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Young Stellar Disks as the Sites of Planetary Evolution

A. J. Weinberger

Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd. NW, Washington, DC 20015

E. E. Becklin

UCLA Division of Astronomy, Los Angeles, CA

G. Schneider

Steward Observatory, University of Arizona, Tucson, AZ

Abstract. The physical conditions of circumstellar disks including their temperature profiles and compositions as a function of distance from their central stars will be influenced and modified by nascent planets within them. Dynamically molded disks may be the best way to infer the presence of planets around stars for which direct planet-finding techniques do not apply. Disks around three stars of age 5-12 Myr – HD 141569A, HR 4796A, and β Pictoris, illustrate what we can learn about disk composition and how embryonic planets may be sculpting their environments.

1. Introduction

The last twenty years have been revolutionary in the study of disks. First, the detection of circumstellar material made possible by early ground based infrared observations was extended enormously by the mid and far-infrared capability of the Infrared Astronomical Satellite (IRAS). Second, techniques for high contrast imaging enabled by coronagraphs, especially on the Hubble Space Telescope (HST), and mid-infrared imaging with 8–10 m class telescopes resulted in spatially resolved images of a handful of disks.

The earliest stages of star and disk formation can be copiously studied in the nearest star formation regions such as Taurus, Scorpius-Ophiuchus, and Scorpius-Centaurus. These studies have revealed that very young stars are indeed surrounded by disks of gas and dust of substantial mass (e.g. Beckwith & Sargent 1996). On the other end of the time sequence, our own solar system planets can be studied in exquisite detail. The intermediate stages of disk evolution are much less well studied as very few nearby stars of age 5–100 Myr have been identified.

The first few million years after star formation is believed to correspond to important eras in the formation of our own solar system planets. Depending on the model for gas giant formation, the gas giants may have already formed by this time through gravitational instability of the gaseous disk (Boss 1997) or have so far formed only their cores and are then accreting their gas (Pollack et al. 1996). In essentially all models, the terrestrial planets are being built throughout this era out of material within a few AU of the star (Wetherill 1990).

New planets acquire their raw material, and therefore their compositions, from disks. Detailed chemical studies, even at a young disk ages, have been hampered by the distance to the T Tauri associations, >130 pc, which means 1 AU scales cannot be effectively probed by even the largest current telescopes.

In the following sections, we compare some detailed studies of young (5–12 Myr old), nearby (< 100 pc), circumstellar disks.

2. A comparison of HD 141569A, HR 4796A, and β Pic

In order to understand the course of disk evolution in terms of general physical parameters, we need to compare disks around stars of the same age and mass. By controlling for as many variables as possible, we have the best opportunity to learn about the commonality as well as the diversity in disk evolution and to identify the controlling variables important to planet formation. Table 1 shows the properties of three similar A-type stars with well studied circumstellar disks.

Table 1. Fundamental properties of three disks and their parent stars

Star	Age (Myr)	Sp. Type	L ($L_\odot$)	L_{IR}/L_* ($\times 10^{-3}$)	D (pc)
HD 141569A	5±3	B9.5Ve	22	8.4	100
HR 4796A	8±2	A0V	20	5	67
β Pic	12^{+8}_{-4}	A5V	7	2.5	19

For HD 141569A, scattered light imaging at visual and near-infrared wavelengths shows an elongated disk that is clearly evident at radii from 150 to 400 AU. At 250 AU an annulus of lower surface brightness, or a "gap" in the disk, can be seen. However, new high angular resolution images from STIS aboard HST show that this gap is not complete. In particular, on its East side, a short arc of material fills in the gap. Forward scattering by the grains at visual and near-infrared wavelengths implies that they are fairly small (a few microns). For more details see Weinberger et al. (1999, 2003).

For HR 4796A, new STIS images of the disk with 70 mas resolution show that it is entirely located in a very narrow ring with a semi-major axis of 70.8 AU. The dust is confined to a 12 AU ring with steeper inner truncation than outward falloff. The NE side of the ring is brighter than the SW side by ~20% in the visual and a similar level in the near-infrared and mid-infrared. This non-azimuthally symmetric feature could be due to a non-uniform distribution of grains in the ring, although given the ~300 yr period for grains, one would expect them to be well mixed unless dynamically constrained by a planet. These results are reported in Schneider et al. (1999, 2003).

For the extremely well-studied β Pic, the disk extends from a few to many hundreds of AU and asymmetries in the disk have been observed in scattered and emitted light at all spatial scales (e.g., Kalas & Jewitt 1995, Heap et al. 2000, Lagage & Pantin 1994). In particular, a warp seem at radii 40–120 AU has been explained by the dynamical perturbations induced by a planet within it (Heap et al. 2000, Augereau et al. 2001). Some new features of this disk are described in the next section.

Despite the apparent similarity in stellar properties and disk content (as measured by the figure of merit of L_{IR}/L_* which gives the infrared excess of a disk), the physical dimensions of the three disks are quite different. For all three, the inferred size of the grains in the disk, <5 μm, 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. Radiation pressure and Poynting-Robertson drag are purely radial, and the morphologies of the disks show many non-azimuthally symmetric features (arcs, clumps and warps). It is primarily these features which suggest the dynamical molding of these disks by planets within them.

3. Detailed Study of β Pic

Its proximity, relatively large infrared excess, and nearly edge-on viewing geometry, make β Pic the easiest debris disk to study. Mid-infrared observations taken at the W. M. Keck Observatory now elucidate its structure and composition very close to the star (Weinberger, Becklin & Zuckerman 2002).

Images of β Pictoris at 11.7 and 17.9 μm reveal that within a radius of $1''$, the disk is tilted 16° west of the previously imaged 1–$5''$portion, which is itself warped at $3^\circ$from the outer disk. Thus the position angle of the disk does not change secularly with increasing radius but rather appears to shift discontinuously and in opposing directions at $1''$and $\sim5''$. The disk is also asymmetric at 12 μm, with the SW side brighter than the NE side. Spatially resolved spectra demonstrate that this asymmetry cannot be due to compositional effects; more likely it betrays enhanced temperatures on one side of the disk.

Shown in Figure 1a are 8 – 13 μm spectra of the southwest (brighter) side of the β Pic disk after subtraction of the photospheric component. The spectrum extracted from within $0.''2$ of the star agrees very well with that observed previously by Knacke et al. (1993) including a flat-topped profile characteristic of a mixture of amorphous and crystalline silicates.

The temperature of the grains at each radius was estimated by the color temperature of the regions on either side of the silicate feature. Temperatures are found in excess of 300 K out to 20 AU. A Planck function at each color temperature was then normalized to the long wavelength flux density and subtracted from each spectrum. The results are shown in 1b. At radii $< 1''$, a clear contribution from silicates is present. For the three spectra with radii $<1''$, the flux to continuum ratios are equal to within the uncertainties. At radii $> 1''$, although flux from the disk is present at a significant level in the spectra, within the uncertainties of the data, it appears to be composed only of continuum. The shape of the silicate peak does not change significantly over the radii where it can be seen at all. This implies that the relative abundances of amorphous and crystalline grains remains approximately constant with radius.

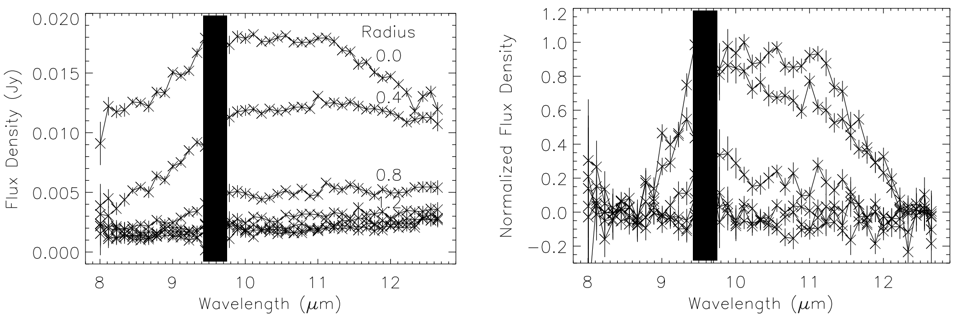

Figure 1. Left (a): Spectra of the disk after subtraction of the contribution of the photosphere shown as a function of radius (curves shown are, from the top down, for radii of 0.0, 0.″4, 0.″8, 1.″2, 1.″6, 2.″0, and 2.″4). Right (b): Spectra after subtraction of a continuum fit to the 12.6/8.2 μm color temperature. Silicates, at approximately the same line/continuum ratio, are seen in the first three spectra, but only continuum is seen at larger radii. The vertical black bar blocks the noisy region contaminated by strong Telluric ozone absorption.

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