High-Resolution Infrared Images of the Dust Disk Orbiting the Main-Sequence Star HD 141569

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HD 141569 (= IRAS 15473-0346 = SAO 140789) is an Ae/Be star, classified as A0Ve (Dunkin et al. 1997). Hipparcos measured its distance as 99 ±9 pc and its visual magnitude as V=7.1 mag (van den Ancker et al. 1998), giving it an absolute luminosity of 22 L_{SUN} (M_V=2.1 mag). Its low luminosity for its color (B-V = 0.095, Teff=10,000 K) is consistent with that of a young main sequence star such as HR 4796A (Jura et al. 1998). Its age has been estimated at approximately 10 million years (Zuckerman et al., 1995). It was first identified as a star with infrared excess by Jaschek et al. (1986) from IRAS measurements; they noted that its observed 12µm flux is nearly eight times larger than predicted based on its stellar type and that its SED peaked at 60 µm. The disk emits substantially, with $\tau = L_{disk}/L_{star} = 8.4 \times 10^{-3}$ (Sylvester et al. 1996)

MIRLIN Mid-Infrared Images

MIRLIN Observations

- Observed: 5, 6, and 14 June 1998 (UT) at the Keck 2 Telescope
- Pixel Scale: 0.14" per pixel
- Direct Imaging

Integration Time	Filter
24.6 min	N5 λ_0=12.5µm, $\Delta\lambda$=1.2µm
36.3 min	Qs λ_0=17.9µm, $\Delta\lambda$=2.0µm
39.0 min	Q3 λ_0=20.8µm, $\Delta\lambda$=1.7µm

- Observation strategy
  5" chop between 4 and 5 Hz
  5" telescope nod
  Each double-differenced chop/nod set includes 4 images of the target.

PSF Observations:

- Observed immediately before or after target observations
- Observed at similar field rotator angle.

MIRLIN Data Analysis and Results

- Image locations in the double-differenced images were derived iteratively through the peak in a matched-filter correlation.
- Chop/nod sets were shifted and added to form a single image.
- The images at all three wavelengths clearly show an extended disk with similar morphology (figure 1).
- Images were modeled by minimizing the residual reduced chi-squared assuming a simple disk morphology. Radial flux profile, position angle, inclination angle, and center position of the disk were free parameters.
- Values for the position angle and disk inclination were adopted from the 12.5 µm filter fits, where the signal-to-noise was highest. Morphology at the longer wavelengths is similar.
- The best-fit values for the models presented in figures 1 and 2 are a position angle of -10 ±3° and an inclination angle of 54 ± 6°.
- Error estimates in the fit values were derived from the variation of the model fits with similar reduced chi-squared values.

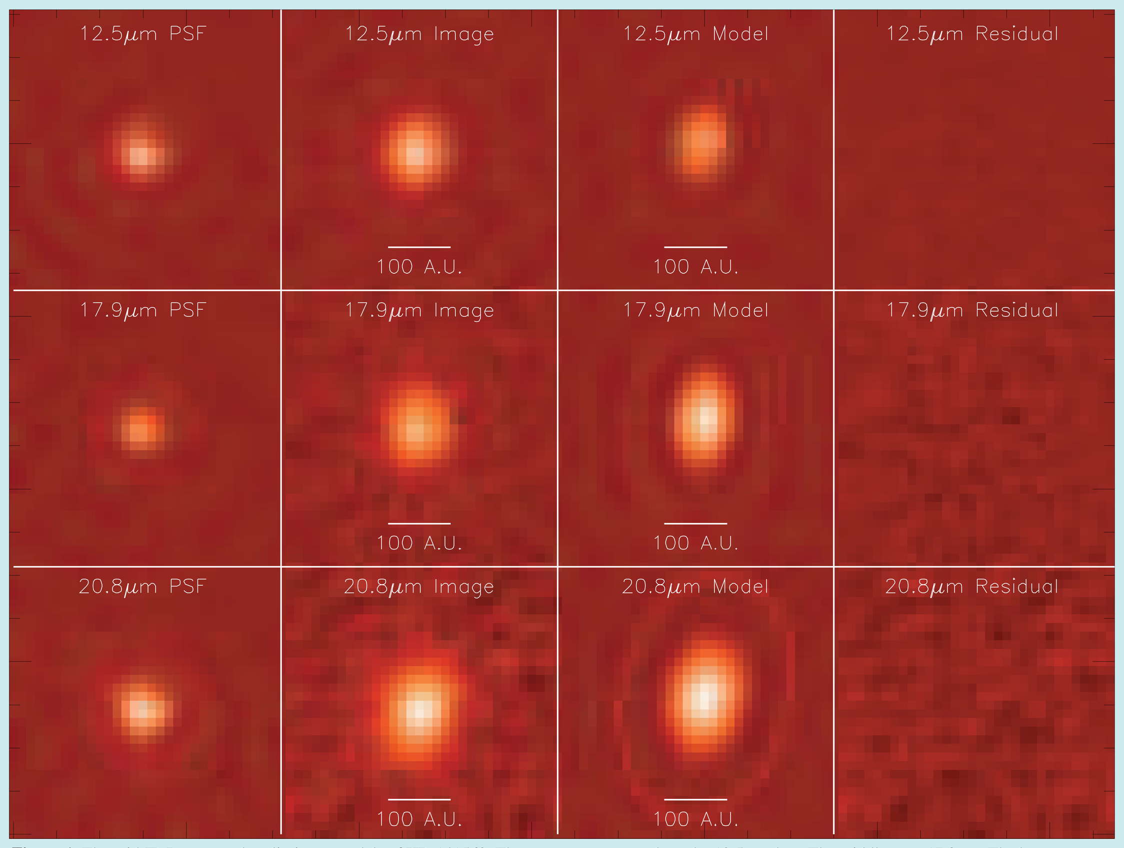

Figure 1. The mid-IR Images and preliminary models of HD 141569. The top row corresponds to the 12.5µm data. The middle row, 17.9µm. The bottom row, 20.8 µm. The first column represents the PSF star observation, whose peak pixel is scaled to the peak of the HD 141569 observation (second column). The third column is a simple model fit to this data, And the fourth column is the residual after the model is convolved with the PSF and subtracted from the data. The faint "rings" in the model images should not be regarded as real, as their flux level is similar to the noise in the observation

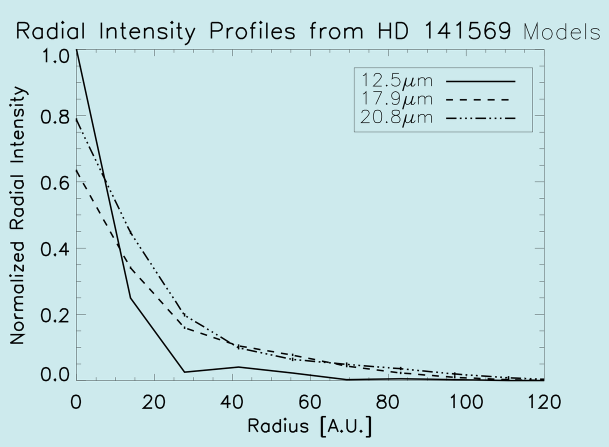

Figure 2. The normalized radial intensity profiles corresponding to the preliminary models in figure 1. A photospheric contribution has been subtracted..The difference between the 17.9 and 20.8 µm profiles outside of 40 A.U. are within the photometric noise.

NICMOS Near-Infrared Images

NICMOS Observations

- Observed: 27 September 1998 (UT)
- Pixel Scale: Camera 2 with 0.076" per pixel
- Direct Imaging (for Coronagraphic Acquisition):
  Integration Time: 1.4 sec
  Filter: F171M (λ_0=1.72µm, $\Delta\lambda$=0.07µm)
- Coronagraphic Imaging:
  Integration Time: 607.8 sec at each of 2 telescope orientations rolled by 8°.
  Filter: F110W (λ_0=1.1µm, $\Delta\lambda$=0.6µm)
  Data Collection: STEP64 and STEP32 MULTIACCUM sequences

PSF Observations:

- Observed: 7 November 1998 (UT)
- Coronagraphic Imaging:
  Integration Time: 640 sec at each orientation (only one used as PSF)
  Filter: F110W

Data Collection: STEP64 MULTIACCUM sequences

NICMOS Data Analysis

Basic Data Reduction:
- Flat Fielding:
  In-orbit F110W flats from August 1997 were augmented with contemporaneous flats in the region within 12 pixels of the center of the coronagraphic hole
- Bias Subtraction:
  Dark files taken on 20 September 1998 were used for bias subtraction
- Processing:
  3 MULTIACCUM sequences were obtained at each roll orientation. Each MULTIACCUM was reduced independently using the Nicreduce software (MacLeod 1997).

  The final 3 images from each roll were averaged together.

PSF Subtraction

There were 11 other sources observed with the F110W filter and the coronagraph as part of the EONS program (see poster 73.13). We chose the one which minimized the subtraction residuals to use as a point-spread-function star for HD 141569. The PSF of each star is different due primarily to thermal "breathing" of the telescope assembly and to the varying location of each star behind the coronagraphic hole.

The PSF was shifted using bi-cubic interpolation to the position which minimized the residuals in the diffraction spikes when it was subtracted from the target image. This was done independently for each roll position.

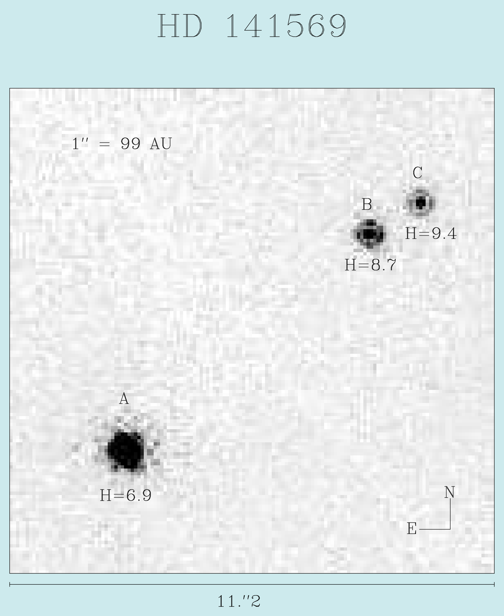

Figure 3. HD 141569 (A) is shown in the short 1.6 µm NICMOS image taken for coronagraphic acquisition. Also visible are two other stars -- B, which is 7.6" away, and C, which is 8.9" away, from A. The H-band magnitudes of the stars, determined from the acquisition images, are also given in the figure. The B/C system was typed by Lindroos (1985) as G0V, and he concluded that this system was not a physical companion to HD 141569 because its absolute magnitude would place it significantly further from the Sun. There are no spectroscopic or V-band photometric data in the literature for each star individually. Pirzkal et al. (1997) do give the K-band flux ratios of B and C with respect to A, making them 8.8 mag and 9.5 mag, respectively.

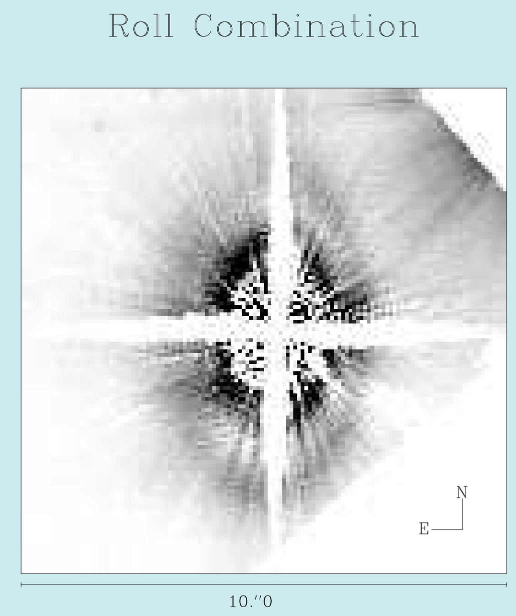

Figure 4. The NICMOS 1.1 micron image of the disk around HD 141569 is shown with a linear stretch. This image is the combination of two separate PSF subtracted images, made at the two telescope orientations, with HD 141569 behind the coronagraphic hole.

Clearly evident is an elliptical disk, approximately north-south in orientation, and therefore inclined (assuming it is intrinsically circular) to our line of sight. The disk extends at least 3.8" or 380 AU from the star. Also evident in this image is a gap in the disk at a radius of 2.5" or 250 AU from the star. The gap is approximately 40 AU wide. No companion object is seen in the region of the gap, to a limiting magnitude of 21.

The diffraction spikes have been set to zero level. Where possible, the pixels in the diffraction spikes in one image were replaced with data from the other image, but because the object was rotated only eight degrees between the two images, the spikes are still evident here. The high residual noise from the PSF subtraction in the central region means no useful information exists within a radius of about 24 pixels (1.8").

At the upper right (NW) of the image can be seen scattered light from star "B" (as labeled in figure 3).

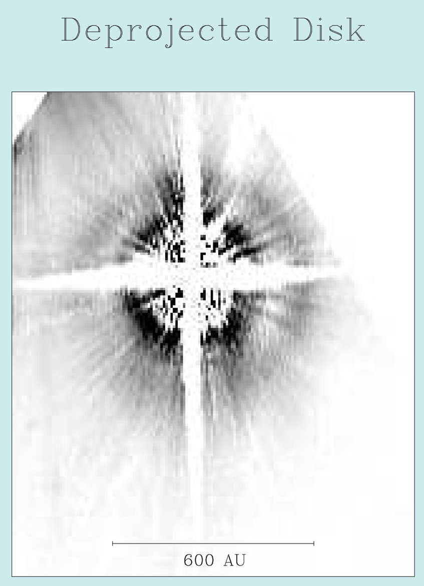

Figure 5. This image shows what HD 141569 would look like if we were viewing its disk face-on. Again, the gap in the disk is clearly evident.

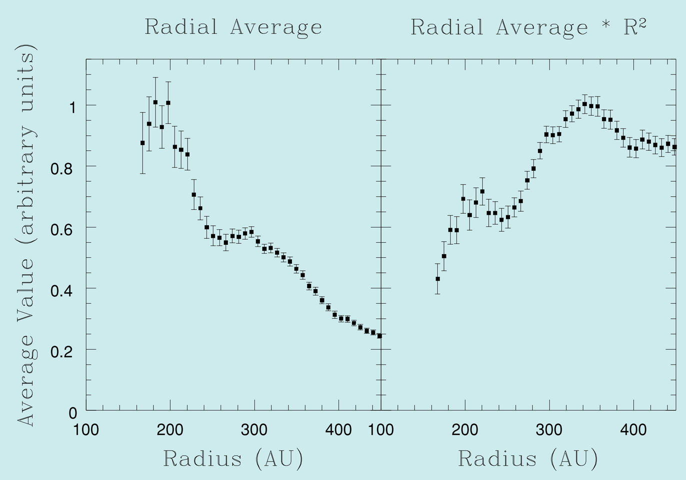

Figure 6. The left panel shows the radially averaged brightness of the disk around HD 141569. The right panel shows the profile multiplied by R^2 to compensate for the fall-off in the incident flux from the star which illuminates the disk. The peak surface brightness in the disk is about 0.2 Jy/sq. arcsec (17.5 mag/sq. arcsec).

Prior to radial averaging, the image was "deprojected" to make the disk appear circular (see figure 5). The gap is apparent in the radial profile at a radius of approximately 250 AU.

The fact that the disk seems to scatter more light at higher radii, as seen from the positive slope in the right-hand panel, suggests that it increases in thickness further from the star. The total amount of 1.1 µm reflected light from the disk is ~ 2×10^{-3} of that produced by the star.

Preliminary Conclusions

- Near and mid-IR images of the HD 141569 both show extended emission with similar morphology, corresponding to a dust disk with position angle -10° and inclination 54°. The reflected near-IR light is detected to a distance of at least 380 A.U. from the central star, and the mid-IR emission (12.5-20.8 µm) is detected to at least 100 A.U.
- The gap in the disk around HD 141569 (figures 4 & 5) is circumstantial evidence for an unseen sub-stellar companion body. Such an object could be driving material from the gap via an orbital resonance or by sweeping it out directly. The young age of the star means that such a body would have had to form in under 10 million years.
- Dust temperatures derived from the radial profiles are hotter than the equilibrium temperatures with the flux of the central star. Thus the thermal emission is probably dominated by small, inefficently radiating grains.
- The fraction of the 1.1 µm stellar flux which is reflected by the disk, 2×10^{-3}, is comperable to the fraction of the stellar flux absorbed and re-emitted in the mid and far-infrared, 8×10^{-3}.
- The disk around HD 141569 is highly reflective and probably flared, that is, much thicker at large distances from the star than near the center.
- The mid-IR radial profiles in figure 2 suggest that a large fraction of the mid-IR flux is emitted in an unresolved component. One possible interpretation is that the dust distribution around HD 141569 is at an intermediate evolutionary state between that of the young Ae star AB Aurigae (Marsh et al., 1995) and HR 4796A

Future Work

Improved models of the disk geometry, composition, and a dynamical model of the disk/companion interaction will be made.

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