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Dust to Dust: Evidence for Planet Formation?

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Abstract.
We discuss the properties of several circumstellar debris disk systems imaged with the Hubble Space Telescope's Near Infrared Camera and Multi-Object Spectrometer in a survey of young stars with known far-IR excesses. These dusty disks around young ($\sim$ 5–8 Myr) unembedded stars exhibit morphological anisotropies and other characteristics which are suggestive of recent or on-going planet formation. We consider evidence for the evolution of populations of collisionally produced disk grains in light of the significant presence of remnant primordial gas in the optically thick disk of the classical T-Tauri star TW Hya; the dust-dominated and Kuiper-belt like circumstellar ring about the young main-sequence star HR 4796A; and a possible "intermediate" case, the complex disk around the Herbig AeBe star HD 141569A. Only a small number of debris disks have been imaged thus far in scattered light. Yet all show structures that may be indicative of dust reprocessing, possibly as a result of planet formation, and speak to the contemporary competing scenarios of disk/planet evolution and formation time scales.

1. Introduction

Warm dust around young stars has been inferred from thermal infrared excesses since IRAS, though until recently the expected "cold" dust component had been imaged in circumstellar scattered light only about β Pictoris. To begin to understand both the evolution and dynamics of circumstellar disks, and the nascent planetary systems which they may harbor, a multi-wavelength attack is required. Mid-IR observations can reveal and trace emission from warm dust. Colder disk components can be detected, and on larger spatial scales mapped, in the submillimeter. Resolved images of dusty disks, at near-IR and optical wavelengths, provide direct information on the spatial distribution of the disk grains. Until recently, however, such observations have been extremely difficult, given the very high disk-to-star contrast ratios, but when successful provide measurements of radial and azimuthal asymmetries in the dust brightness distributions and scattering properties (colors, phase functions, etc.). The presence of rings, gaps, clumps, warps and central holes seen in scattered light images of circumstellar disks may implicate the existence of embedded or co-orbital perturbers.

Studied extensively for fourteen years since first imaged by Smith & Terrile (1984), the disk around the Vega-like star β Pictoris served as the archetype and sole example of a dusty debris system seen in scattered light. Though now thought to be ~ 20 Myr old, throughout this period its age remained uncertain (and controversial) and was estimated from a few hundred Myr to about 10 Myr. The β Pictoris disk was found to possess at least five asymmetries attributed speculatively to dynamical interactions with unseen planetary bodies (Kalas & Jewitt 1995).

Space-based near-IR and optical coronagraphic imaging with the Hubble Space Telescope second generation instruments NICMOS and STIS has provided a powerful new tool for studying the circumstellar environments of nearby stars. Though only a very small number of spatially resolved images of dusty disk systems currently exist, these systems exhibit a diversity in disk sizes, morphologies, and properties (e.g., Figure 1).

The presence and morphologies of disk asymmetries and the derived properties and spatial distributions of the constituent grains may help to better constrain the ages and evolutionary status of the possible fledging extra-solar planetary systems. The presumed time scales for disk evolution will be tested and refined with an accumulation of observations of disk systems such as these.

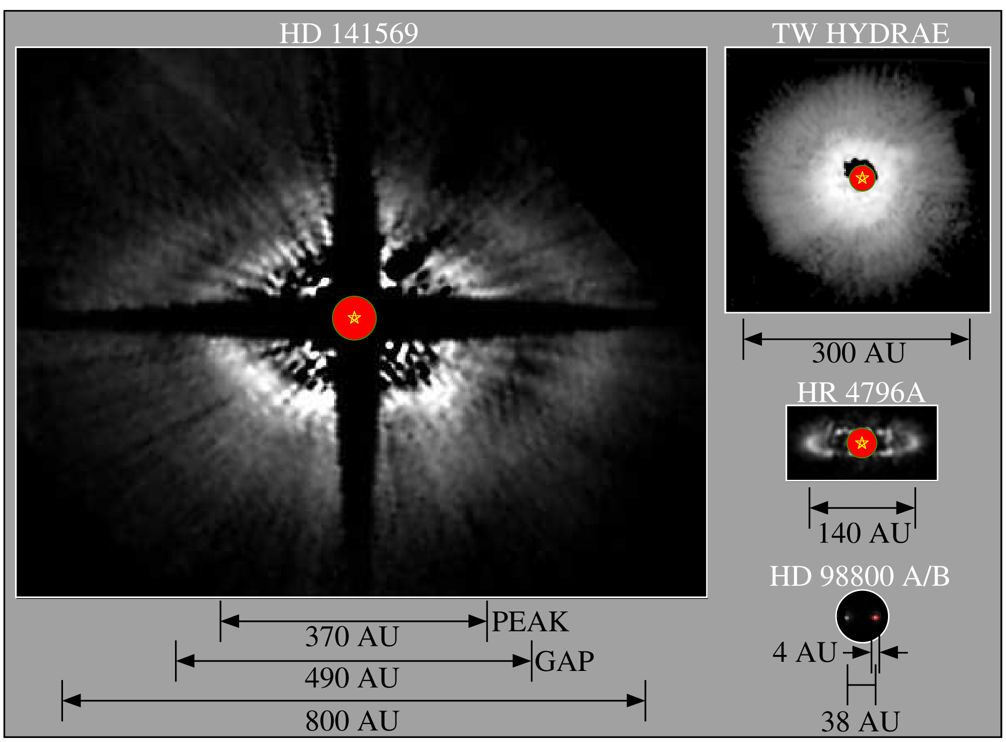

Figure 1. Comparative sizes and morphologies of dust/debris systems around $\sim$ 5-8 Myr stars imaged by NICMOS.

2. Disk Ages and Evolution

It is commonly conjectured that following the early stages of protostellar collapse, as the rocky cores of giant planets form (in $\sim$ 0.1–1 Myr), primordial dust in the circumstellar environment is both dominated (in the ratio of $\sim$ 100:1) by and locked to gas in the disk. Current theories of circumstellar disk evolution suggest a presumed epoch of planet-building, on the order of 1 Myr following the protostellar collapse, via the formation and agglomerative growth of embryonic bodies. Gaseous atmospheres will then accrete onto the giant planet cores on time scales of a few to about 10 Myr attendant with an expected significant decline in the gas-to-dust ratios in the remnant protostellar environments. During these times primordial dust (i.e., ISM-like grains) would be cleared from "typical" systems on shorter time scales by radiation pressure ($\sim 10^4$ yr), and by Poynting-Robertson drag ($\sim$ 1 Myr). In these critical evolutionary phases of newly-formed (or still forming) extra-solar planetary systems, the circumstellar environments become dominated by a second-generation dust population containing larger grains replenished through the collisional erosion of planetesimals, and perhaps, by cometary infall. As the circumstellar regions become optically thin (and the central stars become largely unembedded) the likely-evolving population of dusty debris at these early epochs become more readily observable in scattered light. This scenario suggests a morphological evolutionary sequence which could be modified by the perturbing influence of co-spatial bodies, and which may be explored (and validated) by high contrast imaging.

The presumption of evolution, however, requires a knowledge of the (relative) ages of disk systems, but such knowledge is not necessarily secure. Determining the ages of PMS and ZAMS stars depends strongly upon transforming observable quantities for placement on HR diagrams, and finding their isochronal ages with respect to their birthlines based upon theoretical evolutionary tracks. The fidelity (or lack thereof) of the stellar evolutionary models, and measurement errors in the observables (distances, luminosities, spectral temperatures, etc.) both contribute to uncertainties in derived ages (see Figure 2), which can be significant, particularly for earlier (Vega-like) stars (e.g., β Pic, HR 4796A, HD 141569A). The situation is improved if late spectral type coeval companions can be found, as is the case for HR 4796A (Jura et al. 1993) and HD 141569A (Weinberger et al. 2000), which are discussed in this paper. Three of the four disk systems we discuss (HR 4796A, TW Hya, and HD 98000A/B) are likely members of the TW Hya association (Webb et al. 1999), the nearest site of recent star formation to the earth. Together with HD 141569A, the small sample of young disk systems we discuss here are of similar ages ($\sim$ 5–8 Myrs), yet have very different properties.

3. Four $\sim$ 5–8 Myr Disk Systems

Dusty disks were spatially resolved and imaged around three young ($<$ 10 Myr old) stars. These disks show radial and hemispheric brightness anisotropies and complex morphologies, both possibly indicative of dynamical interactions with unseen planetary mass companions. From these and other observations we describe and compare of the properties of these dusty debris systems:

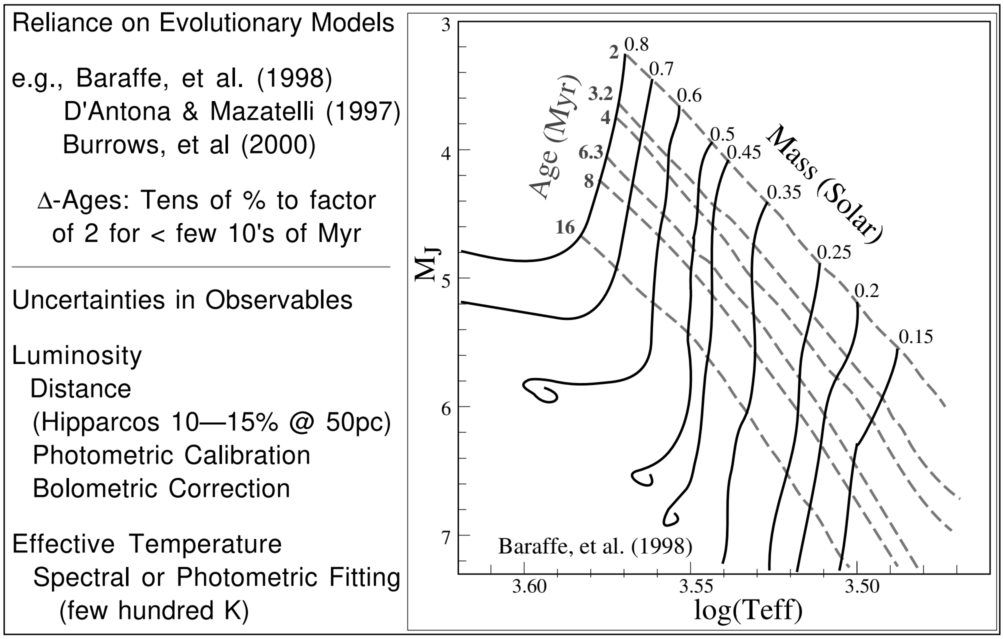

Figure 2. Stellar (and hence, disk) age determinations are dependent upon uncertainties in both stellar models and measurements.

a) TW Hya (a K7Ve T-Tau "old" PMS star) with a pole-on circularly nearly-symmetric disk, a radial break in its surface density of scattering particles, and possibly a radially and azimuthally confined arc-like depression.

b) HD 141569A (a Herbig Ae/Be star, $\sim$ 5 Myr) with a 400 AU radius inclined disk with a 40 AU wide gap at 250 AU.

c) HR 4796A (a A0V star, $\sim$ 8 Myr) with a 70 AU radius ring less than 14 AU wide and unequal ansal flux densities.

Additionally, our non-detection of scattered light and high precision photometry of a fourth system of similar age, HD98800 A/B, coupled with mid-IR imaging and longer wavelength flux density measurments, greatly constrain a likely model for the debris about the B component.

3.1. TW Hydrae (TWA 1)

TW Hya is an isolated classical T-Tauri star (Rucinski & Krautter 1983), exhibiting characteristic Hα and UV excesses and an IRAS far-IR excess with $L_{\rm disk}/L_{\star} \sim 0.3$. Both sub-millimeter continuum (Weintraub et al. 1989) and CO (Zuckerman et al. 1995) emission have been observed. With a Hipparcos determined distance of 56 $\pm$ 7 pc, and estimated age of 6 My, TW Hya is the archetypal member of the young stellar association which bears its name. These characteristics made TW Hya a prime candidate for scattered light disk imaging.

We found TW Hya to harbor an optically thick face-on disk (r $\sim$ 190 AU) seen in NICMOS F110W and F160W coronagraphic images, also imaged by Krist et al. (2000) with WFPC-2. Additionally, we recently observed TW Hya coronagraphically in the optical with STIS, and find the azimuthally averaged surface brightness profile is globally fit very well at all wavelengths with an $r^{-2.6}$ power law. The disk exhibits essentially gray scattering, implicating a characteristic particle size from the NIR colors of at least 2μm, probably evolved from a primordial ISM-grain population. Mid-IR spectroscopy of this disk, obtained at Keck by Weinberger et al. (2001), shows a broad $\sim 10\mu$m emission from amorphous silicates. Silicates of a few microns in size can explain the color, thermal extent, and shape of the mid-IR spectrum and further implicate grain growth from the original ISM population.

The brightness profile is explained by an outwardly flared disk with a central hole. Areal scattering profiles in the NIR bands reveal a break in the surface density of scatterers at R $\sim$ 105 AU, which may be indicative of sculpting of the disk grain distribution. At the same radius, an arc-like depression confined to about 90° in azimuthal extent is seen in both the higher spatial resolution STIS and WFPC-2 images (see Figure 3). This feature might arise from shadowing of the grains due to a discontinuity in the z-height distribution of the flared disk, or to relative deficit of scattering particles at that location. Either might arise from the gravitational effects of an embedded perturber.

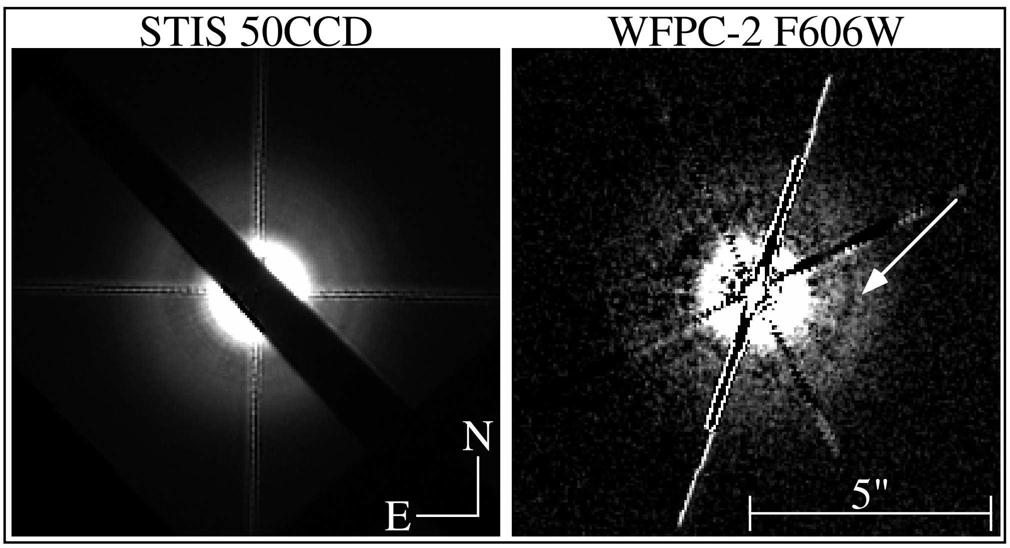

Figure 3. TW Hya circumstellar disk. Left - STIS (0.59 μm, FWHM 0.45μm). Right - WFPC-2 (0.60 μm, FWHM 0.20μm) at the same scale and orientation. Arrow indicates location of the dark arc-like feature (see text), also seen in the STIS image.

3.2. HD 141569A

The Herbig Ae/Be star HD 141569 (B9V, H=6.89, d = 99 $\pm$ 8pc, 2.3 $M_\odot$) was found to possess extended mid-IR emission to a radius of $\sim 1''\!.2$ at 12.5–20.8 μm Marsh et al. (2001). NICMOS 1.1 μm coronagraphic observations revealed a scattered light disk to a radius of at least 400 AU, exhibiting a complex morphology including a 40 AU wide gap in the surface brightness profile at a radius of 250 AU (Weinberger et al. 1999). The disk, with a total 1.1 μm flux density of 8$\pm$2 mJy beyond $0''\!.6$ (peak surface brightness 0.3 mJy arcsec^{-2} at 185 AU) is inclined to our line-of-site by 51°$\pm$ 3°. Augereau et al. (1999) saw a similar morphology in lower-resolution 1.6 μm observations, also obtained with NICMOS. No significant amount of scattered light was detected closer than r $\sim$ $1''\!.2$, so the regions of warmer dust probed in the mid-IR, and the outer (colder) regions imaged in scattered light are mutually exclusive.

The intrinsic scattering function of the disk results in a brightness anisotropy in the ratio 1.5$\pm$0.2, with the brighter side in the direction of forward scattering. The region of the gap may be partially cleared of material by an unseen co-orbital planetary companion. If so, the width/radius ratio of the gap implies a planetary mass of $\sim$ 1.3 Jupiters. This is consistent with a $<$ 3 Jupiter mass point-source detection limit at this radius, where we also estimate the albedo to be 0.35$\pm$0.05. HD 141569A is the brightest member of an $\sim$ 6.5:1 hierarchical triple system (ΔA($\overline{BC}$) = $8''\!.3$, $\Delta\overline{BC}$ = $1''\!.3$), where the presumed coeval M-dwarf dynamical companions were used by Weinberger et al. (2000) to improve the age estimate for the disk system, now $\sim$ 5 Myr. The companions probably influence the dynamics of the circumstellar disk.

3.3. HR 4796A (TWA 11A)

On 15 March 1998 NICMOS obtained the first scattered light image of a circumstellar debris disk since the discovery of the β Pictoris disk. With an age of 8 $\pm$ 2 Myr (Stauffer 1995), a spectral type of A0V, and possessing an M-dwarf companion, HR 4796A is similar to HD 141569A, yet the structure of its disk is very different. The dust in the disk about HR 4796A was found to be confined in a narrow ring 70 AU in radius, as had been suggested from mid-IR imaging by Koerner et al. (1998) and Jayawardhana et al. (1998), and $<$ 14 AU in width (see Figure 1). Earlier, Jura (1991) inferred the presence of large amount of circumstellar dust from IRAS excess and estimated $L_{\rm disk}/L_\star \sim 5 \times 10^{-3}$ (twice that of β Pictoris). Jura et al. (1995) noted their earlier 110K estimate of dust temperature indicated a lack of material at $<$ 40 AU, and inferred grain sizes $>$ 3μm at 40 $<$ r $<$ 200 AU given the time scales for disk-clearing. Schneider et al. (1999) reported on the morphology, geometry and photometry of the ring-like disk from well-resolved NICMOS coronagraphic images at 1.1 and 1.6μm from which, unlike TW Hya, the disk grains appeared to be red (J(F110W)-H(F160W) = 0.6 $\pm$ 0.2). Augereau et al. (1999) successfully reproduced the observed properties of the disk from all of the then-available observations in a two-component model with a) cold amorphous (Si and H_20 ice) grains $>$ 10μm in size (cut-off in size by radiation pressure), with porosity $\sim$0.6, peaking at 70 AU and b) hot dust at $\sim$ 9 AU of "comet-like" composition (crystalline Si and H_20), porosity $\sim$ 0.97. They noted that collisionally evolved gains, with bodies as large as a few meters, were required in their model which also gave rise to a minimum mass of a few earth masses with gas:dust $<$ 1. This is consistent with subsequent sub-millimeter observations by Greaves et al. (2000) wherein they estimated the total mass in gas as 1–7 earth masses. This is also consistent with planetesimal accretion calculations by Kenyon & Wood (1999) in which they find planet formation at 70 AU is possible in 10 Myr in an initial 10–20 minimum mass solar nebula where dust production is then confined to a ring with Δa = 7–15 AU. Possible evidence for one (or more) unseen planets exists in an $\sim$ 10–15% brightness asymmetry in the NE and SW ansae of the ring seen both in the NICMOS images and by Telesco et al. (1999) in 18.2μm OSCIR images, suggesting a pericentric offset possibly due to a gravitational perturber. While HR 4796B, an M-dwarf companion at a projected distance of 500 AU, may serve to truncate the outer radius of the disk, the narrowness of the ring might implicate co-orbital companions confining the dust through a process akin to the shepherding of ring particles in the Saturnian system.

3.4. HD 98800A/B (TWA4 A/B)

HD 98800, historically classified as a binary comprised of two similar K dwarfs (currently separated by $0\farcs8$), was found by IRAS to contain one of the brightest far-IR excesses in the sky. Now a recognized member of the TW Hya Association with a Hipparcos determined distance of 46.7 $\pm$ 6pc, the two PMS components are themselves spectroscopic binaries with periods (Aa+Ab) = 262 days, (Ba+Bb) = 315 days (Torres et al 1995) and separations of $\sim$ 1 AU. Gehrz et al. (1999) showed the debris is centered on the B component from 4.7 and 9.8μm observations, and 20% of the luminosity of B is emitted in a 164 $\pm$ 5K SED from the mid-IR to the sub-millimeter. The SED is fit very well by a single temperature black-body, indicating that the grains co-exist in a very limited radial zone from the central stars. High-precision NICMOS photometry straddling peak of stellar SEDs by Low, Hines & Schneider (1999) find T_{eff}(A) = 3831 $\pm$ 55K, T_{eff}(B) = 3459 $\pm$ 37K, and no detectable 0.9–1.9mμ excess. From this they suggest the scattered:total light from B is $<$ 6% implying an albedo of $<$ 0.3 for the debris system with an inner radius of 4.5 AU, subtending $\sim$ 20% of the sky seen from the B component. Koerner et al. (1999) confirmed the Ba+Bb circumbinary disk, and that the B components are the source of the large IR excess upon which a silicate feature is imposed. From mid-IR imaging they suggest a disk with properties similar to Low et al. (1999). Unblended optical (0.5–1.0 μm) spectra of the A and B components we recently obtained with STIS indicate that the B component closely resembles an M0V star, so it slightly later in spectral type than previously thought (but similar in this regard to TW Hya).

The inferred geometry and properties of the HR 98800B disk bears a resemblance to the Zodiacal bands in our own solar system, and may be similar to the debris system around our Sun as it appeared a few million years after formation. The multiplicty of the system undoubtedly complicates the dynamics, and hence the temporal stability and evolution of the grains. The small size of the B-component circumbinary debris system may be causally related to interactions of the grains with the multiple components in the system.

4. Summary

The four dusty disks considered here exhibit significant variations in sizes, morphologies, and grain properties, despite their similar ages, and differ as well from β Pictoris (of very similar spectral type to HR 4796A and HD 141569A). The desire to construct a "morphological evolutionary sequence" for dusty debris disks is physically complicated by the dispersions in stellar spectral types (and hence masses), compositions and densities of the parent molecular clouds, and disk interactions with stellar and sub-stellar companions. In addition, uncertainties in age determinations by as much as a factor of about two from observable diagnostics and theoretical models, further muddy the waters. The sample of such disks observed to date is very small. Obviously, many more observations are needed to advance our detailed understanding of disk/planet formation mechanisms and time scales.

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