The Edge-On Circumstellar Disk of the Herbig Ae Star PDS 144N

Marshall D. Perrin mperrin@berkeley.edu
James R. Graham, Paul Kalas (UC Berkeley), Gaspard Duchéne (Obs. Grenoble),
Karl Stapelfeldt, Caer McCabe (JPL), Debora Padgett (SSC, Caltech)

See Perrin et al., ApJ, 2006 July 10, or astro-ph/060366

Edge-on disks, such as that of the well-known T Tauri star HH 30, have proven particularly useful for studies of disk morphology and dust grain growth, revealing a rich variety of disk and dust properties. But until recently, no such edge-on disk has been seen around any Herbig Ae or Be star. Here I present our recent discovery of an edge-on disk around the Herbig Ae star PDS 144N, made with the Lick Observatory adaptive optics system, and subsequent observations across a broad range of wavelengths. This rich multiwavelength dataset spans 0.5-70 microns and enables detailed modeling of the physical properties of this disk. In a two-for-one bonus, we have found that PDS 144N's binary companion, also a Herbig Ae star, possesses resolved circumstellar dust of its own. I describe what we have thus far learned about the disk morphologies, dust grain properties, PAH emission, and other characteristics of this intriguing system.

Introduction

Optically thick, edge-on disks are particularly well-suited to spatially resolved observations: The lack of direct starlight greatly reduces the dynamic range needed to image the disk, while modeling the observed light distribution can constrain the disk's physical parameters (D'Alessio et al. 2001; Watson & Stapelfeldt 2004). Edge-on disks are particularly valuable for such studies, as multiwavelength modeling can determine the wavelength dependence of the dust scattering opacity, which provides insight into dust grain properties (Cotera et al. 2001). Edge-on disks in binary systems may additionally shed light on aspects of the binary formation process and disk/disk interactions. Edge-on disks are known around a number of lower-mass T Tauri stars, but until now no edge-on disk has been seen around a Herbig Ae or Be star. We present here our discovery of such a disk around the Herbig Ae star PDS 144N.

PDS 144 was identified as a 5″ binary Herbig Ae system by the Pico dos Dias Survey, a spectroscopic followup to IRAS sources (Torres et al. 1995). Vieira et al. (2003) report a spectral type of A2IV for the northern member and A5V for the southern. We follow their notation in referring to these stars as "PDS 144N" and "PDS 144S", respectively. The physical association of these two stars has not yet been rigorously shown, but given their proximity and the fact that both are Herbig Ae stars which are currently accreting and thus of similar age, it is very likely that they are indeed bound and coeval.

PDS 144N's disk was discovered at Lick Observatory, as part of our ongoing adaptive optics polarimetry survey of Herbig Ae/Be stars (see Perrin et al. 2004). Subsequently, it has been observed with both Keck telescopes, Gemini North, HST, and Spitzer, creating one of the most extensive multiwavelength datasets on any resolved circumstellar disk. The disk is resolved at all wavelengths from 0.5 - 18 μm. This comprehensive dataset enables detailed modeling of the system, work which is currently in progress.

How Distant is PDS 144?

The distance to PDS 144 remains frustratingly uncertain. Previous estimates in the literature range from 140 to 2000 parsecs. The nearer distance was suggested by Teixeira et al. (2000), who assumed that PDS 144 lies in the Upper Scorpius–Ophiucus star forming region, based primarily on its position in the sky. The more distant estimate is from Vieira et al. (2003), who derived an optical photometric distance of 2000 pc for PDS 144N, and 1030 pc for PDS 144S.

Since we see PDS 144N only in scattered light, it seems certain that its 2000 pc photometric distance is an overestimate. But the photometric distance for the less-obscured PDS 144S may be accurate. We estimated the optical fluxes of PDS 144S from the combined UBVRI magnitudes and ΔV from Vieira et al., and then performed a nonlinear least squares fit to PDS 144S using a flux-calibrated ZAMS A5V stellar spectrum reddened by dust. The best fit parameters are d = 1030 ± 130 pc, A_V= 1.1 ± 0.46, R_V= 3.25 ± 0.65.

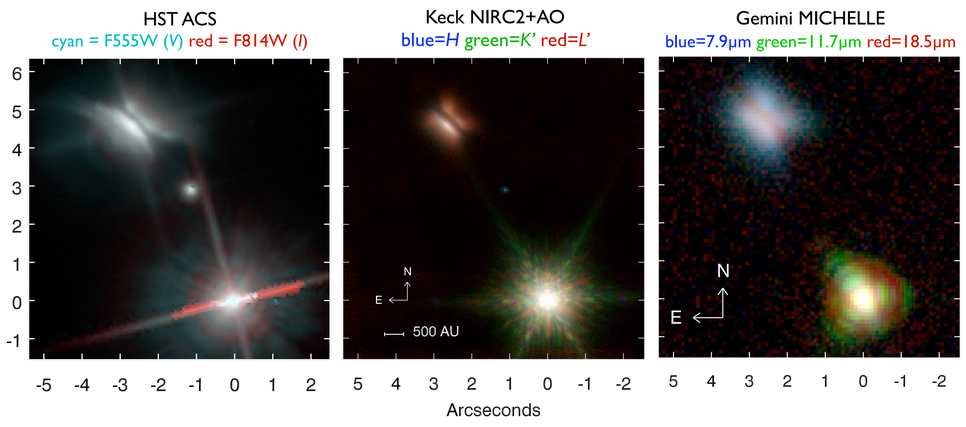
The optical photometry from Vieira et al. seems to rule out any assocation of PDS 144 with Upper Sco at 140 pc. Known Herbig Ae stars at the distance of Upper Sco are either some 3-5 mag. brighter at *V* than PDS 144 (e.g. KK Oph, HD 163296, or TY CrA) or are embedded objects much redder than PDS 144S (e.g. Elias 1, which has V − R = 2.1, versus 0.63 for PDS 144 from Vieira et al.).

Future work is certainly needed to pin down the distance to PDS 144 more precisely! An analysis of recent optical photometry from HST ACS is in progress. For the moment we will adopt 1000 ± 200 pc as a working estimate. However, this 1 kpc distance is not without some difficulty. Combined with a galactic latitude of +21°, this distance implies that PDS 144 is 360± 70 pc above the Galatic plane, a surprising location for such a young system. The resolution of this puzzle remains unclear.

References

Cotera, A. et al., 2001, ApJ, 556, 958
D'Alessio, Calvet, & Hartmann, 2001, ApJ, 553, 321
Perrin, M. D., et al., 2004, Science, 303, 1345
Perrin, M. D., Duchene, G., Kalas., P., & Graham, J. R. 2006, ApJ, 645, 1272
Pontoppidan & Dullemond, 2005, A&A, 435, 595
Teixeira, R., et al. 2000, A&A, 361, 1143
Torres, C., et al 1995, AJ, 109, 2146
Vieira, S. et al. 2003, AJ, 126, 2971
Watson, A & Stapelfeldt, K. 2004, ApJ, 602, 860

Observations



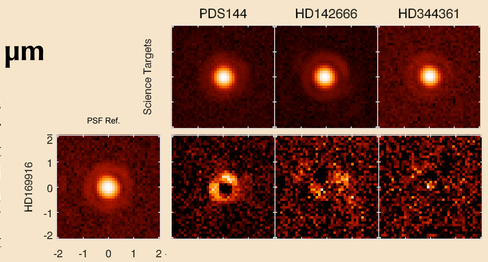
Above: PDS 144 in the optical, near-IR, and mid-IR. Our complete data set contains resolved images of the disk in 17 bands from *V* to *Q*, plus IRAC and MIPS photometry. At all wavelengths up to 18 μm, the exciting star within PDS 144N is hidden from direct view by the dark lane of an edge-on circumstellar disk. In the NIR, the dark lane is 0.15″ in height and extends 0.8″ in the orthogonal direction. Bright scattered-light nebulosity is visible on both sides of the disk plane, with the southeast side being brighter and therefore nearer, assuming the grains are forward scattering.

One of the most striking features of the nebulosity around PDS 144N is the pronounced flaring at its outside edges: it resembles an opposing pair of wingnuts, with the outer vertical extensions being the "wings". The wings are comparatively redder than the inner portions of the nebula; they are most pronounced in the 3.3 μm PAH and L filters. The presence of both a circumstellar disk and a surrounding dusty envelope with a bipolar cavity are required in order to model these wings; a disk alone does not reproduce the morphology. In our recent ACS observations, the envelope is visible over a larger spatial extent, and is cut at its outside edges with dark V-shaped disk shadows (Pontoppidan & Dullemond 2005). The very different colors visible in the mid-IR image are the result of different spectral features (PAHs in PDS 144N vs. silicates in PDS 144S); see the discussion at right.

The third source located between the two brighter stars is most likely an unassociated field star.

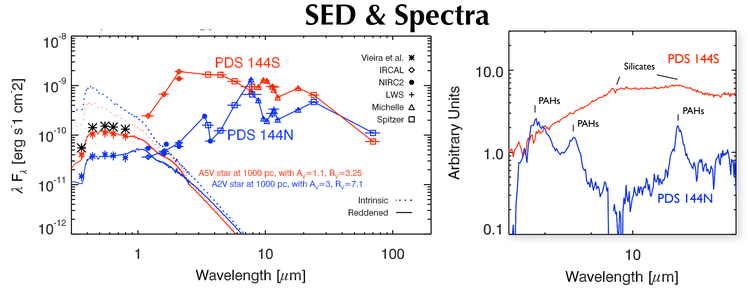
PDS 144S is resolved at 18 μm

The *southern star* in the binary also has substantial amounts of circumstellar dust, first indicated by IR excess but now directly resolved. In our Gemini Michelle 18 μm data, PDS 144S has a FWHM of 0.57″, versus 0.53″ for PSF references and other science targets. At shorter wavelengths it remains unresolved in our data. The donut shape visible at right is an artifact of the relatively simple PSF subtraction method shown here; more sophisticated analyses indicate that the dust is well-modeled by a 0.8″ FWHM Gaussian. Asymmetries in the resolved excess hint that the disk may be inclined to our line of sight by 22°, in contrast to its edge-on neighbor to the north.



Above: 18 μm PSF subtractions for a selection of HAEBEs, showing resolved circumstellar dust around PDS 144S only. The top row shows images of our science targets, while the leftmost column shows a PSF reference star. The intersection of each row and column displays the difference of each science target/PSF pair. At 18 μm, the PSF subtraction residuals for PDS 144S are statistically significant.

SED & Spectra



The spectral energy distribution (SED) for the PDS 144 system is shown above, along with very recent (July 4th!) Michelle low-res spectra. In addition to our own measurements, we include in the SED the optical points from Vieira et al. (2003). PDS 144S's SED rises sharply from 1 to 2 microns before roughly leveling off, while PDS 144N's SED is nearly flat throughout the optical and near IR before spiking repeatedly in the mid-IR. PDS 144N has copious emission from PAHs, with emission several times continuum visible in the 3.3, 7.7, 8.6, and 11.2 μm PAH bands. The SEDs of the two stars are strikingly dissimilar: While PDS 144N shows strong PAHs and has , PDS 144S entirely lacks PAHs. Instead it shows broad silicate features around 10 and 11 μm in emission, with the 11.2 μm shallow bump most likely due to crystalline olivine.

The difference in SEDs can be explained in part by geometry: edge-on PDS 144N is heavily extincted and shows the silicate feature in absorption, while a more nearly face-on PDS 144S allows us to see its inner disk, where warm silicates glow in emission and the near-IR SED rises steeply from thermal emission of hot dust. But this model does not explain the absence of PAHs around PDS 144S, which remains a mystery.

Conclusions

PDS 144N is the first Herbig Ae star with a clearly resolved edge-on circumstellar disk. Its central star is hidden at all wavelengths from 0.5-18 μm by an optically thick disk 0.8″ across. "Wings" extend vertically from the disk, due to light scattering off the walls of an outflow cavity in an infalling envelope. The wings are bright in several PAH features, indicating the presence of small aromatic grains fluorescing due to far-UV illumination. We have assembled an extensive multiwavelength dataset spanning from the optical to the far-IR. Multiwavelength modeling via Monte Carlo radiative transfer is an ongoing project.

One outstanding puzzle - and one which complicates efforts to model PDS 144 - is the great uncertainty in its distance. Optical photometry from the literature implies a distance of 1000 pc, but this results in a surprisingly large height above the galactic plane. Disk models at both 1000 pc and 140 pc can match the broad characteristics of PDS 144N, though with very different physical parameters.

The two stars of PDS 144 pose a fascinating set of contrasts: The northern is hidden behind an edge-on disk and has PAHs in abundance. The southern is resolved only at 18 μm, shows silicate emission features, and apparently lacks PAHs. Variations in disk inclination can explain only some of these differences. Yet the two stars have very similar spectral types: A2 and A5, respectively. PDS 144S surely puts out sufficient UV flux to energize any PAHs present around it, so their absence is a mystery. Many other questions remain open, including such basic properties as ages and mass, whether past interactions have affected the disks, and whether they possess bipolar outflows as seen around other young stars.

As the first Herbig Ae star with a clearly resolved edge-on disk, PDS 144N provides an exciting opportunity for comparison of disk properties between intermediate-mass and lower-mass stars, such as the well-studied HH 30. The geometry and binary nature of PDS 144 makes it a particularly good laboratory for detailed studies of circumstellar material, capable of giving insight into the growth of larger dust particles, and ultimately planets.

The support from the Lick, Keck, and Gemini observatory staffs is always excellent. Thanks in particular to Elinor Gates, Mark Kassis, Randy Campbell, and Scott Fisher. Sergio Vieira and Carlos Torres provided helpful discussions regarding their PDS survey observations.This project has been supported by the NSF Center for Adaptive Optics and NASA. M. Perrin is supported by a NASA Michelson Graduate Fellowship Program.