Observations of Circumstellar Disks

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Abstract.

Approximately 50% of solar-type, pre-main sequence stars are surrounded by disks of gas and dust, many of these disks having masses similar to that expected for the early solar nebula. Disks are present from the earliest observable phases of protostellar evolution and persist for a few million years. High-resolution imaging is beginning to elucidate disk structure, and spectroscopy suggests that circumstellar material moves in Keplerian orbits from scales of a few stellar radii to several 100 AU. The gas and dust in circumstellar disks appears to differ from the interstellar medium, consistent with the freezing-out of molecules from the gas phase onto the surface of dust grains in the disks, and the growth of dust particles into larger bodies.

1. Introduction

The detection of disks around pre-main sequence stars provides the most direct link we have between the star formation process (Lada, Adams, this volume), and main sequence stars surrounded by dusty debris disks (e.g., β Pictoris), or planetary systems (e.g., the Sun). Theory predicts that disks play an essential role in the formation and evolution of low-mass, solar-type stars: conservation of angular momentum during the collapse of a dense, rotating, cloud core results in a protostar surrounded by an accretion disk (cf. Bodenheimer 1995). During early phases the protostar/disk system is embedded in an extended, infalling envelope of gas and dust, and the protostar gains mass by accreting this material through the disk. The envelope initially obscures the star and disk at optical wavelengths, but it gradually dissipates as material is accreted onto the star or is dispersed by an accompanying energetic outflow. After a few $\times\ 10^5$ yr, a pre-main sequence, solar mass (T Tauri) star, surrounded by a disk, is revealed optically (cf. Shu et al. 1993). Most of the evidence for circumstellar disks is based on studies of T Tauri stars associated with nearby ($D \sim 150$ pc) star-forming molecular clouds, such as those in Taurus and ρ Ophiuchus (e.g., Adams et al. 1990; Beckwith et al. 1990; André & Montmerle 1994).

One of the most exciting goals of identifying and studying circumstellar disks around T Tauri stars is to establish the physical and chemical conditions within the early solar nebula. Recent advances in the instrumental resolution and sensitivity available, from optical to millimeter wavelengths, have begun to provide direct evidence for such disks and suggest they may be relatively common (e.g., Beckwith et al. 1990; McCaughrean & Stauffer 1994). Statistics of disk detections have been used to estimate timescales for disk dissipation (e.g., Strom et al. 1993), and disk properties such as the radial distributions of temperature and surface density can now be measured directly (Lay et al. 1997). The dynamics of the disk material are determined using high-resolution spectroscopy from optical through to millimeter wavelengths (e.g., Hartmann & Kenyon 1987; Koerner & Sargent 1995).

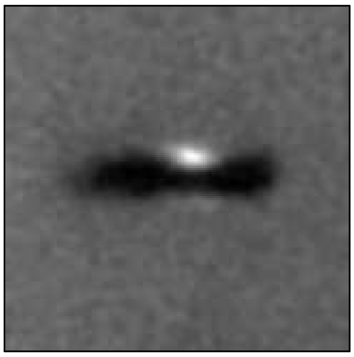
The composition of circumstellar disks defines the raw material from which planets can be made. The gas and dust particles in a disk must initially have been identical to those found in the molecular cloud from which the star formed, and evidence for an evolution of the size of the dust grains, for example, could be essential for establishing the timescale for the formation of planetesimals from the solid material (cf. Beckwith & Sargent 1991). The presence of circumstellar material around T Tauri stars appears to depend on the proximity of massive stars (e.g., Lada, this volume) or close companions (see Ghez, this volume); observations of T Tauri disks can therefore potentially provide considerable constraints on the types of environments in which planetary systems such as our own may form.

Stars with masses greater than a few $M_\odot$ may also be surrounded by disks, but the physical environment in which those disks reside is rather more extreme than the low-mass case (Yorke & Welz 1996) and is less commensurate with the formation of solar system analogues. Regions of high-mass star formation in the Galaxy are also generally more distant, so the linear resolution obtainable is worse than for their lower mass counterparts. At present the observations do not, therefore, constrain the role of disks in high-mass star formation as well as they do for low-mass sources, although some excellent examples of rotating disks around high-mass protostars have been discovered through observations of circumstellar SiO and H_2O masers (e.g., Plambeck et al. 1990; Torrelles et al. 1996).

2. Direct Evidence for Circumstellar Disks

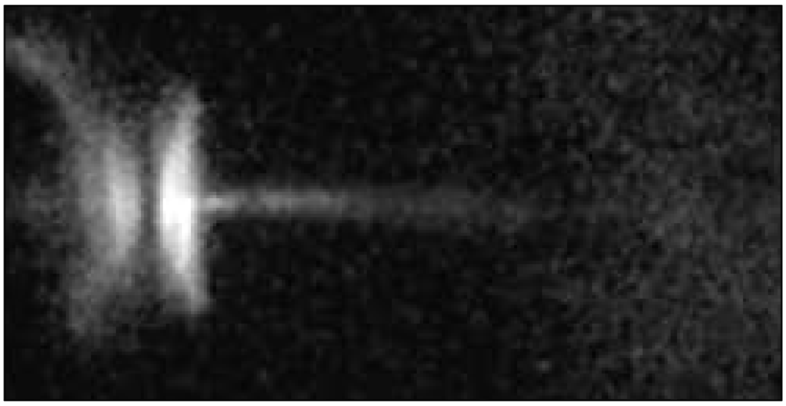
2.1. Optical and Near-Infrared Imaging

Although circumstellar disks have for some time been invoked to explain the asymmetric profiles of optical forbidden emission lines (Appenzeller et al. 1984; Edwards et al. 1987) and broadband spectral energy distributions (SEDs) of young stars (e.g., Rucinski 1985; Bertout et al. 1988; Beckwith et al. 1990), it is only recently that the spatial resolution has been available to image circumstellar disks directly. The Hubble Space Telescope (HST) has provided some of the first direct evidence that the circumstellar material around young stars in Orion ($D \sim 450$ pc) lies in a spatially-flattened distribution. The location of several young stars in front of a bright, background, illuminating source (the HII region M42) has revealed dust disks as dark silhouettes against the nebular emission at optical wavelengths (McCaughrean & O'Dell 1996), with diameters of several hundred AU (Figure 1a). Similar objects located *inside* the HII region have had an outer shell of circumstellar material photoionized by the stars responsible for ionizing the HII region and exhibit tails of ionized gas pointing away from the main ionizing star, θ^1 Ori C (O'Dell & Wen 1994; Figure 1b).



(a) 114−426

(b) 182−413



(c) HH30

Figure 1. Optical HST images of circumstellar disks. (a) 114−426 is detected in absorption against the Orion nebula in a continuum filter centered at 5470 Å (McCaughrean & O'Dell 1996). Scattered stellar light is observed emerging from the poles of the system. (b) 182−413, located inside the nebula, is surrounded by a photoionized shell visible clearly in the narrow-band filters transmitting Hα (6563 Å), [NII] (6583 Å), and [OIII] (5007 Å: O'Dell & Wen 1994). The areas shown for 114−426 and 182−413 are approximately 1800 $\times$ 1800 AU. (c) The disk and jet of HH30 in Taurus observed through R and I band continuum filters (Burrows et al. 1996). The young star is behind the dark dust lane of the disk, and scattered stellar photons trace the disk surfaces. The image size is approximately 900 $\times$ 1700 AU.

In the more nearby star-forming region of Taurus the HST is able to provide a linear resolution of 14 AU. Observations of the young stellar object driving the highly-collimated jet HH30 show that the star itself is hidden behind a dark band of high optical extinction oriented perpendicular to the jet (Burrows et al. 1996; Figure 1c). Extended nebulosity detected on each side of the dark lane arises from stellar photons scattering off dust particles in the surface of a flared disk.

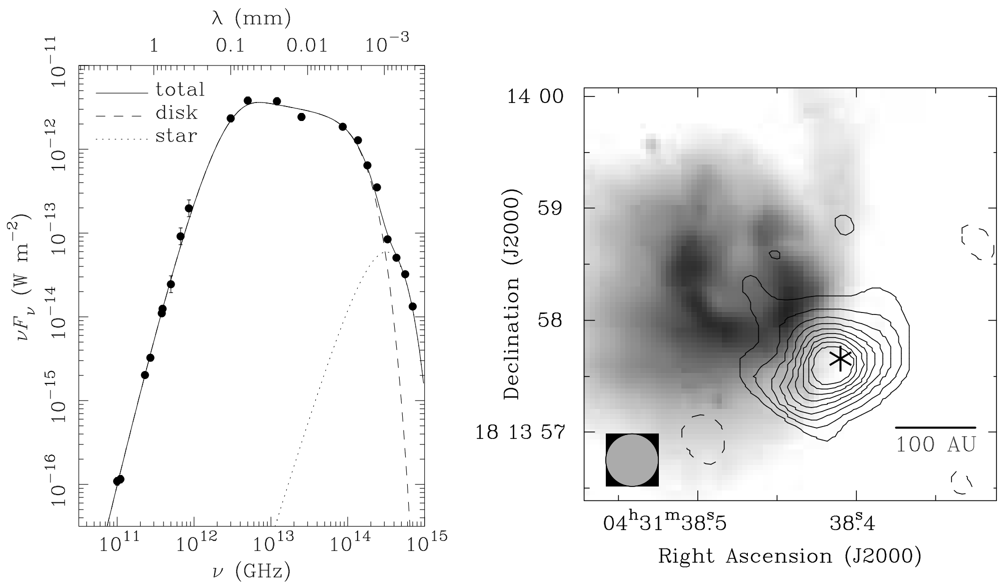
The relative proximity of the main sequence star β Pic compared to the nearest star-forming complexes has for some time allowed ground-based telescopes to image scattered optical light in its circumstellar dust disk (see Smith & Terrile 1984). Ground-based measurements of similar disks around young stellar systems require adaptive optics (AO) techniques to compensate for atmospheric seeing, and some beautiful examples of the capabilities of AO are the images of the near-infrared continuum emission from the ring around the pre-main sequence binary system GG Tau (Roddier et al. 1996).

2.2. Millimeter/Submillimeter Interferometry

At optical and near-infrared wavelengths it should be emphasized that any *extended* emission detected is not direct emission from the disk itself but is scattered light. The typical broadband SED of an optically-visible, pre-main sequence star, surrounded by a disk, comprises a component from the stellar photosphere and an excess throughout the infrared through millimeter due to the emission from dust in the disk (Figure 2a). Even at a wavelength of 2 μm the bulk of the disk emission originates from within only a few stellar radii of the central star. Most of the mass of the disk resides at radii $\gtrsim$ 30 $R_\odot$ and is relatively cool ($T \lesssim 50$ K), emitting most of its energy at far-infrared through millimeter wavelengths. Currently the spatial resolution and sensitivity available using millimeter and submillimeter-wave interferometers are best matched to the requirements of studying the emission from the disk directly.

Observations of the low rotational transitions of ^{12}CO and ^{13}CO have been particularly successful at identifying flattened, disk-like structures around T Tauri stars (Sargent & Beckwith 1987, 1991; Weintraub et al. 1989; Kawabe et al. 1993; Koerner et al. 1993; Dutrey et al. 1994; Kitamura et al. 1996a). However, due to high optical depths in the J=1–0 and 2–1 lines these CO disks are often observed to be $\sim$ 1000 AU in size, an order of magnitude larger than the disks inferred from models of T Tauri dust spectra. The millimeter dust emission is, on the other hand, optically thin, and is therefore well suited to investigating disk structure. Some of the first direct measurements of disk size based on dust emission were made using single-baseline interferometry at the Caltech Submillimeter Observatory (CSO) and the James Clerk Maxwell Telescope (JCMT), on Mauna Kea, Hawaii (Lay et al. 1994). At a wavelength of 870 μm the circumstellar disks around the young stars HL Tauri and L1551-IRS5 in Taurus were found to have radii of 60 and 80 AU respectively, with their major axes oriented perpendicular to the optical jets in both sources.

Sub-arcsecond resolution is now also available using millimeter synthesis arrays, and the dust disk around HL Tau has been imaged by Mundy et al. (1996; Figure 2b). The optical nebulosity detected by the HST and by ground-based AO imaging traces a cavity evacuated by a jet from the central star (Stapelfeldt



(a) SED for HL Tau (b) Contours of λ=2.7mm emission

Figure 2. (a) The SED for HL Tau, illustrating emission from the central star and the disk (see Beckwith et al. 1990; Mundy et al. 1996). (b) Contours of $\lambda = 2.7$ mm dust continuum emission from HL Tau imaged using the BIMA millimeter array (Looney et al. 1997b), overlaid on V band reflection nebulosity observed with the HST (Stapelfeldt et al. 1995). The asterisk is the position of the star, defined by the centimeter radio source. The optical jet lies at a position angle of 45°.

et al. 1995; Close et al. 1997). A flattened disk has also been detected around the young star DG Tau (Kitamura et al. 1996b), and the dust emission from L1551-IRS5 is now resolved into a 50 AU binary at $\lambda = 3$ mm, surrounded by a circumbinary disk (Looney et al. 1997a).

2.3. Disk Frequency and Mass

The detection rate of disks around T Tauri stars may be vital for assessing the frequency of extrasolar planetary systems. The most efficient method of carrying out surveys for disks is to search for excess emission over that expected from the stellar photosphere at infrared or millimeter wavelengths. Near-infrared emission traces hot dust in the inner regions of the disk, and millimeter surveys have been used to infer the presence of cooler material at large radii. Surveys of young stellar clusters which employ infrared colors to distinguish stars with infrared excesses indicate that typically 50% are surrounded by disks (Strom et al. 1989; Lada et al. 1993; McCaughrean & Stauffer 1994). Similar results are obtained from millimeter measurements (Beckwith et al. 1990; Henning et al. 1993; André & Montmerle 1994).

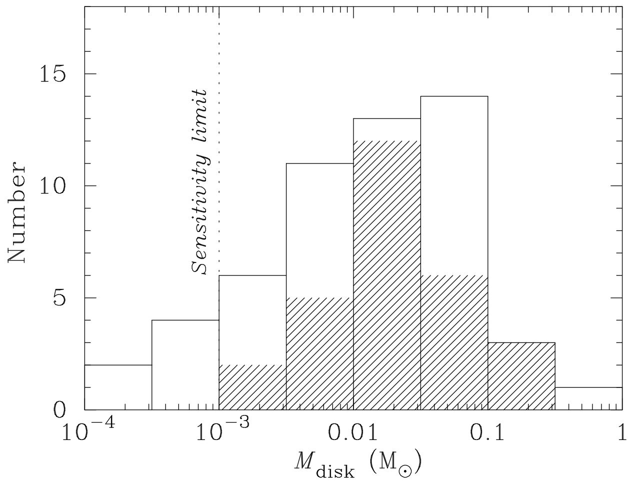


Figure 3. The distribution of disk mass for young stars in Taurus (solid histogram) and ρ Ophiuchus (hatched histogram). The data are taken from surveys by Beckwith et al. (1990) and Osterloh & Beckwith (1995) for Taurus, and from André & Montmerle (1994) for ρ Ophiuchus (after Beckwith & Sargent 1996). The dotted line illustrates the approximate sensitivity limit for the surveys.

Infrared dust emission from disks is usually optically thick, while the millimeter emission is optically thin. Since a large fraction of the mass of a disk is therefore traced by millimeter emission, single-dish surveys at long wavelengths have provided excellent data sets for making statistical analyses of disk frequency and disk mass. Indeed, single-dish millimeter surveys supplied some of the first convincing evidence that the dust detected must be distributed anisotropically around the star, else the extinction implied would render the star itself invisible at optical wavelengths (e.g., Beckwith et al. 1990). Figure 3 shows the distribution of the total disk mass (gas plus dust) derived from disk models of dust SEDs for T Tauri stars in Taurus and Ophiuchus. The absolute values of the disk masses may be in error by factors of 5 to 10 due to uncertainties in the dust opacity (Beckwith & Sargent 1991). Bearing in mind this caveat, the median disk mass is several $\times$ 0.01 $M_\odot$ (Beckwith et al. 1990; André & Montmerle 1994; Osterloh & Beckwith 1995), comparable to the minimum mass needed by models of the solar nebula in order to form the solar system (e.g., Weidenschilling 1977).

3. Disk Formation and Evolution

3.1. Disks in Protostellar Systems

The evidence for dust disks in young protostellar systems is more indirect than for T Tauri stars because the presence of an extended envelope — the remnant of the cloud core from which the protostar is forming — confuses the interpretation of both SEDs and single-dish millimeter measurements. Single-dish observations are generally well-matched to any large-scale structure present. While single-dish measurements of T Tauri stars are therefore dominated by the disk, the fluxes detected from embedded protostars are usually consistent with arising from the envelope (Terebey et al. 1993). Interferometry is therefore essential for studying protostellar disks, providing the high resolution needed to examine the disk structure and acting as a spatial filter in order to isolate any compact dust components (e.g., Keene & Masson 1990). By surveying embedded protostars using the Owens Valley millimeter array at $\lambda = 2.7$ mm, Terebey et al. have shown that the observed fluxes are too high to be accounted for by the emission from an extended envelope. They conclude that an extra compact component is needed, the most likely candidate being a circumstellar disk.

Preliminary interferometric studies suggest that the detection rates of protostellar disks and T Tauri disks are comparable. Ohashi et al. (1996) have detected 2 out of 13 embedded protostars in Taurus using the Nobeyama Millimeter Array at $\lambda = 2.7$ mm. Of the T Tauri stars in Taurus with ages less than 3×10^5 yr surveyed for $\lambda = 1.3$ mm emission by Beckwith et al. (1990) the same fraction (3 out of 18) were detected to the same mass sensitivity limit as the protostars. These statistics are based on small numbers of sources and need to be confirmed with larger samples, but a recent, more sensitive study of several embedded protostars does indicate that disks are common during this phase (Hogerheijde et al. 1997). Compact disk components have now also been identified in at least five systems which are believed to be $\lesssim$ few $\times 10^4$ yr old ("Class 0" protostars: see André et al. 1993), with measurements or upper limits on their radii of 100 to 200 AU (Lay et al. 1995; Chandler et al. 1995b; Pudritz et al. 1996; Gueth et al. 1997; Terebey & Chandler 1997). For objects which are so young and deeply embedded, most of the mass of the protostar/disk/envelope system resides in the envelope, and the compact disk represents only 10% to 20% of the total mass of circumstellar material. However, the absolute value of the disk mass in these young protostars can be similar to that observed in T Tauri stars.

3.2. Disks and Jets

An indirect argument that disks should be present even in the youngest sources arises from the association of protostars with energetic mass-loss during their formation. The mass-loss manifests itself as optical jets in older sources, or as high-velocity emission from molecular gas, swept up by the driving wind or jet, in young protostars (see, e.g., the review by Bachiller 1996). Several observational studies suggest a strong connection between disks and jets or outflows. Cabrit et al. (1990) find a good correlation between the infrared excess emission from T Tauri stars, indicative of a disk, and the equivalent widths of optical forbidden lines which originate in the stellar wind. A connection between the mass of circumstellar material and the presence of powerful and highly-collimated molecular outflows has also been suggested for embedded protostars (Cabrit & André 1991; Bontemps et al. 1996). The association of $\gtrsim 70\%$ of young stars with outflows (Parker et al. 1991), and *all* Class 0 protostars found to date, therefore indicates not only that a phase of mass-loss is essential for star formation but also that the presence of a circumstellar disk is probably intimately associated with this phase.

The origin of protostellar outflows and jets is not yet understood, but the most popular models include disks as an essential ingredient (Königl & Ruden 1993). In models where magneto-hydrodynamic (MHD) winds are launched from the surface of a disk (e.g., Blandford & Payne 1982; Pudritz & Norman 1983, 1986), or from the star/disk boundary layer (Shu et al. 1988), the wind may also be the mechanism by which a significant fraction of the angular momentum in the disk is removed, allowing material to accrete onto the central protostar. A magnetic field threading the disk is wound up by rotation, and disk material is then accelerated outwards along the field lines by centrifugal forces taking with it the angular momentum (Papaloizou & Lin 1995). The flow may then be recollimated to form the observed jets further away from the star (Shu et al. 1995). These models do not necessarily imply particularly massive disks since the primary requirement to explain observed jet speeds of several 100 km s^{-1} is for a deep gravitational potential well at the base of the jet. Nevertheless, the association of all Class 0 protostars with energetic, highly-collimated jets suggests that disks form in the youngest observable phases of star formation.

3.3. Dissipation Timescales

Once pre-main sequence stars have dispersed their circumstellar envelopes and are optically visible their ages can be estimated from model isochrones in the Hertzsprung-Russell diagram. Disk dissipation timescales are therefore rather more easy to assess than their formation timescales, using trends in the presence of excess infrared and millimeter emission as a function of age. In a study of the 1.3 mm dust continuum emission from T Tauri stars, Osterloh & Beckwith (1995) find no correlation between the presence of cool circumstellar material and stellar age for stars up to 10 Myr old. However, the non-detection of millimeter dust emission from post-T Tauri stars, with ages up to $\sim$ 100 Myr, indicates that the mass of cool circumstellar material in these older stars is considerably lower than in T Tauri stars (Gahm et al. 1994; Jewitt 1994; Ray et al. 1995). On the other hand, measurements of optical tracers of accretion activity such as the equivalent width of the Hα emission line, and studies of infrared excess emission, indicate a deficit possibly corresponding to disk clearing or the presence of holes in the inner disk for stars 3 to 10 Myr old (Walter et al. 1988; Strom et al. 1989; Skrutskie et al. 1990). More recent measurements suggest that holes may be appearing in T Tauri disks for stars as young as 1 Myr (Dutkevitch 1995). It is therefore possible that the inner regions of the disk are being cleared before the outer regions responsible for the millimeter emission. If the clearing is due to the presence of large bodies or planets, these observations must be taken into account in models of planet formation (e.g., Lissauer 1987, 1993).

4. Disk Structure

4.1. Predictions from Accretion Disk Theory

The primary role of disks during star formation is to mediate the accretion of material from the surrounding envelope onto the star, by removing angular momentum from the infalling gas and dust [see the recent reviews by Papaloizou & Lin (1995) and Lin & Papaloizou (1996)]. The MHD disk winds described above represent one class of plausible mechanisms for removing angular momentum, but an alternative possibility is that some sort of turbulent viscosity transports the angular momentum outwards in the disk. Using suitable parameterizations for this viscosity, accretion disk theory can be used to derive the expected disk structure analytically.

In the model considered here for a steady accretion disk, material is fed into the disk at large radii at a constant rate $\dot{M}$. At radius r the scale height of the disk, H, is assumed to satisfy $H \ll r$, and the dynamics are assumed to be dominated by the mass of the central star, i.e., the disk is thin and not self-gravitating. The conservation of angular momentum and the conservation of mass can then be used to show that the surface density, Σ, is related to $\dot{M}$, r, and the kinematic viscosity, ν, by

$$\Sigma = \frac{\dot{M}}{3\pi\nu}\left[1 - \left(\frac{R_*}{r}\right)^{1/2}\right],$$

where R_* is the stellar radius (Pringle 1981). The form of the surface density is therefore governed by the nature of the viscosity. A common parameterization for ν is written in terms of a velocity and a scale length of the angular momentum transport process, which can be expressed as a combination of the local sound speed, $C_{\rm s}$, and H, if a dimensionless constant α is introduced:

$$\nu = \alpha C_{\rm s} H,$$

where $\alpha \lesssim 1$ (Shakura & Sunyaev 1973). For $r \gg R_*$ this model results in a power law for the surface density, $\Sigma \propto r^{-p}$, where $p \lesssim 1.5$.

If the gravitational energy released by the accretion is dissipated locally in the disk, and the emission is optically thick, then the temperature distribution is $T \propto r^{-q}$, where $q = 3/4$ (Pringle 1981). Approximately the same value of q is obtained for a disk which is heated purely by absorbing and re-radiating energy from the central star (Adams & Shu 1986; Adams et al. 1988).

4.2. Problems with Steady State Models

The model described above predicts power laws for the temperature and surface density, which explains why data are most often fitted by such distributions. However, observations indicate that several of the assumptions of the model may be invalid, the first problem being that the material from the envelope may not be fed in through the edge of the disk. Especially in young sources infalling material with low specific angular momentum will also land on the disk surface, affecting the disk structure and disk growth (Cassen & Moosman 1981; Stahler et al. 1994).

There is also reason to believe that the mass flux through the disk is not constant. The variability of emission from the class of pre-main sequence objects known as FU Orionis stars is convincing evidence that accretion is not steady. FU Ori stars exhibit spectral features indicative of circumstellar disks (Hartmann & Kenyon 1996). The steep rise and subsequent gradual decline of their light curves can be accounted for by sudden increases in the disk accretion rate by 3 or 4 orders of magnitude, induced by companion stars (Bonnell & Bastien 1992) or thermal instabilities in the disk (e.g., Bell & Lin 1994). If a forming star goes through many of these bursts, most of its mass may actually be accumulated during short ($\sim$ 100 yr) periods of enhanced accretion rather than during a more quiescent (T Tauri) phase; if the accretion is not steady the surface density is unlikely to be a smooth power law.

A further problem is that the mechanism for the viscosity is unknown. Processes considerably more efficient than small-scale molecular viscosity are needed to maintain the accretion rates of 10^{-8} to 10^{-6} $M_{\odot}$ yr^{-1} inferred for T Tauri disks. Convection has been investigated as a mechanism for the viscous transport (e.g., Lin & Papaloizou 1980; Ruden & Pollack 1991), but recent numerical simulations indicate that in fact convection tends to move angular momentum inwards rather than outwards in circumstellar disks (Stone & Balbus 1996; Cabot 1996). A good candidate for driving turbulent viscosity is a hydromagnetic instability in the ionized surface layers of a disk (Balbus & Hawley 1991; Hawley & Balbus 1991, and subsequent work). Away from the surface, in the shielded midplane of the disk, may be a "dead zone" in which no accretion occurs (Gammie 1996). Gravitational instabilities could be important for angular momentum transport during early phases of disk evolution (Lin & Pringle 1990), although the masses of T Tauri disks are generally not large enough for disk self-gravity to be important (compared with the central star) in later phases.

The main observational obstacle to a more detailed understanding of the viscosity in circumstellar disks is the lack of data with sufficient resolution to constrain the form of Σ. This situation is about to be reversed, and several new measurements are beginning to tackle this problem (see below).

4.3. Observational Constraints: Temperature

Where the dust emission is optically thick in the infrared, the temperature distribution can be derived directly from the spectral index, s, of the dust spectrum, defined by $F_\nu \propto \nu^s$. If the temperature is a power-law function of radius with index q, as expected for a circumstellar disk, then $s = 3 - 2/q$ (see, e.g., Emerson 1988). Measurements of q have been obtained for several T Tauri stars (Beckwith et al. 1990; Henning et al. 1993; Osterloh & Beckwith 1995), but very few objects are found with values of q as high as the 0.75 expected for an accretion disk. Most sources have q in the range 0.5 to 0.6 and have become known as flat-spectrum objects, because the spectral energy, νF_ν, is an approximately constant function of frequency.

Several explanations have been invoked to account for the fact that the temperature distribution in T Tauri disks is somewhat flatter than expected. Adams et al. (1987) suggested that the disks could be self-gravitating, providing an extra reservoir of energy to heat the disk at large radii. However, as discussed above, self-gravity is unlikely to be important for most T Tauri disks. Adams et al. (1988) have also suggested non-viscous mass and angular momentum transport, in which the accretion energy is not dissipated locally but is transported outwards, for example, via density waves. Another currently popular explanation is that flat-spectrum sources are surrounded by tenuous dusty envelopes. These envelopes must comprise only a small fraction of the total circumstellar mass, otherwise they would be detected as extended components in high resolution images of the dust emission. Evidence for such an envelope has been found for HL Tau (Grasdalen et al. 1989; Cabrit et al. 1996). The dust in the envelope may be heated by emission from both the star and the disk, scattering and re-emitting radiation, thereby heating the disk at large radii above the value expected for an $r^{-3/4}$ temperature law (Natta 1993). Alternatively, the residual infall of material from the envelope onto the disk surface may be the source of extra heating (Calvet et al. 1994).

4.4. Surface Density

Unlike the radial temperature profile, the surface density distribution must be measured directly from high resolution imaging and so has been much more difficult to determine. Initial estimates of the power-law index, p, have been derived by comparing the total disk mass, obtained from the integrated millimeter dust emission, with disk sizes measured using high-resolution interferometry at $\lambda = 3$ mm (Dutrey et al. 1996; Mundy et al. 1996). These suggest that in order to account for observed disk radii of 50 to 100 AU the surface density distribution must be fairly flat, with $p \lesssim 1$.

An alternative approach to deriving p is illustrated by Burrows et al. (1996), who have analyzed the scattered optical light in the HST images of the disk associated with HH30. By comparing the observed flaring of the disk and the radial intensity profile with scattering models of different geometries they find that the surface density decreases with radius with $p \sim 1$, and that the distribution perpendicular to the disk is Gaussian.

Although the results described above seem to suggest a degree of consistency in the value of p, new multi-wavelength millimeter and submillimeter interferometry measurements of HL Tau indicate that the situation is not quite so simple. By fitting simultaneously all their interferometer data with a disk model Lay et al. (1997) obtain $p > 1$. Such a steep decrease in Σ with radius is inconsistent with the large radii obtained from Gaussian fits to the HL Tau disk at $\lambda = 3$ mm (Mundy et al. 1996) and 7 mm (Wilner et al. 1996), and Lay et al. propose that disk models with a single dust component, and radial power laws for T and Σ, need some adjustment. Data such as these are therefore just beginning to provide constraints for theories of disk structure.

4.5. Dynamics

High-resolution spectroscopy of emission lines can be used to investigate the dynamics of material in T Tauri disks, to search for evidence of outflow, infall, and Keplerian rotation. Unless the disk has a photosphere due to vertical temperature structure these studies are limited to regions where the broadband dust continuum emission through the disk is optically thin. Spectral lines are therefore likely to arise at radii $\sim$ 10 to 100 AU, where the material is cool and mainly emits in the millimeter and submillimeter wavebands (Beckwith & Sargent 1993). Optical and infrared emission features may originate from the very inner regions of the disk, where the dust is destroyed, or irradiation of the disk by the central star and the star/disk boundary layer can cause heating of the surface layers of the disk (e.g., Calvet et al. 1991).

In the youngest protostars the kinematics of the disk material depends on the extent to which the central star dominates over the mass of the envelope and disk. Once protostars have dispersed enough of their circumstellar envelopes to be detected in the infrared ["Class I" sources and older, in the terminology of Lada (1987) — pre-main sequence T Tauri stars fall into Classes II and III] it seems that the star dominates the mass. A rotation velocity of 1 km s^{-1} is reached only on scales $\lesssim 10''$ for the nearest protostars and pre-main sequence stars, so millimeter interferometers have proved to be essential for spatially resolving the kinematics of circumstellar disks. Millimeter emission lines, particularly of CO, can be optically thick, and may therefore be used to study disks out to larger radii than is traced by the dust. In several sources velocity structure typical of that expected for combinations of infall and Keplerian rotation has now been detected on scales of several 100 AU (e.g., Sargent & Beckwith 1991; Koerner et al. 1993; Dutrey et al. 1994; Saito et al. 1995; Cabrit et al. 1996; Zhou et al. 1996; Yang et al. 1997; Ohashi et al. 1997).

Figure 4 illustrates the velocity structure of circumstellar material around the Class I protostar TMC1A, which is $\lesssim$ few $\times 10^5$ yr old. It is still embedded in an envelope which obscures the star at optical wavelengths, but the amount of circumstellar material (~ 0.05 $M_\odot$) is sufficiently small that near-infrared nebulosity around the star is detected and is observed to follow the cavity evacuated by a wind or jet from the central source (Chandler et al. 1996). A distinct velocity gradient is detected running perpendicular to the outflow axis in the emission from ^{13}CO and $C^{18}O$ J=1–0, which traces the circumstellar gas in this source. The velocity as a function of position can be fitted quite well by a model for Keplerian rotation about a 0.7 $M_\odot$ star (Brown & Chandler 1997).

As Figure 4 illustrates, the detection of rotation in the circumstellar material of protostars depends on the molecular tracer used, and can be complicated by the presence of other systematic velocity fields such as infall and outflow. Each of these kinematic components have their own spectral signatures, but even with the high spatial resolution provided by interferometry it can be difficult to disentangle them all. However, if a pre-main sequence star is fairly isolated from any extended molecular cloud emission the velocity structure in its disk can be very well constrained. Guilloteau & Dutrey (1997) are able to demonstrate for the T Tauri star DM Tau that the motion of its disk material follows the $V \propto r^{-0.5}$ expected for Keplerian rotation to a remarkably high degree of accuracy.

On smaller scales the kinematics of the inner disks must be derived from line profiles only, and in this case infrared transitions such as the rotation-vibration bands of CO at 2.3 μm have excitation requirements well matched to the conditions expected within a few stellar radii of the central object (Carr 1989). The first overtone rotation-vibration bands of CO trace material with temperatures of a few 1000 K, and hydrogen number densities of 10^{10} to 10^{11} cm^{-3}. Only a few sources have shown the CO bandheads in emission although several of these have been observed with high spectral resolution (e.g., Carr & Tokunaga 1992; Carr et al. 1993; Chandler et al. 1993). The measured profiles vary quite dramatically from source to source but are generally very broad and comprise considerable structure (Figure 5). Most of the spectra have been successfully modelled by the limb-brightened, double-peaked profile of a disk in Keplerian rotation, with various inclination angles to the line of sight (Chandler et al. 1995a; Najita et al. 1996); for DG Tau, CO absorption features in the stellar

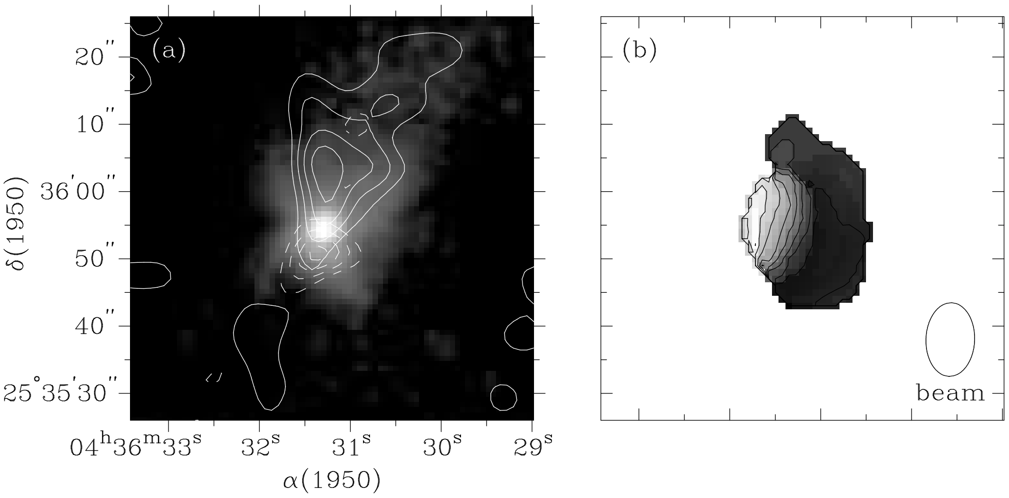


Figure 4. The dynamics of circumstellar material around the Class I protostar TMC1A (IRAS 04365+2535) observed using the Owens Valley millimeter array. (a) The molecular outflow is traced by blueshifted ^{12}CO J=1–0 emission (solid contours) and redshifted emission (dashed contours). The greyscale shows 2 μm reflection nebulosity following the evacuated outflow cavities (Chandler et al. 1996). (b) The intensity-weighted mean velocity of ^{13}CO J=1–0 emission in the rotating disk and envelope (Brown & Chandler 1997). The isovelocity contours are spaced by 0.2 km s^{-1} and the corresponding greyscale runs from blue-shifted (white) to redshifted (black).

photosphere may also need to be taken into account. A lower limit to the size of the CO-emitting region is obtained by assuming the lines are optically thick, giving radii of 3 to 30 $R_\odot$ for the sources in Figure 5.

CO rotation-vibration lines with double-peaked profiles have also been detected in absorption for a number of FU Ori stars during outburst (Hartmann & Kenyon 1987). Comparison of these CO features with optical absorption lines arising at even smaller radii show that the velocity increases closer to the star, consistent with Keplerian rotation (Kenyon & Hartmann 1989).

5. Disk composition

5.1. Dust

Spectroscopy of dust absorption features in the near- and mid-infrared demonstrates that the dust in the interstellar medium (ISM) mainly comprises grains of carbon and silicate compounds (e.g., Pégourié & Papoular 1985; Sandford et al. 1991; Tielens et al. 1996). Measurements of the dust opacity throughout the UV and infrared suggest that in diffuse clouds these particles are typically

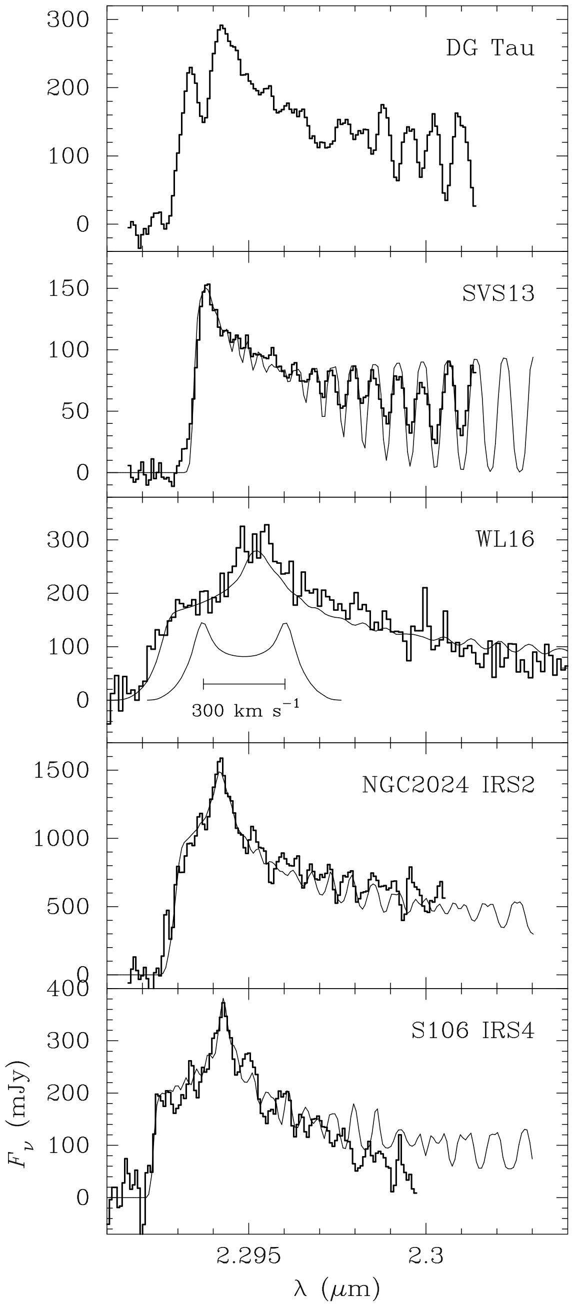


Figure 5. High-resolution spectra of the CO v=2–0 bandhead toward several young stars. Models of the emission from a steady accretion disk in Keplerian rotation (solid lines) are plotted on top of the data (histograms). A scaled profile of just one of the individual rotational transitions at the bandhead is illustrated for WL16. The emission from DG Tau is not well fitted by a disk without photospheric absorption features also being taken into account (from Chandler et al. 1995a).

$\lesssim 1\mu$m in size (see, e.g., the review by Mathis 1990). The detection of evidence for grain evolution from the ISM to circumstellar disks, perhaps due to grain coagulation, may therefore be important for understanding planetary system formation (cf. Beckwith & Sargent 1991).

Because of the lack of a background illuminating source and high optical depths in circumstellar disks the infrared dust features cannot be employed to investigate the dust properties. Instead, the long-wavelength dust opacity must be used to study grain evolution. In the millimeter and submillimeter the dust opacity, κ_ν, is typically parameterized as a power law function of frequency, $\kappa_\nu \propto \nu^\beta$. The normalization of κ_ν, the absorption cross-section per unit *total* mass of gas and dust, depends on the dust composition and the gas to dust ratio, and so in principle could be used to investigate dust evolution. Unfortunately it is very hard to measure κ_ν observationally, and theoretical calculations give values at $\nu = 10^{12}$ Hz in the range 0.02 to 0.6 cm^2 g^{-1} (see, e.g., Krügel & Siebenmorgen 1994; Pollack et al. 1994; Stognienko et al. 1995). The commonly-used value of 0.1 cm^2 g^{-1} therefore results in uncertainties of a factor of 5 or so (Beckwith & Sargent 1991). However, the power-law frequency dependence, β, can be determined, and potentially provides information about the size of the emitting grains. Solution of the Kramers-Kronig dispersion relations suggests a value $\beta = 2$ for small particles where the grain size, a, is much less than the emitting wavelength, λ (e.g., Draine & Lee 1984). Large particles with $a \gg \lambda$ radiate more like black bodies and have $\beta = 0$, which has led to the suggestion that the value of β could serve as a diagnostic of particle coagulation in circumstellar disks (e.g., Miyake & Nakagawa 1993). Recent theoretical and laboratory studies of typical grain constituents, however, demonstrate that β is also affected by grain shape, structure, and chemical composition (Pollack et al. 1994; Agladze et al. 1994, 1996). Nevertheless, an observed variation in β from source to source, or from interstellar to circumstellar material, should still reflect evolution of the dust.

The value of β can be determined from SEDs at long wavelengths using disk models. Surveys of T Tauri disks frequently give β in the range 0 to 1 (e.g., Beckwith & Sargent 1991). Such low values may indicate grain growth (Mannings & Emerson 1994), but at this stage too little is known about the dust opacity to distinguish between an increase in particle size and changes in β caused by some other form of processing. Grain evolution from the ISM to T Tauri disks can, however, be investigated to some extent by studying dust in protostellar disks and envelopes.

In one Class 0 protostar, HH24MMS in the Orion B cloud, the disk has been isolated at several frequencies using millimeter interferometry, enabling β to be determined from its spectral index (Chandler et al. 1995b). The emission is in the Rayleigh-Jeans regime and is optically thin, in which case $F_\nu \propto \nu^{2+\beta}$. Figure 6 illustrates the spectrum of the HH24MMS disk and envelope. The disk is well-fitted by $F_\nu \propto \nu^{2.7}$, implying $\beta \sim 0.7$, similar to that observed for T Tauri stars. The low values of β measured for T Tauri disks may therefore have been established very early in their evolution, rather than indicating grain growth *during* the T Tauri phase.

To examine whether an intermediate evolutionary phase for the dust can be identified in protostellar envelopes Visser et al. (1997) have used submilli-

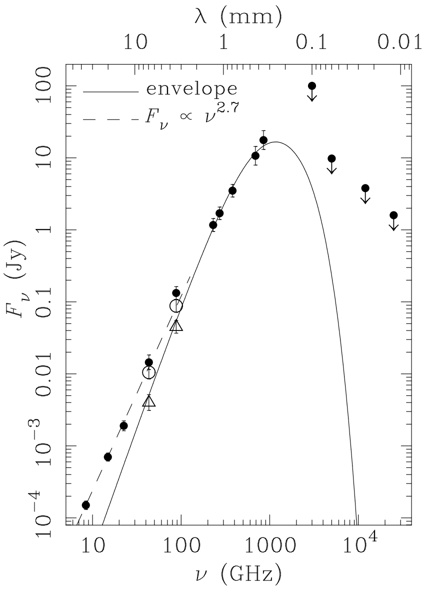


Figure 6. The dust spectrum of the Class 0 protostar HH24MMS in Orion (from Chandler et al. 1995b). At $\lambda = 7$ mm and 3.4 mm interferometry has been used to separate the total emission (solid circles) into components from the disk (open circles) and the extended envelope (open triangles). The disk emission falls onto a power law, $F_\nu \propto \nu^{2.7}$, along with the centimeter measurements (dashed line). Also shown is a model of the emission from an optically-thin envelope with $\beta = 1.5$ (solid line).

meter imaging to investigate the value of β in the dense cores of the NGC 2024 molecular ridge in Orion B. The spectral index of the dust emission is found to be consistently lower at the location of embedded protostars compared with the surrounding cloud, which Visser et al. conclude is most likely to be due to a decrease in β at the sites of star formation. If this is the case, then the value of β in the dense cores is in the range 1.2 to 1.6 compared with 1.8 to 2.1 in the surrounding cloud. Spatial variations in the value of β have also been observed for different components of the Orion A cloud core, which Wright et al. (1992) propose could be due to the processing of dust grains by an interaction with the outflow from the powerful infrared source IRc2. These initial results suggest that the properties of the dust grains depend on local density and proximity to active star formation, with the protostellar envelopes in NGC 2024 possibly representing a dust phase prior to further coagulation or processing in protostellar disks. This effect clearly needs to be confirmed in more sources.

5.2. Gas Phase Chemistry

Measurements of the composition of the gas phase in T Tauri disks are currently severely limited by the sensitivity of the instruments available. An interferometric study of CS emission from the HL Tau disk indicates that the abundance of CS in the disk is a factor of ~ 50 lower than in other dark clouds in Taurus (Blake et al. 1992). A more extensive single-dish survey of the disks around DM Tau and GG Tau has recently been carried out by Dutrey et al. (1997), who detect emission from a number of molecular species. In all cases, however, the abundances of these molecules are found to be lower by factors of ~ 10 to 100 in the disks compared with those observed in molecular clouds. Models of the chemistry in high density environments suggests that the molecules are probably "freezing-out" onto the surface of dust grains (e.g., Aikawa et al. 1996; Bergin & Langer 1997). Low abundances assumed to be caused by the same process have also been measured in the envelopes of Class 0 protostars (e.g., McMullin et al. 1994; Blake et al. 1995; van Dishoeck et al. 1995). It seems likely that the observed evolution of the dust grains and the change in gas phase composition at high densities are closely linked.

6. Disks Around Main Sequence Stars

The Infrared Astronomical Satellite (IRAS) found that more than 15% of nearby, main sequence stars have a far-infrared excess over and above the emission expected from the stellar photosphere (e.g., Backman & Paresce 1993). Three of these, α Lyr, α PsA, and β Pic, were resolved by IRAS at $\lambda = 60\ \mu$m with diameters of ~ 30 arcsec (300 to 500 AU). Optical and mid-infrared images of the most massive and optically-thick disk, that surrounding β Pic, have illustrated beautifully the disk structure on scales of 10s to 100s of AU (e.g., Paresce & Burrows 1987; Lecavelier des Etangs et al. 1993; Lagage & Pantin 1994). Several asymmetries and warps have been detected in the surface of the disk, possibly caused by a substellar companion which has yet to be identified (Kalas & Jewitt 1995; Burrows et al. 1995).

The amount of material in main sequence disks is considerably lower than is observed for T Tauri stars. The mass of dust grains is typically only a few lunar masses (Chini et al. 1991; Zuckerman & Becklin 1993). A search for atomic hydrogen emission from β Pic by Freudling et al. (1995) gives an upper limit of 0.5% of the mass of Jupiter remaining in the form of HI in its disk. Limits on the amount of molecular gas derived from observations of CO are less well defined, due to the unknown abundance of CO relative to molecular hydrogen in main sequence disks. Assuming a CO abundance typical of the ISM, Zuckerman et al. (1995) suggest that for stars older than 10 Myr considerably less than a Jupiter mass of molecular gas remains in their disks. Similar observations of older stars, such as β Pic, place even more stringent constraints on the molecular gas content of main sequence disks, although it is also possible that the $CO{:}H_2$ ratio is very low in these objects due to the selective dissociation of CO by UV radiation (Dent et al. 1995).

7. Conclusions and Prospects for the Future

Studies of T Tauri stars have now conclusively demonstrated that circumstellar disks are relatively common, and that many have masses commensurate with predictions for the early solar system. The dust emission from disks becomes undetectable after several Myr, and consensus is growing that these systems can be used to constrain the timescales of planet formation and the conditions within the solar nebula. Although disks are key to enabling the accretion of material onto a forming protostar during early evolution, measurements of temperature and density structure in T Tauri disks are beginning to show that at later phases models of steady accretion disks do not represent the full picture. Residual infall envelopes are needed to provide heating for T Tauri disks at large radii, and an evolution of the grain properties, perhaps resulting in populations of both small and large grains with different values of β, may be required to explain all the observations of the HL Tau disk (Lay et al. 1997). There is strong evidence that the composition of both the gas and dust in T Tauri disks is considerably different from the ISM.

Many advances in our understanding of circumstellar disks have been made in the last decade but it is clear that significant progress is still needed in many areas. The refinement of disk dissipation timescales is limited at present by our knowledge of the species used to trace the disk mass. The causes of the observed evolution in the dust opacity at high densities are as yet unknown, and the molecules commonly assumed to be good tracers of the molecular component of the ISM, such as CO, have uncertain abundances relative to H_2 in circumstellar disks. The absolute value of κ_ν for dust may constrained if independent measures of the total disk mass can be obtained, perhaps from disk rotation curves. Better estimates of molecular abundances must await more detailed models of T Tauri disk structure, when statistical equilibrium calculations of molecular excitation can establish the H_2 content of the disks.

Magnetic fields are predicted to be very important for disk evolution, especially at small radii, where a magnetic field linking the disk to the star may either brake the stellar rotation or spin-up the disk (Königl 1991). Magnetic fields may also act as the acceleration and collimation mechanism for protostellar jets, and may channel the accretion of disk material onto the central star (Edwards et al. 1994). While models of Keplerian rotation have been used successfully to explain many line profiles, searches for evidence of *deviations* from Keplerian rotation using optical and infrared spectroscopy may therefore be needed to determine the influence of B-fields in disks. Polarized dust emission from grains aligned by a B-field has already been detected in protostellar envelopes at millimeter and submillimeter wavelengths (Tamura et al. 1995; Holland et al. 1996; Akeson et al. 1996), but higher resolution and sensitivity is needed before similar measurements can be made in circumstellar disks.

Recent upgrades to existing millimeter arrays, and the results from the CSO-JCMT submillimeter interferometer, pave the way to studies of disk structure in many more sources. New, sensitive, submillimeter instruments such as SCUBA on the JCMT increase the prospect of detecting disk emission from post-T Tauri stars, hence establishing a link between the T Tauri disks and nearby main sequence stars. Further into the future, high-resolution imaging instruments such as the large millimeter-wave arrays proposed by Japan, the US, and Europe, and the Smithsonian submillimeter interferometer under construction on Mauna Kea, will be essential for solving some of the problems of disk structure and evolution described above. Ground- and space-based optical and near-infrared interferometry will allow gaps and holes in inner disks to be imaged directly on small scales, and spectroscopy using 8-meter class telescopes promises to be indispensable for understanding the origin of jets and the role of magnetic fields.

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