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Anatomy of a Flaring Proto-Planetary Disk Around a Young Intermediate-Mass Star

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While planets are being discovered around stars more massive than the Sun, information about the proto-planetary disks where such planets have built up is sparse. We have imaged mid-infrared emission from polycyclic aromatic hydrocarbons at the surface of the disk surrounding the young intermediate-mass star HD97048 and characterized the disk. The disk is in an early stage of evolution, as indicated by its large content of dust and its hydrostatic flared geometry, indicative of the presence of a large amount of gas well mixed with dust and gravitationally stable. The disk is a precursor of debris disks found around more evolved A stars such as β-Pictoris and provides the rare opportunity to witness the conditions prevailing prior to (or during) planet formation.

Based on the growing number of known planetary systems (*1*) and on the wealth of observations of disks around young stellar objects (*2*, *3*), it is now well established that planets around main-sequence solar-type stars form in massive, gaseous and dusty proto-planetary disks that survive for several million years around the nascent stars (*4*). The situation is less clear for stars of more than ≈2 solar masses. Such stars have a much higher luminosity than solar-type stars and, according to models, processes like photoevaporation may be at work clearing the inner disk in a few million years (*5*). Whereas radial velocity surveys have just started to reveal planets around stars about twice as massive as the sun (*6*), current imaging observations of proto-planetary disks around stars with such a mass remain very sparse (*3*). Most resolved disks are debris disks around A-type stars that are on the main-sequence (*3*, *7*). In such disks, the gas has been dispersed and planets have probably formed already, as indicated by asymmetries and ring-like structures in the disks (*4*). The lack of well-resolved images of proto-planetary disks around much younger A stars, still on the pre-main-sequence, is due to the fact that such stars are less numerous than their solar-type equivalents, the T-Tauri stars, and in general located farther away from us. As a result, the fall-back option to estimate the properties of the disks around these stars has been to fit their spectral energy distribution (SED). By doing so, the pre-main-sequence stars of intermediate mass (≈ 2 - 4 solar masses), the so-called Herbig Ae (HAe) stars, have been classified in two groups; group I members feature a rising SED in the 10–60 microns wavelengths range (mid-, far-infrared (IR)), whereas group II members feature a flatter SED (*8*). The preferred physical interpretation is that group I disks are flared, and group II disks are geometrically flatter. A flaring disk is a disk for which the ratio disk thickness over distance to the star, H/r, increases with r; then any point at the surface of such disks receives direct light from the star, and the disk intercepts a significant part of the stellar radiation out to large distances. Half of the intercepted light is re-radiated away from the disk and the other half down into the disk's deeper layers, providing additional heating to the dust in the optically thick disk interior, which re-radiates in the mid-, far-IR and sub-millimetre wavelengths. The information provided by SED-fitting remains limited, as numerous disk parameters are assumed or not uniquely determined [e.g., (*9*)]. Direct measurements from imaging are therefore required to unambiguously constrain more parameters, such as the disk overall shape (outer radius, height) which determines the amount of starlight captured by the disk. Imaging of disks has been obtained either by observations of the starlight dust scattering in the visible and near-IR radiation or of dust thermal emission or CO lines in the millimetre (*3*, *10*, *11*). Scattered starlight observations suffer from the limited contrast offered by imaging devices and millimetre observations suffer from limited spatial resolution.

A new approach to image disks around HAe stars uses the fact that about half of them have prominent infrared emission bands (IEBs) at 3.3, 6.2, 7.7, 8.6, 11.3 microns (*12*). These IEBs are believed to arise from the cooling of transientlyheated polycyclic aromatic hydrocarbons (PAHs) which can be excited by the intense stellar UV radiation (*13*). For a flaring disk, the PAHs at the surface of the disk are in direct view of the central star and can be excited; the resulting IEBs emission provides unique information on the disk structure up to large distances from the star. In addition, observing in the mid-IR alleviates the problem of too much contrast between the photospheric and disk emission. We have thus undertaken a program of imaging "nearby" HAe stars with VISIR, the Very large telescope Imager and Spectrometer in the mid-InfraRed, at the European Southern Observatory (ESO) (*14*). One of the first targets was HD 97048, a nearby group I HAe star of spectral type Be9.5/A0 located in the Chameleon I dark cloud, at a distance of 180 pc (*15*). The star has a temperature of 10 000 K, a luminosity (L_*) of 40 solar luminosities and a mass (M_*) of 2.5 solar masses (*15*). It is surrounded by a large amount of circumstellar material left from the star formation process, as indicated by the large IR excess (L_{IR}) observed in the SED; L_{IR}~0.40L_* (*16*). Mid-IR extended emission has been detected on scales of a few thousand AU and modelled as originating from a dust shell with an inner cavity of 180 AU in radius (*17*). Recent long-slit mid-IR spectroscopic observations have revealed a strong resolved emission from the inner region (*18*). Imaging this region with the high angular resolution offered by a 8 meter size telescope would be a direct way to assess whether HD97048 is surrounded by a flaring disk, as expected from its rising mid-, far-IR SED (*12*).

The observations of HD 97048, conducted on 17 and 19 June 2005, were performed with filters centred on the IEB at 8.6 microns and on the adjacent continuum at 9 microns. The classical mid-infrared observing technique of chopping and nodding was used, with a chopper throw of 10" (north-south) and a nodding throw of 8" (east-west). The 8.6 microns image (Fig. 1) reveals a large extended emission with a strong east-west asymmetry; the brightness isophotal contours are elliptical in shape and the ellipse centres are offset from the peak of emission. The offset increases when lowering isophote contours up to a semi-major axis of 2.1", (Fig. 2 and fig. S1). Such features are characteristic of a flaring disk, vertically optically thick at the wavelength of the observations and inclined to the line of sight (Fig. 3). Beyond 2.1", the offsets decrease. One possible explanation is that the disk then becomes vertically less optically thick. However, as an alternative explanation, the increasing contribution from the shell emission cannot be disregarded (*17*). We therefore restricted our study to the regions <2.1", corresponding to an astrocentric distance of 370 AU.

To retrieve quantitative information about the disk flaring in these regions, we have fitted the east and west brightness profiles with a simplified model. In this model, the PAH-emitting region is only located at the surface of the disk, whose height, H_s, varies with the astrocentric distance following a power law: $H_s(r)=H_0.(r/r_0)^\beta$, where H_0 is the disk surface height at the astrocentric distance r_0 and β the flaring index. We further assume that the spatial variation of the flux intensity, I, follows a power law: $I(r)=I_0.(r/r_0)^\delta$, where I_0 is the intensity at r_0 and δ the power law index. This hypothesis is only valid once the continuum emission contribution in the filter at 8.6 microns has been removed, which we have done by extrapolating the continuum emission observed at 9 microns (fig. S2). The result of the fit is shown in Fig. 4; the power law index δ for the intensity is found to be -2.3(+0.2,-0.06), close to the expectation of an index -2 for PAH emission (see fig. S2 caption), and the disk inclination is 42.8(+0.8/-2.5) degrees from pole-on. The scale height H_0 is 51.3(+0.7/-3.3) AU at r_0 = 135 AU and the flaring index β is 1.26(+/-0.05), in agreement with the value expected from hydrostatic, radiative equilibrium models of passive flared disks (*9*). In these models, the flaring structure is supported by the gas, whose vertical scale height, H_g, is governed by the balance between gas pressure and gravitational pull; the dust plays the key role to capture the starlight and then heat the gas collisionnally. The surface scale height, H_s, corresponds to the disk upper layers, where the starlight is intercepted by dust, and is about 4 times the gas height (*9*). Given the disk outer radius and scale height, the calculated amount of starlight captured by the disk is 43%, in good agreement with the observed IR excess (*16*).

Our observations also provide information about the disk mass. From the observed west–east asymmetry, we can infer that the vertical optical thickness τ at 370 AU is at least 1, implying that, at 370 AU, the dust mass surface density, Σ_o, is at least 1/1600 g cm^{-2} (*19*). Assuming that the astrocentric variation of mass surface density, Σ, follows a power law: $\Sigma(r) = \Sigma_o\ (r_{AU}/370)^q$, with an index q equal to -3/2, as the one inferred for the solar nebula or for extrasolar nebulae (*20*, *21*), we derive a disk dust mass of 40 Earth masses within 370 AU. This lower limit is compatible with the mass of 500 Earth masses derived from the observed 1.3 millimetre flux (*22*). The dust mass derived here is 3-4 orders of magnitude larger than the dust mass observed in debris disks and Kuiper belt-like structures found around more evolved A stars such as β-Pictoris, Vega, Fomalhaut and HR 4796 (*4*). The dust around these "Vega-like" stars is thought to be produced by collisions of larger bodies whose total mass in the case of β-Pictoris has been estimated to be of the order of 100 Earth masses (*23*). Therefore the dust mass observed around HD 97048 is similar to the mass invoked for the (undetected) parent bodies in more evolved systems. HD 97048's disk is thus most likely a precursor of debris disks observed around more evolved A stars. This is coherent with the HD 97048 age of about 3 million years estimated from evolutionary tracks. Another argument in favour of the early evolutionary stage of the system is the presence of a large amount of gas required to support the flaring structure revealed by our observations. Part of it has been recently detected thanks to observations of the molecular hydrogen emission at 2.12 microns (*24*). Assuming that the canonical interstellar gas to dust mass ratio of 100 holds, we estimate a total minimum disk mass of 0.01 solar mass, similar to the estimated minimum mass for the proto-planetary disk around the Sun (*20*).

Since the disk surrounding HD 97048 has a mass surface density comparable to that of the minimum proto-planetary nebula around the Sun, it is worth studying the prospects for planet formation in this environment. Planet formation models are divided in two categories: gravitational instabilities (*25*) and core accretion (*26*). It seems improbable that giant planets will form via gravitational instabilities, because the Toomre stability criterion coefficient, equal to $H_g/r\ M_*/(r^2\Sigma)$, is >> 1 (*27*). Considering the alternative core accretion scenario by which planets coagulate from initially micron-sized dust (*28*, *29*), it appears improbable also that cores of giant planets are present in the outer regions, due to the very long local orbital timescales. Whereas regions within 40 AU have not been resolved by our observations, it is tempting to extrapolate the surface density from the outer regions and investigate the predictions of planet formation models for the inner regions; inside 10 AU, planetary embryos may be present. Follow-up observations at higher angular resolution with the mid-IR instrument of the ESO VLT interferometer will allow probing these regions.

References and Notes

1. The Extrasolar Planet Encyclopaedia presents a comprehensive list of all known exoplanets. It is available at the following URL: http://www.obspm.fr/planets
2. C. R. O'Dell, S. V. W. Beckwith, *Science* **276**, 1355 (1997).
3. A comprehensive list of spatially resolved disks is available at the following URL: http://www.circumstellardisks.org
4. J. S. Greaves, *Science* **307**, 68 (2005).
5. T. Takeuchi, C. J. Clarke, D. N. C. Lin, *Astrophys. J.* **627-1**, 286 (2005).
6. J. Setiawan *et al.*, *Astron. Astrophys.* **437**, L31 (2005).
7. B. A. Smith, R. J. Terrile, *Science* **226**, 1421 (1984).
8. G. Meeus *et al.*, *Astron. Astrophys.* **365**, 476 (2001).
9. E. I. Chiang *et al.*, *Astrophys. J.* **547**, 1077 (2001).
10. V. Mannings, A. I. Sargent, *Astrophys. J.* **529**, 391 (2000).
11. C. Grady *et al.*, *Astrophys. J.* **630**, 958 (2005).
12. B. Acke, M. E. van den Ancker, *Astron. Astrophys.* **426**, 151 (2004).
13. J. L. Puget, A. Leger, *Annual Rev. Astron. Astrophys.* **27**, 161 (1989).
14. P.-O. Lagage *et al.*, *The Messenger* **117**, 12 (2004).
15. M. E. van den Ancker, D. de Winter, H. R. E. Tjin A Djie, *Astron. Astrophys.* **330**, 145 (1998).
16. C. Van Kerckhoven, A. G. G. Tielens, C. Waelkens, *Astron. Astrophys.* **384**, 568 (2002).
17. T. Prusti, A. Natta, F. Palla, *Astron. Astrophys.* **292**, 593 (1994).
18. R. van Boekel *et al.*, *Astron. Astrophys.* **418**, 177 (2004).
19 V. Ossenkopf, Th. Henning, *Astron. Astrophys.* **291**, 943 (1994).
20. S. J. Weidenschilling, *Astrophys. & Space Science* **51**, 153 (1977).
21. M. J. Kuchner, *Astrophys. J.* **612**, 1147 (2004).
22. Th. Henning, A. Burkert, R. Launhardt, Ch. Leinert, B. Stecklum, *Astron. Astrophys.* **336**, 565 (1998).
23. P. Artymowicz, *Ann. Rev. Earth & Planet Science* **25**, 175 (1997).
24. J. S. Weintraub, J. S. Bary, J. H. Kastner, S. J. Shukla, K. Chynoweth, in Protostars and Planets V, B. Reipurt, D. Jewitt, K. Keil, Eds. (University of Arizona Press, Tucson, 2006), Proceedings of the Conference held October 24-28, 2005, in Hilton Waikoloa Village, Hawaii. LPI Contribution No. 1286., p. 8197.
25. R. H. Durisen *et al.*, in Protostars and Planets V, B. Reipurt, D. Jewitt, K. Keil, Eds. (University of Arizona Press, Tucson, 2006), in press; preprint at http://www.ifa.hawaii.edu/UHNAI/ppv.htm.
26. J. J. Lissauer, *Ann. Rev. Astron. Astrophys.* **31**, 129 (1993).
27. A. Toomre, *Astrophys. J.* **139**, 1217 (1964).
28. S. Ida, D. N. C. Lin, *Astrophys. J.* **604-1**, 388 (2004).
29. P. Goldreich, Y. Lithwick, R. Sari, *Astrophys. J.* **614-1**, 497 (2004).
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Supporting Online Material

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Figs. S1 and S2

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Fig. 1. Left panel: visir false-colour image of the emission from the circumstellar material surrounding the Herbig Ae

star HD 97048 after a deep exposure (36 minutes). VISIR's PAH1 filter was used; it is centered on the IEB at 8.6 microns and has a full-width at half maximum (FWHM) of 0.42 microns. The emission is widely extended as compared with the Point Spread Function (bottom left corner), obtained from the observation of the point-like reference star HD 102964, made 15 minutes before the observation of HD 97048. The measured FWHM of 0.33" is close to the diffraction limit of 0.28", also indicated on the figure. The pixel size is 75 milli-arcsec. The noise level is 1.6 mJy/arc sec^2. The photometry, calibrated with HD 102964, yields a total flux of 5.75 (+/- 0.2) Jy. Right panel : same image but with a cut at the brightness level of 4.4 10^{-3} Jy/arcsec^2 and a fit of the edge of the image by an ellipse. The dashed lines show the ellipse axis; the ellipse center is offset eastward from the peak flux, pointed out by the arrow.

Fig. 2. Offset from the peak flux of the center of the ellipses fitting the image of HD 97048 at various brightness level cuts, as a function of the length of the ellipse semi-major axis (see fig. S1).

Fig. 3. Sketch of a slice of a flaring disk. The observer is viewing the disk from below. The disk is inclined, from pole-on, by an angle i. The disk is optically thick to the ultraviolet and visible starlight along its mid-plane so that the PAH emission only arises from the disk "surfaces", indicated in yellow. When the disk is also optically thick vertically at the wavelengths of the observations (here in the mid-InfraRed), only the front disk surface is seen by the observer. Consider two points C and D of the front disk surface located at equal distances from the star (at O). Due to projection effects, the observer views the centre of emission from C and D at O', middle of JJ', offset from O. For a flaring disk, the disk height, H_s, increases with the distance r to the star, so that the apparent offset increases, as observed for HD 97048. When the disk is vertically optically thin, the front and bottom disk surfaces are both observable and the disk appears symmetrical with respect to the star.

Fig. 4. Fit of the observed east (upper data, solid curve) and west intensity profiles with a simple flaring disk model. The reduced χ^2 of the fit is 0.3, well below 1. The uncertainties in the data are the background noise and photometric uncertainties from the continuum subtraction (+/-5% for each image). The range in model parameters has been calculated by exploring the parameter space which leads to a reduced χ^2 < 1. Below 0.5", there is no data point because it is impossible to disentangle reliably the IEB emission from the much larger continuum thermal emission. The angular distance to the star refers to the projected distance on the plane of the sky.

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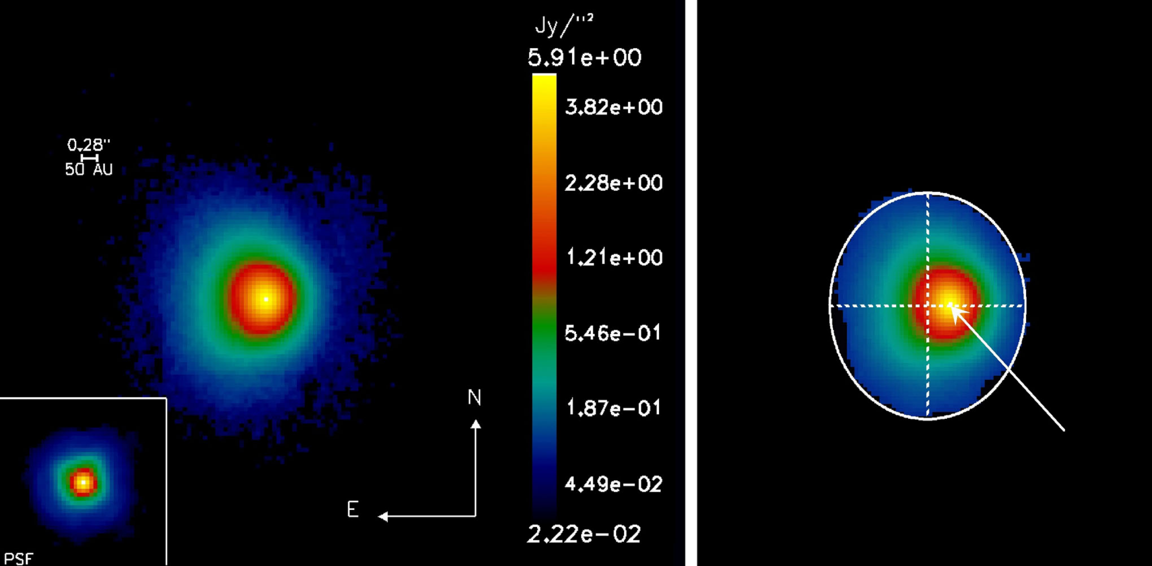
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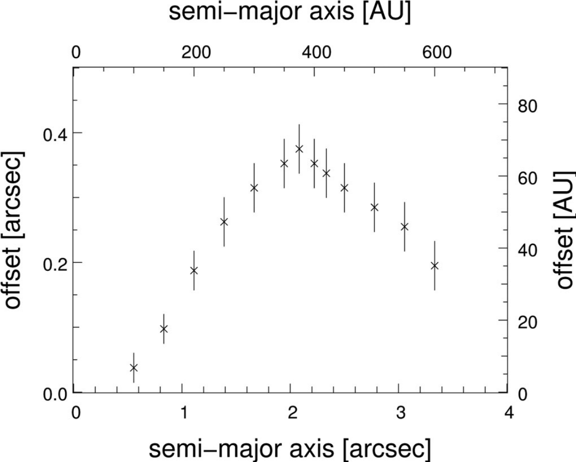
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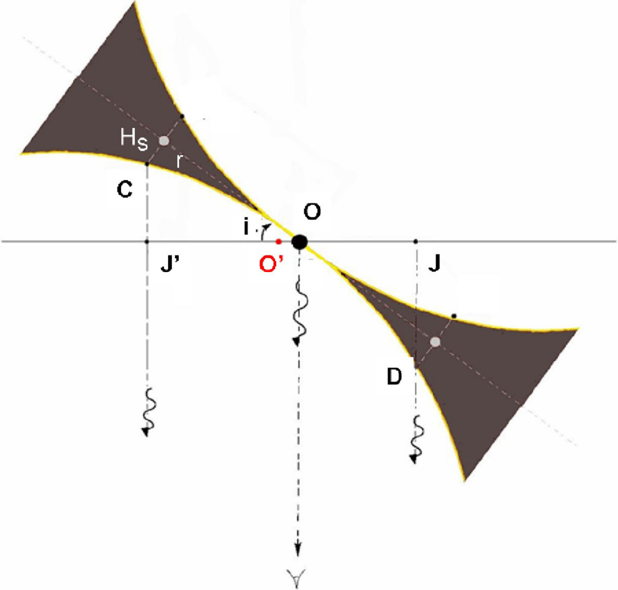
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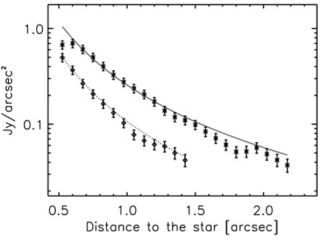
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