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NICMOS Imaging of Dusty Circumstellar Disks

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Abstract. Using the coronagraph in the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument aboard the Hubble Space Telescope, we have imaged circumstellar disks around stars of age ~8 Myr. These dusty disks vary in physical size by over an order of magnitude and exhibit radial anisotropies in their brightness distributions which may be indicative of dynamical confinement or sculpting of the disk particles by unseen planetary bodies. We highlight results from three stars: HD 141569, HR 4796A, and TW Hydra.

1. Introduction

If planets are to form, their cores must begin to build before disks are destroyed; therefore to understand planet formation it is important to know how disk dust particle size and composition evolves. Disks at ages of $\sim 10^7$ yr are thought to exist at a critical juncture in evolution between when most of the original circumstellar material has disappeared and when embryonic bodies formed in the proto-stellar disk begin to collide and generate secondary debris.

We observed 19 disk candidates in our NICMOS program selected on the basis of known IRAS IR excesses with $L_{IR}/L_* \gtrsim 10^{-3}$. Using the NICMOS coronagraph, and taking advantage of the angular resolution and relative stability of the HST/NICMOS PSF, we pushed our investigations into previously and otherwise unreachable sensitivity ranges by reducing the background light at $1''$ to $\sim 10^{-6}$ of the peak stellar intensity. We imaged disks in about $1/3$ of our candidates with a wide range of sizes, shapes and surface brightnesses. Stars which are all $\sim 10^7$ yr old, including HD 141569 (Weinberger et al. 1999), HR 4796A (Schneider et al. 1999), and TW Hya (Weinberger et al. 2000b) have radically different disk morphologies suggesting that dynamical influences are already at work and planets may already be forming at this age.

2. Data Analysis

In the reduced and calibrated NICMOS images, scattered and diffracted light from the star still dominates the disk flux levels at radii of 1–5$''$, so in order to see any disk which may be present, a PSF must be subtracted. The detailed character of the HST PSF changes on multi-orbit timescales; hence some star subtractions produce much lower residuals than others. In our coronagraphic program, 15 stars were observed with the F110W filter and ~50 stars of spectral type A–K were observed with the F160W filter. Targets which do not show extended disk emission form a library of possible PSFs.

Each PSF star brighter than the target was registered using cubic convolution interpolation to the target, and the PSF which minimized the subtraction residuals in the diffraction spikes and in annuli between $0.''3$ and $4''$ was chosen. The magnitudes of the target and PSF were extrapolated from their H-band magnitudes, and the uncertainty in their flux ratio completely dominates the uncertainty in the photometry of the observed disk. A change of a few percent in the subtracted PSF flux can make an order of magnitude larger difference in the integrated disk flux density. All targets were observed at two telescope rolls, and the two PSF-subtracted images were rotated to a common orientation and averaged. Regions of the image obscured by the diffraction spikes in one roll were replaced where possible by uncorrupted regions in the other roll.

3. HD 141569

HD 141569, classified as B9.5Ve (Jaschek & Jaschek 1992), is a Herbig Ae/Be star at a distance of 100 pc. Our full results on HD 141569 are presented elsewhere (Weinberger et al. 1999, 2000a). We also direct the reader to the NICMOS coronagraphic results of Augereau et al. (1999 and this proceedings).

Scattered light imaging at 1.1 μm shows an elongated disk that is clearly evident at radii from ~1.6 to $4''$ (160 to 400 AU) from the star (Figure 1a). The disk major axis position angle is $356 \pm 5°$ and ratio of the minor to major axes of 0.63 ± 0.04. If the disk is intrinsically circular, the axial ratio implies an inclination of $51{\pm}3°$ from face-on. The azimuthally averaged disk surface brightness peaks at 0.3 mJy arcsec^{-2} at a radius of 185 AU and falls off to larger and smaller radii. At 250 AU an annulus of lower surface brightness, or a "gap" in the disk, can be seen.

The eastern side of the disk is $1.5{\pm}0.2$ times brighter than the western side. This difference is not an artifact of the PSF subtraction and can be explained by dust particles which preferentially scatter in the forward direction. The brighter side, therefore, is inclined toward us, and the ratio of forward to backward scattering implies an asymmetry parameter, g, of 0.11 in the analytic phase function of Henyey & Greenstein (1941).

The optical depth to visual absorption (τ) implied by the far infrared excess is $8.4{\times}10^{-3}$; if this is also the absorption optical depth at 1.1 μm, then the albedo of the scatterers is ~0.3. However, about $^1/_3$ of the mid-infrared luminosity arises from a region within 150 AU of the star (Fisher et al. 2000). So, the total infrared τ overestimates the optical depth seen in scattered light; in the region at $\sim 1.''9$ (190 AU), the albedo is probably more like 0.4. This is similar to the albedos of mineral mixtures and ices found in ISO spectra of Herbig Ae/Be disks (Malfait et al. 1998).

We have investigated two stars close to HD 141569 on the plane of the sky (hereafter HD 141569 B and C) via optical spectroscopy and near infrared imaging. Our spectra from the Keck Telescope show that they are of type M2

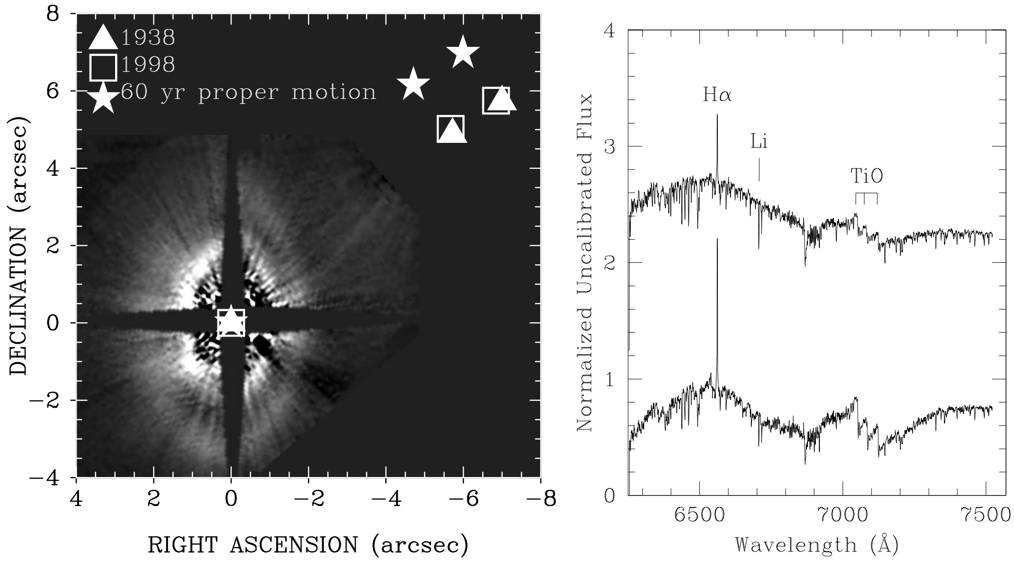

Figure 1. (a: left) NICMOS 1.1μm image of HD 141569 and the relative locations of the two companion stars in 1938 (filled triangles) and 1998 (open squares). If B and C were stationary background stars, the proper motion of A would predict a vastly different location for B and C in 1998 (filled stars). (b: right) Low-resolution spectra of HD 141569 B and C show that they are young M-type stars.

and M4, respectively and show Hα in emission and Li in absorption (Figure 1b). Furthermore, they have radial velocities consistent with that of A. Using astrometry from NICMOS and from historical measurements of Rossiter (1955), we see that the three stars have had the same proper motion over the last 60 years (Figure 1a). Therefore, they almost certainly form a triple star system, although they may not be bound. From their x-ray flux, lithium absorption and location on pre-main-sequence evolutionary tracks, the companions appear to be 5 Myr old. HD 141569 A is now one of the few stars with a circumstellar disk that has a well-determined age.

The inferred size of the grains in the HD 141569A disk, <5 μm (Fisher et al. 2000), implies that radiation pressure blows them away in at least an order of magnitude less time than our derived stellar age. Thus, they must be continuously regenerated, probably through collisions of larger bodies.

4. TW Hya and HR 4796A

Both TW Hya (K7 V) and HR 4796A (A0 V) are young ($\sim$8 Myr old) members of the eponymous "TW Hya Association" at a distance of $\sim$60 pc (Webb et al. 1999). At about the same age as HD 141569, these three stars show the variety of evolutionary influences at work on circumstellar disks over short timescales.

NICMOS images of HR 4796A at 1.1μm and 1.6μm show a ring at a position angle of 26.8° with a semimajor axis of 70 AU ($1.''05$). The disk appears to be

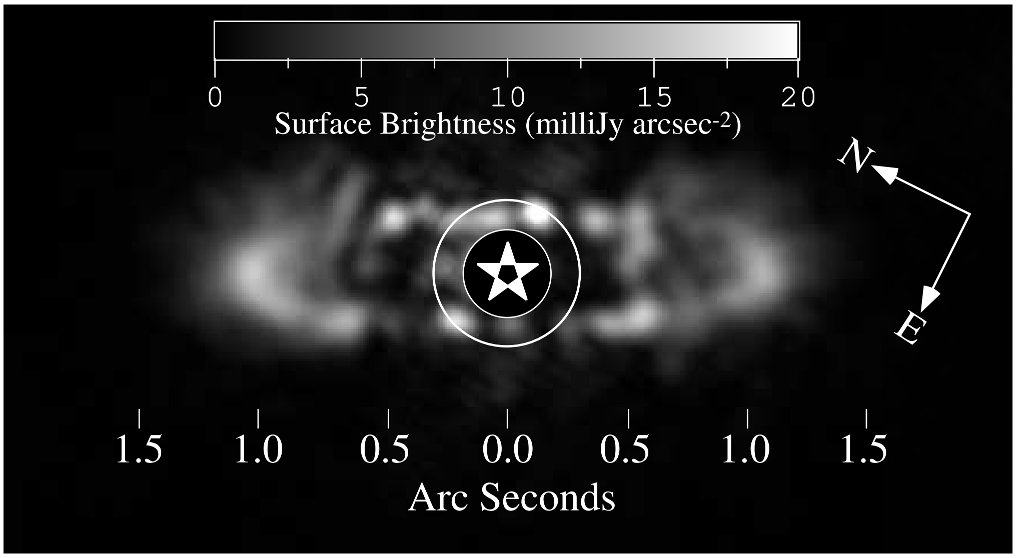

Figure 2. NICMOS 1.1μm image of HR 4796A after reprocessing to remove background due to PSF residuals. The outer white circle is the size of the coronagraphic hole, and the annulus is the width of the PSF. Thus the filled circle shows the region where the PSF is fully occulted. Compare to Figure 1b of Schneider et al. (1999).

abruptly bounded both interior and exterior to the mid-ring. A one-dimensional deconvolution along the major axis using a NICMOS PSF sets an upper limit to the ring width of 14 AU. The northeast ansa is brighter than the southwest ansa by ∼15%. The observed flux ratios of the disk to the central star are 0.0014 at 1.1 μm and 0.0024 at 1.6μm indicating somewhat red reflection. This implies a mean particle size that is large compared to these wavelengths. Assuming $\tau_{dust} \sim L_{disk}/L_*(\lambda)$, there is reasonable agreement between the scattered stellar flux in the near infrared and that which is absorbed in the visible and reradiated in the thermal infrared (Koerner et al. 1999, Telesco et al. 2000).

Since the time of the published images in Schneider et al. (1999), we have reprocessed the data to model and remove the PSF subtraction residuals. The background at the location of the ring was inferred by interpolating the background inside and outside the ring over a spatial scale of ∼5 pixels. This corrects for the local non-uniformity of the subtraction residuals. The result is that the ring can now be seen nearly all the way around the star (Figure 2). Most if not all of the lumpiness in the image is likely to be induced by incomplete and imperfect modeling of the PSF residuals and should not be interpreted as real azimuthal discontinuities, or clumps, in the ring.

Unlike the tightly confined ring of HR 4796A, the T Tauri star TW Hya is surrounded by a broad, face-on disk (Figure 3). From 0.″7 (40 AU) where the disk begins to dominate the PSF subtraction residuals, to 3.″1 (175 AU), the disk is visible at both 1.1 and 1.6 μm. The surface brightness declines smoothly with radius, peaking close to the star at 2–4 mJy/arcsec^2. The disk isophotes appear to be circular and assuming the disk is intrinsically circular, it is therefore

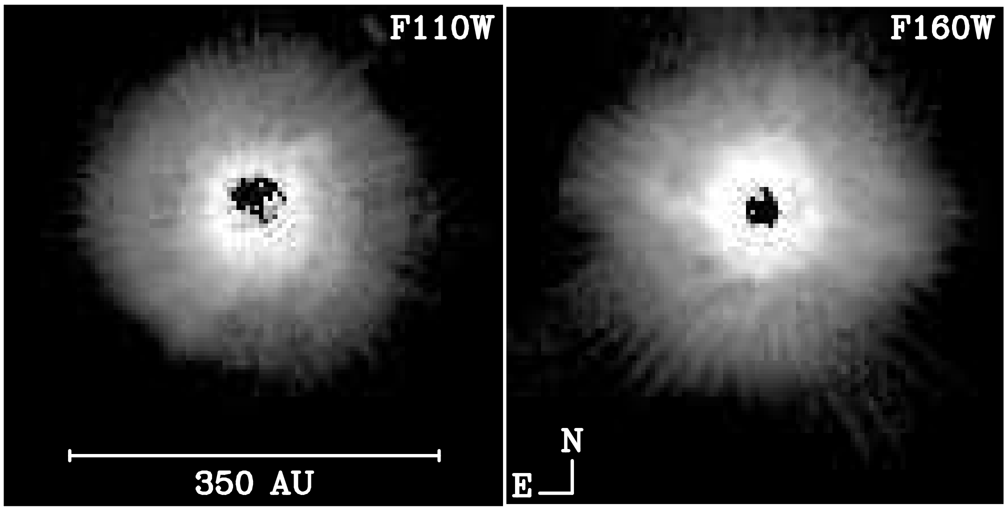

Figure 3. NICMOS PSF subtracted images of TW Hya at 1.1 and 1.6 μm.

viewed face-on. Between radii of 40 AU and 135 AU, the disk is well fit by a single power law, $r^{-2.6}$, at both wavelengths. Between 135 and 175 AU, the disk falls off more sharply. Visible light WFPC images also show the disk with approximately the same extent and surface brightness profile (Krist et al. 2000).

The average color of the disk is, within the uncertainties, exactly that of the star. Since the two observations were taken at different telescope orientations, the PSF features do not appear in the same place in the images from the two filters, so no color map can be made. The ratio of the total scattered light to the flux density from the star is 0.02 at both wavelengths, but the mid-far-infrared τ=0.2, so the disk must be optically thick. For single scattering by a geometrically thin, optically thick disk, the flux density per square arcsec goes as r^{-3} (Whitney & Hartmann 1992). This is steeper than the $r^{-2.6}$ we measured and clearly does not fit our data. Furthermore, the thin disk model does not reproduce the observed amount of scattered light at the distances from the star at which it is observed, but is low by a factor of $\sim 10^4$. The TW Hya disk therefore must be flared so that the outer parts of the disk are able to intercept and scatter stellar photons.

The amount of scattered light at any given radius is determined not just by the surface density of scatterers but also by the extinction along the line of sight from the star to that part of the disk. At $\sim$80 AU from the star, the disk scattered light is somewhat lower over a region of $\sim$20 AU. This depression in the amount of scatter could be caused by a small bump in the disk that creates a "shadow," or by a decrease in the surface density of the disk at that location. Either way, it may indicate dynamical effects.

In conclusion, we see that by an early age, 5–10 Myr, stellar disks can have dramatically different morphologies. The disks presented here span sizes of 70–400 AU. TW Hya's disk is optically thick whereas HD 141569 and HR 4796A's are thin; the destruction of gas and grains is expected to be faster in the luminous, massive, early-type stars. However, HD 141569 and HR 4796A are similar in spectral type, age, and amount of infrared excess, yet their disks differ greatly in size and character.

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