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Multiplicity Among the Young Stars

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ABSTRACT: Our survey for companions of the young stars now includes 45 systems in the Taurus star–forming region (SFR) and 21 in the Ophiuchus SFR. It is carried out by lunar occultation and imaging in the IR and can identify binaries in the separation range $0''.005$ to $10''$ in systems brighter than K=10 mag. The observed multiplicity in Taurus is ~1.6 stars/system which is comparable to that of the nearby solarlike stars but corrections for incompleteness increase the multiplicity to at least 1.8.

Inner active disks are equally represented among the single and multiple systems. The multiple systems have less massive outer disks than the single systems, but there are significant exceptions. The binary UZ Tau W contains a circumstellar disk or disks of mass $\sim 0.024\ \mathcal{M}_\odot$ and size ~ 13 AU. The quadruple GG Tau system has a remarkably extensive circumbinary disk of mass $\sim 0.07\mathcal{M}_\odot$. These mass estimates are comparable to the minimum values required for the proto-planetary disk of the Solar System.

The specific angular momenta of the most widely spaced binaries in our sample adjoin the lowest values that can be measured for molecular cloud cores. The actual distributions probably overlap which suggests that the origin of the angular momentum of binaries is in their molecular cloud birthplaces.

1. INTRODUCTION

Surveys for multiplicity among the young stars are revealing that many of the stars previously regarded as single are in fact in multiple systems (Ghez *et al.* 1992, Leinert *et al.* 1992, Mathieu 1992, Simon *et al.* 1992). This is not altogether surprising because most solarlike field stars have companions, and it is recognized that these *have* to be primordial in some sense (Abt 1983, Duquennoy & Mayor 1991 (DM), Binney & Tremaine 1987). Nonetheless, the sample of young–star binaries represents a gold mine for astrophysical research. There are at least three reasons why the study of young star binaries is important.

The first is to learn how they form. While the formation of single stars is now understood, at least in broad outline (see Lada (1991) for an excellent review), the formation of binaries is still an unsolved problem. In Taurus at least, star formation produces mostly binaries so this gap in our knowledge is serious. Processes thought to be important include fragmentation into smaller components at the start of protostellar collapse, capture of independently formed stars, and instabilities in massive disks surrounding pre-existing stars. The current status of theoretical work in these areas is described in this Colloquium by Adams, Bonnell, Boss, and Clarke. Well characterized systematic surveys of young star multiplicity will define the parameters of the binary formation problem — the initial conditions and the nature of the products — and will discriminate between the possible mechanisms.

Second, young stars have observable circumstellar disks (Adams *et al.* 1987, Basri & Bertout 1989). The disks are believed to be the sites of planet formation (e.g., Lissauer 1987). Studies of the evolution, structure, and composition of solar system–forming disks in single and binary star environments are thus of vital interest.

Finally, we have become so accustomed to thinking of the young stars as unresolved single objects that we must assess how the fact that they are actually in binaries affects our understanding of their evolution. (e.g., Which star dominates the luminosity? Which is the source of the outflow?) We need to determine the stellar parameters of the companions.

This review summarizes current results of our survey, describes some initial studies of the astrophysics of the binaries, and suggests directions for future research.

2. THE BINARY FREQUENCY

The seminal discoveries of T Tau's companion by IR speckle interferometry and of a spectroscopic binary among the X-ray selected pre-ms stars provided the hint that systematic application of these techniques to the young stars might be fruitful (Dyck *et al.* 1982, Mundt *et al.* 1983). Indeed, Ghez, Leinert, Mathieu, and Zinnecker describe in this volume the results of their IR speckle, spectroscopic, and CCD imaging surveys that are large–scale and "complete" in specifiable ways. The period distribution of the solarlike binaries peaks at $\sim 10^5$ d, corresponding to a separation of $\sim$ 40 AU or $0\overset{''}{.}3$ at the 150 pc distance of the Taurus star–forming region (SFR). Identification of binaries well below the expected peak of the distribution requires resolutions higher than can be attained at present by IR speckle interferometry. The occultation technique can reach angular resolution $0\overset{''}{.}005$ (0.7 AU) for objects brighter than K=10 mag. The binaries with separations < 1 AU have short periods so can be identified by spectroscopic techniques. The occultation technique thus has a very useful resolution niche and we have been using it, supplemented by IR imaging, to survey the young stars in the Taurus and Ophiuchus SFRs for circumstellar matter and companions (Chen *et al.* 1992, Simon *et al.* 1992).

The systems in our survey have been successfully observed by occultation and by IR imaging to extend the angular separation range surveyed. The objects in our survey are thus occultation–selected and the survey progresses at the rate at which the stars in Taurus and Ophiuchus SFRs have observable occultations. In Taurus, the opportunities present themselves quite steadily over the years because the SFR is so extensive, but, in Ophiuchus, at least for its core which is much more centrally concentrated, the opportunities come in bursts at intervals of $\sim$ 6 and 12 years.

Our survey of the Taurus SFR now includes 45 young systems (Simon *et al.* in preparation). Of the 45 systems, 21 have no detected companions in the angular separation range $0\overset{''}{.}005$ to $10''$, 20 are doubles, and 4 are triples. All the triples are hierarchical in the sense that (greatest separation/smallest separation) > 10. At the field star density towards Taurus, the probability of finding a field star interloper within $10''$ radius of *one* the 45 targets is $\sim$ 0.6 so we can be confident that the targets and companions are associated. All the systems for which Hayashi track ages are available (Beckwith *et al.* , BSCG) are younger than 3×10^6 y.

The observed multiplicity of our sample is $\sim$ 1.6 stars/system. Abt (1983) and DM find approximately the same multiplicity for the solarlike stars. How-

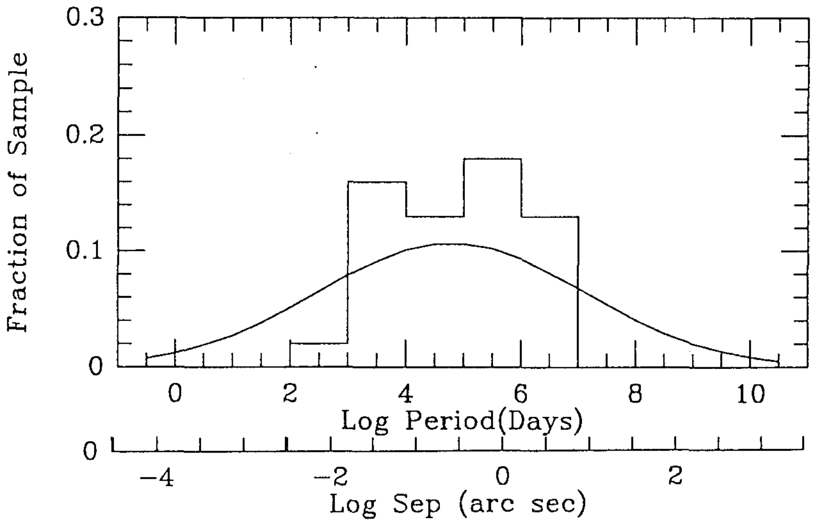

FIGURE 1. **The observed distribution of separations in the Taurus SFR compared with the binary period distribution of the solarlike stars (DM).**

ever, our value refers only to the range of separations ∼ 1 to 1400 AU while the field star multiplicity refers to the entire range. Our survey is insensitive to the systems with separations < 1 AU, which are nonetheless known to be present (Mathieu *et al.* 1989), and excludes systems with separations >1400 AU. The young star multiplicity thus must exceed that of the solarlike stars.

Figure 1 compares the observed distribution of separations with the distribution for the nearby solarlike stars (DM).

We assumed the young star binaries contain 0.5 $\mathcal{M}_\odot$ stars and ignored orbital projection effects to convert the observed separations to periods. The incidence of binaries among the young stars exceeds that of the solarlike stars in the range $3 < \log P(\text{days}) < 7$. The actual peak of the young star distribution occurs in the bin centered at $\log P(\text{days}) = 5.5$, corresponding to separation $\sim 0\farcs65$ in Taurus. The solarlike distribution peaks at $\log P = 4.8$ (DM); the difference is not significant. Figure 1 shows our survey is incomplete below $\log P(\text{days}) = 3$, as expected, and the cut off above $\log P(\text{days}) = 7$. To correct the observed multiplicity for the binaries our survey misses, the distribution of the solarlike stars suggests we should add ∼ 0.10 for the systems unresolved at $\log P < 3$ and ∼ 0.09 for the systems at $\log P > 7$. The young star multiplicity in Taurus is therefore at least ∼ 1.8. This is a lower bound because our survey surely misses some of the faint companions. The high multiplicity is consistent with results of Ghez *et al.* (1992) and Leinert *et al.* (1992) who also find a high binary frequency in Taurus.

Star formation in Taurus thus produces more binaries than single stars and the hierarchical structure of multiples is established very early in the star formation process. Surveys of other star–forming regions are needed to learn whether this is typical. Ghez *et al.* (1992) find no difference in binary frequency between the Taurus and Ophiuchus SFRs. So far our survey of Ophiuchus includes 21 objects; we are finding a surprisingly low multiplicity. With luck, we will be able to clarify the situation with more data later this year when the current Ophiuchus occultation season ends. It would be useful to carry out surveys of other SFRs as well. The Chamaleon I, Lupus, and R CrA SFRs are sufficiently nearby that high resolution imaging and speckle interferometry would provide useful estimates of their binary frequency. Chen (1992) describes the beginnings of such a survey.

3. THE ASTROPHYSICS OF YOUNG STAR BINARIES

3.1. Disks in the Binary Environment

The star plus circumstellar paradigm has proved enormously successful in accounting for the properties of young stars (e.g., Lada 1991). The observations suggest a distinction between inner and outer disk regions. The inner disks, extending to a few photospheric radii, are responsible for boundary layer emission phenomena and near IR excess emission (Basri & Bertout 1989). The dusty outer disks are identified by their continuum emission at IR and mm wavelengths and may extend to $\sim$ 100 AU (Adams *et al.* 1987, BSCG) Are there observable differences between the disks in single and multiple systems?

We use Hα equivalent width as an indicator of inner disk activity. Strong Hα emission is a defining characteristic of the classic (emission line) T Tauri stars (cTTs). Since Hα is easily excited it is not the best indicator of active disks, but it has the virtue that a large database exists (e.g., Herbig & Bell 1988). Figure 2 shows that there is no obvious difference in the Hα EW distributions of the singles and multiples.

Active inner disks are present in both groups. 1.3 mm continuum emission is a reliable indicator of the dusty outer disks (BSCG). Figure 3 shows that multiple systems are in general weaker 1.3 mm continuum sources than the single stars, indicating that their extensive dusty disks are less massive.

We do not however find any convincing evidence for a correlation between disk mass and binary component separation.

Not all the multiples are weak mm wavelength sources. The UZ Tau system is the strongest 1.3 mm source of the multiples in our survey (Figure 3). It is a triple, consisting of a close binary, UZ Tau W (apparent separation $0''.34$), and a third member, UZ Tau E, $4''$ away (Simon *et al.* 1992). Both UZ Tau E and W, considered as single stars are cTTs. UZ Tau E and W were not resolved by BSCG. GG Tau, also a cTT, the second strongest 1.3 mm source in the BSCG survey, is a quadruple. Speckle interferometry shows it contains a pair of binaries, GG Tau (sep. $0''.26$) and GG Tau/c (sep. $1''.4$) separated by $\sim 10''$ (Leinert *et al.* 1991).

We imaged the UZ Tau and GG Tau systems with the IRAM Plateau de Bure Interferometer operating in the continuum at 2.6 mm wavelength to investigate the structure of their dusty disks (Simon & Guilloteau 1992). UZ Tau E and W (Figure 4) are each $\sim$ 13 mJy sources, unresolved at even the longest baselines. The spectrum indicates that the 2.6 mm emission is at least partially optically thick. This implies an origin in disks of size $\sim$13 AU and mass, esti-

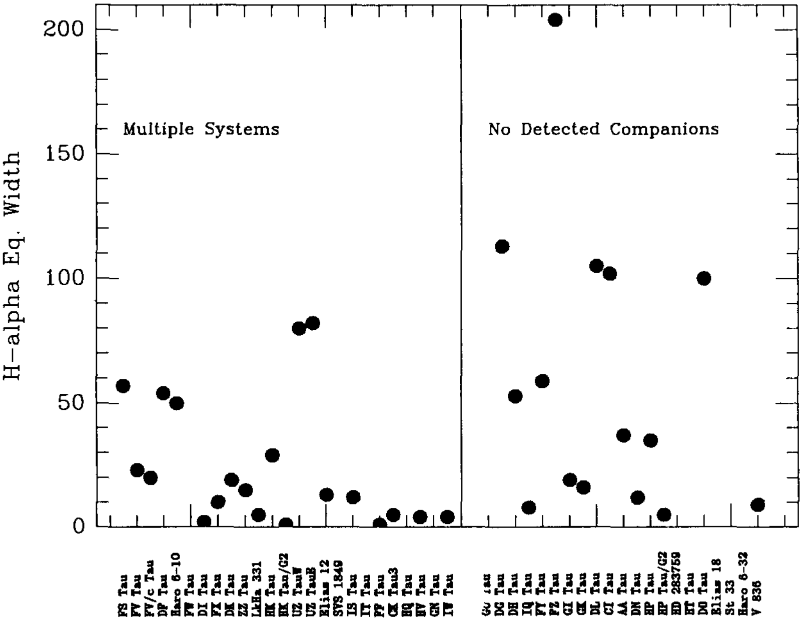

FIGURE 2. The abscissa gives the Hα equivalent widths (Herbig & Bell 1988) for the systems listed along the ordinate.

mated following the procedure of BSCG, ~0.024 $\mathcal{M}_\odot$. The disks of UZ Tau E and W are thus relatively small. The disk or disks within the UZ Tau W binary are smaller than the separation of its stars so are truly circumstellar.

The disk structure associated with GG Tau is very different (Figure 4). Its emission peaks at GG Tau with a secondary peak at GG Tau/c. The emission is remarkable for its strength, 90 mJy, and large extent, ~ 300 × 850 AU. Much of the dust in the GG Tau is thus circumbinary. The disk mass is uncertain but is probably ~ 0.07 $\mathcal{M}_\odot$. The masses of the disks within the UZ Tau and GG Tau systems are comparable to the "minimum mass" models of the solar system's protoplanetary disk (Lissauer 1987).

3.2. The Companions

How does the fact that most of the well studied young stars in Taurus have companions affect our understanding of their evolution? In Taurus, the companions we have identified radiate about 10% of the K-band total flux of the systems; in the visual the fraction must be much less. Properties such as spectral type and Hayashi track age of the component brighter in visual light are probably reliable. Inferences based on the IR flux, however, where the companions are brighter, are suspect. In the near IR, where photospheric emission dominates and disk emission is weak, the presence of companions complicates interpretation of the

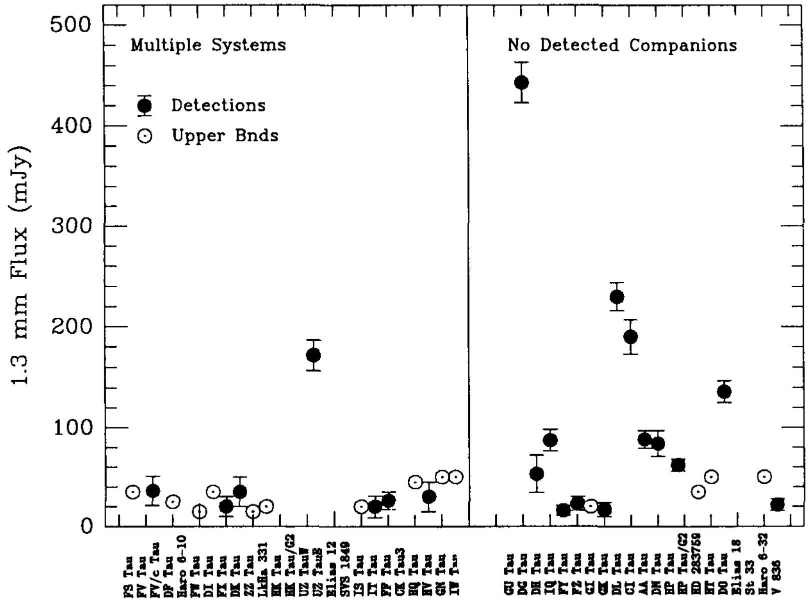

FIGURE 3. Same as Figure 2 but showing the 1.3 mm flux density (BSCG).

total system colors. For example, anomalies which might be interpreted in terms of circumstellar disk emission or spots, may be attributable to companions. At the longer IR wavelengths dusty disks can be very luminous. Without resolving a system it cannot be assumed that an IR-luminous disk is associated with the visually luminous star. The T Tau and Haro 6-10 binaries are extreme examples. In the former, the IR companion which is undetectable in the visible, radiates about half the total luminosity of the system (Ghez *et al.* 1991). In Haro 6-10 the IR-discovered companion probably dominates the system luminosity (Leinert & Haas 1989). (Which component then is the "primary"?) The evolutionary status of the IR-luminous companions is completely unknown.

Angularly resolved spectral energy distributions of the multiple systems are required to unravel the luminosity of the components. The observations are within reach by speckle interferometry and direct imaging at sites with excellent image quality in the IR. Angularly resolved spectra are needed to probe the source of luminosity in the IR-luminous companions (star or disk?) and to investigate disk evolution in the binaries. In a binary system classified as cTT, are both stars cTTs? If not, why did one disk evolve more rapidly than the other? If both, how does this affect our understanding of the activity previously attributed to the visible stars? Instrumentation to enable an attack on these questions is becoming available.

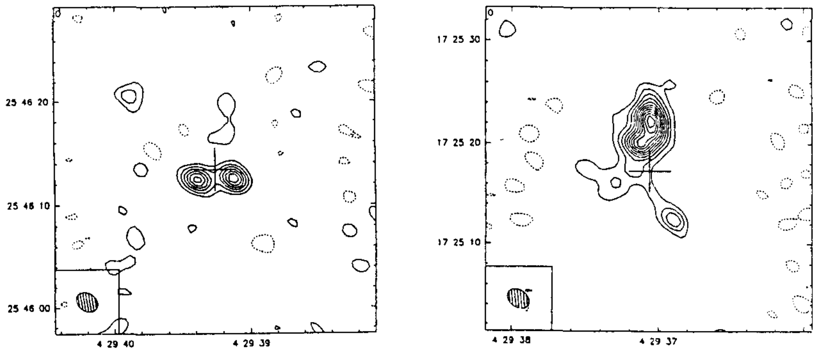

FIGURE 4. *Left:* **The triple UZ Tau imaged with the IRAM interferometer at 2.6 mm. The unresolved radio sources coincide with UZ Tau W (the binary) and UZ Tau E. The inset shows the $\sim 2''.4 \times 1''.8$ half power size of the synthesized beam.** ***Right:*** **Same but for the quadruple GG Tau. The peak of the resolved emission coincides with the GG Tau binary and the secondary peak $\sim 10''$ to the south coincides with the optically brighter member of the GG Tau/c binary.**

3.3. Binary Angular Momentum

The young stars in Taurus are believed to have formed in dense elongated molecular cloud cores such as those described by Benson & Myers (1989). Goodman *et al.* (1992) succeeded in measuring the rotation of a large number of cloud cores in Taurus and other star–forming regions. Figure 5 compares their specific angular momentum with that of the young star binaries in our sample (calculated by assuming two 0.5 $\mathcal{M}_\odot$ stars in circular orbits).

The lowest specific angular momenta of the molecular cloud cores adjoin the young star binaries with the highest values. In reality, the two distributions surely overlap. The young star distribution deliberately excludes the widely spaced systems (see §2) which have the highest angular momenta. Measurement of the rotation of slowly rotating clouds is very difficult so slow rotators are probably not represented in Figure 5.

The origin of the angular momenta of the binaries seems to be in the rotation of the molecular cloud cores. The orbital motion of the stars in a binary represents nearly all the angular momentum of the system. The typical angular momentum, 10^{53} to 10^{54} gm cm^2 s^{-1}, is more than order of magnitude greater than that of the extensive circumstellar disks (BSCG), and about three orders of magnitude greater than the rotational momenta of the T Tauri stars (Hartmann *et al.* 1986). It seems that molecular cloud cores collapsing to form stars solve their angular momentum problem by forming binaries.

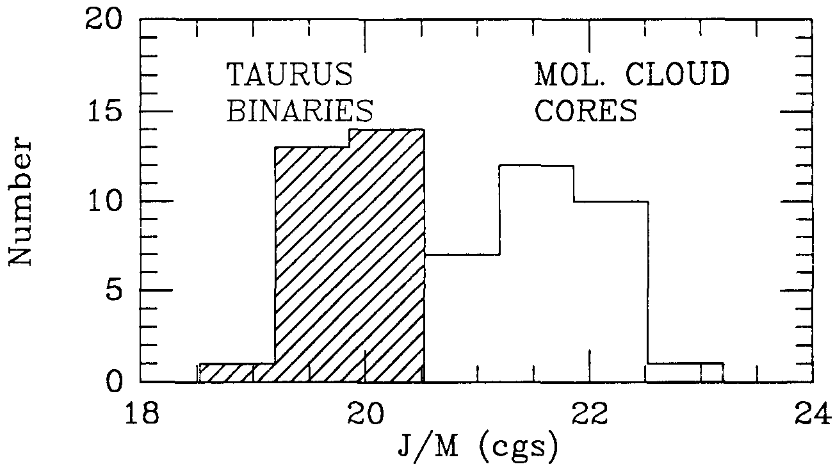

FIGURE 5. **The specific angular momentum distribution of the young star binaries (same sample as in Figure 1 but binned in intervals twice as large and given in terms of number in each bin) compared with that of the molecular cloud cores studied by Goodman *et al.* (1992).**

4. FUTURE PROSPECTS

The transition from the discovery phase to the study of the astrophysics of young star binaries has begun. Montmerle & André (1989) pointed out that young stars and their associated disks have lives of their own because disk and stellar evolution are essentially decoupled. Binaries provide the perfect opportunity to study disk evolution because the stars are coeval, as similar as we will find in astronomy, differing only in their mass.

Measurement of the mass of the components must be a fundamental goal of the study of the young star binaries. There are still no pre-main sequence stars with reliably known masses. This is an embarrasment because it means that calculations of pre-ms evolution are essentially uncalibrated. Masses of the young stars will provide an assumption–free estimate of the initial mass function. The astrometric capabilities of the HST and the planned IR interferometers suggest the prospects are good.

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6. REFERENCES

Abt, H.A. 1983, *ARA&A*, **21**, 343

Adams, F.C., Lada, C.J., & Shu, F.H. 1987, *ApJ*, **312**, 788

Basri, G. and Bertout, C. 1989, *ApJ*, **341**, 340

Beckwith, S.V.W., Sargent, A.I, Chini, R.S., & Güsten, R. 1990, *AJ*, **99**, 924 (BSCG)

Benson, P.J. & Myers, P.C. 1989, *ApJS*, **71**, 89

Binney, J. & Tremaine S. 1987, *Galactic Dynamics*, (Princeton Univ. Press, Princeton)

Chen, W.P., Howell, R.R., Simon, M., & Benson, J.A. 1992, *ApJ*, **387**, L43

Chen, W.P. 1992, this Colloquium

Duquennoy, A. & Mayor, M. 1991, *A&A*, **248**, 485 (DM)

Dyck, H.M., Simon, T., & Zuckerman, B. 1982, *ApJ*, **255**, L103

Ghez, A., Neugebauer, G., Gorham, P.W., Haniff, C.A., Kulkarni, S.R., & Matthews, K. 1991, *AJ*, **102**, 2070

Ghez, A., Neugebauer, G., Matthew, K., Beckwith, S., Koresko, C., & Walter,F., 1992, this volume

Goodman, A.A., Benson, P.J., Fuller, G.A., & Myers, P.C. 1992, *ApJ*, submitted

Hartmann l., Hewett, R., Stahler, S. & Mathieu, R.D., 1986, *ApJ*, **309**, 275

Herbig, G., & Bell, K.R. 1988, *Lick. Obs. Bull.*, No. 1111

Lada, C.J. 1991, in *The Physics of Star Formation and Early Stellar Evolution*, eds. C.J. Lada and N.K. Kylafis (Kluwer, Dordrecht) p. 329

Leinert, Ch., Haas, M., Richichi, A., Zinnecker, H., & Mundt, R. 1991, *A&A*, **250**, 407

Leinert, Ch. & Haas, M. 1989, *ApJ*, **342**, L39

Leinert, Ch., Weitzel, N., Lenzen, R., Haas, M., Zinnecker, H., Christou, J., Ridgway, S., Jameson, R., & Richichi, A. 1992, this volume

Lissauer, J.J. 1987, *Icarus*, **69**, 249

Mathieu, R.D. 1992, this volume

Mathieu, R.D., Walter, F.M., & Myers, P.C. 1989, *AJ*, **98**, 987

Mundt, R., Walter, F.M., Feigelson, E.D., Finkenzeller, U., Herbig, G.H., & Odell, A.P. 1983, *ApJ*, **269**, 229

Simon, M., Chen, W.P., Howell, R.R., Benson, J.A., & Slowik, D. 1992, *ApJ*, **384**, 212

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

Simon, M., & Guilloteau, S. 1992, *ApJ*, submitted

Zinnecker, H. & Reipurth, B. 1992, this Colloquium