Dust disks around old Pre Main-Sequence stars: HST/NICMOS2 scattered light images and modeling

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Abstract. We present recent near-infrared detections of circumstellar disks around the two old PMS Herbig stars HD 141569 and HD 100546 obtained with the HST/NICMOS2 camera. They reveal extended structures larger than 350–400 AU in radius. While the HD 100546 disk appears as a continuous disk down to 40 AU, the HD 141569 environment seems more complex, splitted at least into two dust populations. As a convincing example, the full modeling of the disk surrounding HR 4796, another old PMS star, is detailed and confronted with more recent observations.

1. Introduction

The presence of massive disks with large gas to dust ratios around T Tauri stars is now well established (see a recent review by Dutrey 1999). Most recent near-IR and millimeter resolved images reveal optically thick disks in Keplerian rotation around single or multiple systems (e.g. GG Tau, Guilloteau et al. 1999). The dust appears to be the direct remnant of the primordial nebula and in a theoretical point of view, Weidenschilling et al. (1993) have shown that planetesimals may form during this stage.

It is also known that a large fraction of Main-Sequence (MS) stars are surrounded by material heated by their central star (see a recent review by Lagrange et al. 2000). Among these Vega-like stars, the β Pictoris circumstellar disk has been for a long time the only one imaged till recently. Submillimetric observations resolved for the first time dust emission around a few isolated MS stars (e.g. Greaves et al. 1998). Vega-like stars bear optically thin disks with small gas to dust ratios and continuously replenished in smallest grains by collision and/or evaporation among larger bodies (Backman et Paresce 1993). We have also direct (e.g. 55 Cnc, Butler et al. 1997) or indirect (β Pictoris: e.g. Beust & Morbidelli 2000) evidences for planets in these systems.

To better understand the full evolutionary scenario which lead to planetary systems formation, one must answer the following questions: what are the time-scales for dissipating disks? How does it depend on the spectral type and multiplicity? What are the dynamical dominant processes? How do gas and dust couple? What is the origin and nature of the dust? And finally, how does
it correlate with planet formation? To do so, one must study circumstellar disks of intermediate ages which represent the missing link between embedded young disks and evolved ones. Full spectral energy distributions (SEDs) give precious constraints on the chemical composition of the grains (e.g. HD 100546, Malfait et al. 1998 with ISO) but only qualitative informations on the dust distribution itself. Resolved data are needed on these objects.

In section 2, we present HST/NICMOS2 images of two Herbig (Vega-like?) stars: HD 141569 and HD 100546. We then discuss in section 3 how we can infer valuable constraints on the dust composition and distribution as well as on the dynamics of the system by combining all available data (SED and multi-λ images) through a consistent model. The case of HR 4796 will be detailed.

2. HST/NICMOS2 observations of HD 141569 and HD 100546

2.1. Targets and coronagraphic data

HD 141569 is a B9.5Ve star older than 10 Myr and 99\(^{+9}_{-8}\) pc away (Hipparcos measurements, Van den Ancker et al. 1998). This star was selected due to its IRAS infrared (IR) excess and also to the small intrinsic polarization (Yudin & Evans 1998) which are both clues for suspecting the presence of an extended optically thin disk. Moreover, the \(^{12}\)CO \(J=2-1\) detection by Zuckerman et al. (1995) ensures that gas is present at a level consistent with a young MS star.

The Herbig B9V star HD 100546, associated to the dark cloud DC 296.2-7.9, shows a strong IR excess peaked at about 25 \(\mu\)m (IRAS) due to a large amount of circumstellar material. The interpretation of photometric, polarization and spectroscopic events (e.g. Van den Ancker et al. 1998; Yudin & Evans 1998; Grady et al. 1997) remains uncertain but are characteristic of Herbig Ae/Be stars. HD 100546 is 103\(^{+7}_{-6}\) pc away and 10 Myr old according to Van den Ancker et al. (1998) and appears to be in a less evolved state than HD 141569.

We have performed, \(\lambda=1.6\;\mu\)m coronagraphic images of HD 141569 and HD 100546 with the HST/NICMOS2 camera. During the same orbit (so as to avoid PSF variations), a close star free of known circumstellar material so far and with similar spectral type and magnitude was observed. The reduction procedure consists in subtracting this reference star carefully scaled to the star of interest. The determination of the scaling factor is critical since a small change can significantly modify the photometry or in the worst case be responsible for the presence of not realistic features. It is found by azimuthally averaging the division between the star of interest and the reference star images.

2.2. Results for HD 141569

The final reduced image of HD 141569 shown in the left panel of Figure 1 is interpreted as an inclined dust ring peaked at 325\(\pm10\) AU from the star which scatters a small fraction (a few \(10^{-3}\)) of the stellar light. We derive from least-squares ellipse fitting (Figure 1, right panel) a position angle (PA) of 355.4\(^{\circ}\pm1^{\circ}\) and a disk inclination from edge-on of 37.5\(^{\circ}\pm4.5^{\circ}\) assuming that the disk is axisymmetrical with respect to the star. The radial surface brightness indicates that the outer edge of the ring steeply decreases with the distance from the star following a \(r^{-6.87\pm0.14}\) radial power law between 360 AU and 420 AU.
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2.3. Results for HD 100546

The reduced image of HD 100546 shown in Figure 2 also reveals a large elliptical circumstellar structure centered on and bright close to the star. This observation seems consistent with preliminary results from Pantin et al. (2000) obtained with the adaptive optics system ADONIS (ESO). Contrary to HD 141569, the HD 100546 disk does not shape a ring-like morphology but rather exhibits a continuous surface brightness distribution from the very close edge of the coronagraphic mask (∼40 AU) up to ∼350 AU. Isophotes ellipse-fitting constrains the PA of the disk to be 161°±5° and provides an upper limit of 51°±3° for the inclination of the disk with respect to the line of sight. The measured flux density of 84±8 mJy leads to a lower limit of 10^{-2} ± 15% to the scattered to photospheric flux, assuming that 55% to 60% of the total flux (star+disk) at 1.6 μm is due to thermal emission of very hot unresolved grains.

Basic radial power-laws fit very well the measured surface brightness profile with indexes -2.92±0.04 in the radial range 40 AU–250 AU and -5.5±0.2 further 270 AU. This implies a surface density roughly proportional to r^{-1} which coincides with results for less massive young stars (Dutrey et al. 1999 and references therein). Subtracting a synthetic disk, supposed to exhibit an axisymmetrical surface brightness as described above and inclined at 51° towards PA=161°, to
Figure 2. Scattered light image (1.6 µm) of the HD 100546 circumstellar disk (from Augereau et al. 2000). The lowest contour level is 17 mag/arcsec². The isophotes spacing is 1 mag/arcsec² in increasing order. The small panel in the upper right corner highlights both the fix patterns (labeled (a) to (i)) which blurs the image and the result of isophotes ellipse fitting. Plain lines: major and minor axis of the disk; dashed lines: position of spider arms.

The observed image reveals a NE-SW brightness asymmetry: more precisely, an excess of flux up to 1.1 mag/arcsec² at 0.5–0.6″ collimated in a direction which coincides well with the precise minor axis of the disk. Anisotropic scattering dust grains properties can explain this effect (e.g. Fig. 12 of Augereau et al. 1999a).

3. Modeling of dust disks around old PMS stars

3.1. Short overview of model assumptions

We developed an optically thin disk model able to reproduce, in a consistent way, scattered and thermal observations as well as SEDs. The dust distribution is described by a smooth combination of radial power-laws. The vertical distribution is assumed to follow an exponential shape with height depending on the distance from the star as a radial power-law. A key step in the modeling are the grain optical properties. We assume that grains are porous aggregates made of a silicate core coated by an organic refractory mantle (Greenberg 1986). Vacuum is assumed to fill the holes due to porosity which can be partially taken up by H₂O ice if the grain temperature falls below 110-120 K. We adopt two types of grains: amorphous "ISM-like grains" with porosity of about 50% and crystalline "comet-like grains" with large porosities (≈ 95%). Dust optical properties are computed using Mie theory. They depend on the complex index of refraction of the mixture and on the grain size a. We adopt the Maxwell-Garnett effective medium theory to compute these indexes and assume a collisional grain size distribution following a $a^{-3.5}$ power-law between $a_{\text{min}}$ and $a_{\text{max}}$. A more detailed description of model assumptions can be found in Augereau et al. (1999a).
3.2. An example: the HR 4796 disk

HR 4796 is a wide binary A0V star showing an infrared excess twice that of $\beta$ Pictoris and 5 to 15 times younger ($8 \pm 2$ Myr according to Stauffer et al. 1995). HR 4796 thus traces an evolutionary stage prior to that of $\beta$ Pictoris. We used the model described above to reproduce all available observations of the HR 4796 circumstellar system before 1999 (Augereau et al. 1999a). We find that two dust populations are required to account for the full SED compatible with thermal and scattered light resolved images.

The first population shapes a sharp and cold ring peaked at 70 AU from the star and made of "ISM-like grains". It is responsible for the 25 $\mu$m–1 mm dust continuum emission (see Fig. 11 of Augereau et al. 1999a). This implies grains larger than $a_{\text{min}} = 10 \mu$m which exactly corresponds to the blow-out size limit for grains produced by larger bodies on circular orbits. Also, such large bodies must be present either to reproduce millimeter measurements and to resupply the ring in smallest grains. Indeed, the 10 $\mu$m grains have very short time-scales under collisions ($\sim 1000$ yr) compared to the star age.

The second hot dust population is poorly constrained but would rather be composed of large crystalline grains at 9–10 AU from the star. This population is necessary to fit the 10 $\mu$m measurements which can not be reproduced with a single ring at 70 AU as sharp as required by scattered light images (Schneider et al. 1999). Interestingly, Telesco et al. (2000) latter marginally resolved the HR 4796 disk in N band ($\lambda = 10.8 \mu$m, $\Delta \lambda = 5 \mu$m) and show that a significant fraction of this emission comes from the outer ring. To check the consistency of proposed model with these observations, we convolve with the observed PSF from Telesco et al. (2000) a simulated disk at 10.8 $\mu$m. We also simulate a second disk at 12.8 $\mu$m since the N band is wide and since the disk emission across this band varies considerably (Fig. 11 of Augereau et al. 1999a). Figure 3 shows that the outer ring detection is predicted by the model at a level fully consistent with the observations given the spectral width of the N band. This implies in particular that the relative fractions of flux coming from the inner and outer disks are correctly predicted.

4. Concluding remarks

Further modeling, and especially dynamical modeling, is necessary to improve our knowledge of disks at different stages. In the case of HR 4796, Wyatt et al. (1999), Kenyon et al. (2000) and Klahr et al. (2000) have proposed models either to explain the ring-shaped structure nor brightness asymmetries. Further studies of HD 141569 and HD 100546 will allow to evidence which dynamical processes are generic or particular to such old PMS stars. But actually, very few observations of these circumstellar environments are available. As a new example, SED fitting of the HD 141569 disk using the radial dust distribution derived from the 1.6 $\mu$m images has predicted the presence of an inner dust population (Augereau et al. 1999b), recently confirmed by Fisher et al. (2000).

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Figure 3. Simulated thermal images of the HR 4796 disk convolved with the N band observed PSF from Telesco et al. (2000). To allow direct comparison, the contours levels are strictly the same as those of Figure 1a from these last authors. The white crosses indicate the position of outer ring.

References

Augereau, J.C., Lagrange, A.M., Mouillet, D. et al. 1999a, A&A, 348, 557
Augereau, J.C., Lagrange, A.M., Mouillet, D. et al. 1999b, A&AL, 350, 51
Augereau, J.C., Lagrange, A.M., Mouillet, D. et al. 2000, A&A, submitted
Backman, D., Paresce, F. 1993 in PPIII, eds. Levy, Lunine, p. 1253
Beust, H., Morbidelli, A. 2000, Icarus, 143, 170
Butler, R.P., Marcy G.W., Williams E. 1997, ApJ, 474, 119
Dutrey, A. 1999 in Planets outside the Solar System, Theory and Observations, eds. J.M. Mariotti and D.Alloin, NATO-ASI Series C, Kluwer, Dordrecht
Fisher, R.S., Telesco, C.M., Piña, R.K. et al. 2000, ApJL, 532, 141
Grady, C.A., Sitko, M.L., Bjorkman et al. 1997, ApJ, 483, 449
Greaves, J.S., Holland, W.S., Moriarty-Schieven G. et al. 1998, ApJL, 506, 133
Greenberg, J.M. 1986 in Light on Dark Matter, eds. Israel F., Reidel, Dordrecht
Guilloteau, S., Dutrey, A., Simon, M. 1999, A&A, 348, 570
Kenyon, S.J., Wood, K., Whitney, B.A., Wolff, M. 1999, ApJL, 524, 119
Klahr, H.H., Lin, D.N.C. 2000, ApJ, submitted
Lagrange, A.M., Backman, D., Artymowicz, P. 2000 in PPIV, in press
Malfait, K., Waelkens, C., Waters, L.B.F.M et al. 1998, A&AL, 332, 25
Pantin, E., Lagage, P.O. 2000, A&AL, submitted
Schneider, G., Smith, B.A., Becklin, E.E. et al. 1999, ApJL, 513, 127
Stauffer, J.R., Hartmann, L.W., Barrado y Navascues, D. 1995, ApJ, 454, 910
Telesco, C.M., Fisher R.S., Piña, R.K. et al. 2000, ApJ, 530, 329
Van den Ancker, M.E., de Winter, D., Tjin A Djie, H.R.E 1998, A&A, 330, 145
Weidenschilling, S.J., Cruzz, J.N. 1993 in PPIII, eds. Levy, Lunine, p. 1031
Weinberger, A., Becklin, E.E., Schneider G. et al. 1999, ApJL, 525, 53
Wyatt, M.C., Dermott, S.F., Telesco, C.M. et al. 1999, ApJ, 527, 918
Yudin, R.V., Evans, A. 1998, A&AS, 131, 401
Zuckerman, B., Forveille, T., Kastner, J.H. 1995, Nature, 373, 494