 5). This, in turn, was reflected in an increasingly redder [30/13.5] color as the gap size widened. The disk images were subsequently convolved with an Airy pattern with FWHM = 0.65″ (assumed to represent the telescope beam; see the bottom panels of Figure 4). We measured Φ_d and derived Φ_i from these final images in the same manner as described in Section 3 (see Figure 6). As can be seen, the models with outer gap radii smaller than 20 AU are comparable with the “nogap” model (equivalent within uncertainties), implying that they would either be unresolved or only marginally resolved at best. On the other hand, when the outer gap radius ≥30 AU, they would easily be resolved at 25 μm. Thus our 25 μm imaging survey is sensitive to the presence of a large (≥30 AU) gap. Figure 7 is the same as Figure 3, except we added the models points. In our sample models, disks with [30/13.5] ≥ 4.2 can be achieved when the gap outer radius becomes ≳25 AU and such a disk can be well-resolved in our observations. This trend is almost consistent with our observational findings that the well-extended Herbig Ae/Be sources show MIR indexes larger than 4.2. Again, this demonstrates that our 25 μm imaging survey is sensitive to disks with large gaps.

4.4. Group I Sources as (Pre-)transitional Disks

Since the presence of an inner hole and/or gap has been shown to be a common characteristic for group I Herbig Ae/Be stars (e.g., Bouwman et al. 2003; Fujisawa et al. 2006; Fukagawa et al. 2006; Lin et al. 2006; Li et al. 2007; Grady et al. 2007; Brown et al. 2009; Grady et al. 2009; Benisty et al. 2010; Isella et al. 2010; Honda et al. 2010, 2012; Maaskant et al. 2013; Matter et al. 2014), Honda et al. (2012) and Maaskant et al. (2013) suggest that most group I sources can be classified as (pre-)transitional disks. Transitional or pre-transitional disks, which were originally suggested for low-mass young stars such as T Tauri stars, are protoplanetary disks with an inner hole and/or gaps indicated by weak NIR excess in the SED (Strom et al. 1989; Espaillat et al. 2007). Because the primordial disk is thought to have a continuous distribution of dust without gaps and because planet formation could produce a hole and/or gaps in the disk, those disks with a (large) inner hole and/or gaps must be in a transitional phase from a primordial to an evolved stage.

On the other hand, an evolutionary scenario for Herbig Ae/Be stars is still a matter of debate. Meeus et al. (2001) proposed that a group I disk is flared while that of group II is flat, based on the analysis of the SED. A possible evolutionary scenario was suggested in which a group I flaring disk evolves into a group II flat disk through grain growth and sedimentation/settling of grains onto the disk mid-plane. However, the present study indicates that the group I disk is a (pre-)transitional disk with an inner clear region and/or gaps, while the group II disk is a continuous disk. These observational pieces of information imply that evolution from group I to group II is unlikely. As Meeus et al. (2001) pointed out, there is no significant difference in age between groups I and II; therefore, it is more likely that both sources have evolved along different paths from
a primordial continuous flaring disk, a common ancestor, as discussed in Maaskant et al. (2013). This scenario is quite similar to the T Tauri disk evolutionary scenario proposed by Currie (2010). He presented two main pathways for the evolution of T Tauri disks: those that form an inner hole/gap and others that deplete more homologously. The present study suggests a similarity between the evolutionary scenarios of T Tauri and Herbig Ae/Be disks.

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