Mid-Infrared imaging of the circumstellar dust around three Herbig Ae stars: HD 135344, CQ Tau, HD 163296 *

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ABSTRACT

Aims. Planet formation has been known for many years to be tied to the spatial distribution of gas and dust in disks around young stars. To constrain planet formation models, imaging observations of protoplanetary disks are required. Methods. In this framework, we have undertaken a mid-infrared imaging survey of Herbig Ae stars, which are pre-main sequence stars of intermediate mass still surrounded by a large amount of circumstellar material. The observations were made at a wavelength of 20.5 µm with the CAMIRAS camera mounted at the Cassegrain focus of the Canada France Hawaii Telescope. Results. We report the observations of three stars, HD135344, CQ Tau and HD163296. The circumstellar material around the three objects is spatially resolved. The extensions feature a disk like shape. The images provide direct information on two key parameters of the disk: its inclination and its outer radius. The outer radius is found to be quite different from the one deduced from disk models only constrained by fitting the Spectral Energy Distribution of the object. Other parameters of the disk, such as flaring, dust mass have been deduced from fitting both the observed extension and the spectral energy distribution with sophisticated disk models. Conclusions. Our results show how important imaging data are to tighten constraints on the disk model parameters.

Key words. Circumstellar matter – Stars: formation – Stars: pre-main-sequence – individual objects: HD 163296, CQ Tau, HD 135344

1. Introduction

The formation of circumstellar disks is a natural outcome of the star formation process by which a molecular core collapses to form a star (Shu et al. 1987). Circumstellar disks can outlive the period during which stars form and still be present when the star is in its Pre-Main-Sequence (PMS) phase. In these disks, composed of gas and dust, various physical processes can lead to the growth of dust grains and eventually to the formation of planets. Understanding the physical conditions that prevail in these objects is of crucial importance when studying planet formation.

The study of circumstellar disks is a field in fast development both from the observational and the modeling point of view (e.g. Nattá 2004 and references there-in). The Infrared Space Observatory (ISO) has given clues to make conjectures on how the disks’ geometry looks like; spatially resolved imaging data of those disks are absolutely necessary to verify theories and models’ assumptions. For instance, key parameters, such as the disk surface density profile with radius, are still very poor constrained when fitting SEDs.

Models of protoplanetary disks are increasingly successful at accounting for much of the observed properties. For instance, they can justify that disks SEDs are generally rather flat in $\nu F_\nu$, where $\nu$ is the frequency and $F_\nu$ the flux (Kenyon & Hartmann 1987). Furthermore, models can explain that dust features are almost all seen in emission (Calvet et al. 1991), Chiang & Goldreich (1997), hereafter CG97), the presence of a near-infrared excess in the SEDs of Herbig Ae stars (Natta et al. 2001), Dullemond et al. 2002, hereafter DDN01) and interpret the differences observed in the far-IR excesses (Dullemond et al. 2002, Dullemond & Dominik 2004). Fitting the SED only allow to make conjectures on how the disks’ geometry looks like; spatially resolved imaging data of those disks are absolutely necessary to verify theories and models’ assumptions. For instance, key parameters, such as the disk surface density profile with radius, are still very poor constrained when fitting SEDs.

Mid-infrared imaging observations from a large ground-based telescope are potentially well suited to bring spatial information on disk around Herbig Ae (HAe) stars. HAe stars represent the middle stage of PMS evolution of intermediate-mass stars ($\sim 2-3 M_\odot$); they are bright enough to heat sub-micron dust grains at 100 AU to a temperature of about 150 K. Grains at such a temperature have their peak of thermal emission in the mid-InfraRed (mid-
2 Observations and data reduction

The three objects of the sample are spatially resolved. This can be seen on Fig. 1 where we have compared the average annular profile of the object with those of the Point Spread Function (PSF), obtained from the observation of a reference point-like star. Extended emission is detected up to 100-300 AU.

We carefully checked that the observed extensions are not artifacts, but the result of true extended emission from the objects. Several arguments lead us to reject explanations of the extensions in terms of temporal variations of the PSF between the observation of the object and the reference star. One possible cause of such temporal PSF variations could be variations of the seeing. This hypothesis is however rejected for the following reasons:

1. Conclusions and perspective are drawn in Sect. 7.

2. Observations and data reduction

We have observed a sample of three Herbig Ae stars: HD 135344, CQ Tau and HD 163296. Table 1 presents the main stellar parameters of the sample. The objects were selected from the catalogue of Thé et al. (1994) and Malfait et al. (1998) according to the following criteria: the objects are bright in the mid-IR, relatively close and isolated, i.e. not associated to extended diffuse emission due to the parental cloud.

CQ Tau is located at a distance of 100±25 pc and has an age of 10 Myr (Natta et al. 2008). HD 163296 is at a distance of 122±13 pc and has an age of 7 ± 5 Myr (van Boekel et al. 2005). The distance and age of HD 135344 are more controversial. Until 2001, a distance of 84 pc (Adeus et al. 2001) with an age of 17 ± 3 Myr (Thi et al. 2001) were used for this object. But, in a recent paper (van Boekel et al. 2005), the distance was re-evaluated to 140±42 pc and the age to 8 ± 4 Myr; these latter values will be used in the following.

The observations were performed with the mid-IR camera CAMIRAS (Lagage et al. 1992) installed as a visiting instrument at the Cassegrain focus of the Canada France Hawaii Telescope (CFHT). The camera is equipped with a Boeing 128x128 pixels Blocked Impurity Band (BiB) detector sensitive up to a wavelength, λ, of ~27 μm. A filter centered at 20.5 μm with a Full Width Half Maximum (FWHM) bandpass, Δλ, of 1.11 μm was used.

The Pixel Field of View (PFOV) on the sky was 0.29 arcsec; such a PFOV provides a good sampling of the diffraction pattern which is of 1.5 arcsec FWHM.

The objects were observed between 2000 March, 18th and 2000 March, 24th. During the run, seeing and weather conditions were extremely favorable and stable in time. HD 163296 and CQ Tau were observed at a median airmass of 1.4, and HD 135344 at an airmass around 1.9, which is the best achievable when observing from CFHT. Standard chopping and nodding techniques were applied to suppress atmosphere and telescope background emissions; the chopping throw was 16 arcsec to the North and the frequency used was 3.33 Hz; the nodding amplitude was 20 arcsec to the West. The nodding direction was perpendicular to the chopping direction, in order to get the best spatial resolution; given the low chopping and nodding throw and the field of view of the camera, the source always remained within the detector field of view, the obtained images contain thus 4 beams (2 positive, 2 negative). Given the huge photon background in the mid-IR, the elementary integration time was set to 15 ms, and the images were co-added in real time in order to store only two co-added images (one for each chopping position) every second.

The basic data reduction is standard. The data cubes of one observation are carefully stacked with rejection of corrupted planes. A shift-and-add procedure is applied to each cube of images using a correlation based method with a re-sampling factor of 8:1. The four beams are then combined in one image by a source extraction algorithm followed by a shift-and-add procedure. Finally, flux calibration is achieved via aperture photometry of a set of photometric standard stars such as α Tau, α Boo, β Gem or γ Dra (Cohen et al. 1999). The photometry gives a total flux of 6.3±0.6 Jy for HD 135344, 23±3 Jy for CQ Tau and 18±4 Jy for HD 163296, in good agreement with the IRAS values (Tab. 1).

3. Extended emission

The three objects of the sample are spatially resolved. This can be seen on Fig. 1 where we have compared the average annular profile of the object with those of the Point Spread Function (PSF), obtained from the observation of a reference point-like star. Extended emission is detected up to 100-300 AU.

We carefully checked that the observed extensions are not artifacts, but the result of true extended emission from the objects. Several arguments lead us to reject explanations of the extensions in terms of temporal variations of the PSF between the observation of the object and the observation of the reference star. One possible cause of such temporal PSF variations could be variations of the seeing. This hypothesis is however rejected for the following rea-
Table 1. Properties of the three Herbig Ae stars observed with the CAMIRAS mid-InfraRed camera; first two columns: coordinates of the objects (right ascension and declination); third column: their spectral type; fourth column: their distance, as deduced from Hipparcos data; fifth column: flux in the IRAS 25 µm band; sixth column: flux at 20 µm obtained in this paper; seventh column: age of the objects in Myrs. References: (1) Coulson et al. (1998), (2) Dominik et al. (2003), (3) Jayawardhana et al. (2001), (4) Meeus et al. (2001), (5) Mannings & Sargent (1997), (6) Mannings & Sargent (2000), (7) Natta et al. (2001), (8) Sylvester et al. (1996), (9) Testi et al. (2001), (10) Thi et al. (2001), (11) van Boekel et al. (2003), (12) van den Ancker et al. (1998).

| Object  | RA (2000) | Dec (2000) | Spectral type | Distance (pc) | $F_{25}$ (Jy) | $F_{20}$ (Jy) | age (Myrs) | References |
|---------|-----------|------------|---------------|---------------|--------------|--------------|------------|------------|
| HD 135344 | 15 15 48.4 | - 37 09 16 | F4V | 140$^{+42}_{-32}$ | 6.7 | 5 ± 1 | 8±4 | 1,2,4,8,10,11 |
| HD 163296 | 17 56 21.4 | - 21 57 20 | A3Ve | 122$^{+16}_{-12}$ | 21 | 18 ± 4 | 7±5 | 3,4,5,11,12 |
| CQ Tau | 05 35 58.4 | +24 44 54 | A1-F5IVe | 100$^{+17}_{-15}$ | 20.6 | 23 ± 3 | 10 | 6,7,9,12 |

Fig. 1. Annular averages intensity aperture for the source (solid line) and PSF (dashed line) normalized to the peak value, as function of radius. The error drawn are 1 σ-errors RMS. The reference star for HD 135344 is α Boo, for HD 163296 γ Dra and for CQ Tau, β Gem. The plot labeled '2 PSF' shows two reference stars α Boo and γ Dra as observed on the 24th of March 2000. Although the two reference stars have very different fluxes (γDra with 43 Jy and α Boo with 170 Jy, Van Malderen et al. (2004)), the two profiles are similar.

sons. First, concerning the limitations of the spatial resolution, the seeing contribution at 20.5 µm is negligible with respect to the diffraction: for a typical seeing value of 0.8” FWHM in the visible range, one can estimate a seeing contribution at 20.5 µm around 0.4”, when using the $\lambda^{-(1/5)}$ scaling law; thus, seeing induces PSF changes of the order of 1 pixel FWHM, which is much smaller than the widths of observed extensions. Secondly, the seeing was quite stable during the observations; thus we estimated seeing variation effects to be much lower than one pixel. Note also that two of the objects were observed during different nights. HD 135344 was observed for four different nights: on the March, 18th, 2000 (exposure time 6 mn), on the March, 19th (exposure time: 3 mn), on the March, 21st (exposure time: 6 mn) and on the March, 24th (exposure time: 2 mn 30). Its extension is confirmed over the 4 nights. CQ Tau was observed during 2 different nights on the 20th of March and on the 21st of March (respectively with 3 and 6 mn of
HD 163296 was observed only once (exposure time: 3 min) on the 24th of March.

Another possible source of fake extensions could be chromatic effects. Indeed, HAe stars have large infrared excesses, and thus have SEDs quite different from that of the PSF reference stars. Any filter leak, either on the blue or on the red side of the nominal filter bandpass, would then potentially lead to PSF variations between point-like HAe objects and PSF reference stars. We double checked the filter transmission at the operating temperature of the filter (10K) using a Fourier Transform Spectrometer with a spectral resolution of 4 cm\(^{-1}\). The rejection rate outside the filter bandpass is typically better than 10\(^{-3}\). We simulated the PSF variations due to such a filter using the mid-IR spectra of the objects obtained with ISO (Meeus et al. 2001) for two of the three extended objects; (CQ Tau was not observed by ISO SWS). The simulated PSF variations lead to some extended emission, but much fainter than observed, both in intensity and in spatial extension. Thus, explanation of the observed extensions in terms of chromatic variations of the PSF can be discarded.

Note also that not all the observed HAe stars observed are extended. In order to make comparison, a far away HAe star, with a similar (even more) IR excess, HD179218 located at 240 pc (Meeus et al. 2001), was observed. This object does not show extended emission at 20.5 \(\mu\)m (Fig. 2). This is an additional argument to conclude that the extension observed in HD 135344, CQ Tau, HD 163296 is really due to an extended emission from the objects.

Fig. 2. Same as Fig. 1 to make a comparison with HD179218 for which there is no extended emission detected.

4. Inclination of the disk

Extensions around two out of the three objects, namely CQ Tau and HD 163296, were already observed at other wavelengths. Testi et al. (2001) have resolved the emission around CQ Tau at 7 mm and concluded that it was compatible with a disk-like geometry. Grady et al. (2001) have obtained coronographic images of HD 163296 with the Space Telescope Imaging Spectrograph on board the Hubble Space Telescope which revealed a circumstellar disk with a radius of 450 AU. Therefore, our modeling of the extensions seen in the mid-IR range assumes a priori a disk-like geometry.

Disks inclinations can be relatively easily determined if their emission are spatially resolved. However, HAe disks are generally dominated in the mid-IR by the innermost regions (1-30 AU). Our goal was to detect the emission from the intermediate regions of the disks (30-200 AU). The disk emission can be decomposed, in our image, in a central unresolved component plus an extended one (which geometry should reflect the true disk geometry at the distance scales achievable for our data). We first removed the "point-like" central emission component by subtracting a scaled PSF to the image of the object. The parameters of the point-like component (intensity, position) were computed automatically using a penalty functional (in order to avoid any visual bias) and then cross-checked visually using a dedicated graphical interface built in IDL. The resulting image, called residuals, is free from the central emission, so that the extended emission is enhanced and it is easier to determine the disk geometry. For each target, this processing was done using all available PSF measurements. The errors on the putative extensions were assessed when applying the same procedure to two PSF reference stars and, when possible, when comparing the extensions obtained from different nights. The results are shown in Fig. 6, 7 and 8.

The first result is the elliptical shape of the extensions, which is characteristic of the emission of disks inclined with respect to the line of sight. An ellipse fit of the residuals gives an estimate of the disks inclinations and position angles. The results in terms of inclination and position angles are shown in Tab. 2.

The inclination of 33° ± 5 found here for CQ Tau is in the middle range of values found in the literature, which range from 63° (Testi et al. 2001) to 14° (Dent et al. 2003); in between we can find 48° ± 5 (PA = 105° ± 5) (Eisner et al. 2004).

For HD 163296, the disk inclination of 60° ± 5° is in good agreement with that found by Mannings & Sargent (1997) of 58°. Concerning the position angle of the disk, Mannings & Sargent (1997) found 126° ± 3 with CO observations. Grady et al. (2001) found 140° ± 5 thanks to optical coronographic images. We found a value of 105° ± 10 when fitting our mid-IR data. This difference in the position angle could be related to the fact that our data are only sensitive to warm dust of which geometry could slightly differ from that seen at shorter or longer wavelengths, if the disk contains for instance non axisymmetric structures.

5. Modeling

We have used a relatively simple parameterized model to investigate the dependence of the emission in the mid-IR on each parameter. We consider disks heated by irradiation from the central star. The density profile of the gas is parameterized as a function of \(r\) (radius) and \(z\) (vertical height above the disk mid-plane):

\[
\rho(r, z) = \frac{\Sigma(r)}{\sqrt{2\pi H_p(r)}} \exp\left(-\frac{z^2}{2H_p(r)}\right).
\]
and it is assumed that the dust is well mixed with the gas. The surface density is assumed to follow a power-law: \( \Sigma(r) = \Sigma_0(r/r_0)^{-p} \), with \( r_0 \) a fiducial radius. The scale height of the disk \( H_p(r) \) is also assumed to be a power-law: \( H_p(r) = H_0(r/r_0)^q \). The inner radius of the disk \( (r=R_{in}) \) is located at the dust evaporation radius \( (1400 \text{ - } 1500\text{K for silicate dust}) \). The inner boundary (rim) is directly exposed to the stellar flux and is puffed up since it is hotter than the rest of the disk. Here, we mimic the puffing-up of the rim predicted by DDN01 by a specified value of \( H_{p,\text{in}} \) at \( r = R_{in} \), which is a parameter of the model. It should be noted that whether such an inner rim is indeed puffed-up is still a matter of debate. Moreover, Isella & Natta (2003) have shown that the rim is probably rounded-off due to the density-dependence of the dust sublimation temperature. This effect is not included here.

For the dust opacities, we use those of Draine & Li (2001). We use a MRN (Mathis et al. 1977) distribution of grains \( n(a) \propto a^{-3.5} \) with a size between 0.01 and 0.3 \( \mu m \). It is the disk surface layer which dominates the SED in the mid-IR range. The emission of the surface is made by small grains which trace the disk geometry. We will focus in this paper on this component. Since the objects have no PAH (Polycyclic Aromatic Hydrocarbon) emission (or weak concerning HD 135344), we do not take into account this population of grains.

Once the density profile is set, the dust opacities and stellar parameters given, the code RADMC (Dullemond & Dominik 2004; Pontoppidan & Dullemond 2003) solves the temperature structure of the disk in a Monte-Carlo way using a variant of the algorithm of Bjorkman & Wood (1997). This Monte-Carlo code also produces the source terms for scattering, in the isotropic-scattering approximation. With a ray-tracing tool (which is part of the code RADICAL, see Dullemond & Turolla 2000 for a detailed description) the SED and images can then be produced and compared to the observations. Comparative images are obtained by first resampling the maps to CAMIRAS sampling and then by convolving them with the PSF.

6. Comparison model versus observation

For each object, the best model shall fit simultaneously the SED (Fig. 1) and the extension found at 20.5 \( \mu m \) with our observations (Fig. 3). Concerning HD 135344 and HD 163296, we used mainly the ISO spectrum to constrain the SED; as far as CQ Tau is concerned, IRAS photometry and BASS points obtained by Grady et al. (2003) are used. Figure 4 shows the structure of the disk in terms of pressure and surface scale height.

Multiple runs of the model are performed until a satisfactory fit to the observed spectrum and the extension found at 20.5 \( \mu m \) is obtained. In the fitting procedure, the stellar parameters \( (T_{\text{eff}}, M_*, R_*, \text{ see Tab. } 3) \), the dust evaporation temperature (i.e. the position of the inner rim) at 1400 K, the outer radius and the inclination of the disk, the dust composition and size distribution are fixed. Other parameters, such as the pressure scale height for the inner rim (eventually puffed-up) and the outer pressure scale height \( (H_0) \), the power-law index of the pressure scale height (i.e. \( q \)) which has been fixed in the case of flared disk to 9/7, a value determined by hydrostatic equilibrium (Chiang & Goldreich 1997), the mass of the disk and the power-law index of the surface density (i.e. \( p \)) are estimated. Fitting the SED gives one solution among several degenerate combinations. A minimum value of the outer radius is derived from 20 \( \mu m \) observations, which is a very strong constrain on the true disk size, thus removing largely the degeneracy on the set of model parameters.

As first guesses, we used those parameters found when fitting the SED by Dominik et al. (2003) for HD 135344 and 163296 and by Chiang et al. (2001) for CQ Tau. Trying to fit the SED, we focused mainly on the Near-IR and mid-IR regions. Indeed, those regions are the regions where most of the reprocessed stellar energy (by the disk’s surface layer) emerged, and therefore the most strongly affected by the model and the geometry of the disk.

Not all the parameters are sensitive to the spatial distribution at 20.5 \( \mu m \) (Tab. 4). The strong constrain that put the CAMIRAS images is the minimum outer radius, and we have to find a solution with all the free parameters to reproduce the shape of the SED, the extension and the total flux at 20.5 \( \mu m \).

For HD135344, the disk parameters deduced from fitting only the SED of HD135344 were close to those which allows to fit both the SED and our observations.

For CQ Tau, in addition to previous studies fitting only the SED, we had to take into account that the disk is quite extended at 20 \( \mu m \) (about 300 AU) and is observed with an inclination of 33° ± 5. The fast increase of the disk emission in the [10-30] \( \mu m \) range can be modeled only with a flared disk (with \( H_{p,\text{out}}/R_{\text{out}} > 0.1 \)). In the framework of our modeling, we found that the only manner to obtain simultaneously a quite low far-IR excess (as seen in the spectrum) with the observed extended 20 \( \mu m \) emission is a low-mass disk of only 0.005 M_\odot with a pressure scale height of 58 AU at 450 AU. The total flux in the infrared excess compared to the stellar flux is determined by the fraction of the central star energy intercepted by the disk. This covering fraction is linked to \( H_{p,\text{out}}/R_{\text{out}} \), where the disk geometry thickness is maximum. Here, this parameter is the same as the previous study (energy conservation) but for a different outer radius. That means that the disk is less flared than deduced earlier. We obtain for CQ Tau a disk mass 10 times smaller than already found (Testi et al. 2003; Chiang et al. 2001) and this mass only traces the small grains. The disk emission at mm wavelength is determined by the mid-plane grain and disk properties, and it is not affected by the nature of the surface dust. Consequently, in this paper, we have not tried to select the best parameters for the mid-
planar dust to fit mm observations. Our underestimated flux at mm wavelength suggests that there must be big grains in the disk mid-plane of CQ Tau to recover the measured flux at these wavelengths (Testi et al. 2003).

HD 163296 is classified as a group II object (interpreted as being surrounded by flat or a self-shadowed disk); it should be in principle much more difficult to resolve the disk in the mid-IR range. Surprisingly, some extended mid-IR emission at 20 μm, although less prominent than for group I objects, is however observed. In the modeling, we used as first guess the parameter found in Dominik et al. (2003), who modelized the SED with a flared disk cut at 50 AU. Here, we modified the large-scale pressure-scale-height in order to mimic a weakly flared disk. The SED is well reproduced with a disk having little flaring (Fig. 4 and Tab. 3) while the extension at 20 μm (Fig. 3) constrains the disk to have a minimum outer radius of 200 AU with a disk mass of 0.01 \( M_\odot \).

7. Conclusions and future work

We have shown the strength of mid-IR imaging to constrain the disk properties. There are still a very limited number of objects with extended emission spatially resolved and it is not yet possible to draw statistical conclusions about the spatial structure of disk around HAe stars. With the advance of mid-IR instruments on 8 meter class telescope, such as the VISIR (Lagage et al. 2004) instrument available on the MELIPAL Very Large Telescope (VLT) at the European Southern Observatory (ESO), higher angular resolution will be available and the field will further develop; more quantitative studies will be possible and the goal of retrieving detailed disk surface density profiles from the observations should be achievable.

Observations should not be limited to the 20 μm atmospheric window; observations in the 10 μm atmospheric window are also very promising, especially for those HAe stars whose spectrum features the so-called PAH bands features at 3.3, 6.2, 7.7, 8.6, 11.2, 12.7 μm. PAH bands are attributed to vibrational relaxation of UV-pumped Polycyclic Aromatic Hydrocarbon molecules containing about 50-100 carbon atoms (Allamandola et al. 1989; Puget & Leger 1989). Their emission, as a function of the distance \( r \) to the star, drops with a \( r^{-2} \) power-law, much slower than thermal emission from large grains in thermal equilibrium. PAHs emission is thus a promising probe to study flaring disks at large distances from the star, with the good angular resolution achieved now on large ground-based telescopes at 10 microns. Fitting by sophisticated models a combination of interferometric observations in the near- and mid-IR, which probe the inner-most disk regions, with single dish observations in the near and mid-IR which probe intermediate disk regions, is clearly the way to clear up the field in the next few years.

Fig. 3. Annular average intensity aperture normalized to the peak for the observations (full line), model (dashed line) and the PSF associated (dot-dashed line). We have constructed an image with the DD04 model that we have convolved with the PSF of the night associated. The error in the profile comes from the noise RMS in the image.
Table 3. Stellar properties and fit parameters. The stellar parameters of CQ Tau are taken in Chiang et al. (2001). For HD 135344 and HD 163296, the parameters are taken from Meeus et al. (2001) and van Boekel et al. (2005). $H_p^in/R_{in}$ characterizes the puffed inner rim. $q$ is the power-law index of the scale height and $p$ that of the surface density. $H_p^out/R_{out}$ characterizes the flaring angle of the disk. The last column is the flux at 20.5 $\mu$m calculated from the modeled image.

| Object      | distance (pc) | $M_\star$ ($M_\odot$) | $T_{eff}$ (K) | $R_\star$ ($R_\odot$) | $R_{in}$ (AU) | $H_p^in/R_{in}$ | $R_{out}$ (AU) | $H_p^out/R_{out}$ | $p$ | $q$ | $i$ (degrees) | $F$(20.5 $\mu$m) (Jy) |
|-------------|---------------|------------------------|----------------|------------------------|---------------|----------------|----------------|-------------------|-----|-----|---------------|------------------------|
| HD 135344 (DDN03) | 84            | 1.3                    | 6750           | 2.1                    | 0.24          | 0.065          | 800            | 0.21              | 0.8 | 9/7 | 60            | -                      |
| (in this study)       |               |                        |                |                        |               |                |                |                   |     |      |               |                        |
| HD 135344 (DDN03) | 140           | 1.3                    | 6750           | 2.1                    | 0.24          | 0.065          | 200            | 0.12              | 0.8 | 9/7 | 45            | 5.7                    |
| HD 163296 (DDN03)   | 122           | 2.5                    | 10500          | 1.7                    | 0.45          | 0.033          | 50             | 0.07              | 0.2 | 9/7 | 65            | -                      |
| (in this study)       |               |                        |                |                        |               |                |                |                   |     |      |               |                        |
| HD 163296 (DDN03)   | 100           | 2.5                    | 10500          | 1.7                    | 0.45          | 0.033          | 200            | 0.05              | 1.07 | 60  | 16.6         | -                      |
| HD 135344 (DDN03)   | 100           | 1.7                    | 7130           | 1.3                    | 0.23          | 0.0002         | 180            | 0.13              | 1.5 | 9/7 | -             | -                      |
| (in this study)       |               |                        |                |                        |               |                |                |                   |     |      |               |                        |
| HD 135344 (DDN03)   | 100           | 1.7                    | 7130           | 1.9                    | 0.23          | 0.018          | 450            | 0.13              | 0.3 | 9/7 | 33            | 20                     |

$^a$ Disk size compatible with new measurement due to the re-evaluation of the distance.

Table 4. Effects of the free parameters of the model on the SED and spatial distribution of the 20.5 $\mu$m emission in the CAMIRAS image.

| Parameter | Influence on SED | Spatial distribution at 20.5 $\mu$m |
|-----------|------------------|-------------------------------------|
| $\Sigma_0$ | Influence on the total flux in the mid-IR and more strongly for $\lambda \geq 60$ $\mu$m | No influence |
| $p$       | No influence in the mid-IR | little influence |
| $H_p^in/R_{in}$ | modify contrast mid/near-IR (structure inner rim/shadow) | No influence (inner rim + shadow in the first pixel) |
| $q$       | modify the whole shape of the SED | large influence |
| $H_p^out/R_{out}$ | modify flux in the mid and far-IR | little influence |
| $R_{out}$ | modify far-IR emission | large influence |
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Fig. 4. Modeled spectrum (dashed line) between 1 and 100 µm. For HD 135344 and HD 163296, the ISO spectrum is overplotted in bold line. For CQ Tau, there are some photometric points from Grady et al. (2005); we have added the one from this study at 20.5 µm and IRAS points at 60 and 100 µm (full circle).

Fig. 5. Modelized vertical structure versus the radius. The pressure height scale ($H_p/R$) is in full line and the surface height scale (i.e. the height of the disk photosphere above the mid-plane $H_s/R$) is the dashed line.
Fig. 6. HD 163296 extended emission (central point source removed). West is up, North on the left. The pixel size is 0.29 arcsec. The disk has a surface brightness of 0.59 Jy/"^2 (S/N=27 for σ ~ 0.002 Jy) for the brightness part in the direction east/west and 0.23 Jy/"^2 (S/N=11) for the less bright part in the direction north/south. The noise is calculated using a sigma-clipping technique.

Fig. 7. CQ Tau extended emission (central point source removed). The same orientation as Fig 6. The pixel size is 0.29 arcsec. At 0.9" from the center, the surface brightness is 0.94 Jy/"^2 (S/N=15 for σ ~ 0.004 Jy). At 2" from the center, the surface brightness is 0.23 Jy/"^2 (S/N=5).

Fig. 8. HD 135344 extended emission (central point source removed). The same orientation as Fig 6. The pixel size is 0.29 arcsec. At 0.9" from the center, the surface brightness is 0.25 Jy/"^2 (S/N=15 for σ ~ 0.0015 Jy).