IRAM-343

Disk-like Structures around Young Stars

P. André

Saclay

IRAM N°343

To appear in the proceedings of the 10th IAP Meeting
Circumstellar Dust Disks and Planet Formation
July 4-8, 1994

DISK–LIKE STRUCTURES AROUND YOUNG STARS

Philippe ANDRÉ[1]

[1] *CEA, Service d'Astrophysique, Centre d'Etudes de Saclay, F–91191 Gif-sur-Yvette Cedex.*

Abstract

Low-mass ($\lesssim 1\ M_{\odot}$) young stellar objects (YSOs) are thought to be the progenitors of solar-type stars, and some of them are therefore expected to be surrounded by circumstellar disks. Indeed, various observational lines of evidence, which are briefly reviewed, point to the presence of disk-like structures around many YSOs. The IR domain is very effective at distinguishing between optically thick and optically thin disk structures and also provides good information on the temperature distribution of optically thick YSO disks. On the other hand, submillimeter continuum observations provide the best way to measure circumstellar disk masses. Based on the results of several recent submm surveys of young stars, the frequency of occurrence of disks more massive than the minimum mass solar nebula is discussed. The tentative presence of "inner holes" in some dusty disks as well as the peculiar frequency dependence of the dust opacity coefficient in T Tauri disks are also emphasized. These observations possibly trace the early stages of the growth of dust grains into planetesimals and/or the formation of planets in some cases.

1 Introduction: Existence of disks around low-mass YSOs

Although the idea that the solar system formed from a disk can be traced back to Kant and Laplace, it is only recently that disks have become a major ingredient of most observational and theoretical discussions on the close environment of pre-main sequence (PMS) stars. Only ten years ago most models of the T Tauri phenomenon did not invoke a disk at all (see review by [14]). This is partly because, observationally, jet and outflow features associated with T Tauri stars (TTSs) are much more conspicuous than circumstellar disks. For instance, in the case of the extreme TTS HL Tau, there is clear evidence for energetic, collimated ejection in the form of a spectacular optical jet (e.g., [56]), but the disk has been much more difficult to detect and study, requiring the advent of sensitive millimeter-wave interferometers (e.g., [73]). A flattened ^{13}CO circumstellar structure is indeed observed perpendicular to the optical jet (see Fig. 1), but its nature is the subject of some controversy. Although this structure was first interpreted as an (approximately) edge-on disk in Keplerian rotation about the star ([73]), it is probably too big ($\sim$ 3000 AU) to be a centrifugally supported disk resulting from the collapse of a slowly rotating cloud core (expected disk radius $\sim$ 10-100 AU for an initial

cloud rotation rate $\Omega \sim 10^{-14}$-10^{-13} rad s^{-1}; cf. [84]). Recent studies with the Nobeyama ([30]) and Plateau de Bure ([18]) interferometers rather suggest it is a remnant envelope dominated by infall and/or outflow motions. More generally, no *direct* disk image comparable to those existing for the (much closer) β Pictoris disk (e.g., [41]) has yet been obtained in the case of a young star.

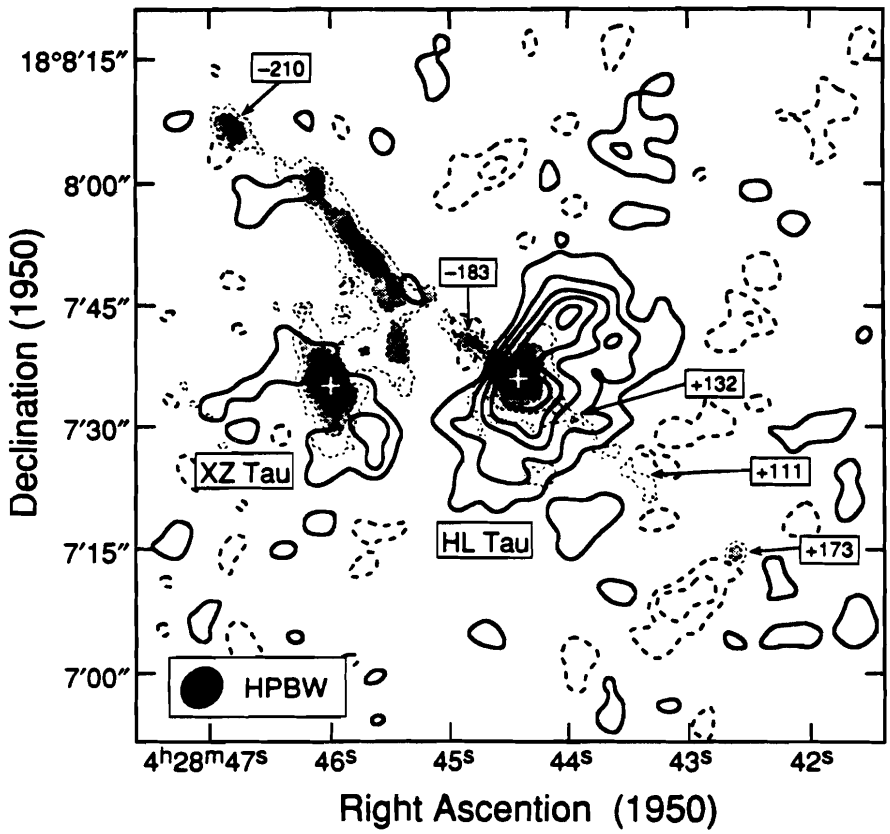

Figure 1. Integrated intensity map of the ^{13}CO(1-0) emission from the HL Tau flattened circumstellar structure (thick lines). This disk-like structure is perpendicular to an optical jet observed in [SII] (superposed here in gray scale). (Adapted from [30] and [56].)

There are, however, a large number of independent, *indirect* arguments for the presence of circumstellar disks around PMS objects. In particular, the optical forbidden (e.g., [OI]) lines detected toward many TTSs tend to show only blueshifted components; since these lines are formed in the winds from these stars, the fact that the redshifted components are not seen is most easily explained if an opaque circumstellar disk ($\sim$ 100 AU in size) occults the receding part of the wind (e.g., [25]). Also, optical and near-IR linear polarization maps show patterns characteristic of multiple scattering in optically thick circumstellar disks, and can be used to infer the disk inclination angle (e.g., [9]). Another argument is that, in spite of the often large amounts of circumstellar material surrounding them (see § 2.2), TTSs are optically visible stars which suffer only small to moderate visual extinctions; if the spatial distribution of the observed circumstellar material were spherically symmetric, the resulting visual extinctions would be such ($A_V \gtrsim 100$) that the stars would be invisible; given that the observation of highly collimated jets points to an axi-symmetric geometry, a rotating disk perpendicular to the jet is the most plausible configuration for the circumstellar material, especially in view of dynamical stability constraints (e.g., [13]). Finally, the spectral energy distributions (SEDs) of classical T Tauri stars (CTTSs) are characterized by strong UV and IR excesses which are simultaneously well reproduced in the framework of an accretion disk model (e.g., [15]).

Although none of the above arguments is really compelling, taken together they make the existence of disks around TTSs, and more generally low-mass YSOs, extremely likely. As a result, the disk hypothesis has now become a standard paradigm within which most observations of TTSs are interpreted. Since several excellent reviews about TTSs and their disks are available in the literature

(e.g., [8], [5], [11]), I will focus the present contribution on the nature and evolution of YSO disks.

2 Are T Tauri disks protoplanetary ?

Since T Tauri disks are basically unresolved by present observational techniques, the only practical way to assess their possible protoplanetary nature is to try and measure their mass, taking the minimum mass necessary to form the solar system, the so-called "minimum mass solar nebula" ($M_{msn} \approx 0.01\ M_\odot$, e.g., [20]), as a reference. Our present estimates of the frequency of occurrence of PMS disks with $M_{disk} > M_{msn}$ are almost entirely based on infrared and (sub)millimeter continuum surveys of nearby star-forming regions, which are discussed in § 2.1 and § 2.2 below. (For a different approach, based on optical and radio continuum images of partially ionized nebulae/disks in the Trapezium cluster of the Orion Nebula, see [61] and [79].)

2.1 Infrared studies of disks

Before summarizing the results of statistical analyses of the IR excesses of TTSs, it is necessary to recall a few basic facts about disk continuum emission. First, very little mass is enough to make a disk optically thick in the infrared. For instance, a minimum-solar-nebula disk ($M_{disk} = 0.01\ M_\odot$) with a radius $R_{disk} = 100$ AU and a power-law surface density distribution ($\Sigma(r) \propto r^{-p}$) will have $\Sigma \sim 3$ g cm^{-2} everywhere if $p = 0$ (uniform disk) and $\Sigma \sim 3$ g cm^{-2} at 40 AU if $p = 1.5$ (surface distribution expected after viscous evolution of a disk formed during protostellar collapse; cf. [44]). This corresponds to optical depths $\tau(\lambda) \geq 1$ at all wavelengths shorter than $\sim 100\ \mu$m (e.g., [77], [13]). Second, in most circumstances, one expects that the disk temperature falls continuously with increasing distance from the star, so that different wavelength regimes, which are sensitive to different blackbody temperatures, probe different regions of the disk. In particular, for a perfectly flat, optically thick "reprocessing" disk (i.e., disk heated only by absorption of stellar photons) around a star of luminosity L_*, one expects a power-law distribution for the (effective) disk temperature (see, e.g., [1]):

$$T_{disk}(r) \approx 90K\,(r/1AU)^{-3/4}(L_*/1L_\odot)^{1/4}(R_*/2R_\odot)^{1/4}. \tag{1}$$

It turns out that the same power-law index of $-3/4$ (but with a somewhat warmer temperature) is expected in the case of an optically thick, Keplerian viscous accretion disk ([45]). In practice, wavelengths shorter than 10 μm are sensitive only to radii smaller than ~ 1 AU, i.e., to the inner portion of circumstellar disks. It is easy to show that a power-law temperature distribution ($T(r) \propto r^{-q}$) implies a power-law SED in the optically thick regime: $\lambda F_\lambda \propto \lambda^{\alpha_{IR}}$ with $\alpha_{IR} = 2/q - 4$ (e.g., [10]). Quite remarkably, the SEDs of a large number of TTSs are indeed well approximated by a power-law from $\sim 1\ \mu$m to $\sim 100\ \mu$m (e.g., [71] and Fig. 2a), which may be taken as an argument in favor of the standard disk hypothesis (see § 1). However, most T Tauri disks appear to have shallower SEDs than expected in the case of either a reprocessing disk or a viscous accretion disk (see Fig. 2a). Understanding the origin of these relatively "flat" spectra remains a major open problem, although several explanations have been proposed, in terms of, e.g., curved or "flared" disks ([37]), non-viscous accretion ([1]), or warps tidally-induced by a binary companion ([85]). The most promising interpretation is perhaps to invoke the presence of a remnant circumstellar envelope around the disk, which will either yield higher disk temperatures through "backwarming" ([59]) or produce excess IR emission by itself ([19], [33], [49]).

In any case, a perfectly flat, optically thick disk has a minimum temperature set by reprocessing of stellar light (see equation 1), implying a minimum excess emission above the PMS star photosphere at any given IR wavelength. On this basis, S. Strom and collaborators (e.g., [77], [80]) have classified low-mass PMS stars in three categories: (i) Classical T Tauri stars (CTTSs) which are candidates for being surrounded by (accretion) disks optically thick in the K (2.2 μm) and N (10 μm) bands; (ii) Weak T Tauri stars (WTTSs) whose disks are most likely optically thin (if existent) at 2.2 and 10 μm; and (iii) transition stars, which may be surrounded by disks with inner holes, optically thin

at 2.2 μm but optically thick at 10 μm. This classification of TTSs based on near-/mid-IR excess is closely related to the YSO classification introduced by C. Lada on the basis of IR spectral slope ([40]), and can therefore be extended to IR sources embedded in molecular clouds: PMS stars of types (i) and (ii) above roughly correspond to optically visible 'Class II' and 'Class III' sources, respectively (see [3]).

After a detailed infrared study of 83 solar-type PMS stars of Taurus-Auriga, Strom et al. find that $\sim$ 50% of the stars younger than $\sim$ 3 Myr have optically thick disks [type (i) above], and suggest that these have $M_{disk} > M_{msn}$. On the other hand, by an age of $\sim$ 10 Myr, the majority (> 90%) of TTSs appear to have optically thin disks [type (ii) above]. Finally, very few (< 10%) transition disks are found, suggesting a transition time shorter than a few 0.1 Myr (see also [87]).

Several other young stellar populations have now been surveyed with large near-IR array cameras, confirming that the fraction of young stars with optically thick inner disks is $\sim$ 50% (see [81] for the case of L1641). However, because wavelengths $\lambda \leq 10$ μm are only sensitive to the warm, inner ($r \lesssim 1$ AU) regions of disks, it is necessary to go to longer (e.g. submillimeter) wavelengths to measure total disk masses and identify protoplanetary disks (with $M_{disk} > M_{msn}$).

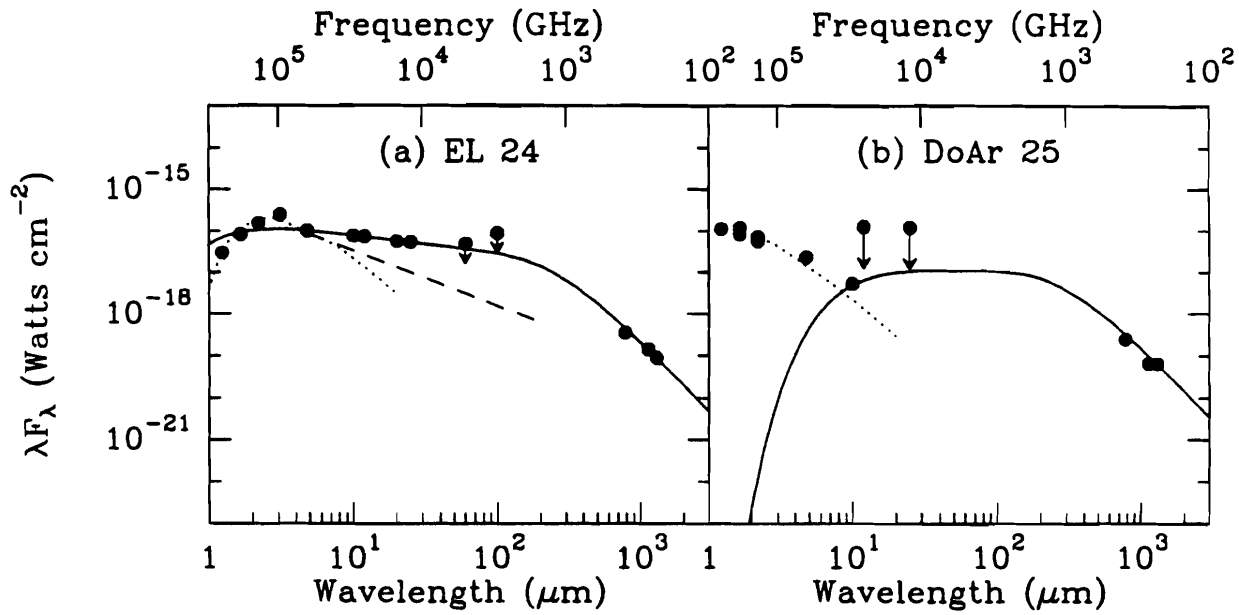

Figure 2. Spectral energy distributions of EL 24 (a) and DoAr 25 (b), along with disk model fits (solid lines) (adapted from [3]). The SED of EL 24 is shallower than that expected for a "reprocessing" disk (dashed line), but consistent with a warmer disk extending all the way down to the stellar surface. DoAr 25, which has a strong submm emission but virtually no IR excess over a reddened stellar blackbody (dotted line), is a candidate transition star with a "hollow" disk [the model shown by the solid line in (b) has an inner hole of radius $R_{in} = 0.2$ AU].

2.2 Submillimeter continuum surveys of disk mass

YSOs in three major nearby ($d \lesssim 160$ pc) star-forming regions, Taurus-Auriga ([13]), ρ Ophiuchi ([3]), and Chamaeleon ([31]), have now been surveyed at 1.3 mm for circumstellar dust continuum emission. In particular, S. Beckwith and collaborators ([13], [65]) used the IRAM 30 m telescope to extensively search for disks around PMS stars in Taurus-Auriga; they observed 86 (mostly classical) TTSs at 1.3 mm and detected about 40 % of them, with disk masses ranging from a few 0.001 $M_\odot$ to $\gtrsim 0.1$ $M_\odot$. Submillimeter continuum surveys of specific classes of objects like Herbig-Haro exciting stars ([70]), Herbig Ae/Be stars ([34], [47]), WTTSs ([76]) or "post" TTSs ([26]) have also been carried out using the IRAM 30 m, SEST 15 m, JCMT 15 m, or CSO 10 m radiotelescopes. All these studies achieved high detection rates except those on weak and post TTSs. As an example, we focus in § 2.2.2 below on our study of the ρ Ophiuchi cloud core region.

2.2.1 *Dust opacity and mass estimates*

The main advantage of the submillimeter regime is that dust emission is generally optically thin at these wavelengths and therefore provides a relatively direct measure of the dust mass in circumstellar disks. It can also be used as a tracer of the total (dust + gas) circumstellar mass M_{c*}, provided the gas-to-dust ratio is known or can be calibrated; this is especially useful in the case of young stars for which this ratio is expected to be quite close to its normal interstellar value of ~ 100. For an optically thin source of temperature T_{dust}, M_{c*} is directly proportional to the observed flux density S_ν:

$$M_{c*} = \frac{S_\nu \, d^2}{\kappa_\nu \, B_\nu(T_{dust})}, \tag{2}$$

where $B_\nu(T_{dust})$ is the Planck function. The average dust temperature in the disk may be estimated from modeling of the infrared SED (e.g., [13]), and has relatively little effect on the mass determinations (e.g., [3]). The dust opacity per unit mass column density κ_ν (which here implicitly includes the dust-to-gas ratio) is much more critical in this respect and unfortunately somewhat uncertain. However, a detailed comparison between observations and existing dust models shows that, for a given source under given physical conditions, the appropriate range of κ_ν is rather well-defined ([50], [23]). For circumstellar disks around young stars, the recommended value is $\kappa_\nu = 0.02$ cm^2 g^{-1} (e.g., [13]) with less than a factor 5 uncertainty ([64], [68]).

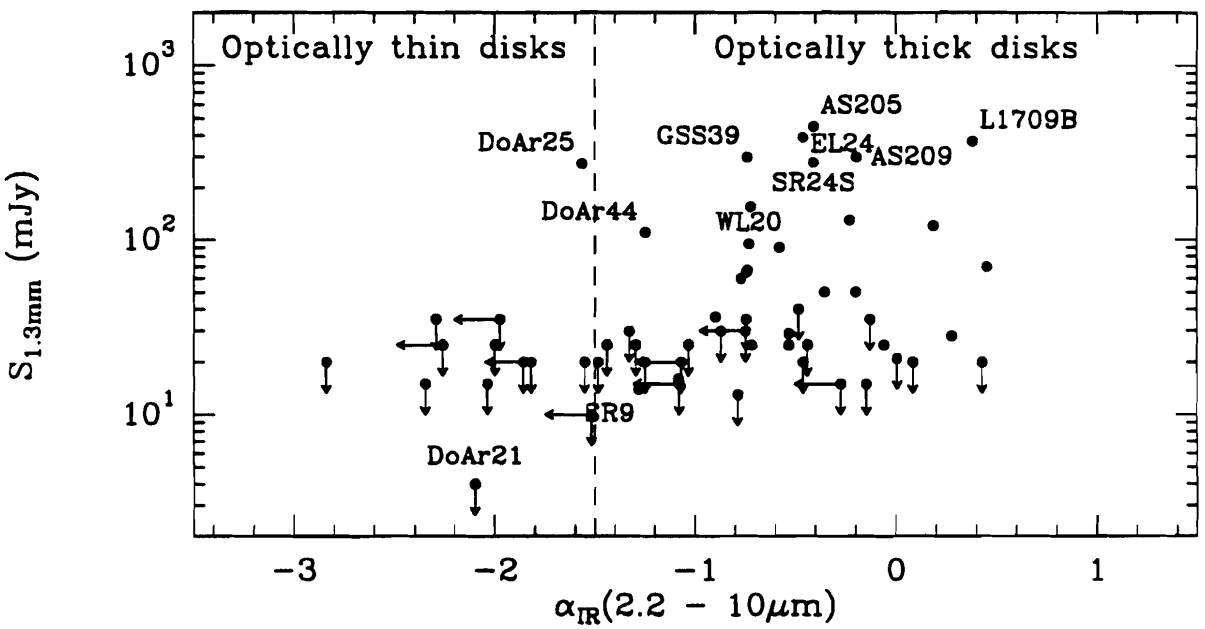

Figure 3. Millimeter flux against near-infrared spectral index for T Tauri-like objects in ρ Ophiuchi (adapted from [3]). The dashed line at $\alpha_{IR} = -1.5$ marks the rough boundary between optically thin and optically thick inner disks (corresponding to Class III and Class II sources, respectively).

2.2.2 *Summary of results in ρ Ophiuchi*

In ρ Ophiuchi ($d \sim 160$ pc), we[3] used the IRAM 30 m telescope equipped with the MPIfR bolometer to conduct a major 1.3 mm continuum survey of ~ 120 YSOs, comprising all well-documented members of the IR cluster embedded in the central region of the cloud ([88]). Limiting ourselves to Class II and Class III near-IR sources (i.e., embedded CTTSs and WTTSs, respectively) for the moment, our main results can be summarized as follows. Bolometer maps of these sources show that they are unresolved in the 12" beam of the 30 m telescope, consistent with emission from circumstellar disks with $R_{disk} < 1000$ AU (see the example of DoAr 25 in Fig. 5a below) . We find a sharp threshold in millimeter flux density at the infrared spectral index $\alpha_{IR}(2.2 - 10\mu m) \simeq -1.5$ marking the transition between optically thin and optically thick disks at $\lambda = 10$ μm, i.e., between Class III and Class II near-IR sources (Fig. 3; see [3] for details). Strong mm continuum emission is detected only for disks which are optically thick in their inner regions ($r < 1$ AU), while no or at most weak mm emission arises

from optically thin disks. The same threshold is also visible in the Taurus-Auriga and Chamaeleon surveys ([13], [31]). There are, however, a few potentially interesting sources detected close to the Class III/Class II boundary in Fig. 3, which represent candidate transition objects with "hollow" disks. An example is the embedded TTS DoAr 25, whose near-IR spectrum is nearly consistent with a pure 4500 K stellar blackbody (reddened by $A_V = 4.2$), while its strong, pointlike submm emission implies the presence of a relatively massive ($\lesssim 0.1\ M_\odot$) outer disk (see Figs. 2b and 5a). Such stars are good candidates for systems in which agglomeration of disk material into planetesimals or planets has begun and proceeds from the 'inside-out' (as a result of smaller dynamical timescales in the inner disk; e.g., [29]).

It is important to note that, among Class II sources (CTTSs), millimeter continuum emission is largely uncorrelated with infrared excess (see Fig. 3). In particular, some of these sources are *not* detected above our (3σ) sensitivity limit of $S_{1.3mm} \sim$ 20–30 mJy/beam, corresponding to a disk mass of $\sim$ 3-5 $\times 10^{-3}\ M_\odot$. Thus, Class II disks (which are optically thick in the near-/mid-IR) may, in some instances, be *less* massive than the minimum solar nebula, indicating that the frequency of occurrence of TTS disks with $M_{disk} > M_{msn}$ derived from IR studies (e.g., § 2.1 above) is probably overestimated. Indeed, a detailed statistical study of disk mass among ρ Oph Class II sources suggests that only $\sim$ 30% of them have $M_{disk} > M_{msn}$ (see Fig. 4). Since the central ρ Oph IR cluster contains at least as many (young) X-ray detected Class III sources (WTTSs) ([21]) and has an estimated age $\lesssim$ 3.5 Myr (e.g., [88]), this implies that, at least in the ρ Oph cloud, the fraction of young PMS stars with protoplanetary disks ($M_{disk} > M_{msn}$) may be as low as $\sim$ 15 %.

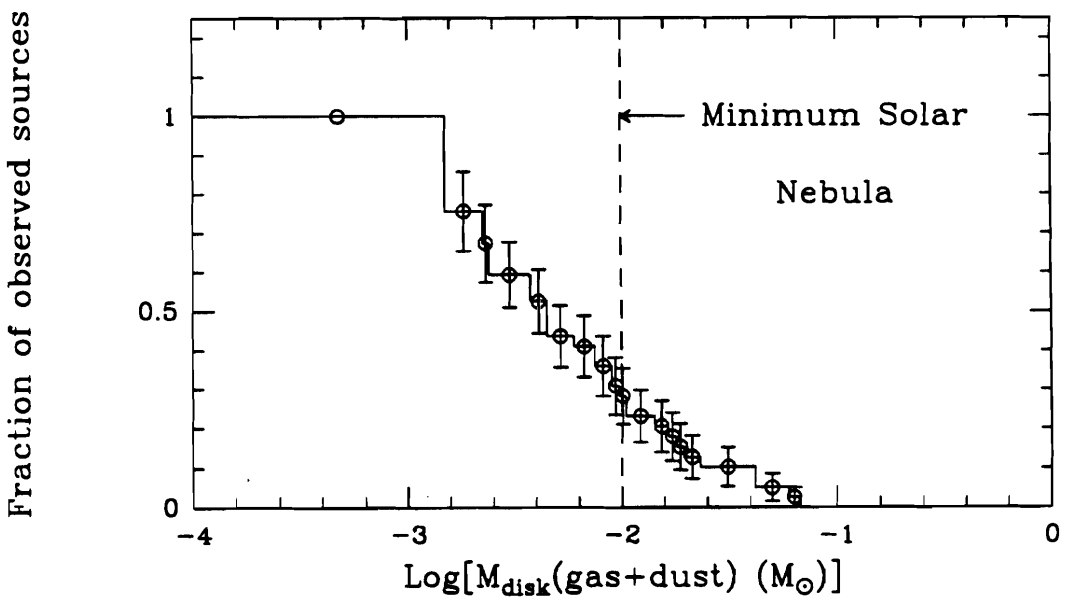

Figure 4. Cumulative distribution of M_{disk} for ρ Oph Class II sources (i.e., embedded classical T Tauri stars). About 30 % of these sources have $M_{disk} \geq M_{msn}$. (Adapted from [3].)

On the basis of the above infrared and millimeter results, Table 1 summarizes our best present guesses about the structure of a typical T Tauri disk.

Table 1. Plausible parameters for a typical T Tauri disk ($M_{disk} = 0.01\ M_\odot$; $R_{disk} = 100$ AU).

Quantity	Radial dependence	Value at 1 AU	Average value
Temperature(*)	$T \propto r^{-0.6}$	150 K	70 K
Surface density	$\Sigma \propto r^{-1.5}$	710 g cm^{-2}	3 g cm^{-2}
Scale height	$H \propto r^{1.2}$	0.04 AU	7 AU
Volume density	$\rho \propto r^{-2.7}$	6.4×10^{-10} g cm^{-3}	1.6×10^{-14} g cm^{-3}

(*): Effective disk temperature. The mid-plane temperature is higher (e.g., [42]).

3 Evolutionary aspects

In addition to Class II and Class III PMS objects (e.g., optically-visible TTSs), at least two types of more deeply embedded YSOs can be distinguished ([40], [3]). 'Class I' near-IR sources, which are characterized by flat or rising SEDs in the far-IR and only moderate submm continuum emission, are interpreted as evolved protostars surrounded by both a disk and a residual infalling envelope. In contrast, 'Class 0' sources, of which the ρ Oph jet-like outflow source VLA 1623 is the prototype ([4]), are very strong in the submm continuum and undetected at near-/mid-IR wavelengths; they correspond to younger, colder protostars whose dense circumstellar envelope/cocoon still contains more mass than the nascent central star. Based on the number of YSOs observed in each class, one estimates that the lifetime of the Class 0 submm stage is $t \sim 10^4$ yr, i.e., ~ 10 times as short as the lifetime of the Class I IR stage ($t \sim 10^5$ yr), itself an order of magnitude shorter than the TTS phase (e.g., [3], [28]).

3.1 Disks and envelopes around embedded protostellar sources

Continuum mapping with the IRAM 30 m telescope shows that, in contrast to Class II objects, Class I and Class 0 embedded sources are resolved at 1.3 mm (with typical FWHM sizes of a few 1000 AU), consistent with the combined dust emission from an extended circumstellar envelope and a more compact disk component ([3], see Fig. 5).

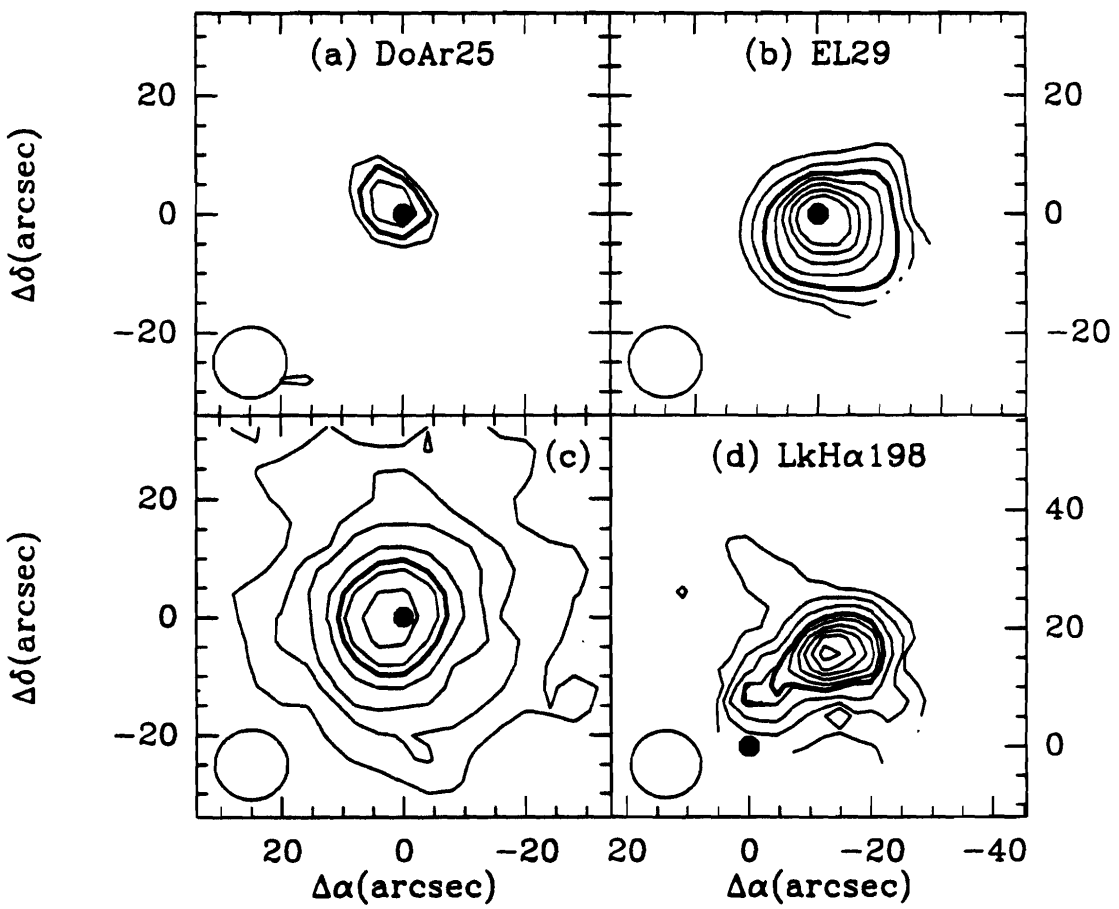

Figure 5. Millimeter continuum maps of the Class II source DoAr25 (a), the Class I source EL 29 (b), the Class 0 source IRAS 16293 (c), and the Herbig Ae/Be star LkHα 198 (d) (adapted from [3] and [17]). The half-power contour is highlighted for comparison with the beam (shown at the bottom left corner of each panel). In (a), (b), and (c), the detected dust emission is well peaked at the nominal YSO position (shown as a black dot) and clearly circumstellar. This is not the case in (d), where the emission arises from a dense dust clump not directly related to the star LkHα 198.

Separating the relative contributions of the disk and the envelope requires the use of additional interferometric measurements ([36], [83]): While the disk component shows up as an unresolved (or barely resolved) core in interferometer maps at 2.7 mm, the extended envelope dominates at 1.3 mm with the resolution of the largest single-dish telescopes. Combining interferometer and single-dish data for a large number of embedded sources, it is thus possible to investigate the question of disk mass and disk formation during the protostellar phase ([83]). 'Massive' disks (i.e., disks of mass comparable with, or larger than, the mass of the central star) are rare, occurring around at most 10 % of young embedded YSOs. In fact, the typical disk mass during the 'self-embedded' Class I phase is nearly the same or even less than the typical disk mass at the TTS stage ([3], [62], [83]). This implies that infalling material, which cannot fall directly onto the star because of rotation (e.g., [84]), does not accumulate in the disk during most of the protostellar stage, but instead is efficiently transported through the disk to the central protostar. Thus, the transport of mass and angular momentum in the disk is very efficient and occurs rapidly with respect to the ($\sim 10^5$ yr) lifetime of Class I sources. In a sense, then, disks during the (Class I) protostar phase may perhaps be viewed as 'feeding machines' evolving with no significant change in mass: they would merely process the protostellar material from the outer envelope reservoir to the central star, while simultaneously transporting angular momentum outward with the probable help of an outflow (see, e.g., [54], [86], [66]).

The only embedded YSOs which may be surrounded by massive, protostellar (as opposed to protoplanetary) disks are the youngest (Class 0) protostars. However, partly because these objects have only recently been identified and very few of them are known, the question of whether they have already formed a disk or not is still a matter of debate. On the theoretical side, disks are often called upon to drive/collimate outflows (e.g., [66]), although a recent MHD 'cored-apple' model suggests that a thin disk may not be necessary ([32]). On the observational side, while it has been suggested that no significant disk has developed yet in the case of VLA 1623 ([4]), a high-resolution study with the Owens Valley mm interferometer points to the presence of two massive disks in the (perhaps more evolved) protobinary IRAS 16293 ([58]).

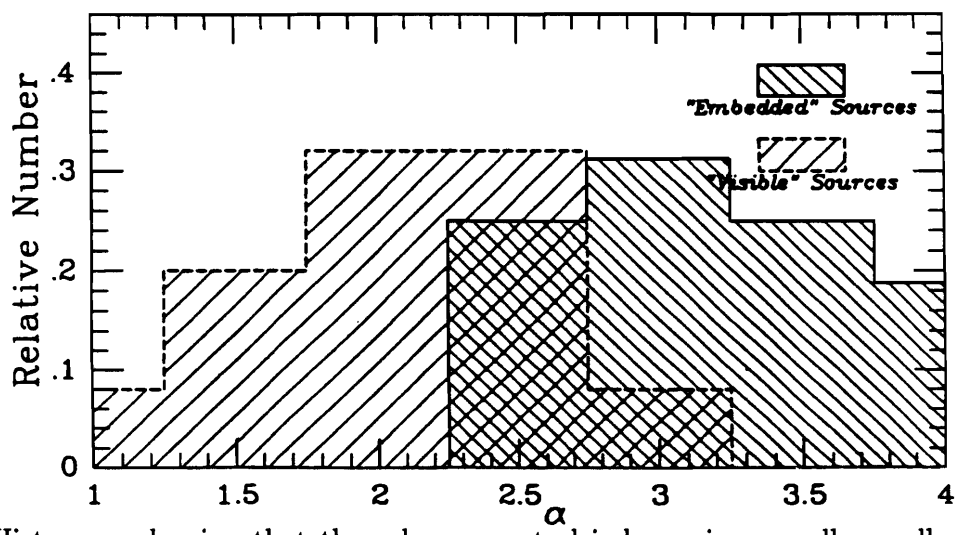

Figure 6. Histogram showing that the submm spectral index α is generally smaller for optically visible TTSs than for embedded protostellar sources (adapted from [55]).

3.2 Grain growth in T Tauri disks ?

Apart from the spatial extent of the circumstellar material, there is another clear evolutionary difference between embedded (Class 0 and Class I) protostars and (Class II) T Tauri stars: the submm spectral slopes α ($S_\nu \propto \nu^\alpha$) of optically visible TTSs are generally shallower than those of embedded sources (see Fig. 6, [55]). The shallow spectra of TTSs may in some cases result from partially optically thick disk emission (as opposed to optically thin envelope emission). However, this is unlikely to affect all but the most massive disks, and the fact that the trend is systematic rather suggests the

dust emissivity index β (such that $\kappa_\nu \propto \nu^\beta$) is smaller in disks than in envelopes, with typical values $\beta_{disk} \sim 1$ and $\beta_{env} \sim 1.5$-2, respectively. This is probably the signature of significant grain growth or even planetesimal formation in the disks surrounding T Tauri stars ([12], [57], [48]). Recent theoretical models of dust grains in cloud cores and accretion disks ([51], [68], [39]) indeed indicate that the value of β in the submm regime depends critically on the upper bound a_+ of the grain size distribution. As long as a_+ remains below ~ 100 μm (as is likely the case in protostellar envelopes), β is expected to retain its "normal" interstellar value of 1.5-2, but, if a_+ reaches a few millimeters or more (as a result of grain coagulation in dense disks), very low β values (between 0 and 1) can be achieved.

3.3 Circumstellar mass as a function of time

Among optically visible TTSs (i.e., ages between $t \lesssim 10^6$ yr and $t \sim 10^7$ yr), there is virtually no correlation between mm continuum flux and stellar age ([13], [65]). However, when one considers a larger time span, from deeply embedded (Class 0 and Class I) YSOs ($t \gtrsim 10^4$ yr) to young main sequence stars ($t \lesssim 10^9$ yr), a clear, overall decrease of circumstellar mass with time becomes apparent ([3], [90]). This is illustrated in Fig. 7 which shows a global decline in the median circumstellar *dust* mass going approximately as $(\text{age})^{-1}$ or $(\text{age})^{-2}$. (In this figure, the ages of Class 0 and Class I YSOs have been assumed to equal their respective lifetimes as derived from statistical arguments, while those of optically visible stars are estimated from position in the HR diagram.) The decline in *total* (gas + dust) circumstellar mass is likely to be even more rapid since the gas-to-dust ratio probably evolves itself from a value of ~ 100 in embedded sources to perhaps ~ 10 in TTSs (e.g., [24]) and ~ 1 in young main sequence stars ([89]).

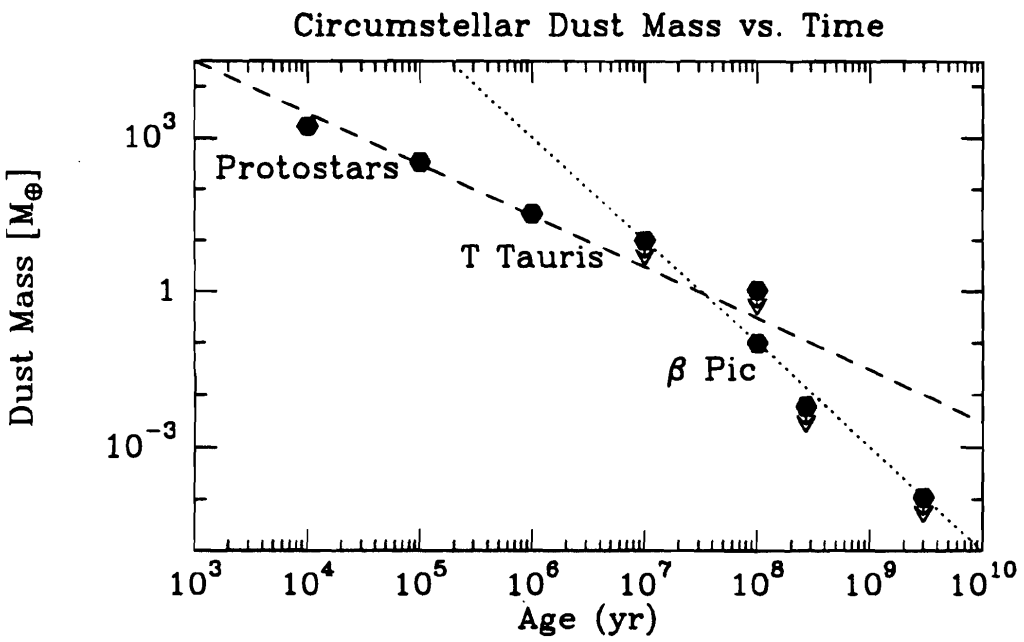

Figure 7. Circumstellar dust mass (in earth masses) as a function of time, from low-mass protostars to young (G-type) main-sequence stars (based on [3] and [90]). For comparison, the dashed and dotted lines show t^{-1} and t^{-2} variations of dust mass with time, respectively.

4 Open problems

Although circumstellar mass generally decreases as time proceeds, the details of this evolution appear to differ from object to object and are likely to depend on initial conditions. For instance, a number of WTTSs with no detectable circumstellar disks ($M_{disk} < 3\times10^{-3}$ $M_\odot$ of dust + gas at ~ 150 pc) lie close to the 'birthline' for PMS stars in the HR diagram (e.g., [78]) and are thus quite young ($t \lesssim 1$ Myr). This implies that, to some extent at least, *circumstellar* evolution is decoupled from *stellar* evolution

(e.g., [87], [53]). A major unsolved issue is to understand whether there is a main disk dissipation mechanism common to all PMS stars or several mechanisms yielding different dissipation timescales in different stars. (A more extreme possibility is that some stars form without a disk at all.) This is relevant to the problem of planetary formation because planet building must presumably occur prior to the dissipation of the disk. Gravitational instabilities (e.g., [72]) are unlikely to be effective as the disk mass is typically much less than the stellar mass (except perhaps during the Class 0 protostar stage). Two more plausible dissipation mechanisms are briefly discussed below.

4.1 Influence of companion stars

Present evidence suggests that a majority ($\gtrsim$ 60 %) of young stars form in multiple systems (e.g., [27]). The distribution and evolution of circumstellar matter in a binary system is expected to crucially depend on the separation a between the two stellar components. In only a few orbital periods, resonant interactions induced by the companion will tidally clear an annular gap containing its orbit and extending roughly from $0.5a$ to $2a$ in radius ([43], [7]). Subsequent disk–binary interaction occurs on slower (e.g., viscous) timescales, which are nevertheless probably short ($\gtrsim 10^4$ yr) compared with the total PMS lifetime (cf. [6], [46]). Thus, while circumstellar evolution should be virtually unaffected in wide binaries with a separations exceeding the typical disk radius ($\sim$ 100 AU), one expects early disruption of the individual circumstellar disks in close binaries with $a \sim$ 10-50 AU or less. In the former case, one may expect that circumstellar disks of "normal" size will exist, as indeed observed around UZ TauE and UZ TauW separated by $\sim$ 560 AU ([75]). In the latter case, a circumbinary disk or ring (with an evacuated inner cavity) might still be present, as the example of the GG Tau binary ($\sim$ 50 AU separation) nicely shows ([24]). However, GG Tau is the only 'close' binary with a 'large' circumstellar mass ($\sim 0.1\ M_\odot$) in Taurus-Auriga, while, in general, binary systems with projected separations $\leq$ 50 AU have significantly lower (sub)mm continuum fluxes than wider binaries or single stars ([74]; [35]). Since GG Tau is particularly young ($0.3 \lesssim t \lesssim 1$ Myr; cf. [13], [77]), this suggests that the lifetime of circumbinary disks is short and that planets may not have time to form in the circumstellar environment of close binaries.

4.2 Influence of the magnetic field

The inner regions of circumstellar disks are also expected to be in close interaction with the stellar magnetic field. In particular, if the central PMS star has a dipolar magnetosphere that threads the accretion disk beyond the corotation radius (typically a few $R_\star$), then a rotational equilibrium may be achieved in which the stellar angular velocity is held constant, in spite of the spin-up torque applied by accreting disk material ([38]). This magnetospheric coupling between the star and the disk has been proposed as a possible regulating mechanism to explain the low rotation rates of TTSs in general, and the fact that WTTSs (i.e., PMS stars without accretion disks) rotate a factor of 2 faster than CTTSs on average (e.g., [16]). (The idea is that only those stars which have dissipated their disks can spin up as a result of PMS contraction.) The required dipolar magnetic field seems, however, quite large, on the order of a kilogauss or more ([38]). Observational evidence for intense, large-scale stellar fields has been found in the radio range (see below), but only around some WTT-like objects, casting doubt on the existence of such fields in CTTSs.

Extensive VLA surveys of the ρ Ophiuchi and Taurus-Auriga star-forming regions have shown that 'strong' nonthermal radio continuum emission is detected only in a sub-fraction ($\sim$ 10 %) of Class III ('diskless') YSOs (e.g., [52], [63]). Furthermore, these radio stars, which lie close to the centers of dense cloud cores are presumably quite young, i.e., probably younger than some CTTSs or Class II objects found far from dense cores (and undetected by the VLA). Follow-up VLBI studies of these 'young', diskless YSOs have established that they emit gyrosynchrotron radio emission from giant, dipolar-like magnetospheres $\sim$ 3-10 $R_\star$ in radius ([2], [67]). Although the absence of a disk may be explained by the disrupting effect of a close companion in some of these objects, a more general possibility is that, compared to CTTSs, the young, radio-emitting Class III YSOs have conserved particularly strong

fossil magnetic fields, which caused fast clearing of their circumstellar material ([2]). This suggests that dense circumstellar disks and strong dipolar fields cannot simultaneously survive very long around PMS stars, possibly as a result of magnetic instabilities (e.g., [82]).

5 Conclusions

Submillimeter continuum surveys suggest that only $\sim$ 15-25 % of all young ($t \leq 3$ Myr), low-mass PMS stars (CTTSs *and* WTTSs) have protoplanetary disks more massive than the minimum mass solar nebula ($M_{msn} \sim 0.01\ M_{\odot}$). Although circumstellar mass generally decreases with time, the absolute time of the transition between $M_{disk} > M_{msn}$ and $M_{disk} < M_{msn}$ varies from star to star and probably depends on initial conditions such as rotation and magnetic field of the parent core. Nevertheless, the fact that, by an age of $\sim$ 10 Myr, virtually all stars seem to have $M_{disk} < M_{msn}$ indicates that this transition occurs sometime during the pre-main sequence phase (1 Myr $\lesssim t \lesssim$ 10 Myr). The small fraction ($\lesssim$ 10 %) of PMS stars with 'transition' disks, optically thin in their inner regions but with still substantial amounts of material in their outer parts, shows that, when it occurs, the transition is short, lasting probably less than a few 10^5 yr. Since millimeter continuum measurements are sensitive to dust particles only up to a few mm in size, the above results suggest that the agglomeration of disk material into planetesimals (particles larger than a few cm) takes place during the PMS phase, probably in an 'inside-out' fashion. However, little can be said about the formation of terrestrial planets themselves. As to the formation of binary/multiple systems (and possibly giant planets as well), it must occur very early on, i.e., at (or before) the youngest 'Class 0' protostar stage, since there appears not to be enough available mass at later stages.

It is at present unclear whether intermediate-mass PMS stars (Herbig Ae/Be stars), which are the progenitors of Vega-type stars such as β Pictoris, have disks similar to (or more massive than) TTSs (e.g., [60], [69], [22]). Because these stars are generally more distant than TTSs, most existing observations do not have enough sensitivity or spatial resolution to detect and study their circumstellar material (see, e.g., Fig. 5d above).

Acknowledgements. I am grateful to Thierry Montmerle for useful comments and suggestions.

References

[1] Adams, F.C., Lada, C.J., & Shu, F.H. 1988. *Astrophys. J.* **326**, 865

[2] André, P., Deeney, B.D., Phillips, R.B., & Lestrade, J.-F. 1992. *Astrophys. J.* **401**, 667

[3] André, P., & Montmerle, T. 1994. *Astrophys. J.* **420**, 837

[4] André, P., Ward-Thompson, D., & Barsony, M. 1993. *Astrophys. J.* **406**, 122

[5] Appenzeller, I., & Mundt, R. 1989. *Astron. Astrophys. Rev.*, **1**, 291

[6] Artymowicz, P., Clarke, C.J., Lubow, S.H., & Pringle, J.E. 1991. *Astrophys. J.* **370**, L35

[7] Artymowicz, P., & Lubow, S.H. 1994. *Astrophys. J.* **421**, 651

[8] Basri, G., & Bertout, C. 1993. in *Protostars and Planets III* p. 543, eds. E.H. Levy & J.I. Lunine (U. Arizona Press, Tucson)

[9] Bastien, P., & Ménard, F. 1990. *Astrophys. J.* **364**, 232

[10] Beall, J.H. 1987. *Astrophys. J.* **316**, 227

[11] Beckwith, S.V.W. 1994. in *Theory of Accretion Disks-2* p. 1, eds. Duschl et al.

[12] Beckwith, S.V.W., & Sargent, A.I. 1991. *Astrophys. J.* **381**, 250

[13] Beckwith, S.V.W., Sargent, A.I., Chini, R., & Güsten, R. 1990. *Astron. J.* **99**, 924

[14] Bertout, C. 1984. *Rep. Prog. Phys.*, **47**, 111

[15] Bertout, C., Basri, G., & Bouvier, J. 1988. *Astrophys. J.* **330**, 350

[16] Bouvier, J., Cabrit, S., Fernández, M., Martín, E.L., & Matthews, J.M. 1993. *Astr. Astrophys.* **272**, 176

[17] Cabrit, S., André, P., Ménard, F., Thum, C., & Motte, F., in preparation

[18] Cabrit, S., Guilloteau, S., André, P., Bertout, C., Montmerle, T., & Schuster, K. 1995. *Astr. Astrophys.* submitted

[19] Calvet N., Hartmann, L., Kenyon, S.J., & Whitney, B.A. 1994. *Astrophys. J.* **434**, 330

[20] Cameron, A.G.W. 1988. *Ann. Rev. Astron. Astrophys.*, **26**, 441

[21] Casanova, S., Montmerle, T., Feigelson, E.D., & André, P. 1995. *Astrophys. J.* Feb. 1st issue

[22] de Winter, D., van Duuren, P., Thé, P., & van den Ancker, M. 1995. this volume

[23] Dorschner, J., & Henning, T. 1994. *Astron. Astrophys. Rev.*, in prep.

[24] Dutrey, A., Guilloteau, S., & Simon, M. 1994., *Astr. Astrophys.* in press

[25] Edwards, S., Cabrit, S., Strom, S.E., Heyer, I., Strom, K.M., & Anderson, E. 1987. *Astrophys. J.* **321**, 473

[26] Gahm, G.F., Zinnecker, H., Pallavicini, R., & Pasquini, L. 1994. *Astr. Astrophys.* **282**, 123

[27] Ghez, A.M., Neugebauer, G., & Matthews, K. 1993. *Astron. J.* **106**, 2005

[28] Greene, T.P., Wilking, B.A., André, P., Young, E.T., & Lada, C.J. 1994. *Astrophys. J.* **434**, 614

[29] Hayashi, C., Nakazawa, K., & Nakagawa, Y. 1985. in *Protostars and Planets II* p. 1100, eds. D.C. Black & M.S. Matthews (U. Arizona Press, Tucson)

[30] Hayashi, M., Ohashi, N., & Miyama, S.M. 1993. *Astrophys. J.* **418**, L71

[31] Henning, T., Pfau, W., Zinnecker, H., & Prusti, T. 1993. *Astr. Astrophys.* **276**, 129

[32] Henriksen, R.N., & Valls-Gabaud, D, 1994. *Mon. Not. R. astr. Soc* **266**, 681

[33] Hetem, A., Gregorio-Hetem, J., & Lépine, J.R. 1994. this volume

[34] Hillenbrand, L.A., Strom, S.E., Vrba, F.J., & Keene, J. 1992. *Astrophys. J.* **397**, 613

[35] Jensen, E.L.N., Mathieu, R.D., & Fuller, G.A. 1994. *Astrophys. J.* **429**, L29

[36] Keene, J., & Masson, C.R. 1990. *Astrophys. J.* **355**, , 635

[37] Kenyon, S.J., & Hartmann, L. 1987. *Astrophys. J.* **323**, 714

[38] Königl, A. 1991. *Astrophys. J.* **370**, L39

[39] Krügel, E., & Siebenmorgen, R. 1994. *Astr. Astrophys.* **288**, 929

[40] Lada, C.J. 1987. in *Star Forming Regions* p. 1, eds. M. Peimbert & J. Jugaku (Kluwer, Dordrecht)

[41] Lagage, P.O.L., & Pantin, E. 1994. *Nature* **369**, 628

[42] Lin, D.N.C., & Papaloizou, J.C.B. 1985. in *Protostars and Planets II* p. 981, eds. D.C. Black & M.S. Matthews (U. Arizona Press, Tucson)

[43] Lin, D.N.C., & Papaloizou, J.C.B. 1993. in *Protostars and Planets III* p. 749, eds. E.H. Levy & J.I. Lunine (U. Arizona Press, Tucson)

[44] Lin, D.N.C., & Pringle, J.E. 1990. *Astrophys. J.* **358**, 515

[45] Lynden-Bell, D., & Pringle, J. 1974. *Mon. Not. R. astr. Soc* **168**, 603

[46] Mathieu, R.D. 1994. *Ann. Rev. Astr. Astrophys.*, **32**, 465

[47] Mannings, V. 1994. *Mon. Not. R. astr. Soc* in press

[48] Mannings, V., & Emerson, J.P. 1994. *Mon. Not. R. astr. Soc* **267**, 361

[49] Men'shchikov, A.B., & Henning, T. 1994. this volume

[50] Mezger, P.G. 1990. in *Physics and Composition of Interstellar Matter* p. 97, eds. J. Krelowski & J. Papaj (Institute of Astronomy, Nicolaus Copernicus University, Torun)

[51] Miyake, K., & Nakagawa, Y. 1993. *Icarus*, **106**, 20

[52] Montmerle, T., & André, P. 1998. in *Formation and Evolution of Low Mass Stars* p. 225, eds. A.K. Dupree & M.T.V.T. Lago (Kluwer, Dordrecht)

[53] Montmerle, T., & André, P. 1989. in *Low Mass Star Formation and Pre-Main Sequence Objects* p. 407, ed. B. Reipurth (ESO, Garching)

[54] Morfill, G.E., Tscharnuter, W., & Völk, H.J. 1985. in *Protostars and Planets II* p. 493, eds. D.C. Black & M.S. Matthews (U. Arizona Press, Tucson)

[55] Moriarty-Schieven, G.H., Wannier, P.G., Keene, J., & Tamura, M. 1994. *Astrophys. J.* in press

[56] Mundt, R., Ray, T., Burkhe, T., Raga, A.C., & Solf, J. 1990. *Astr. Astrophys.* **232**, 37

[57] Mundy, L.G., McMullin, J.P., Grossman, A.W., & Sandell, G. 1993. *Icarus*, **106**, 11

[58] Mundy, L.G., Wootten, H.A., Wilking, B.A., Blake, G.A., & Sargent, A.I. 1992. *Astrophys. J.* **385**, 306

[59] Natta, A. 1993. *Astrophys. J.* **412**, 761

[60] Natta, A. 1994. in *The Cold Universe* p. 261, eds. T. Montmerle, C.J. Lada, I.F. Mirabel, & J. Trân Thanh Vân (Editions Frontières, Gif-sur-Yvette)

[61] O'Dell, C.R., & Wen, Z. 1994. *Astrophys. J.* **436**, 194

[62] Ohashi, N., Kawabe, R., Ishiguro, M., & Hayashi, M. 1994. *Ap. Space Sci.*, **212**, 239

[63] O'Neal, D.B., Feigelson, E.D., Mathieu, R.D., & Myers, P.C. 1990. *Astron. J.* **100**, 1610

[64] Ossenkopf, V., & Henning, T. 1994. *Astr. Astrophys.* in press

[65] Osterloh, M., & Beckwith, S.V.W. 1995. *Astrophys. J.* Jan. 20 issue

[66] Pelletier, G., & Pudritz, R.E. 1992. *Astrophys. J.* **394**, 117

[67] Phillips, R.B., Lonsdale, C.J., & Feigelson, E.D. 1991. *Astrophys. J.* **382**, 261

[68] Pollack, J.B., Hollenbach, D., Beckwith, S., Simonelli, D.P., Roush, T., Fong, W. 1994. *Astrophys. J.* **421**, 615

[69] Ray, T.P. 1994. in *The Cold Universe* p. 255, eds. T. Montmerle, C.J. Lada, I.F. Mirabel, & J. Trân Thanh Vân (Editions Frontières, Gif-sur-Yvette)

[70] Reipurth, B., Chini, R., Krügel, E., Kreysa, E., & Sievers, A. 1993. *Astr. Astrophys.* **273**, 221

[71] Rucinski, S.M. 1985. *Astron. J.* **90**, 2321

[72] Ruden, S.P. 1994. in *The Cold Universe* p. 285, eds. T. Montmerle, C.J. Lada, I.F. Mirabel, & J. Trân Thanh Vân (Editions Frontières, Gif-sur-Yvette)

[73] Sargent, A.I., & Beckwith, S.V.W. 1987. *Astrophys. J.* **323**, 294

[74] Simon, M., Chen, W.P., Howell, R.R., Benson, J.A., & Slowik, D. 1992. *Astrophys. J.* **384**, 212

[75] Simon, M., & Guilloteau, S. 1992. *Astrophys. J.* **397**, L47

[76] Skinner, S.L., Brown, A., & Walter, F.M. 1991. *Astron. J.* **102**, 1742

[77] Skrutskie, M.F., Dutkevitch, D., Strom, S.E., Edwards, S., Strom, K., & Shure, M.A. 1990. *Astron. J.* **99**, 1187

[78] Stahler, S.W., & Walter, F.M. 1993. in *Protostars and Planets III* p. 405, eds. E.H. Levy & J.I. Lunine (U. Arizona Press, Tucson)

[79] Stauffer, J.R., Prosser, C.F., Hartmann, L., & McCaughrean, M.J. 1994. *Astron. J.* **108**, 1375

[80] Strom, S.E., Edwards, S., & Skrutskie, M.F. 1993. in *Protostars and Planets III* p. 837, eds. E.H. Levy & J.I. Lunine (U. Arizona Press, Tucson)

[81] Strom, K.M., Strom, S.E., & Merrill, K.M. 1993. *Astrophys. J.* **412**, 233

[82] Tagger, M., Henriksen, R.N., Sygnet, J.F., & Pellat, R. 1990. *Astrophys. J.* **353**, 654

[83] Terebey, S., Chandler, C.J., & André, P. 1993. *Astrophys. J.* **414**, 759

[84] Terebey, S., Shu, F.H., & Cassen, P. 1984. *Astrophys. J.* **286**, 529

[85] Terquem, C., & Bertout, C. 1993, *Astr. Astrophys.* **274**, 291

[86] Völk, H.J., & Morfill, G.E. 1991. *Space Sci. Rev*, **56**, 65

[87] Walter, F.M., Brown, A., Mathieu, R.D., Myers, P.C., & Vrba, F.J. 1988. *Astron. J.* **96**, 297

[88] Wilking, B.A., Lada, C.J., & Young, E.T. 1989. *Astrophys. J.* **340**, 823

[89] Zuckerman, B. 1994. this volume

[90] Zuckerman, B., & Becklin, E.E. 1993. *Astrophys. J.* **414**, 793