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# Pre-Main Sequence Binaries: The ESO Imaging Survey

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**ABSTRACT: We have observed a complete sample of southern Hα emission line pre-main sequence (PMS) stars associated with the nearby dark clouds Chamaeleon and Ophiuchus in an effort to detect binary companions. We have used the high resolution CCD camera SUSI (0.13″ /pixel) at the ESO 3.5m New Technology Telescope (NTT). The observations were carried out in the Gunn *z* filter (0.95μ). As a result, we have discovered 28 companions out of 160 objects surveyed in the range of angular separation 0″.5 – 10″ . We present histograms of semi-major axes and of brightness ratios of these PMS binaries. Taking small incompleteness corrections into account, the frequency of PMS binaries with semi-major axes in the range 100–1500 AU is 20%, while it is only 15% in same range for solar-type Main Sequence (MS) stars. Extrapolation yields a total PMS binary frequency of 70%. Evolutionary and environmental implications are briefly discussed.**

## 1. MOTIVATION AND AIMS

More than half (60%) of all solar-type main-sequence stars are members of binary or multiple systems (Duquennoy & Mayor 1991, Herczeg 1984, Halbwachs 1983, Abt 1983, Batten 1973, Heintz 1969). Given that most stars are binaries, understanding star formation processes means to a large extent understanding the processes of binary star formation. Observations of PMS binaries may hold the key to reveal these processes. Moreover PMS binaries, in particular if the components are spatially resolved, allow us to study differential PMS stellar and circumstellar evolution (e.g., Zinnecker 1989, Moneti & Zinnecker 1991).

Among the crucial questions to be answered for PMS binaries are the following:

1. What is the global frequency of PMS binaries?
2. What is the distribution of component separations?
3. What is the distribution of component mass–ratios?
4. Are these PMS binary properties the same as on the Main–Sequence?
5. Is the multiplicity different in different clouds?

Here we present results of a red CCD survey of low–mass PMS binaries in two southern star forming regions (Chamaeleon and Ophiuchus), in an attempt to answer some of the above questions. A full account of the whole data set as well as further discussion will be given in Reipurth & Zinnecker (1992).

## 2. TECHNICAL DETAILS

We obtained our data during two nights in April 1991 at La Silla, Chile with the ESO New Technology Telescope (NTT). The observations were made with SUSI (SUperb Seeing Instrument), which consists of a direct camera with a Tektronix TEK1024M CCD chip. This chip has $1024 \times 1024$ pixels and the scale was $0\farcs13$ pixel$^{-1}$, giving a field size of about $130'' \times 130''$. In order to reduce the read–out time, only the central $75'' \times 75''$ of the whole field were extracted. A deep–red Gunn $z$ filter was employed to facilitate the detection of very red companions. This filter cuts on at $0.85\mu$ and is open–ended so that the cut off is set by the CCD's diminishing responsive quantum efficiency (RQE) at $1.1\mu$. Therefore the effective observing wavelength is between $0.9\mu$ and $1.0\mu$. The exposure times ranged between 1 and 30 seconds, suitable for most objects ($V$ = 12–15 mag). The average seeing was $0\farcs8$ (FWHM) in the first night and $0\farcs7$ in the second. As all our data were acquired with the same equipment and under rather similar conditions, it represents quite a homogeneous data set. Finally, we emphasize that our sample is not a magnitude–limited sample.

## 3. SELECTION CRITERIA

In order to observe a complete sample of nearby PMS stars associated with dark clouds, we have selected H$\alpha$ emission line objects in Chamaeleon and Ophiuchus from the lists of Schwartz (1977, 1991) and Wilking *et al.* (1987), respectively. These objects were identified on H$\alpha$ prism plates and are good candidates for young stars. The list of Schwartz (1991), including additional members from Whittet *et al.* (1987), contains 55 visible PMS objects in Chamaeleon I and 19 objects in Chamaeleon II. The list of Wilking *et al.* contains 86 H$\alpha$ objects. We have imaged all these objects to search for multiplicity (duplicity). Here we assume that H$\alpha$ emission does not *a priori* prejudice for or against binarity. This assumption is justified *a posteriori* by the observational result that weak line and classical T Tauri stars have a similar incidence of duplicity (see Ghez *et al.* and Leinert *et al.*, this Colloquium).

In order to ensure that our sample consists only of physical binaries, we limited the maximum separation between components to $10''$ (about 1500 AU at the distance of the nearby dark clouds). With increasing projected distance the probability to observe optical instead of physical pairs increases (contamination by foreground or background field stars). The foreground contamination can easily be estimated. With a stellar density of 0.1 stars/pc$^3$ in the solar neighbourhood, the probability of any foreground star lying within a cone of depth 150pc and a base radius of $10''$ is 0.1%, which is negligibly small.

Background contamination by G and K type giants can be estimated to be of the order of 1%. This estimate ignores the shielding due to extinction provided by the dark clouds at $1\mu$ (note that at $2.2\mu$ shielding is less effective).

## 4. DETECTION LIMITS

The lower limit for detection was set by the seeing. Figure 1 illustrates a simulation on detectability of companions with separations equal to the seeing. We

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conclude that the minimum distance to detect all weak companions is 1″ so that the binary statistics does not suffer from incompleteness for $s \geq 1''$ .

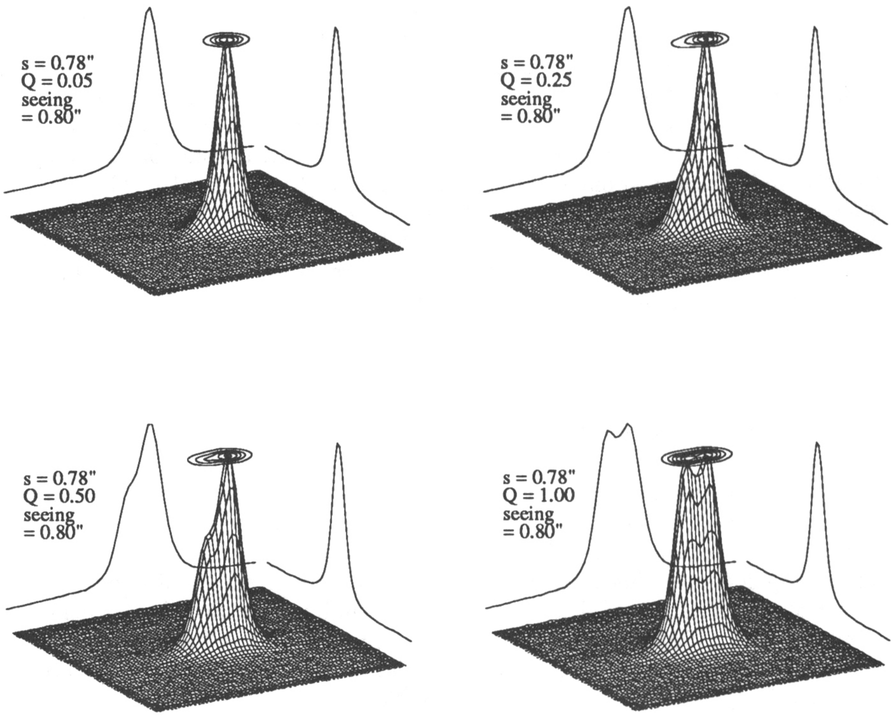


**FIGURE 1. Example of a computer simulation on the detectability of faint companions. s is the projected separation and Q is the brightness ratio. The FWHM of the seeing was 0″.8 and the CCD image scale was 0″.13/pixel. From this particular simulation we deduce that with binary separations equal to the seeing the brightness ratio must be at least 0.25 for companions to be detected by direct imaging.**

## 5. EXAMPLES OF PMS BINARIES

Here we present images to illustrate some examples of the observed PMS binaries and the very good image quality of the NTT. Figure 2 shows a mosaic of Chamaeleon binaries, Figure 3 a mosaic of Ophiuchus binaries. The parameters (projected separations s and light ratios Q) are indicated in each frame and listed in Tables 1 and 2. Note the sub-arcsec binaries Sz59 and WSB3. Further sub-arcsec PMS binaries, not shown, include Sz20 (s=0″.82), Sz24 (s=0″.69), and WSB11 (s=0″.53). Note that none of the images is sharpened by any image restoration or deconvolution technique.

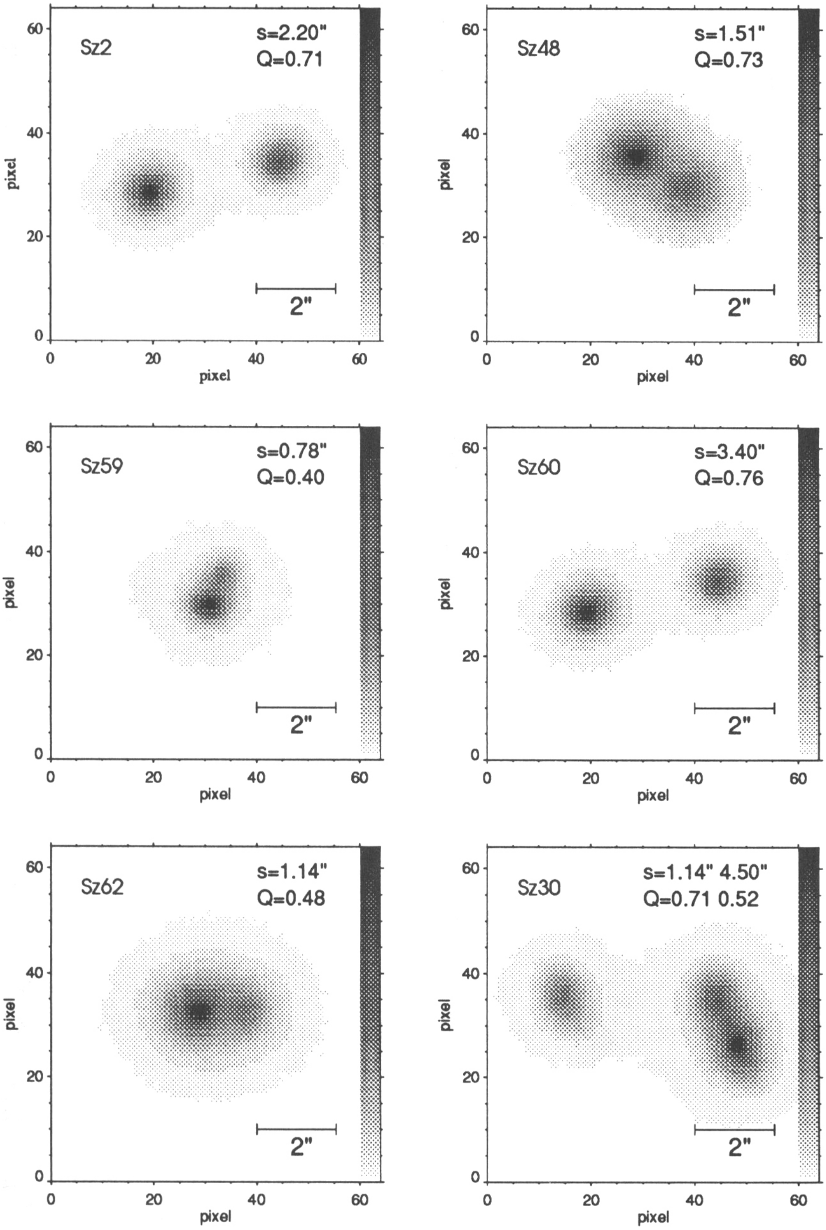


**FIGURE 2.** PMS binaries in Chamaeleon I and II. North is up and East is to the left.

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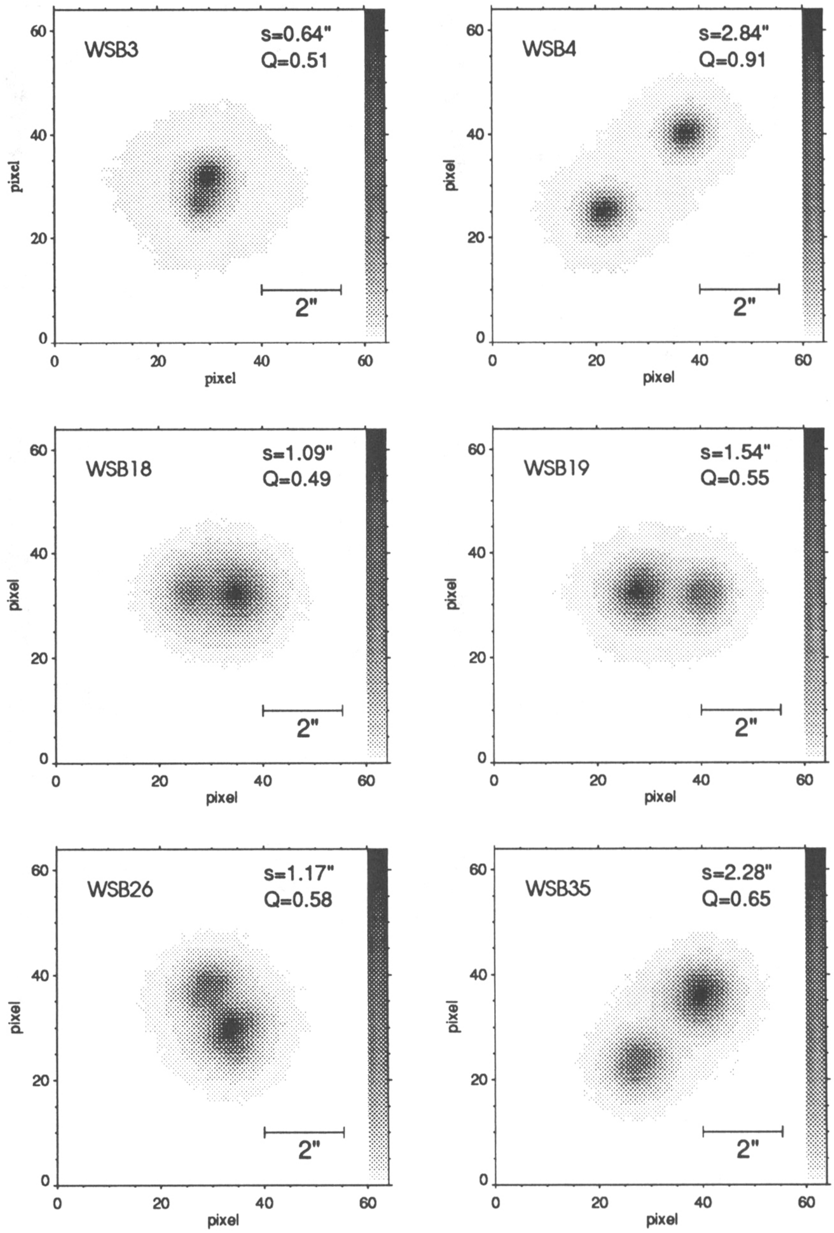


**FIGURE 3.** PMS binaries in Ophiuchus. North is up and East is to the left.

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## 6. DISTRIBUTION OF PROJECTED SEPARATIONS

Figure 4 shows the distribution of projected separations which are approximately equal to the semi-major axes (e.g., Halbwachs 1983). The decline for separations less than 200 AU is due to the incompleteness. The dashed line is an approximative fit to the data yielding

$$f(a) \sim \exp\left\{-\frac{\log^2(a/30AU)}{2 \times 1.0^2}\right\}$$

This log–normal shape is similar to the MS distribution proposed by Duquennoy & Mayor (1991, hereafter D&M) for their nearby G–dwarf sample; see Figure 5. However the width of our PMS distribution is somewhat narrower than their MS distribution (D&M: $\sigma_{\log a} = 1.5$). We note that our fit is derived on the constraint that the position of the maximum of our distribution (30 AU) and their distribution is the same (30 AU corresponds to their 180 yr for the median period, assuming $\mathcal{M}_1 + \mathcal{M}_2 = 1.2\ \mathcal{M}_\odot$). The hatched areas in Figure 4 and Figure 5 correspond to each other, enabling a comparison between the MS and PMS binaries in the same range of separation. While D&M find a total binary frequency of 60%, extrapolation of our curve given in Figure 4 suggests 70%, although fits yielding 80% are also possible.

This could suggest that there is evolution of the semi-major axis from PMS binaries to MS binaries. On the other hand, the bulk of MS binaries with which we compare our PMS statistics may not originate from loose T associations like Chamaeleon and Ophiuchus but from initially denser OB associations like Orion where most low–mass stars appear to be born (Miller & Scalo 1978). If so, the differences between MS and PMS binary properties that we have encountered here might be a hint that denser systems of stars such as OB clusters and OB associations form fewer binary stars. We additionally studied the distribution of brightness ratios (see Figure 6 and Tables 1 and 2).

## 7. FUTURE PROSPECTS

In the near future we will perform multi-wavelength photometry of the resolved components in the optical and near infrared; we will also study the dust continuum emission of the systems in the mm/submm regime. This will give us more information on circumstellar disks. By resolving the component spectral energy distributions, we hope to derive the component luminosities By disentangling the component spectra, we hope to obtain the individual effective temperatures. Then we can place the objects into the Hertzsprung–Russell diagram and calibrate the masses and ages more accurately than today. One particular point will be to investigate in detail the differences between 'naked' and 'dressed' T Tauri binaries. Such data may enable us to discriminate PMS stellar evolution from PMS circumstellar evolution, especially when the ESO–VLT becomes operational.

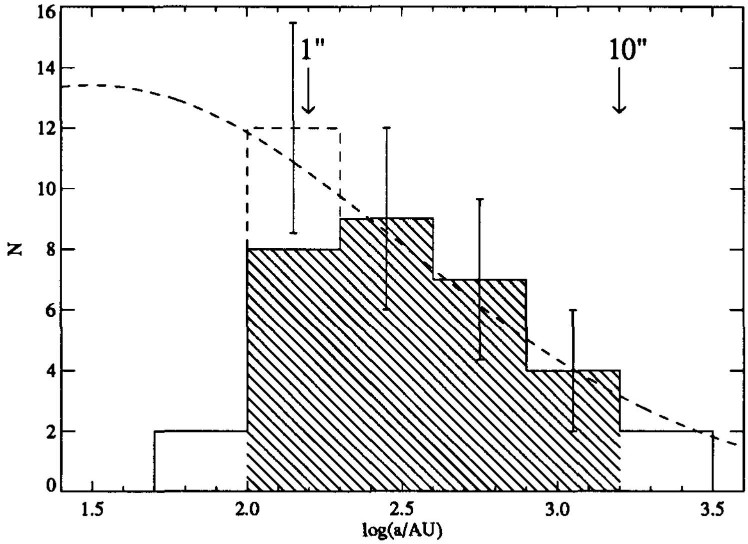


**FIGURE 4.** Distribution of semi-major axes for our PMS binaries

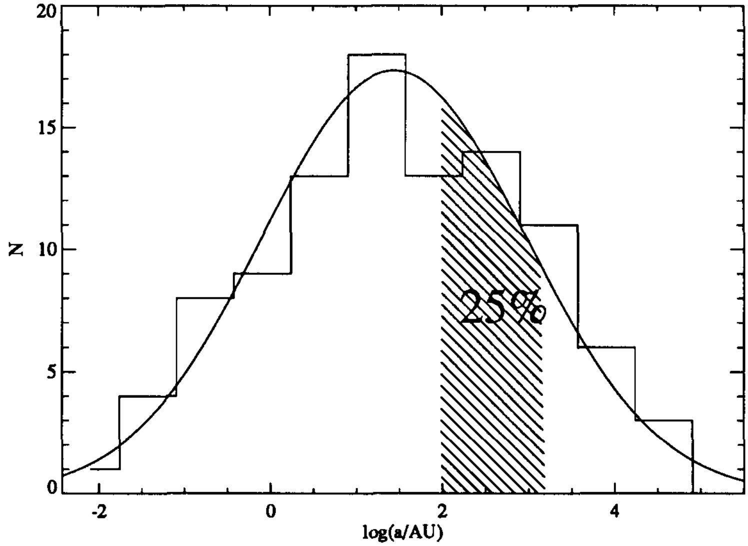


**FIGURE 5.** Distribution of semi-major axes for MS binaries, after Duquennoy & Mayor (1991), assuming $\mathcal{M}_1 + \mathcal{M}_2 = 1.2\ \mathcal{M}_\odot$.

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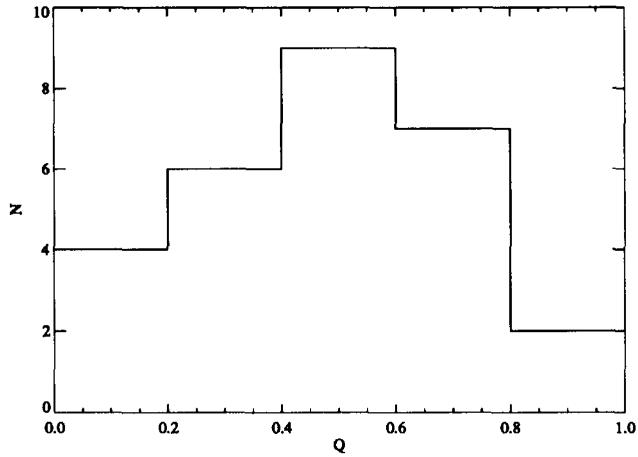


**FIGURE 6.** Distribution of brightness ratios Q for PMS binaries in Chamaeleon I and II and Ophiuchus (see Tables 1 and 2)

## 8. CONCLUSIONS

1. The frequency of PMS binaries in the semi-major axes range 100–1500 AU is 20%.
2. Extrapolation predicts a total PMS binary frequency of 70–80%, slightly higher than for solar-type Main Sequence stars.
3. The majority of field MS star binaries observed in the solar neighbourhood may not originate from T associations but from OB associations.

**TABLE 1.** Chamaeleon I and II binaries.

| name | Sz2 | Sz15 | Sz19 | Sz20 | Sz24 | Sz30 | | Sz41 |
|---|---|---|---|---|---|---|---|---|
| s in ″ | 2.2 | 10.6 | 4.6 | 0.82 | 0.69 | 1.1 | 4.5 | 2.0 |
| Q | 0.58 | 0.14 | 0.23 | 0.68 | 0.72 | 0.72 | 0.52 | 0.10 |

| name | SZ Cha | TZ Cha | Glass I | Sz48 | Sz59 | Sz60 | Sz62 |
|---|---|---|---|---|---|---|---|
| s in ″ | 5.1 | 6.8 | 2.4 | 1.5 | 0.78 | 3.4 | 1.14 |
| Q | sat. | 0.23 | 0.59 | 0.73 | 0.38 | 0.84 | 0.48 |

**TABLE 2.** Ophiuchus binaries.

| WSB | 3 | 4 | 11 | 18 | 19 | 20 | 26 |
|---|---|---|---|---|---|---|---|
| s in ″ | 0.63 | 2.8 | 0.53 | 1.09 | 1.54 | <1.0 | 1.17 |
| Q | 0.50 | 0.91 | 0.73 | 0.49 | 0.55 | sat. | 0.58 |

| WSB | 28 | 30 | 35 | 41–42 | | 45–46 | 71 | 83 |
|---|---|---|---|---|---|---|---|---|
| s in ″ | 5.1 | 2.2 | 2.3 | 5.2 | 10.3 | 10.3 | 3.7 | 10.1 |
| Q | 0.06 | sat. | 0.65 | 0.34 | 1.60 | 2.30 | sat. | 0.99 |

## 9. ACKNOWLEDGMENTS

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## 11. DISCUSSION

**ABT:** Can you say anything about the distribution of magnitude differences? Is it similar to a van Rhijn distribution?

**ZINNECKER:** The distribution of the flux ratio of the binary components is shown in Figure 6. Converting flux ratios into mass ratios is a tricky business for PMS binaries, because the flux ratios are time–dependent. Using a simple–minded theory of PMS evolution (Zinnecker & McCaughrean 1991, *Mem. S. A.*

*It.*, **62**, 761), we have calculated mass–ratios from light–ratios; at face value it appears that there is no evidence for a preponderance of extreme mass–ratios as expected for 'random pairing' according to a van Rhijn distribution. However, there is a some fraction of the PMS binaries for which the images suffer from saturation effects, so that the final answer cannot be given at present.

**LEINERT:** You mentioned a mass–luminosity relation of $L \sim \mathcal{M}^{1.6}$ on the Hayashi track. To what extent would this relation be independent of the wavelength of observation?

**ZINNECKER:** In the Hayashi phase, low–mass stars of mass $\mathcal{M}$ evolve almost vertically in the HR diagram ($T_{eff} \approx const$, $T_{eff} \sim \mathcal{M}^{0.2}$). As the effective temperature of the late–type T Tauri stars is well–matched to our observing wavelength ($\lambda \approx 1\mu$), the $L \sim \mathcal{M}^{1.6}$ luminosity–mass ($L$–$\mathcal{M}$) relation, although derived in terms of bolometric luminosity, is approximately valid. Application of this PMS $L$–$\mathcal{M}$ relation at shorter wavelengths (e.g., $B$ or $V$) requires more caution. At longer wavelengths the exponent in our power law decreases. In the K band, i.e. closer to the Rayleigh–Jeans regime, we have a luminosity–mass relation of $L \sim \mathcal{M}^{1.2}$, provided that circumstellar dust emission does not contribute significantly to total flux. Therefore, for coeval binary components, we may use $L_2/L_1 = (\mathcal{M}_2/\mathcal{M}_1)^\beta$ with $\beta = 1.6$ near $1\mu$ and $\beta = 1.2$ near $2\mu$.

**CHEN:** In the computer simulations to assess detection limits, such as $\geq 1''$ and 10% light ratio, what is the combined flux (magnitude) assumed?

**ZINNECKER:** If I understand the question correctly, you are concerned about the signal–to–noise ratio assumed in our simulations. Well, we have used real stars in the images to construct our point spread function used to convolve the two delta functions representing a particular binary (i.e. with a particular separation and a particular brightness ratio). There is always a sufficient number of counts, both in the simulated and in the real images, to ensure good signal–to–noise ratios, even in the wings of the point spread function.

**MAZEH:** What is the separation ratio for the triplets that you have found? A 1:4 ratio might not be stable, especially because the present separation might not be the minimum separation ratio.

**ZINNECKER:** I agree. It is conceivable that the triple system Sz30, where the projected separations are $1''.1$ and $4''.5$ (see Figure 2), may evolve from the present configuration into a truly hierarchical system. However, we don't know to what extent the projected separations reflect the true separations. Actually we have found no more triples of a kind similar to Sz30 (except a few in the Taurus region), and this may be consistent with rapid decay of Trapezium type triples into hierarchical triples where we can no longer resolve the close pair by direct imaging.