PROTOSTELLAR AND PROTOPLANETARY DISKS

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1. Introduction

It is barely a decade since the first molecular line images of disks around embedded and pre-main sequence stars were published (Beckwith *et al.,* 1986; Mundy *et al.,* 1986; Sargent & Beckwith 1987). In the intervening years there has been steady progress in detecting and analyzing these disks, which are an expected by-product of the star formation process (*cf.* Shu *et al.,* 1987; Shu *et al.,* 1993), and there is now a veritable flood of new and intriguing results as millimeter-wave instrumentation improves (*cf.* Sargent & Welch 1993).

Observations across the wavelength spectrum provide indirect evidence on size scales from 0.01 to 1000 AU that disks are associated with very young stars (*cf.* Beckwith 1994, and references therein; Sargent 1995, and references therein). Indeed, infrared and millimeter-wavelength continuum emission from many solar-mass pre-main sequence objects can be reproduced by models of star-disk systems (Adams *et al.,* 1987), furnishing a powerful tool for characterizing disks. Masses appear to range from 0.001 to 2 $M_\odot$; radii are of order 100 AU; and at 1 AU radius, temperatures are less than a few $\times$ 100 K (*cf.* Adams *et al.,* 1990; Beckwith *et al.,* 1990; Beckwith & Sargent 1993a). These properties are quite consistent with those of the pre-solar nebula so that studies of young disks may inform our understanding of how planetary systems form and evolve.

Detailed disk investigations require high spatial resolution since 100 AU is equivalent to $0.7''$ at the 140 pc distance of the nearest star-forming clouds. Aperture synthesis imaging of millimeter-wave line and continuum emission can not only achieve the desired resolution to sample the physical and chemical properties of the cool, outer disks, but also discriminates against the smooth, large-scale emission expected from their parent molecular clouds. The hotter, inner disk regions can be probed at near infrared wavelengths through, for example, observations and modelling of the 2 μm CO bandhead emission (*cf.* Chandler *et al.,* 1995; Carr 1995, and references therein). In view of the Symposium theme, my review will focus mainly on gas in disks. The dust component is discussed in a number of other reviews (*e.g.* Beckwith 1994; Kenyon 1995; Sargent 1995). There are many open questions, particularly with regard to circumstellar grain properties (*cf.* Pollack *et al.,* 1994) and the nature of the envelopes that may surround many star/disk systems (*cf.* Calvet *et al.,* 1994; Natta 1994; Chandler *et al.,* 1995).

2. Outstanding Questions

Although much has been learned about proto-stellar and proto-planetary disks, many questions remain. Among the most important problems:

• It is not clear how the fraction of young stars exhibiting disks varies with such factors as age and environment. Since these may be planetary systems in the making, disk frequency is important for theories of cosmogony.

• Most stars form in binaries or multiple groups (Simon *et al.,* 1992; Leinert *et al.,* 1993; Ghez *et al.,* 1993; Reipurth & Zinnecker 1994), but the effects of companions on circumstellar or circumbinary disks is not well understood (*cf.* Mathieu 1994).

• It is not known how disks evolve, although this has important implications for star and planet formation. Morphological evolution has been inferred from the fact that the infrared emission from some systems can be reproduced by invoking the presence of disks with cleared, central holes (Skrutskie *et al.,* 1990; Beckwith *et al.,* 1990; Marsh & Mahoney 1992; Strom *et al.,* 1993; Osterloh & Beckwith 1995). However, there are alternative interpretations (Boss & Yorke 1993).

• Kinematic evolution of disks remains an enigma. Gravitational infall is expected for true protostars, but supporting observational evidence is limited (*cf.* Zhou *et al.,* 1993; Chandler & Sargent 1993; Zhou & Evans 1994). Images of the disks around pre-main sequence systems have been interpreted in terms of infall, rotation, and outflow motions (*e.g.* Sargent & Beckwith 1991; Koerner *et al.,* 1993; Hayashi *et al.,* 1993; Guilloteau & Dutrey 1994; Cabrit *et al.,* 1995; Koerner & Sargent 1995), but no evolutionary pattern has been identified.

• Disk mass estimates based on dust continuum fluxes are frequently much larger than those derived from molecular line maps (*e.g.* Guilloteau & Dutrey 1994; Koerner & Sargent 1995; Dutrey *et al.,* 1995). The cause of the discrepancy has yet to be established. It could result from the fact that disk emission in the low-lying rotational transitions of CO and ^{13}CO is often optically thick (Beckwith & Sargent 1993b) or because the molecular species used to trace the presence of molecular hydrogen is depleted (*cf.* Blake *et al.,* 1992; Dutrey *et al.,* 1994, 1995).

• Dispersal times for the dust and gas components of disks are tied to the mass determinations and are therefore difficult to establish. Nevertheless, these time-scales are critical for proto-planetary disks since they strongly constrain theories of how giant planets form (*cf.* Lissauer *et al.,* 1994; Podosek & Cassen 1994).

3. Recent Pertinent Observations

3.1. ENVIRONMENT

Far-infrared and mm-wave continuum excesses indicate that a substantial fraction, perhaps 50%, of young, low-mass stars in the nearby Taurus, Ophiuchus and Chamaeleon clouds are surrounded by disks (Strom *et al.,* 1989; Beckwith *et al.,* 1990; Henning & Thamm 1994; André & Montmerle 1994; Mannings & Emerson 1994; Osterloh & Beckwith 1995). Near-infrared excesses also suggest a very high fraction of associated disks for the members of young embedded clusters (Ladd *et al.,* 1993; Lada & Lada 1995).

Recently, arcsec-size, externally-illuminated nebulae have been detected in the Trapezium cluster in Orion (O'Dell *et al.,* 1993; O'Dell & Wen 1994). Many are associated with young stars of age $\sim 10^6$ years (Prosser *et al.,* 1994; McCaughrean & Stauffer 1994). It seems likely that these are star/disk systems where the neutral circumstellar material is being ablated by radiation from nearby OB stars, (Bally *et al.,* 1995). This interpretation is strengthened by the observation that some disk-like structures, each associated with a young star, are seen silhouetted against the nebula. As in the quiescent dark clouds, inferred disk properties are consistent with those of the pre-solar nebula (McCaughrean & O'Dell 1996). The fraction of stars that might support pre-planetary disks does not appear to be diminished even in a dense cluster environment like the Trapezium.

3.2. MULTIPLICITY

Very few binary systems have been mapped to date but the results are intriguing. The IRAS 16293-2422 disk was one of the earliest imaged (Mundy *et al.,* 1986). In subsequent higher resolution centimeter- and millimeter-wavelength maps, two continuum sources, separated by about 800 AU, were discovered within a rotating, circumbinary disk (Wootten 1989; Mundy *et al.,* 1992; Walker *et al.,* 1993). The detection of vibrationally excited $C^{32}S$, possibly from self-gravitating instabilities in an accretion disk (Walker *et al.,* 1994), suggests that at least one element of the binary is a star/disk system.

Many pre-main sequence stars have recently proven to be binaries. The prototype of the class, T Tau, is no exception. The optically-visible T TauN and its infrared companion, T TauS, are separated by $\approx$ 100 AU. Evidence for a circumbinary disk was presented by Weintraub *et al.,* (1989) but very high resolution, 267 GHz continuum images imply that only T TauN is surrounded by an accretion disk (van Langevelde *et al.,* 1996).

The separations of the two sources in IRAS 16293-2422 and T Tau are important. On the whole, mm-wave continuum flux, presumably from a circumbinary disk, appears to be suppressed when binary elements are separated by less than about 100 AU (*cf.* Beckwith & Sargent 1993a; Osterloh & Beckwith 1995; Jensen *et al.* 1996a). Interferometer maps of the triple system UZ Tau at 1 mm by Jensen *et al.* (1996b) nicely illustrate this point. Strong 1 mm continumm and CO(2$\rightarrow$1) emission, consistent with a rotating disk, are associated with UZ TauE; only weak continuum and no line emission are detected from the companion at 530 AU, UZ TauW, which is itself a close binary with element separation 50 AU. Circumbinary disks are in fact likely to be truncated at an inner radius defined by the binary orbit, with concomitant reduction in disk surface area and infrared/millimeter flux (Artymowicz & Lubow 1994). Indeed, high resolution, ^{13}CO(1$\rightarrow$0) and continuum images of the binary GG Tau can be fit by a model circumbinary disk of radius 800 AU with a cleared inner cavity of radius 180 AU (Dutrey *et al.,* 1994). The subject of how disks evolve in a binary environment needs to be pursued.

3.3. DEPLETION

Dutrey *et al.* (1994) point out that the disk mass derived from their ^{13}CO measurements of GG Tau is much lower than estimated from the dust continuum fluxes (*e.g.* Beckwith & Sargent 1991). Similar discrepancies (up to factors of 100) are noted in other T Tauri stars (Koerner *et al.,* 1993; Guilloteau & Dutrey 1995; Koerner & Sargent 1995; Dutrey *et al.,* 1995). Masses based on continuum flux are probably correct to within a factor of 3 (*cf.* Pollack *et al.,* 1994; Agladze *et al.,* 1995) but factors such as beam dilution, optical depth effects (Beckwith & Sargent 1993b), and depletion of some molecular species (Aikawa *et al.,* 1995) could result in erroneously low masses of molecular hydrogen (*cf.* Dutrey *et al.,* 1995). For example, a multi-transition study of CS suggests it is much less abundant in the HL Tau disk than in interstellar clouds (Blake *et al.,* 1992). Not surprisingly, very few disks are detected around visible pre-main sequence stars in interferometric CS surveys (Ohashi *et al.,* 1991; Ohashi *et al.,* 1994;

Ohashi & Hayashi 1995).

3.4. KINEMATIC EVOLUTION

The spectral line shapes that result from radially infalling and rotating gas in disks are disconcertingly similar. It is sometimes possible to distinguish between these kinematic extremes using aperture synthesis molecular line maps (*e.g.* Koerner & Sargent 1995), but uncertain disk inclination or azimuthal structure can cause confusion. Thus, in early ^{13}CO(1$\rightarrow$0) aperture synthesis maps of HL Tau, it appeared that the circumstellar gas was centrifugally supported out to radii of 1000 AU (Sargent & Beckwith 1987; 1991). More recent position-velocity (*p*-*v*) diagrams indicate a relatively small, rotating inner disk surrounded by a substantial radially-infalling envelope (Hayashi et al. 1993), although an entrained outflow interpretation has also been proposed (Cabrit *et al.,* 1995).

Unambiguous interpretation of molecular line emission from disks can be effected by comparing synthetic maps based on model disks with the observations (*e.g.* Koerner *et al.,* 1993; Dutrey *et al.,* 1994; Koerner, this volume). For this purpose, imaging is best carried out in the CO or ^{13}CO (2$\rightarrow$1) lines at λ = 1.3 mm, where the Planck function and the larger statistical weight of the higher rotational level combine to ensure stronger emission. In this way, Koerner *et al.* (1993) showed that a 0.1 M$_\odot$ disk with radius $\sim$ 1000 AU is gravitationally bound to the pre-main sequence star GM Aur; there is little evidence for infalling material. A similar analysis for DM Tau demonstrates that rotation *and* infall are probably occurring in this disk (Spangler *et al.,* 1995; but see also Saito *et al.,* this volume)

Reliable knowledge about the velocity fields in a sample of proto-stellar and proto-planetary disks could help determine how initially infall-dominated motions gradually evolve to a rotationally-dominated state where planets may form. Table 1 is a compilation of relevant properties for apparently single stars. Stellar ages and masses, as well as disk masses, are from Beckwith *et al.* (1990), except for HL Tau, where the age is that proposed by Stapelfeldt *et al.* (1995) based on their discovery that this star is still heavily embedded. Inside the centrifugal radius, R_{C}, all material is rotating; R_{C} and the outer radius, R_{D}, are derived from mm-array maps and synthetic images (Koerner 1994; Koerner & Sargent 1995; Spangler *et al.,* 1995; Sargent & Koerner 1996, in preparation). The region of radial infall is defined by ($R_{\mathrm{D}} - R_{\mathrm{C}}$).

The values of R_{C} in Table 1 are still tentative. However, it is noteworthy that for HL Tau the rotating core radius derived from molecular line analysis, 80 AU, is very close to the disk radius, 70 AU, obtained from sub-arcsecond images at 2.6 mm (Mundy *et al.,* 1995), and through sin-

TABLE 1. Disk Infall Regions ($R_D - R_C$)

Star	M_* $M_\odot$	Age yrs	M_D $M_\odot$	R_C AU	R_D AU
HL Tau	1.1	$\leq 10^5$	0.1	$\sim 80^*$	1000
RY Tau	1.25	2×10^5	0.04	~ 150	200
DO Tau	1.6	6×10^5	0.02	350	500
DL Tau	0.25	1×10^6	0.08	200	200
GM Aur	0.72	2×10^6	0.08	1000	1000
DM Tau	0.62	3×10^6	0.03	160	500
Elias 3-1	1.03	$\leq 10^7$	0.01	~ 400	600

gle baseline interferometry at 850 μm (Lay *et al.,* 1994). In addition, disk masses derived from rotation curves agree quite well with M_D. There is no obvious trend in ($R_D - R_C$) with stellar age, but the sample is very small. As might be expected, ($R_D - R_C$) is dramatically larger for the extremely young HL Tau.

4. Future Steps

The observations summarized above should be regarded as the tip of the iceberg. With the advent of infrared arrays, upgrades to Hubble Space Telescope, and the launch of the Infrared Space Observatory (ISO), great strides will be made in understanding disk frequency as a function of environment. Increasing sensitivity with telescopes such as Keck and Gemini will help determine which young stars are in multiple systems and what are the properties of each star, as well as providing samples for molecular line disk studies. The increased resolution and sensitivity expected from the expanding millimeter-wave arrays, from the SAO sub-millimeter array, and from the planned national mm-wave array will allow more rapid surveys of disks in a wide variety of molecular species so that mass problems, and related questions regarding dust and gas dispersal times, can be settled. Detailed investigations of disk morphology and velocity fields will also be more straightforward, increasing the viability of disk evolution studies. For example, the size of the HL Tau dust disk was established with a relatively modest gain in resolution (Mundy *et al.,* 1995), and similar measurements for other disks should soon become routine.

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