SUBARCSECOND MM AND SUBMM OBSERVATIONS OF CIRCUMSTELLAR DISKS

DAVID J. WILNER
Harvard-Smithsonian Center for Astrophysics

and

OLIVER P. LAY
University of California, Berkeley

Millimeter and submillimeter observations provide a valuable tool for probing the cool, dusty material in the disks around young stars. With ongoing instrumental upgrades, the technique of interferometry now obtains subarcsecond resolution at these wavelengths, capable of spatially resolving the size scales associated with planet formation in nearby star forming dark clouds. We describe in detail the subarcsecond millimeter and submillimeter observations of the well known low mass young stellar objects HL Tau and L1551 IRS5 to illustrate what may be learned from such observations. High resolution multi-frequency continuum observations yield estimates of surface mass density distributions and optical depths, providing important constraints on accretion mechanisms as well as starting points for modeling the evolution of the primitive solar nebula. Drawing on observations of several low mass pre-main-sequence systems, we examine power law disk models, departures from simple power law structure, and the influence of companion bodies. We also discuss observations of maser emission as subarcsecond probes of gas kinematics in some sources.

I. INTRODUCTION

A large fraction of young stars exhibits emission from small particles thought to be distributed in disks with properties similar to the early Solar System, and these disks provide a direct link between the birth of stars and the formation of planetary systems. By the time of *Protostars and Planets III*, spectral energy distributions of young stellar objects spanning wavelengths from the optical to the millimeter were commonly modeled as arising from combinations of stellar photospheres, extended envelopes, and circumstellar disks of Solar System dimensions. Yet there existed little, if any, direct support for the disk paradigm in the form of spatially resolved observations, largely because of the high angular resolution required. In nearby star forming dark clouds such as Taurus–Auriga and Ophiuchus (distance 140 pc), a circumstellar disk with extent comparable to the planetary system around our Sun subtends less than $0\farcs5$ (70 AU). While progress continues to be made characterizing the physical properties of the circumstellar environment through increasingly complex modeling of spatially unresolved measurements, observations with high angular resolution are ultimately essential to validate the underlying constructs of these models.

The intervening years have seen remarkable instrumental advances that allow observations with subarcsecond resolution at optical, infrared, and millimeter wavelengths. With these new capabilities, it has become possible to observe directly the disks that had been long invoked to explain the photometric and spectroscopic peculiarities of young stars. At optical wavelengths, where the Hubble Space Telescope provides the required resolution, spectacular observations in the Orion Nebula resolve a few circumstellar disks as dark ovals in dramatic silhouette against the nebular background (McCaughrean and O'Dell 1996). In Taurus, sources such as HH30 (Burrows et al. 1996) and HK Tau/c (Stapelfeldt et al. 1998) are viewed nearly equator on, obscuring the stellar photosphere and allowing scattered light from the central star to provide exceptionally clear pictures of the disk geometry. For these sources, it is important to keep in mind that the extended emission arises entirely from scattering. In rare cases, the scattered light shows a correspondence with extended cold gas imaged in low lying transitions of CO (e.g. GM Aur; Stapelfeldt et al. 1995, Dutrey et al. 1998). However, no information may be extracted from these tracers on the inner disk regions of high column density that remain opaque.

The disk material beyond a few stellar radii is at low temperatures, less than a few hundred degrees, and emits most of its energy at far-infrared through millimeter wavelengths. In this chapter, we review the development and impact of subarcsecond resolution millimeter and submillimeter observations of circumstellar material. We refer the reader to the chapter by McCaughrean et al. for a discussion of optical and infrared observations of disks, and to the chapter by Mundy et al. for a review of millimeter emission from protostellar envelopes and the relationship of disks to these larger scale structures.

A. Millimeter/Submillimeter Emission

At millimeter and submillimeter wavelengths, emission from heated dust in the circumstellar environment of a low mass star dominates any emission from the stellar photosphere by many orders of magnitude. Surveys with single dish telescopes detect millimeter emission from a substantial fraction of pre-main-sequence systems, and the inferred disk properties are thought to correspond to analogs of the protosolar nebula before the onset of planet formation (Beckwith et al. 1990). However, these low resolution ($> 7''$) measurements cannot separate the disk flux component from the extended envelope, which is largely optically thin at these wavelengths and often dominates the disk contribution in young systems. Interferometers act as spatial filters, so that observations using long baselines are insensitive to the extended envelopes. The combination of wavelength and resolution therefore make millimeter and submillimeter interferometry an especially powerful probe of the compact disks that surround young stellar objects.

The push towards subarcsecond resolution at millimeter and submillimeter wavelengths capable of resolving the structure of the circumstellar disks has been made possible through advances in instrumentation, including low noise receivers, wider bandwidths, and longer interferometer baselines. Table 1 summarizes the subarcsecond capabilities of existing and future arrays. An important point is that as the synthesized beam becomes smaller, the sensitivity to surface brightness goes down; there is simply less flux from the smaller patch of sky. When observing a source with brightness temperature T_B at a wavelength λ with a Gaussian beam of angular diameter θ, the flux density in the beam (in the Rayleigh–Jeans regime) is given by

$$\left(\frac{S}{\mathrm{mJy}}\right) = 5.7\left(\frac{\lambda}{3\ \mathrm{mm}}\right)^{-2}\left(\frac{T_B}{100\ \mathrm{K}}\right)\left(\frac{\theta}{0.1''}\right)^{2}.$$

High resolution observations of low brightness emission therefore require very high sensitivity. Much of the recent progress comes from observations of dust continuum emission where full advantage may be taken of the maximum available bandwidths. Spectral line emission, by contrast, is generally limited in bandwidth by the velocities of Doppler motions, and currently only very high brightness temperatures may be detected from these narrow bandwidth signals at subarcsecond resolution. Maser action provides one natural mechanism for establishing very high brightness spectral line emission, and we describe observations of masers in the circumstellar environment in §IV.

The effect of atmospheric fluctuations has not been included in Table 1. These fluctuations disrupt the wavefronts and impose a "seeing" limit on the angular resolution that may be achieved. It is only recently that the calibration techniques of fast-switching (between the target and a reference source) and water vapor radiometry have been introduced to overcome the seeing limit. Advances in this technology will continue to improve instrument performance and greatly increase the fraction of time available for observations with subarcsecond resolution. The next generation of millimeter arrays planned for deployment in Chile offer spectacular increases in sensitivity, approximately two orders of magnitude for dust continuum emission (a factor of 10^4 in observing speed), and will revolutionize the field.

B. Models of Dust Emission from Disks

Compact millimeter continuum emission from low mass stars is commonly attributed to dusty circumstellar disks, and a model is required to interpret the observations. Following the work of Adams et al. (1988) and Beckwith et al. (1990), it has been the common practice to assume that the disks are flat, thin, and circularly symmetric, with dust emission originating from an inner radius, $r_{\rm in}$, at the edge of the dust destruction zone, to an outer cut-off radius, $r_{\rm out}$. The temperature T and surface density Σ are assumed to follow power law dependencies with the radius:

$$\Sigma(r) = \Sigma_{50}\left(\frac{r}{50{\rm AU}}\right)^{-p}, \qquad T(r) = T_{50}\left(\frac{r}{50{\rm AU}}\right)^{-q}.$$

We adopt the value of 50 AU as a representative radius in the disk appropriate for the normalization. The flux (units: W Hz^{-1} ster^{-1}) emitted by a disk element of area dA is

$$dS = \frac{1}{D^2}B_\nu(T)(1-e^{-\tau})\cos i\; dA,$$

where D is the distance to the star, $B_\nu(T)$ is the Planck function, i is the inclination of the disk ($i=0$ is face-on), and the optical depth $\tau = \Sigma(r)\kappa_\nu/\cos i$. The dust emissivity κ_ν (units: cm^2 g^{-1}) is parameterized as a power law in frequency: $\kappa_\nu = \kappa_o(\nu/\nu_o)^\beta$, with the index β depending on the nature (size, structure and composition) of the emitting grains (see Beckwith et al., this volume). For small interstellar grains, simple physical considerations suggest that $\kappa_\nu \propto \nu^2$ (e.g. Draine and Lee 1984), while detailed calculations of the dust mixtures expected in the disk environment suggest a less steep frequency dependence may be appropriate (e.g. Pollack et al. 1994). Note that grains large compared to the observing wavelength have emissivity that depends only on physical cross section, i.e. $\beta = 0$. The brightness distribution of the model disk as seen by an observer is generated by mapping each area element to its appropriate sky coordinates, a transformation that depends on the position angle γ and inclination i of the disk.

The power law indices for disks are expected to lie in the ranges $0 < p < 2$, $0.5 < q < 0.75$, $0 < \beta < 2$. Although a temperature distribution of the form T $\propto r^{-3/4}$ is thought to characterize both viscous accretion disks and simple reprocessing disks (Adams et al. 1988), the spectral energy distributions often imply significantly less steep radial temperature gradients, in particular values of q as low as 0.5 are inferred for "flat spectrum" sources. Several explanations for these non-standard temperature distributions have been proposed, including variations of geometric flaring whereby the disk intercepts more stellar energy (Kenyon and Hartmann 1987, Natta 1993, Calvet et al. 1994, Chiang and Goldreich 1997) as well as more exotic ideas such as wave heating through spiral instabilities (Shu et al. 1990).

Regardless of the nature of the heating mechanism, in the limit of very low frequency and very low optical depth, $\tau \ll 1$, the dust continuum emission is proportional to a product of the column density and temperature: $dS \propto r^{-(p+q)}$. For $p + q < 2$ the outer radii will be the dominant source of emission. For higher frequencies, this effect is accentuated as the disk becomes increasingly optically thick towards the axis ($dS \propto r^{-q}$ for optically thick emission). For low mass stars, the inner cut-off radius is of order 0.05 AU, where heating destroys grains. This inner radius has no significant effect on the millimeter and submillimeter brightness distribution, since the emission is predicted to be optically thick and the solid angle subtended by this region is very small.

The flat, thin, circularly symmetric model is of course an extreme simplification. For example, the dust properties probably change as a function of radius, and it is unlikely that there is a sharp cut-off at the outer radius. It is also likely that geometry plays an important role through flaring and shadowing, in which case the simple model will break down at high inclinations and a three dimensional model becomes necessary. While detailed and complex disk models are becoming available, the simple power law model described above lends itself more readily to a comparison with current data. There are eight free parameters: γ, i, $r_{\rm out}$, p, q, β, $(\Sigma_{50}\kappa_o)$ and T_{50}. Note that it is not possible to separate the contributions from the surface density and the dust emissivity normalizations. In addition, a minimum disk temperature, $T_{\rm min}$, is usually specified, to account for external heating (Dutrey et al. 1996) or back-warming from an envelope (Natta 1993). Robust estimates for the disk parameters can be obtained by fitting the simple model to the data. The disk mass is given by $\int 2\pi r \Sigma {\rm d}r$. The dust emissivity index β is a possible diagnostic for grain growth in the disk (Beckwith and Sargent 1991), and the value of p relates the observations to models of the accretion process and planet formation.

A simple steady disk model illustrates the connection between disk structure, as quantified by the value of p, and predictions of accretion theory. For a thin disk with material fed in at large radii at a constant rate $\dot{M}$, conservation of mass and angular momentum combine to relate the disk surface density, Σ, to $\dot{M}$, r, and the kinematic viscosity, ν, by

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

where R_* is the stellar radius. The kinematic viscosity is often parameterized in terms of a velocity and a scale length of the angular momentum transport process, $\nu = \alpha c_s H$, where c_s is the local sound speed, H is the scale height, and α (< 1) is a dimensionless number. For $r >> R_*$ and $\alpha = const$, the surface density may be represented by a power law, $\Sigma \propto (r^{3/2} T_m)^{-1} \sim r^{-p}$, where T_m is the local midplane temperature whose value is governed by the balance of heating, largely through viscous processes, and cooling, through radiative losses. For an isothermal disk, $\Sigma \propto r^{-3/2}$. On the other hand, an optically thick disk with opacities appropriate to a mix of low temperature ices and grains will develop $T_m \propto r^{-3/2}$ and $\Sigma \approx const$. (Lin and Papaloizou 1985). Of course, if the mass flux through the disk is not constant, or if any other model assumptions are strongly violated, then the viscosity will manifest itself less directly in the surface density distribution.

II. HL TAU & L1551 IRS 5: LOW MASS PROTOTYPES

HL Tau and L1551 IRS 5 are two of the best-studied low-mass, embedded protostars, and we adopt them as examples to illustrate what can be learned from millimeter and submillimeter data with subarcsecond resolution. In §III we discuss subarcsecond resolution observations of other low-mass pre-main-sequence stars, building on the information developed below.

A. Background and Early Work

Both HL Tau and L1551 IRS 5 are located in the Taurus–Auriga molecular cloud complex at a distance of ∼140 pc (Elias 1978), so that $1''$ corresponds to 140 AU. Both have well developed outflows (Mundt et al. 1987, Snell, Loren and Plambeck 1980), and large envelopes of molecular gas. Early observations with the OVRO array provided the first estimates of the masses of the disks around these objects. For HL Tau, the 2.7 mm flux measured by Beckwith et al. (1986) and Sargent and Beckwith (1987, 1991) was about 0.11 Jy, with associated mass of 0.14 $M_\odot$. For L1551 IRS 5, the 2.7 mm flux measured by Keene and Masson (1990) in an unresolved component was 0.13 Jy, with associated mass of 0.16 $M_\odot$. Note that conversion of an unresolved flux into a mass implicitly assumes specific profiles of surface density and temperature within the disk, as well as an estimate of the dust emissivity, and the results must be viewed with appropriate caution.

The spectral energy distribution of HL Tau is well modeled by either a thin accretion disk (Beckwith et al. 1990) or a disk and residual extended envelope (Calvet et al. 1994). The nature of the envelope is still unclear. Early OVRO observations of the ^{13}CO $J = 1 - 0$ transition revealed a flattened circumstellar structure of size $\sim 30''$ (4000 AU) that was interpreted as a circumstellar disk with a Keplerian rotation curve (Beckwith et al. 1986; Sargent and Beckwith 1987, 1991). More recent ^{13}CO studies indicate that this structure is more likely a magnetically produced "pseudodisk" with kinematics dominated by infall (Hayashi et al. 1993) or by entrained outflow material (Cabrit et al. 1996). All of these studies showed the presence of a continuum component, unresolved by beams as small as 2.7″ (Woody et al. 1989; Ohashi et al. 1991), indicating that most of the circumstellar material was concentrated in a much more compact structure. Although there is an envelope of molecular gas, HL Tau is not a deeply embedded object; indeed, the protostar was originally thought to be optically visible, and only through recent Hubble Space Telescope observations has it been shown that this is scattered light, and the protostar is hidden (Stapelfeldt et al. 1995).

Keene and Masson (1990) were the first to show that L1551 IRS 5 consisted of an extended envelope and a bright, compact core. The latter appeared point-like in the 2.6″ synthesized beam of the three element OVRO array, but they were able to estimate a radius of 45 ± 20 AU, based on the measured flux and the expected dust temperature as a function of distance from the central source. Butner et al. (1994) modeled the spectral energy distribution of L1551 IRS 5, but were unable to separate the contributions of the disk and envelope. The spectral energy distribution suggests that this source is younger and more embedded than HL Tau.

B. CSO–JCMT: Visibility Curves

The first millimeter or submillimeter instrument capable of subarcsecond resolution was the CSO–JCMT Interferometer. With only a single fixed baseline, the interferometer does not sample sufficient Fourier components to synthesize an image of the brightness distribution. Instead, models must be fitted directly to the measured Fourier components. Although the physical baseline is fixed, it is the baseline vector projected along the line of sight that determines which Fourier component the interferometer is sensitive to. As the target rises above the horizon, transits and sets, this projected baseline vector traces out an ellipse (Figure 1a). Also shown in the figure are schematic contours for the Fourier Transform of a disk-like object (remember that the major axis in the Fourier Transform plane corresponds to the minor axis on the sky, and vice versa). Figures 1b and 1c show the Fourier amplitudes for an observing wavelength of 0.87 mm measured as a function of hour angle for HL Tau and L1551 IRS 5 (Lay et al. 1994). An unresolved point-like object would have a constant Fourier amplitude equal to its total flux, so both objects have been clearly resolved. The dashed lines show the best fitting elliptical Gaussian models. This simple model gives a flux, major and minor radii and a position angle.

The spatial filtering of the interferometer means that the fluxes are almost totally insensitive to the extended envelope emission. It was found that the disk is the source of almost all of the 0.87 mm continuum emission from HL Tau, but only 25% of that from L1551 IRS 5, indicating that the latter is much more embedded, and therefore probably younger. The major radii to half-maximum brightness were determined to be 60^{+10}_{-8} AU (HL Tau) and 80^{+20}_{-10} AU (L1551 IRS 5), and an upper limit of 52 AU was set on the minor radius in each case (i.e. the inclination is not well-constrained). The position angles of 126° (HL Tau) and 162° (L1551 IRS 5) are almost perpendicular to the outflow directions from each source, consistent with the accretion disk interpretation of the data, although the profiles of surface density and temperature were not well constrained. Data have since been obtained at 460 GHz with the CSO–JCMT Interferometer (Lay et al. 1997), and the implications of these additional observations for disk structure are discussed in §II.E.

C. Subarcsecond Images with Millimeter Arrays

The first subarcsecond *image* of the HL Tau dust disk was obtained by Mundy et al. (1996) at 2.7 mm using the six element BIMA array with two outrigger stations linked by optical fiber. The upper panel of Figure 2 shows contours of 2.7 mm emission superposed on the optical nebulosity observed by the Hubble Space Telescope. The image shows a southeast-northwest extension, consistent with the CSO–JCMT result. The optical emission traces the cavity evacuated by the bipolar flow from the central star, and the millimeter emission coincides nicely with the sharp edge of dust extinction.

Figure 3 shows the 2.7 mm emission from L1551 IRS5 imaged at a variety of resolutions with the ten element BIMA array (Looney et al. 1997). On the largest scales, the emission is dominated by the inner regions of the envelope, and has close to circular symmetry. At an angular resolution of about $1''$, the source appears elongated at a position angle of 157°, very similar to the CSO–JCMT measurement. At the highest resolution of $0\farcs3$ these larger structures are almost entirely resolved out and the emission is consistent with two point sources. These are coincident with peaks in free-free emission that originate in ionized outflowing gas, most likely marking the two stars of a protobinary system (Bieging and Cohen 1995, Rodriguez et al. 1986). Thus the millimeter continuum features, in order of descending size scale, may be identified with an extended envelope, a circumbinary structure, and the individual circumstellar disks surrounding each member of the binary.

D. Very Large Array

The Very Large Array (VLA) of the National Radio Astronomy Observatory has the potential to advance our understanding of the protostellar environment through observations at an angular resolution unmatched by other currently operating facilities. In the most extended antenna configuration currently available, the synthesized beam at the shortest operating wavelength of 7 mm is 40 milliarcseconds, comparable to the orbital radius of Jupiter at 140 pc distance. An upgrade to include the Pie Town VLBA antenna is underway and will soon halve the synthesized beam size. Since dust emissivity drops steeply toward long wavelengths, the thermal emission from disks is not strong. Nonetheless, the sensitivity available is sufficient to detect planetary masses of interstellar dust in reasonable integration times, and the low dust optical depth allows penetration of high surface density regions. However, care must be taken to separate dust and free-free emission at these wavelengths.

The high resolution VLA data provide stringent tests of the inferences from lower resolution. The lower panels of Figure 2 show VLA 7 mm images of HL Tau at two resolutions (Wilner et al. 1998). At this long wavelength, emission from ionized plasma is comparable to dust emission from the circumstellar disk. The right panel shows the image obtained from baselines $> 1000k\lambda$, which highlights the small scale high surface brightness structure, identified with the ionized protostellar wind; this component accounts for $\sim 30\%$ of the 7 mm flux. The left panel shows a lower resolution image obtained after subtracting the wind component, which isolates emission from the dusty disk. The structure and orientation of the disk emission are similar to that observed at 2.7 mm at lower resolution by Mundy et al. (1996). Remarkably, the disk emission is almost entirely absent in the highest resolution VLA image; all that can be seen is emission from the relatively bright wind component. The flux density and angular size of this structure varies with frequency approximately as predicted by the biconical wind theory (see the chapter by Eislöffel et al. for details).

The VLA 7 mm maps of HL Tau in Figure 2 demonstrate the dramatic effect of surface brightness sensitivity on the appearance of a disk at high angular resolution. A disk with a steep surface density profile would have substantial emission at radii close to the central star due to the confluence of high surface density and temperature. However, a disk with a flat surface density profile exhibits much weaker emission at small radii. For HL Tau, the 7 mm data agree best with models having surface density falling off less steeply than r^{-1}. These models match the extended emission visible at $0.25''$ resolution and the absence of detectable disk emission at 40 milliarcsecond resolution. The long wavelength data support a shallow fall-off in disk emission from large radii well into the giant planet zone.

The VLA 7 mm map of L1551 IRS5 shown in Figure 3 has angular resolution of 50 milliarcseconds, about an order of magnitude higher than the previous millimeter observations described in §II.C. This image clearly resolves two individual millimeter sources with projected separation 45 AU. Two arguments support the contention that the 7 mm emission traces disks around each of the two stars. First, the 7 mm sources are elongated approximately in the north-south direction, while centimeter emission and other outflow tracers extend east-west, consistent with expectations for disks and jets. Second, the 7 mm flux densities are too large to be accounted for by ionized plasma and are more likely due to dust, as illustrated by the resolved spectra of each source shown in Figure 3. The average brightness temperatures are high, about 400 K, which suggests these compact disks are relatively hot and have substantial optical depth even with the low dust emissivity expected at this long wavelength. The 7 mm observations, together with the constraints of the bolometric luminosity and the radio continuum flux densities, can be modeled as viscous disks with radii ~ 10 AU, total masses of $\sim 0.06\ M_{\odot}$ (north component) and $\sim 0.03\ M_{\odot}$ (south component). These viscous disks are hotter in the interior than at the surfaces, and the millimeter observations penetrate deeper in the disk and "see" hotter material than infrared observations that do not penetrate as deeply (D'Alessio et al. 1997). It is interesting that both disks have similar dimensions and masses, properties that may reflect the way mass is accreted from circumbinary material. The relatively small size of these disks could inhibit the formation of outer, icy planets at distances similar to Uranus and Neptune.

E. Multi-Frequency Analysis

It is possible to fit a range of different disk models to any one of the existing data sets, since the distribution of emission depends on a combination of dust emissivity, temperature, and surface density. To break this degeneracy, it is clearly advantageous to fit models *simultaneously* in both the spatial and spectral domains; this approach will set tighter constraints than fitting the spectral energy distribution and spatially resolved data sets separately. Since the accretion disk model of §I.B is unlikely to remain a good representation of the disk at small radii (see e.g. Bell et al. 1997) it may not be appropriate to use infrared data to draw conclusions about the larger scale properties of the disk that are probed by millimeter and submillimeter data. Similarly, centimeter-wave data are contaminated by free-free emission in some cases, and may be included only if a reliable spectral decomposition has been performed.

The first attempt was made by Mundy et al. (1996), who made a joint analysis of the 3 mm BIMA data and the 0.87 mm CSO–JCMT data for HL Tau. The position angle was fixed, and both the temperature distribution and dust opacity index were first estimated from the spectral energy distribution. This leaves the different combinations of outer radius, inclination and surface density distribution as free parameters. Each accretion disk model was first convolved with a $0\farcs5$ circular

Gaussian, representing the synthesized beam. An elliptical Gaussian model was then fitted to this model image and a value of χ^2 obtained by comparing these fitted parameters to those obtained from the real data. The model disks were also Fourier transformed to compare them with the CSO–JCMT data, and the χ^2 from this fit was simply averaged with that from the 3 mm data. While the outer radius (90–180 AU) and inclination (20–55°) were not tightly constrained, it was found that shallow surface density profiles ($p < 1$) were favored.

Lay et al. (1997) performed the most extensive multi-frequency analysis of HL Tau. They fitted accretion disk models directly to the measured visibilities at 220 GHz ($\lambda = 1.4$ mm OVRO data), 345 GHz ($\lambda = 0.87$ mm CSO–JCMT data) and 460 GHz ($\lambda = 0.65$ mm CSO–JCMT data), and a disk flux measured at 110 GHz ($\lambda = 2.7$ mm BIMA data). A model for each combination of the nine free parameters was Fourier transformed and compared to the data, and a relative likelihood was calculated. This method avoids any intermediate Gaussian fitting and accounts for uncertainties in the data such as the flux calibration at each frequency, but is computationally intensive; over 5 million different models were evaluated at each frequency. The likelihood distributions obtained for each parameter are shown in Figure 4. Surprisingly, this analysis favors relatively high values of the power law index p, corresponding to centrally concentrated density distributions. Such models predict that the apparent disk size (e.g. obtained from a Gaussian fit) will decrease at longer wavelengths as the emission becomes optically thin. This is not consistent with the sizes determined from the VLA and BIMA data, which appear very similar to the submillimeter values. This disagreement points to the possible inadequacy of the disk model described in §I.B. More sophisticated models that incorporate multiple dust components and allow for flaring need to be explored to see if they can reconcile the long wavelength data (7 and 3 mm) with the shorter wavelengths (1.1, 0.87 and 0.65 mm).

III. OTHER EXAMPLES

While HL Tau and L1551 IRS5 are the brightest millimeter disk sources in Taurus, millimeter interferometers routinely detect compact emission from other low mass pre-main-sequence stars, and these observations are increasingly providing information at subarcsecond scales. Data from a large sample are crucial to identify general properties, free from the idiosynchrasies of the "prototype" objects described in §II, and to address the complications introduced by evolution and environment. We refer the reader to the chapter by Natta et al. for results from millimeter imaging of Herbig Ae/Be stars, a class of more massive pre-main-sequence objects.

A. Low-Mass Pre-Main-Sequence Stars

The most extensive millimeter interferometer observations of pre-main-sequence disks to date was performed by Dutrey et al. (1996) at 2.7 mm using the IRAM Plateau de Bure interferometer. From a survey of 33 T Tauri stars at 2.7 mm, angular sizes typically $1\farcs5$ were inferred from fitting visibilities for those sources with sufficient signal-to-noise. In the context of power law disk models, these results suggest relatively flat surface density distributions and outer radii of 100 to 200 AU, similar to the properties derived for the HL Tau disk. Guilloteau et al. (1997) describe follow up data at 1.3 mm obtained for a subset of the IRAM survey sources. Because the angular size at a particular wavelength can be produced by various combinations of radial temperature and opacity distributions, as discussed in §II.E, spatially resolved observations at multiple wavelengths are needed. The 1.3 mm data apparently show angular sizes comparable to those found at longer wavelengths, despite the large difference in dust opacity. This result is most easily understood if the brightness distributions are similar at the two wavelengths, consistent with shallow radial emissivity profiles, though this is not the only possibility.

The GM Aur system, which is located in a region of low extinction near the edge of the Taurus complex, provides an especially nice example. Dutrey et al. (1998) present high resolution images of GM Aur from the IRAM Plateau de Bure interferometer, taking advantage of the recent baseline extensions and capabilities for operation in the 1.3 millimeter atmospheric window to fully resolve the disk material (Figure 5). For the continuum emission, these observations indicate angular sizes of $\sim 1\farcs1$ at both 2.7 mm and 1.3 mm. According to simple power law models, the observed sizes imply a minimum outer radius of $\sim$ 200 AU and a surface density distribution that cannot be too steep, though a value for the power law index p as high as 1.5 is not excluded. The high sensitivity images of the ^{12}CO J=2-1 line build on the early results from Koerner et al. (1993) using the OVRO array to define the kinematics, inclination, and orientation of the extended cold gas in Keplerian rotation around the central star in this system.

For DO Tau, a system where the CO observations of Koerner and Sargent (1995) suggest a centrifugally supported disk within a radius of 350 AU, an early attempt using the VLA at 7 mm provided subarcsecond resolution continuum observations that bear on the nature of dust particles (Koerner et al. 1995). Although plagued by atmospheric phase fluctuations, dust emission at 7 mm was clearly detected, unresolved in the $0\farcs6$ synthesized beam. These data, coupled with additional high resolution observations at millimeter and centimeter wavelengths from OVRO and the VLA allow for limits to be set on any contribution of ionized plasma and densely sample the long wavelength spectral energy distribution. Since the emission is well into the Rayleigh-Jeans regime and the bulk of the dust is very likely optically thin at wavelengths longer than 3 mm, the spectral slope directly constrains β, the power law index of the dust opacity. The result $\beta \approx 0.5$, with small fractional error, provides evidence for grains with sizes of order one millimeter or larger, perhaps the first stage of planetesimal formation. A goal of future millimeter observations will be to elucidate changes in dust properties in large samples of circumstellar disks, eventually taking account of spatially resolved radial variations.

B. Multiple Systems: UZ Tau, T Tau, and GG Tau

Multiplicity clearly plays an important role in shaping the circumstellar environment and may affect the development of disk structure and subsequent evolution. The UZ Tau system was among the first multiple pre-main-sequence disk systems to be spatially resolved through millimeter interferometry (Jensen et al. 1996a; Mathieu et al., this volume). This hierarchical quadruple system consists of a spectroscopic binary, UZ Tau E, and a 50 AU binary, UZ Tau W, separated by a projected distance of 500 AU. Images with the OVRO array at 1.3 mm and 3 mm show strong dust emission around the compact binary, typical of single stars, and weaker dust emission around the wider separation pair. Disk-binary interactions may explain the relative weakness of dust continuum emission in systems with separations in the range 30 to 300 AU (Jensen et al. 1996b). Wide binaries may be able to support individual circumstellar disks with radii of order 100 AU, while closer binaries may be able to maintain circumbinary structures with radii larger than about 100 AU.

The young stellar object T Tauri, the prototype of the class, is also a binary. The system consists of an optically visible star, T Tau N, and an infrared companion, T Tau S, with a projected separation of 100 AU. The combination of millimeter flux and disparity between components has prompted considerable observational attention, with reports of subarcsecond observations at 2.7 mm with the BIMA array (Akeson et al. 1998) and at 1.3 mm with the OVRO array and at 0.87 mm with the CSO–JCMT Interferometer (Hogerheijde et al. 1997). Surprisingly, these high resolution observations show that the compact dust emission in the T Tau system is confined to the surroundings of the visible star, T Tau N. Multifrequency analysis using the technique described in §II.E suggests properties mostly similar to those derived for disks around single pre-main-sequence stars. However, the disk is quite small, with outer radius no more than 70 AU, possibly because the T Tau N disk is truncated by the presence of T Tau S. If so, it is possible that the variable infrared nature of T Tau S may be explained by obscuration by the tenuous outer edges of the T Tau N disk. The reason for the relative absense of dust continuum emission associated with T Tau-S is not known.

Perhaps the most interesting direction for subarcsecond millimeter imaging of circumstellar disks is to uncover major departures from simple power law structure. One important prediction is for large gaps or inner holes in disks due to density waves driven by companion bodies. The hierarchical quadruple system GG Tau provides a nice illustration of this idea. Dutrey et al. (1994) discovered a huge hole extending 160 to 180 AU in radius in the disk surrounding the northern close binary pair in the GG Tau system (see the recent subarcsecond resolution millimeter continuum map obtained with the IRAM Plateau de Bure interferometer from Guilloteau et al. (1998) in the chapter by Mathieu et al.). A beautiful correspondence exists between the central hole in the circumbinary disk and near infrared scattered light imaged with adaptive optics (Roddier et al. 1996). The parameters of this circumbinary structure are well explained by resonances in the disk-binary interaction (see Artymowicz et al. 1991; Lubow and Artymowicz, this volume).

The circumbinary holes observed in systems like GG Tau are the large scale analogs of the effects of giant planets in formation. Calculations by Takeuchi et al. (1996), among others, show that the formation of a Jupiter mass object at a radius of 5 AU will quickly clear out the inner disk and leave a largely empty hole. The large area of the hole makes it much more readily detectable than the object responsible for clearing it. Other global distortions are also potentially observable with sufficient resolution and sensitivity. For example, one idea put forward to explain the flat infrared spectra of some T Tauri stars is an m=1 spiral perturbation that allows for higher temperatures at large radii (Shu et al. 1990). Such global distortions may be detectable with existing capabilities.

IV. Masers

A. Maser Properties

Maser emission can provide a tracer of protostellar disk kinematics with very high spatial resolution. When the physical conditions are right, a population inversion can be created between two states of an atom or molecule and the process of stimulated emission provides coherent amplification of a light source (see Elitzur 1992 for more details). The radiation is strongly beamed, producing small 'spots' of emission; these are the projection of long columns of gas along which the line-of-sight velocity dispersion is very small. The spots are typically milliarcseconds across and have brightness temperatures in excess of 1000 K. An interferometer can measure the *relative* position of the maser emission *centroid* at each velocity to very high accuracy, e.g. the centroid for a $1''$ synthesized beam can be determined to within

10 mas for a signal-to-noise ratio of 100. Two examples are shown in Figure 6, corresponding to SiO maser emission at 86 GHz from Orion IRc2 (Baudry et al. 1998) and hydrogen recombination line emission from MWC 349 (White et al. 1998).

In addition to the kinematic information, masers can potentially provide information about physical conditions – temperature, density, infrared flux, for example – in the environments where they are found. This requires a detailed model of the maser mechanism, and there is still debate about specific examples (e.g. Elitzur 1992; Bujarrabal 1994; Thum et al. 1994; Baudry et al. 1998). It is clear that the subarcsecond spatial resolution provided by interferometers has greatly helped in the interpretation of masing regions, for which previously only a spectral profile had been available.

B. SiO

The Orion IRc2 region is the most well-studied example of high mass star formation. A large bipolar outflow is oriented in the NW–SE direction and is believed to originate from the object observed in the radio continuum known as Source I. The ^{28}SiO $v = 1, J = 2 - 1$ maser emission has a flux in excess of 1000 Jy at 86 GHz, and was first mapped by Plambeck et al. (1990), who demonstrated that the data are consistent with an expanding and rotating disk with a radius of 80 AU, oriented perpendicular to the outflow. Subsequent observations (Wright et al. 1995; Guilloteau et al. 1992; Baudry et al. 1998) show that the broad pattern of emission is preserved over time, although the detailed positions have changed. These changes are probably due to variations in the relative amplitude of the spots that contribute to each centroid. The current scenario is that the maser emission arises at the interface between the rotating protostellar disk and the ionized wind blowing out from Source I. Wright et al. (1995) also mapped the more weakly masing $v = 0, J = 2 - 1$ ground state transition with $0\farcs5$ resolution, which appears to trace a larger ($\sim$ 1000 AU diameter) flared disk. However, the combination of insufficient angular resolution and nonthermal emission suggests care in interpretation. Recent observations of the SiO maser emission made with the VLBA directly resolves the spatial distribution of maser spots for the first time, and they appear to outline a conical outflow cavity (Doeleman et al. 1999, Greenhill et al. 1998). The kinematics do not appear consistent with the disk inferred from the maser centroid locations, and the physical nature of the structure centered on Source I remains unclear.

C. Hydrogen

The young, high mass star MWC 349 is similar to the Orion maser source in many ways. It also has an ionized bipolar outflow and a characteristic double peaked spectrum. In this case, population inversion arises from the recombination of electrons with hydrogen ions, which generates a whole series of masing transitions as the electron cascades down to the ground state. Planesas et al. (1992) were the first to map the H30α line emission at 232 GHz, and argued that it arose from the ionized surface of a disk seen close to edge on, oriented roughly E-W. The map shown in Figure 6b is a more recent version, clearly showing red- and blue-shifted clumps separated by 60 mas (70 AU for a distance of 1.2 kpc). A similar map was made for the H26α transition at 353 GHz by the CSO–JCMT Interferometer. The data are consistent with Keplerian rotation about a central mass of 26 $M_\odot$.

D. H_2O

Unlike the extremely rare SiO and hydrogen masers described above, H_2O masers are commonly found to be associated with young stellar objects. The 22 GHz H_2O $6_{16} - 5_{23}$ transition masers require temperatures of 200 to 1000 K and densities from 10^8 to 10^{10} cm^{-3}, well matched to the circumstellar environment. The individual maser spots may be localized to very high accuracy relatively easily using the VLA, and in some cases proper motions of the maser spots can be measured using Very Long Baseline techniques. However, the kinematics of the H_2O masers are often complex and difficult to interpret. This difficulty is often exacerbated by the variability of maser features, many of which persist no longer than a few weeks. In some sources, bound rotational motions have been claimed from the maser spot kinematics (e.g. NGC 2071 IRS3, Torrelles et al. 1998), while in other cases the maser spots show clear evidence for bipolar outflow motions (e.g. L1448C, Chernin 1995). From VLA observations of several H_2O maser clusters in the W75(N) and NGC 2071 regions, Torrelles et al. (1997) have suggested that H_2O masers may trace rotating disks in younger objects, while the maser spots in older objects preferentially trace outflowing jets. A conclusive test of this proposed evolutionary scheme will require observations of H_2O maser distributions around many more young stars.

V. FUTURE PROSPECTS

The new instrumentation at millimeter and submillimeter wavelengths makes possible the investigation of circumstellar structure at subarcsecond resolution in many sources. At this resolution, the most interesting structures are the disks capable of forming Solar Systems like our own. The last decade has witnessed the basic confirmation of the disk paradigm through direct imaging observations, and the studies reviewed in this chapter represent just the first glimpses at the complexities that become apparent at this physical scale. There is room for substantial progress in many areas.

It has not yet been possible to address evolutionary trends with the limited data currently available. The mechanism for viscous accretion remains unknown, and further development is needed of physical models that take into account the spatial constraints now becoming obtainable. The next generation of millimeter and submillimeter arrays will bring spectacular gains in sensitivity, making subarcsecond imaging routine for protostellar systems over the full planetary formation timescale, and it will be feasible to search for gaps in the disk indicative of clearing by large bodies.

The understanding of dust properties has advanced considerably over the last decade, but there is a long way to go before the nature and distribution of dust within disks are fully characterized. This will only be possible through high resolution studies spanning infrared to millimeter wavelengths, from which the spectral properties of different dust components can be separated. In addition, non-masing spectral line emission will become detectable at subarcsecond resolution, providing a wealth of further information on kinematics, density, temperature and chemistry within the protostellar environment.

FIGURE CAPTIONS

Figure 1. CSO–JCMT Interferometer data for HL Tau and L1551 IRS 5 at 0.87 mm, from Lay et al. (1994). (a) The $u - v$ plane showing the sampled Fourier components (black squares) and contours of the Fourier Transform of a schematic disk. The measured visibility amplitudes are plotted for HL Tau (b) and L1551 IRS 5 (c), each with best fitting elliptical Gaussian model (dashed line).

Figure 2. Subarcsecond views of HL Tau. (*upper*) Contours of 2.7 mm dust continuum emission from HL Tau imaged with the BIMA array (Looney et al. 1998) superposed on the V band nebulosity imaged with the Hubble Space Telescope (Stapelfeldt et al. 1995). The millimeter emission traces the high column density extincting material that hides the direct starlight. The asterisk marks the position of the protostar, defined by the centimeter radio emission. (*lower*) Two images of the 7 mm emission from HL Tau obtained with the VLA (Wilner et al. 1999). The image on the right shows the map from data limited to baselines $> 1000\ k\lambda$, which highlights the compact ionized wind component. The image on the left shows a lower resolution map obtained after subtracting the wind component, which isolates dust emission from the disk.

Figure 3. Dust emission from L1551 IRS5. (*upper*) Maps of the 2.7 mm emission from L1551 IRS5 observed with increasing angular resolution using the BIMA array (Looney et al. 1997). The images show that the L1551 system is composed of two circumstellar disks located within a flattened circumbinary structure embedded in an approximately spherical large scale envelope. (*lower*) The VLA 7 mm image with 50 milliarcsecond (7 AU) resolution clearly resolves the individual dust disks surrounding the members of the protobinary system (Rodriguez et al. 1998). The spectral decomposition demonstrates that the long centimeter wavelengths are dominated by optically thin free-free emission, while emission at wavelengths shorter than about 7 mm originates in heated dust in the circumstellar disks.

Figure 4. Histograms showing the relative likelihood of different disk model parameter values for HL Tau, based on fits to data at 110, 220, 345 and 460 GHz, from Lay et al. (1997).

Figure 5. IRAM Plateau de Bure images of GM Aur. The 1.3 mm dust continuum emission is fully resolved and shown in greyscale; the cross marks the position, orientation, and aspect ratio of the continuum peak. Contours of ^{12}CO J=2-1 line emission from redshifted (dashed), systemic (light), and blueshifted (dark) velocities show the rotation of the circumstellar disk along the axis of elongation. The inset (*upper right*) shows the 1.3 mm continuum emission in contour form together with the $0\farcs7 \times 0\farcs6$ synthesized beam.

Figure 6. (a) Positions of ^{28}SiO $v = 1, J = 2 - 1$ maser centroids for Orion IRc2 (Baudry et al. 1998). The labels correspond to the LSR velocity and adjacent have been connected. The units are in arcseconds. (b) Positions of the H30α recombination line centroids for MWC 349 (White et al. 1999).

REFERENCES

Adams, F.C., Shu, F.H., and Lada, C.J. 1988. The disks of T Tauri stars with flat infrared spectra. *Astrophys. J.* 326:865–883.

Akeson, R.L., Koerner, D.W., and Jensen, E.L.N. 1998. A circumstellar dust disk around T Tau N: Sub-arcsecond imaging at lambda = 3mm. *Astrophys. J.* in press.

Artymowicz, P., Clarke, C.J., Lubow, S.H., and Pringle, J.E. 1991. The effect of an external disk on the orbital elements of a central binary. *Astrophys. J. Lett.* 370:L35–L88.

Baudry, A., Herpin, F., and Lucas, R. 1998. ^{29}SiO (v=0) and ^{28}SiO (v=1) J=2-1 maser emission from Orion IRc2. *Astron. Astrophys.* 335:654–660.

Beckwith, S., Sargent, A.I., Scoville, N.Z., Masson, C.R., Zuckerman, B., and Phillips, T.G. 1986. Small-scale structure of the circumstellar gas of HL Tauri and R Monocerotis. *Astrophys. J.* 309:755–761.

Beckwith, S.V.W., Sargent, A.I., Chini, R.S., and Guesten, R. 1990. A survey for circumstellar disks around young stellar objects. *Astron. J.* 99:924–945.

Beckwith, S.V.W. and Sargent, A.I. 1991. Particle Emissivity in Circumstellar Disks. *Astrophys. J.* 381:250–258.

Bell, K.R., Cassen, P.M., Klahr, H.H., and Henning, T. 1997. The Structure and Appearance of Protostellar Accretion Disks: Limits on Disk Flaring. *Astrophys. J.* 486:372–387.

Bieging, J.H. and Cohen, M. 1985. Multifrequency radio images of L1551 IRS 5. *Astrophys. J. Lett.* 289:L5–L8.

Bujarrabal, V. 1994. Numerical calculations of SiO maser emission. I. Intensity and variability. *Astron. Astrophys.* 285:953–970.

Burrows, C.J. et al. 1996. Hubble Space Telescope Observations of the Disk and Jet of HH 30 *Astrophys. J.* 473:437–451.

Butner, H.M., Natta, A., and Evans, N.J. II 1994. 'Spherical' disks: Moving toward a unified source model for L1551. *Astrophys. J.* 420:326–335.

Cabrit, S., Guilloteau, S., Andre, P., Bertout, C., Montmerle, T., and Schuster, K. 1996. Plateau de Bure observations of HL Tauri: outflow motions in a remnant circumstellar envelope. *Astron. Astrophys.* 305:527–540.

Calvet, N., Hartmann, L., Kenyon, S.J., and Whitney, B.A. 1994. Flat spectrum T Tauri stars: The case for infall. *Astrophys. J.* 434:330–340.

Chernin, L.M. 1995. Water masers in the L1448C outflow. *Astrophys. J. Lett.* 440:L97–L99.

Chiang, E.I. and Goldreich, P. 1997. Spectral Energy Distributions of T Tauri Stars with Passive Circumstellar Disks. *Astrophys. J.* 490:368–376.

D'Alessio, P., Canto, J., Calvet, N., and Lizano, S. 1998. Accretion Disks around Young Objects. I. The Detailed Vertical Structure. *Astrophys. J.* 500:411–427.

Doeleman, S.S., Lonsdale, C.J., and Pelkey, S. 1999. A Molecular Outflow Traced by SIO Masers in Orion KL. *Astrophys. J. Lett.* 510:L55–L58.

Draine, B. and Lee, H.M. 1984. Optical properties of interstellar graphite and silicate grains. *Astrophys. J.* 285:89–108.

Dutrey, A., Guilloteau, S., and Simon, M. 1994. Images of the GG Tauri rotating ring. *Astron. Astrophys.* 286:149–159.

Dutrey, A., Guilloteau, S., Duvert, G., Prato, L., Simon, M., Schuster, K., and Menard, F. 1996. Dust and gas distribution around T Tauri stars in Taurus-Auriga. I. Interferometric 2.7mm continuum and ^{13}CO J=1-0 observations *Astron. Astrophys.* 309:493–504.

Dutrey, A., Guilloteau, S., Prato, L., Simon, M., Duvert, G., Schuster, K., and Menard, F. 1998. CO study of the GM Aurigae Keplerian disk *Astron. Astrophys.* 338:L63–L66.

Elias, J.H. 1978. A study of the Taurus dark cloud complex. *Astrophys. J.* 224:857–872.

Elitzur, M. 1992. *Astronomical Masers* (Dordrecht: Kluwer Academic Publishers)

Greenhill, L.J., Gwinn, C.R., Schwartz, C., Moran, J.M., and Diamond, P.J. 1998. Coexisting Conical Bipolar and Equatorial Outflows from a High Mass Protostar. *Nature/* 396:650–653.

Guilloteau, S., Delannoy, J., Downes, D., Greve, A., Guelin, M., Morris, D., Radford, S.J.E., Wink, J., Cernicharo, J., Forveille, T., Garcia-Burillo, S., Neri, R., Blondel, J., Perrigourad, A., Plathner, D., Torres, M. 1992. The IRAM interferometer on Plateau de Bure. *Astron. Astrophys.* 262:624–633.

Guilloteau, S., Dutrey, A., and Gueth, F. 1997. Disks and Outflows as seen from the IRAM Interferometer. In *Herbig-Haro Flows and the Birth of Low Mass Stars*, eds. B. Reipurth and C. Bertout (Dordrecht: Kluwer), pp. 365–380.

Guilloteau, S., Dutrey, A., and Simon, M. 1998. *Astron. Astrophys.* submitted.

Hayashi, M., Ohashi, N., and Miyama, S.M. 1993. A Dynamically Accreting Gas Disk around HL Tauri *Astrophys. J. Lett.* 418:L71–L74.

Hogerheijde, M.R., van Langevelde, H.J., Mundy, L.G., Blake, G.A., and van Dishoeck, E.F. 1997. Subarcsecond Imaging at 267 GHz of a Young Binary System: Detection of a Dust Disk of Radius Less than 70 AU around T Tauri N. *Astrophys. J. Lett.* 490:L99–L102.

Jensen, E.L.N., Mathieu, R.D., and Fuller, G.A. 1996a. The Connection between Submillimeter Continuum Flux and Binary Separation in Young Binaries: Evidence of Interaction between Stars and Disks. *Astrophys. J.* 458:312–326.

Jensen, E.L.N., Koerner, D.W., and Mathieu, R.D. 1996b. High-Resolution Imaging of Circumstellar Gas and Dust in UZ Tauri: Comparing Binary and Single-Star Disk Properties. *Astron. J.* 111:2431–2438.

Keene, J. and Masson, C.R. 1990. Detection of A 45 AU radius source around L1551-IRS5 – A possible accretion disk. *Astrophys. J.* 355:635–644.

Kenyon, S.J. and Hartmann, L. 1987. Spectral energy distributions of T Tauri stars - Disk flaring and limits on accretion. *Astrophys. J.* 323:714–733.

Koerner, D.W., Sargent, A.I., and Beckwith, S.V.W. 1993. A Rotating Gaseous Disk Around the T Tauri Star GM Aurigae. *Icarus, 106:2-10.*

Koerner, D.W. and Sargent, A.I. 1995. Imaging the Small-Scale Circumstellar Gas Around T Tauri Stars. *Astron. J.* 109:2138–2145.

Koerner, D.W., Chandler, C.J., and Sargent, A.I. 1995. Aperture Synthesis Imaging of the Circumstellar Dust Disk around DO Tauri. *Astrophys. J. Lett.* 452:L69–L72.

Lay, O.P., Carlstrom, J.E., Hills, R.E., and Phillips, T.G. 1994. Protostellar accretion disks resolved with the JCMT-CSO interferometer. *Astrophys. J. Lett.* 434:L75–L78.

Lay, O.P., Carlstrom, J.E., and Hills, R.E. 1997. Constraints on the HL Tauri Protostellar Disk from Millimeter- and Submillimeter-Wave Interferometry. *Astrophys. J.* 489:917–927.

Lin, D.N.C. and Papaloizou, J. 1985. On the dynamical origin of the solar system. In *Protostars & Planets II*, eds. D.C. Black and M.S. Matthews (Tucson: Univ. of Arizona Press), pp. 981–1072.

Looney, L.W., Mundy, L.G., and Welch, W.J. 1997. High-Resolution lambda = 2.7 Millimeter Observations of L1551 IRS 5. *Astrophys. J. Lett.* 484:L157–L160.

McCaughrean, M.J. and O'Dell, C.R. 1996. Direct Imaging of Circumstellar Disks in the Orion Nebula. *Astron. J.* 111:1977–1986.

Mundt, R., Brugel, E.W., and Buhrke, T. 1987. Jets from young stars - CCD imaging, long-slit spectroscopy, and interpretation of existing data. *Astrophys. J.* 319:275–303.

Mundy, L.G., Looney, L.W., Erickson, W. Grossman, A., Welch, W.J., Forster, J.R., Wright, M.C.H., Plambeck, R.L., Lugten, J., and Thornton, D.D. 1996. Imaging the HL Tauri Disk at lambda = 2.7 Millimeters with the BIMA Array. *Astrophys. J. Lett.* 464:L169–

L173.

Natta, A. 1993. The temperature profile of T Tauri disks. *Astrophys. J.* 412:761–770.

Ohashi, N., Kawabe, R., Ishiguro, M., and Hayashi, M. 1991. Observations of 11 protostars in Taurus with the Nobeyama millimeter array – Growth of circumstellar disks. *Astron. J.* 102:2054–2065.

Plambeck, R.L., Wright, M.C.H., and Carlstrom, J.E. 1990. Velocity structure of the Orion-IRc2 SiO maser - Evidence for an 80 AU diameter circumstellar disk. *Astrophys. J. Lett.* 348:L65–L68.

Planesas, P., Martin-Pintado, J., and Serbayn, E. 1992. Positions of the radio recombination line masers in MWC 349. *Astrophys. J. Lett.* 386:L23–L26.

Pollack, J.B., Hollenbach, D., Beeckwith, S., Simonelli, D.P., Roush, T., and Welsey, F. Composition and radiative properties of grains in molecular clouds and accretion disks. *Astrophys. J.* 421:615–639.

Roddier, C., Roddier, F., Northcott, M.J., Graves, J.E., and Jim, K. 1996. Adaptive Optics Imaging of GG Tauri: Optical Detection of the Circumbinary Ring. *Astrophys. J.* 463:326–335.

Rodriguez, L.F., Canto, J., Torrelles, J.M., and Ho, P.T.P. 1986. The double radio source associated with L1551 IRS 5 - Binary system or ionized circumstellar torus? *Astrophys. J. Lett.* 301:L25–L28.

Rodriguez, L.F., D'Alessio, P., Wilner, D.J., Ho, P.T.P., Torrelles, J.M., Curiel, S., Gomez, Y., Lizano, S., Pedlar, A., Canto, J., and Raga, A.C. 1998. Compact Protoplanetary Disks in a Binary System in L1551. *Nature*, in press.

Sargent, A.I. and Beckwith, S. 1987. Kinematics of the circumstellar gas of HL Tauri and R Monocerotis *Astrophys. J.* 323:294–305.

Sargent, A.I. and Beckwith, S. 1991. The molecular structure around HL Tauri. *Astrophys. J. Lett.* 382:L31–L35.

Shu, F.H., Tremaine, S., Adams, F.C., and Ruden, S.P. 1990. Sling amplification and eccentric gravitational instabilities in gaseous disks. *Astrophys. J.* 358:495–514.

Snell, R.L., Loren, R.B., and Plambeck, R.L. 1980. Observations of CO in L1551 - Evidence for stellar wind driven shocks. *Astrophys. J. Lett.* 239:L17–L22.

Stapelfeldt, K.R. et al. 1995. WFPC2 Imaging of the Circumstellar Nebulosity of HL Tauri. *Astrophys. J.* 449:888–893.

Stapelfeldt, K.R. et al. 1995. WFPC2 Imaging of GM Aurigae: A Circumstellar Disk Seen in Scattered Light. *American Astronomical Society Meeting, 187, #113.04.*

Stapelfeldt, K.R., Krist, J.E., Menard, F., Bouvier, J., Padgett, D.L. and Burrows, C.J. 1998. An Edge-On Circumstellar Disk in the Young Binary System HK Tauri. *Astrophys. J. Lett.* 502:L65–L69.

Takeuchi, T., Miyama, S.M., and Lin, D.N.C. 1996. Gap Formation in Protoplanetary Disks. *Astrophys. J.* 460:832–847.

Thum, C., Matthews, H.E., Harris, A.I., Tacconi, L.J., Schuster, K.F., and Martín-Pintado, J. 1994. Detection of H21α maser emission at 662 GHz in MWC349. *Astron. Astrophys.* 288:L25–L28.

Torrelles, J.M., Gomez, J.F., Rodriguez, L.F., Ho, P.T.P., Curiel, S., and Vazquez, R. 1997. A Radio Jet–H_2O Maser System in W75 N(B) at a 200 AU Scale: Exploring the Evolutionary Stages of Young Stellar Objects. *Astrophys. J.* 489:744–752.

Torrelles, J.M., Gomez, J.F., Rodriguez, L.F., Curiel, S., Anglada, G., and Ho, P.T.P. 1998. Radio Continuum–H_2O Maser Systems in NGC 2071: H_2O Masers Tracing a Jet (IRS 1) and a Rotating Protoplanetry Disk of Radius 20 AU (IRS 3). *Astrophys. J.* in press.

White, S.M., Welch, W.J., Vogel, S.N., and Lim, J. 1999. in preparation.

Wilner, D.J., Ho, P.T.P., and Rodriguez, L.F. 1999. 7 millimeter Imaging of HL Tauri at 5 AU Resolution. *Astrophys. J.* in preparation.

Woody, D.P., Scott, S.L., Scoville, N.Z., Mundy, L.G., Sargent, A.I., Padin, S., Tinney, C.G., and Wilson, C.D. 1989. Interferometric observations of 1.4 mm continuum sources. *Astrophys. J. Lett.* 337:L41–L44.

Wright, M.C.H., Plambeck, R.L., Mundy, L.G., and Looney, L.W. 1995. SiO Emission from a 1000 AU Disk in Orion KL. *Astrophys. J. Lett.* 455:L185–L188.