

PART 7.

Circumstellar Disks

Evolution of Gas and Dust in Circumstellar Disks

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Abstract. A clear understanding of the chemical processing of matter as it is transferred from a molecular cloud to a planetary system depends heavily on the physical conditions endured by gas and dust as these accrete onto a disk and are incorporated into planetary bodies. Reviewed here are astrophysical observations of circumstellar disks which trace their evolving properties. Accretion disks that are massive enough to produce a solar system like our own are typically larger than 100 AU. This suggests that the chemistry of a large fraction of the infalling material is not radically altered upon contact with a vigorous accretion shock. The mechanisms of accretion onto the star and eventual dispersal are not yet well understood, but timescales for the removal of gas and optically thick dust appear to be a few times 10^6 yrs. At later times, tenuous “debris disks” of dust remain around stars as old as a few times 10^8 yrs. Features in the morphology of the latter, such as inner holes, warps, and azimuthal asymmetries, are likely to be the result of the dynamical influence of large planetary bodies. Future observations will enlighten our understanding of chemical evolution and will focus on the search for disks in transition from a viscous accretion stage to one represented by a gas-free assemblage of colliding planetesimals. In the near future, comparative analysis of circumstellar dust and gas properties within a statistically significant sample of young stars at various ages will be possible with instrumentation such as SIRTf and SOFIA. Well-designed surveys will help place solar system analogs in a general context of a diversity of possible pathways for circumstellar evolution, one which encompasses the formation of stellar and brown-dwarf companions as well as planetary systems.

1. Introduction

The chemical history of solar system materials took place within a wide diversity of physical and chemical environments, as gas and dust were transported from a molecular cloud core to a destination in planetary bodies and atmospheres. Until recently, reconstruction of the relevant initial conditions and evolutionary processes relied solely on vestigial evidence wrested from analyses of the chemical composition of matter in the present-day solar system. This method of investigation is limited, however, by difficulties inherent in bridging a temporal discontinuity of over 4 billion years. It is especially challenging to disentangle the signatures of antecedent conditions from those of more recent processes occur-

ring within the solar system. Improvements in observational methods have now made it possible to leap across this gap in time and directly observe analogs of the milieu in which early solar system materials were forged. Circumstellar disks and envelopes around currently-forming young stars have become the subject of increasingly detailed investigations with high-resolution astronomical techniques operating across a broad range of wavelengths (see reviews by Beckwith & Sargent 1996 and Koerner 1997).

The presence of protostellar envelopes and accretion disks around young stars was disclosed as soon as appropriate long-wavelength detectors became available. Observations extending from near infrared to millimeter wavelengths revealed excess radiation with a range of properties that implied an evolutionary sequence of states for the circumstellar material (Myers & Benson 1983; Lada & Wilking 1984; Strom et al. 1989; Beckwith et al. 1990). Models of the associated "Spectral Energy Distributions" (SEDs) accounted for diverse spectral shapes by locating dust at various distances from the young star, partitioned between spherical, flared disk, or flat disk configurations (Adams, Lada, & Shu 1987; Kenyon & Hartmann 1987; cf. Beckwith & Sargent 1993 and Shu et al. 1993).

The first images to confirm the above interpretations also validated the idea that differing SED properties were due to the time dependence of circumstellar disk properties. Aperture synthesis imaging of CO $J=2\rightarrow 1$ emission from the very young ($t \sim 10^5$ yr) stellar object, HL Tauri, revealed circumstellar dust and gas in an elongated structure with a mass several times that of the minimum required to form a solar system like our own (Beckwith et al. 1986; Sargent & Beckwith 1987, 1991). Coronagraphic imaging of dust around the much older ($t \sim 10^{7-8}$ yr) main sequence star, β Pictoris, revealed a far more tenuous dust disk (Smith & Terrile 1984). The small mass of material and its short lifetime against dispersal implied that any associated planet formation had largely taken place (cf. Backman & Paresce 1993). It now appears that these objects represent snapshots at times which bracket most of the early evolution of protoplanetary disk systems. Gaps in the sequence are rapidly being filled in with new high-quality images of a wide range of objects.

2. Imaging the Stages of Disk Evolution

2.1. The embedded protostar stage

Chemical processing of protostellar and protoplanetary gas and dust begins even before it encounters a shock front at the disk-envelope interface. Radiation from the central protostar, enhanced density in the molecular cloud core, and interaction with far-reaching ionized jets and bipolar outflows all contribute to distort the original interstellar chemical signature (see Bergin, Hogerheijde, and Ohashi, this volume). These changes may vary systematically in a time-dependent way, making it possible to use chemical abundances as a chronometer which traces the evolution of the infalling envelope (cf. Langer et al. 2000).

As infalling matter impacts a circumstellar accretion disk, it is subject to shock heating and gas drag with an intensity that depends sensitively on the radial distance of the impact from the star and concomitant impact velocity (see review by Lunine 1997 and references therein). In particular, icy grains accreting at distances greater than 30 AU from a Sun-like star are likely to suffer



Figure 1. HST/NICMOS image of the nebulosity in IRAS 04302 (taken from Padgett et al. 1999). The dust lane, corresponding to an edge-on disk embedded within a flattened envelope, is nearly 1000 AU in diameter.

little sublimation of volatiles, and gas molecules are unlikely to be dissociated. Consequently, disk material originally at this radius is unlikely to bear much of the imprint of its entry into the disk.

High-resolution images now reveal that much of the material incorporated into circumstellar disks does indeed originally arrive at radial distances much greater than 30 AU. Although much of the material in the outer regions of the flattened structure around HL Tauri is now known to be infalling (Hayashi et al. 1993), continuum images indicate the presence of a central disk, presumably centrifugally supported, with a radius of order 100 AU (Lay et al. 1994; Mundy et al. 1996). Flattened structures of similar size and kinematics have recently been imaged around a small sample of other embedded young stars, in both CO line emission (cf. Ohashi, this volume), and in scattered light (Padgett et al. 1999). One example, IRAS 04302, is displayed in Fig. 1 and appears as a 450-AU-radius circumstellar structure oriented edge on with a highly flattened morphology (Padgett et al. 1999). Kinematic analysis of CO spectral line images indicates that rotational motions dominate the velocity field of this structure. These results strongly suggest that most of the gas in solar nebula analogs originally arrives at distances greater than 100 AU where little processing takes place. The large sizes of more-evolved centrifugally supported disks bear this out.

GM Aurigae

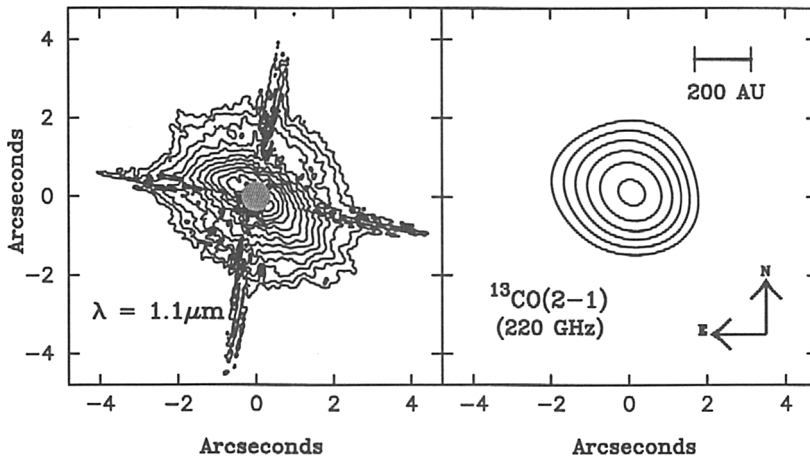


Figure 2. (Left) HST/NICMOS coronagraphic image of the cTTs GM Aurigae and (right) OVRO aperture synthesis image of ^{13}CO ($2\rightarrow 1$) from the same star. The HST image reveals a flattened circumstellar reflection nebula extending symmetrically from the star to radial distances of $3''$ (450 AU) and aligned with the long axis of molecular emission. Kinematic analysis of the gas establishes that the disk is in Keplerian rotation about the star (Koerner et al. 1999).

2.2. The “T-Tauri” phase

Young stars first become optically visible when their infall envelope has dispersed enough to become transparent. Surveys of unresolved infrared and millimeter-wave emission from these “T Tauri stars” (TTs) provided initial evidence that circumstellar disks are the dominant component in the dust configuration at this stage (Strom et al. 1989; Beckwith et al. 1990). A large fraction of TTs are detected with associated SEDs that can be attributed to dusty disks, similar to those expected for planetary systems in formation (cf. Beckwith & Sargent 1993). The overwhelming majority of these are associated with “classical” T Tauri stars (cTTs), for which diagnostics of protostellar accretion such as H α emission are still robust (cf. Calvet, Hartmann, & Strom 2000). Optically thick dust emission is not as readily detected from disks around T Tauri stars without strong evidence of protostellar accretion, the so-called “weak-line T Tauri stars” (wTTs) (cf. Osterloh & Beckwith 1995).

Aperture synthesis imaging of the disk around GM Aurigae was the first to demonstrate that gas was rotationally supported throughout the radial extent of a circumstellar disk around a cTTs (Koerner et al. 1993). High-resolution coronagraphic imaging with HST confirms the picture from mm-wave interferometry and is displayed in Fig. 2 (Koerner et al. 1999). Light scattered from the concave surface of a flared disk is consistent with an orientation like that derived from aperture synthesis images of the molecular emission. The disk is

several hundred AU in radius and has a mass several times that required to form our own solar system (cf. Dutrey et al. 1998).

Additional observations of CO emission from cTTs have demonstrated that the properties of the disk around GM Aur are not at all unusual. TTs which exhibit similar mm-wave continuum luminosity are typically surrounded by disks with radii greater than 100 AU (Koerner & Sargent 1995; Dutrey, this volume). The occurrence frequency for mm-wave detection at the associated luminosity level is about 10% for TTs, generally. These are the only objects which can be appropriately considered to be analogs of the early solar nebula, since disk masses derived for TTs with lower mm-wave continuum luminosity are well below the minimum required to produce a solar system like our own.

The timescale and associated mechanism by which disks eventually disperse is not conclusively determined. Photo-evaporation may provide a way to deplete disk gas from the outside in (see Johnstone, this volume), while accretion onto the star may remove material from the inner disk. Infrared surveys establish that inner-disk dust is depleted in TTs older than 3×10^6 yrs (Skrutskie et al. 1990), but it is unclear whether the underlying cause is pre-planetary grain accumulation, protostellar accretion, or some other dispersal mechanism. Surveys at millimeter and sub-millimeter wavelengths fail to reveal a correlation between stellar age and associated disk mass (Beckwith et al. 1990; Beckwith & Sargent 1991), but such an effect may be masked by the failure of studies to discriminate between single and binary stars (Jensen et al. 1994; Osterloh & Beckwith 1995). Evidence for the persistence time of gas in disks is scarcer than for dust, even though 99% of the mass of protoplanetary disks is thought to consist of molecular gas. There is some suggestion that gaseous disks are dispersed on timescales of 10^7 – 10^8 years (Skrutskie et al. 1991; Zuckerman, Forveille, & Kastner 1995), but the number of objects observed with sufficient sensitivity is still quite small. In any event, gaseous disks similar to those imaged around cTTs have not been imaged for any weak-line T Tauri stars, except for a couple of borderline cases (Duvert et al. 2000).

2.3. Debris disks

The presence of remnant circumstellar dust around “Vega-type” stars – A-type stars with infrared excess and ages between ten and a few hundred million yrs – may signal a more evolved stage of planet formation (cf. Backman & Paresce 1993; Lagrange, Backman, & Artymowicz 2000 and references therein). The infrared signature of optically thin dust is present in IRAS measurements, but the correlation with early spectral type may be due simply to the ability of hotter stars to heat circumstellar dust at several 10’s of AU to temperatures characteristic of infrared radiation. Images of these tenuous “debris disks” have been obtained in both scattered light and thermal infrared emission for β Pictoris (Smith & Terrile 1984; Lagage & Pantin 1994; Heap et al. 1997), HR 4796A (Jayawardhana et al. 1998; Koerner et al. 1998; Schneider et al. 1999), HD 141569 (Augereau et al. 1999; Weinberger et al. 1999), and at sub-millimeter wavelengths for several nearby stars (Holland et al. 1998; Greaves et al. 1998). In many cases, the images confirm what was deduced by models of the spectral distribution of radiated energy, namely that the disks surround large inner holes with sizes like that of our solar system. This is readily apparent in thermal IR

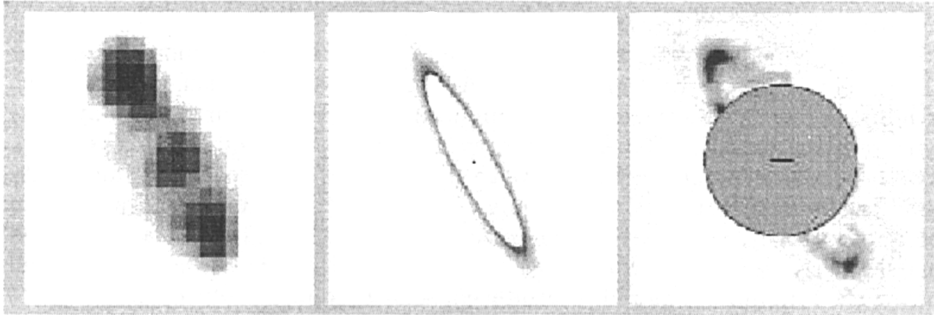


Figure 3. (Left) Keck/MIRLIN image of HR 4796A at $24.5 \mu\text{m}$. The elongated structure is $\sim 2''$ in diameter, corresponding to ~ 150 AU. (Center) A model of the underlying emission structure that was obtained by fitting to an image at $20 \mu\text{m}$ from Koerner et al. (1998). (Right) HST/NICMOS coronagraphic image of scattered light from the ring around HR 4796A at $\lambda = 1.1 \mu\text{m}$ taken from Schneider et al. (1999).

and HST images of HR 4796A shown in Figure 3, where the dust is confined largely to a circumstellar ring.

The presence of a large hole in the disk around HR 4796 was originally implied by the shape of its SED (Jura et al. 1995), a characteristic that applies to many other debris-disk examples as well. Modeling of thermal infrared imaging like that shown in Fig. 3 demonstrated unequivocally that the disk did not extend all the way to the star (Koerner et al. 1998). This result was dramatically confirmed in coronagraphic imaging with the Hubble Space Telescope (Schneider et al. 1999), also displayed in Fig. 3. New analysis of imaging at $24.5 \mu\text{m}$ reveals that most of the emission at the stellar position is well in excess of the photosphere. The color temperature of dust close to the star is ~ 170 K, similar to that expected for an ice condensation front like that which may have assisted in the formation of Jupiter. For HR 4796A, a star considerably warmer than the Sun, this temperature corresponds to a radial distance of about 10 AU (Wahhaj et al. 2000).

The presence of an inner hole in the disk around β Pictoris is also implied by its SED (Backman et al. 1992), but is not quite as readily apparent as for HR 4796A. This is clear from the thermal infrared image in Fig. 4. The appearance of continuity is deceiving, however, since the emission intensity depends heavily on temperature and will be preferentially greater for the material close to the star. Modeling of such images indicates that an inner region of reduced density is indeed present (cf. Lagage & Pantin 1994; Pantin et al. 1997). Additional evidence for planetary bodies is apparent in the form of a warp sharply identified in HST images (Burrows et al. 1995; Heap et al. 1997). It appears in Fig. 4 as a variation in the angle of the long axis of intermediate contour levels. The warp may be the result of the dynamic influence of a planetary body with an orbit which is inclined with respect to the plane of the disk.

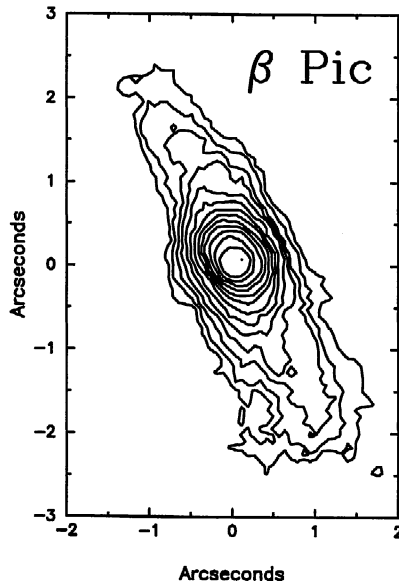


Figure 4. Keck/MIRLIN image of β Pictoris at $\lambda = 20 \mu\text{m}$. The long axis of intermediate contours is slightly offset relative to other contours, in keeping with the discovery of a warp in the inner disk. This warp may signal the presence of a planetary body with an orbit that is inclined relative to the circumstellar disk plane.

Holes and/or gaps are evident in a few other extant disk images, including those for α PsA, ϵ Eri, and HD 141569 (Holland et al. 1998; Greaves et al. 1998; Augereau et al. 1999; Weinberger et al. 1999). These features strengthen the interpretation of debris disks as representing a late protoplanetary phase in which the system is largely devoid of molecular gas and contains fully formed planets and/or planetesimals which generate remnant debris via mutual collisions. The implied connection between disks and planets has become even more explicit with the ground-based coronagraphic detection of dust around a star for which a planet has actually been detected. Dust detected around 55 Cnc, a star with a radial-velocity signature of a planet (Marcy et al. 1999), lies well outside of the orbit of the detected body, but implies an orbital plane which confirms a planetary mass for the companion (Trilling & Brown 1998).

3. Discussion

The images reviewed above help establish and refine a picture of the evolution of protoplanetary disks that is inferred from long-wavelength spectral properties. It is now clear that the typical size for solar-system-analog disks is larger than the canonical solar system ($R \sim 50$ AU) by factors of several. This suggests that a large fraction of the initial molecular reservoir was not heavily modified by an accretion shock. The timescales for survival of optically thick dust and molecular gas seems to be similar, of order a few times 10^6 yr. Disks of tenuous

debris frequently survive for another 100 million years and show evidence of the dynamic influence of larger bodies.

Many questions remain unanswered in the above picture. It would be especially useful to obtain images of disks in transition between a viscously accreting stage and one in which gas and dust are largely dispersed. These would help refine estimates of the timescales involved and could enlighten our understanding of the dispersal mechanisms as well. In addition, it is not always clear whether differences between individual disks are the result of evolution or simply of different initial conditions. In order to sort this out, the statistical properties of circumstellar matter around a large unbiased sample of young stars must be obtained. High-resolution imaging of such a sample is currently infeasible, but broadband spectral characteristics will be accessible to infrared surveys taken with instruments such as SIRTf and SOFIA. These are designed to operate above the atmosphere with the sensitivity required for detection of waning disks in star-forming regions. Interpretations of such surveys will, of course, be helped by the “ground truth” afforded by available images, but they may not require detailed imaging of every source. It is expected that the broadband spectral properties of hundreds of young stars can be surveyed with currently planned instrumentation. This will allow us to begin to answer questions, not just about the evolution of solar system analogs, but about the place of our solar system within a diversity of possible circumstellar environments.

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Discussion

Y. Aikawa: Are there any ice features observed in β Pic phase?

E. F. van Dishoeck: Comment: With improved instrumentation (SIRTF, SOFIA, NGST, ...), one may attempt to observe the infrared absorption at 3–20 μm of ices toward stars with near edge-on circumstellar disks. The ISO-LWS and SWS have detected the long wavelength emission ($\sim 43 \mu\text{m}$, $60 \mu\text{m}$) of crystalline H_2O -ice in some disks (Waelkens, this volume; Creech - Eakman et al., in preparation).