

Binary fraction in low-mass star forming regions: a reexamination of the possible excesses and implications

G. Duchêne

Laboratoire d’Astrophysique, Observatoire de Grenoble, Université Joseph Fourier, B.P. 53, F-38041 Grenoble Cedex 9, France

Received 23 July 1998 / Accepted 27 October 1998

Abstract. Various surveys of low-mass binaries in star forming regions have been performed in recent years. They reached opposite conclusions concerning possible binary excesses in some of these associations. I develop a consistent method to reanalyze all these studies, so that I can compare all data consistently, and understand the previous findings. I also report the detection of five new companions to Taurus members.

It appears that binary fraction in Taurus exceeds the main sequence value by a factor of 1.7 in the range 4–2000 AU. The companion star fraction in this separation range is the same as the *overall* main sequence fraction. Ophiuchus, Chameleon, and possibly Lupus show similar excesses, although with lower confidence levels. Binaries in Ophiuchus seem to have larger flux ratios (towards faint companions) than in Taurus.

It appears very unlikely that all very young star forming regions have binary excesses. The binary fraction seems to be established after ~ 1 Myr, but the precise nature of the difference between various regions is still unclear (overall binary fraction, orbital period distribution). It is not currently possible to put constraints on the binary formation models: higher angular resolution and larger sample sizes will be required.

Key words: stars: binaries: general – stars: pre-main sequence – stars: statistics

1. Introduction

Surveys for low-mass main sequence (MS) binaries have pointed out that multiple systems are numerous (53% for G dwarfs, Duquennoy & Mayor 1991, hereafter DM). Only three years after DM’s paper, it was discovered that the Taurus star forming region (SFR) had a very large number of binaries (Leinert et al. 1993, Ghez et al. 1993), many more than expected, while the Orion Trapezium was “normal”, as far as its binary fraction is concerned (Prosser et al. 1994). Why is there such a difference between the two best studied SFR? Taurus or the Trapezium could be exceptions, but it could also give strong constraints on binary formation models.

What about the other well-known SFRs? Some studies have pointed out binary excesses in Ophiuchus, Chameleon, Lupus

and even in the Trapezium cluster (Reipurth & Zinnecker 1993, Ghez et al. 1997, Padgett et al. 1997), but some authors have also concluded that there was no excess in the same regions (Simon et al. 1995, Brandner et al. 1996, Petr et al. 1998). Based on some of these results, Ghez et al. (1993) and Patience et al. (1998) have proposed that the binary fraction was decreasing with time, from high excess to MS values, while Bouvier et al. (1997) propose that the main factor driving the binary’s properties are the physical condition of the parent cloud.

This paper intends to clarify previous results by analyzing all available sets of data with a single consistent method allowing for meaningful comparisons (Sects. 2 and 3). I also review the results on the older Hyades and Pleiades stars (Patience et al. 1998, Bouvier et al. 1997). Finally, an attempt to find a global trend will be presented (Sect. 4).

2. Method and hypotheses

The main purpose of this work is to allow for direct comparisons between all previous papers. Up to now, there are about as many observational techniques as papers, and each has its own limitations. Here, I will compare the results for each SFR to that of the MS, and *then*, a comparison of the results with each other will be meaningful; this method slightly increases the error bars by accounting twice for the MS uncertainties, but it is usually a small value.

As the largest low-mass MS survey is DM, only stars later than F7 on the MS will be considered here. This corresponds to an early-G spectral type for a 1 Myr star. Thus, A and F stars will be excluded from all SFR surveys. To take into account all companions, I calculate the *companion star fraction*, which is the number of companions per primary ($csf = \frac{B+2T+3Q}{S+B+T+Q}$, where S , B , T and Q are the numbers of single, binary, triple and quadruple systems; see Patience et al. 1998), instead of the *binary fraction* ($bf = \frac{B+T+Q}{S+B+T+Q}$); also, DM only estimate csf . Finally, for each study, I tried to choose a separation range over which the sensitivity is high enough so that all companions can be found. These ranges are presented in Appendix A.

The intuitive way of comparing all clusters is to select a wide separation range and to count the number of binaries in this range for each region. Due to the different distances involved, however, the common separation range is narrow and leads to

Table 1. Comparison of star forming regions and MS samples regarding the companion star fraction.

	N_{obs}	N_{comp}	$csf(1\sigma)$	$csf_{MS}(1\sigma)$	$\log \frac{csf}{csf_{MS}}$	statistical	ref.	distance	references
			[%]	[%]		significance		[pc]	for distance
PMS associations and clusters									
Tau-Aur	117	67.1	57(8)	34(4)	0.22±0.08	2.8σ	1,2,3,4	140	Elias (1978)
Oph	114	35.0	31(5)	20(3)	0.19±0.10	1.9σ	2,3,4	160	Chini (1981)
Oph	95	24.6	26(5)	13(2)	0.30±0.11	2.7σ	2,4	–	–
Trapez.	291	31	11(2)	14(2)	-0.10±0.10	1.0σ	5	450	5,6,7 ^a
Trapez.	34	2	6(4)	8(1)	-0.12±0.29	$< 1\sigma$	6	–	–
outer Trapez.	50	6.6	13(5)	10(1)	0.11±0.17	$< 1\sigma$	7	–	–
NGCs Ori	99	12.4	13(4)	10(1)	0.10±0.15	$< 1\sigma$	7	–	–
Cha I	85	19.2	23(6)	16(2)	0.16±0.13	1.2σ	4,8,9	140	Schwartz (1991)
Cha II	23	5.0	22(10)	13(2)	0.23±0.21	1.1σ	4,8,9	200	Hughes & Hartigan (1992)
Lup	61	11.1	18(6)	15(2)	0.08±0.16	$< 1\sigma$	4,8	150	Krautter (1991)
CrA	10	3.0	30(17)	11(2)	0.44±0.26	1.6σ	4,8	130	Marraco & Rydgren (1981)
ROSAT sources									
Tau-Aur	68.6	25.1	37(12)	26(4)	0.15±0.16	$< 1\sigma$	10	140	<i>assumed</i>
Cha	86.8	4.4	5(3)	7.5(1)	-0.21±0.31	$< 1\sigma$	9	140	–
Sco-Lup	64.4	7.5	12(7)	7.5(1)	0.20±0.26	$< 1\sigma$	9	150	–
Older open clusters									
Pleiades	144	40.8	28(6)	27(3)	0.02±0.10	$< 1\sigma$	11	130	11
Hyades	97	17.8	18(5)	16(2)	0.05±0.13	$< 1\sigma$	12	46.3	Perryman et al. (1997)

^a the distance to the Orion complex is an average value.

References: 1 – Leinert et al. (1993), 2 – Ghez et al. (1993), 3 – Simon et al. (1995), 4 – Reipurth & Zinnecker (1993), 5 – Prosser et al. (1994), 6 – Petr et al. (1998), 7 – Padgett et al. (1997), 8 – Ghez et al. (1997), 9 – Brandner et al. (1996), 10 – Köhler & Leinert (1998), 11 – Bouvier et al. (1997), 12 – Patience et al. (1998).

small numbers of companions. The statistical significance of the results is thus quite low.

The most powerful comparison of all clusters is obtained by comparing each csf to that of the MS in the same separation range; each SFR, however, has been surveyed in different ranges by different studies. I calculate the total csf of the SFR from all surveys and, concerning the MS value, I estimate it in the same separation range for each survey (by integration of the analytic period distribution given by DM) and I average these values using the number of targets as a weight. In Table 1, csf_{MS} is the averaged MS value to be compared with the csf in the 4th column. N_{obs} is the total number of targets.

Two non critical assumptions are made: the total system mass is $1 M_{\odot}$ and the actual semi major-axis a is linked to the apparent separation ρ via $\log a = \log \rho + 0.1$ (Reipurth & Zinnecker 1993); reasonable changes in these parameters does not change the csf by more than 1%.

Also, some corrections have been applied in some cases (see Sect. 3) to take into account poor and non homogeneous dynamic range or selection biases. Concerning the dynamic range, it has to be large enough to detect binaries with mass ratio $q = 0.1^1$, which is the lower limit of DM’s survey (they cannot observe binaries with $q < 0.3$ for all targets, but they estimate a correction down to this limit). Using Baraffe et al. (1998)’s mass-luminosity relation at 2 Myr, it appears that such a mass

ratio is equivalent to $\Delta K = 2.9$, $\Delta I = 3.6$ and $\Delta V = 4.3$ mag at this age. These limits are reached in all pre-main sequence (PMS) surveys except when a speckle technique is used (these studies are limited to absolute magnitude and not flux ratios, so that some stars were observed with worse sensitivities); in this case, a correction has been applied to take into account the strongly non uniform sensitivity of the survey. All companions with $q < 0.1$ were excluded from the statistics to allow significant comparisons with DM; this has not been done in the previous studies. Determining mass ratios from flux ratios is somewhat hazardous for PMS stars because of possible infrared excesses and different ages, but I assume that this does not lead to any systematic bias. In older clusters, as the mass-luminosity relation steepens with increasing time, the incompleteness correction becomes important, and cannot be neglected for the Hyades and the Pleiades.

3. Details of the calculation by clusters

Table 1 presents all the results developed in this section. For each SFR, I explain what has been done (if anything) after simply collecting the data from the literature.

3.1. Taurus

The speckle results of Ghez et al. (1993) does not need any correction, as all stars were observed with a large enough dynamic range. The lunar occultation survey of Simon et al. (1995), also

¹ for systems with $M_1 \sim 0.5 M_{\odot}$, this limit would be well within the brown dwarfs domain and this could modify the results.

reporting results from Richichi et al. (1994), however, suffers from a poor dynamic range, and I applied a correction similar to Ghez et al. (1993). This method takes into account the fact that all stars were not surveyed with the same dynamic range: the targets are binned by relative brightness of approximately equal magnitude steps, and the number of detected binaries in each bin is rescaled to the total number of targets. Here, it adds ~ 4 companions. The final uncertainties are estimated from Poisson statistics on the *observed* number of companions and corrected for *each flux ratio bin* (this method gives a conservative estimation of the error), and not on the final, corrected number of companions.

Recent *HST* and adaptive optics images of the binary system HK Tau have revealed a circumstellar disk around the secondary (Stapelfeldt et al. 1998). As it is seen edge-on, the star is totally hidden, and we can only see scattered light. This explains why $\Delta H = 3.1$ mag while the mass ratio is estimated to be about $q \sim 0.5$ from the spectral types of both components (Stapelfeldt et al.). This system has not been excluded here. Otherwise, three faint companions had to be excluded from the Leinert et al. (1993) survey. In some cases, Leinert et al. (1993) report the imaging results from Reipurth & Zinnecker (1993) without further high angular resolution observations. New images with adaptive optics have revealed new subarcseconds companions to four of these systems (see Appendix B), which were added in this study.

3.2. Ophiuchus

Both Ghez et al. (1993) and Simon et al. (1995) results were corrected for incompleteness with the same method as in Taurus, leading to an estimation of ~ 4 missed companions.

3.3. Orion clusters

In the Trapezium, the results from Petr et al. (1998) are uncorrected while Prosser et al. (1994) evaluated the number of unbound pairs (chance projection by crowded fields). Here, I use their final results, where these non physical pairs have been excluded.

In their study of the outer parts of the Trapezium and of NGC 2024, 2068 and 2071, Padgett et al. (1997) evaluated the probability for each companion to be a real companion. As they find high *individual* probabilities, no correction is applied in the study. The probability for *all companions* to be bound, however, is rather small (55 and 62% in the NGC clusters and the Trapezium respectively), indicating that a correction is actually needed. The average probabilities for each companion to be unbound are 4.0 and 6.2% in the two subsamples. This is in agreement with the averaged background companions probabilities given in Padgett et al.'s Table 3: the predicted numbers of false detections are 0.6 and 0.4 respectively. I subtracted these numbers in Table 1, as well as two companions below the $q = 0.1$ limit, with increased error bars (Poisson statistics were applied to the unbound pairs, too).

3.4. Chameleon, Lupus, Corona Australis

I applied the correction from Ghez et al. (1993, 1997) to the limited subsample of low-mass stars in Ghez et al. (1997), again with increased uncertainties. The addition of the *csf* from two independent subsamples, proposed by Ghez et al., leads to the same excess ratio as the method used here.

3.5. ROSAT population

In all three SFRs, corrections for too faint companions ($q < 0.1$) and background projections are performed with the values given in Brandner et al. (1996) and Köhler & Leinert (1998). The third correction to apply is to take into account the bias induced by the X-ray selection of the targets: a binary has two sources and can thus be detected more easily in the *ROSAT* survey. I used a similar method to Brandner et al. (I assume that the X-ray flux of the secondary is independent of the primary's), but I replaced their formula for ΔN by:

$$\Delta N = \int_{0.5L_{\text{lim}}}^{L_{\text{lim}}} \rho(L_{1x}) \int_{L_{\text{lim}}-L_{1x}}^{L_{1x}} \rho^{\circ}(L_{2x}) dL_{1x} dL_{2x} \times bf$$

with $\rho^{\circ} = \frac{\rho}{\int_{L_{\text{min}}}^{L_{1x}} \rho(L) dL}$, the normalized distribution of X-ray fluxes, *i.e.* the density of probability for the secondary's flux; $L_{\text{min}} = 10^{21.5} \text{W}$ and $L_{\text{max}} = 10^{23.5} \text{W}$ are the limits of validity for the flux distribution, and L_{lim} is the sensitivity limit of the X-ray surveys in each SFR. I then applied a method similar to Brandner et al., which both modifies the sample size and the number of companions; I chose $bf = 53\%$, *i.e.* the main sequence value, but a value of 90% does not change the results in Table 1 by more than 2%. I find 9 faint, 4.3 background and 5.5 X-bias companions in Taurus; equivalent figures in Chameleon and Scorpius are respectively (0, 1.0, 1.0) and (1, 1.5, 3.0). The final number of targets is also a fractional number ($N_{\text{obs}} = N - \Delta N$). If x is the fraction of biased binaries actually detected in the separation range of a survey, then $N_{\text{comp}} = N_{\text{comp,obs}} - x \times \Delta N$. The corrections I evaluate for Chameleon and Scorpius are smaller than that of Brandner et al., because these were overestimations; in Taurus, the correction estimated in Köhler & Leinert is similar to that quoted in Tab 1. Poisson uncertainties are associated to each correction.

3.6. Pleiades

As already mentioned, a completeness correction is needed for this cluster: from Henry & McCarthy (1993), $q = 0.1$ corresponds to $\Delta K = 6$ mag, which is not reached for all separations. The assumption made by Bouvier et al. (1997) is that the DM's mass-ratio distribution can be used in the Pleiades, which seems compatible with their results. The uncertainties, however, must be increased, as Poisson statistics again apply to the observed numbers of companions (e.g., in the first bin of their Table 2, the total number of companions is 15 ± 7.5 and not 15 ± 3.9 , since they detect 4 companions).

3.7. Hyades

As in the Pleiades, a correction is needed, but it must be evaluated *and* applied only to the subsample of low-mass stars (Patience et al. 1998 evaluate the correction on the whole sample, but apply it to the low-mass stars). After excluding all stars with spectral type earlier than F7, $M > 1.25 M_{\odot}$ and evolved stars (see Tables 2, 3 and 4 in Patience et al.; all stars with no spectral type in their Table 2 are excluded here), I checked that the average detectable mass-ratio is unchanged ($q_{\min} = 0.23$). With the same correction as in the Pleiades, I estimate that 79% of the companions were detected in this survey. With a correction similar to that proposed by Patience et al., this number becomes 70%; the slight difference is due to the fact that Patience et al. do not dismiss binaries with $q < 0.1$. The 54% reported in the original study is due to the fact that a lot of higher mass stars ($M \sim 2M_{\odot}$) could hide many low-mass companions.

4. Results and implications

4.1. Binary excesses in star forming regions

As already mentioned, the binary excess is strongly significant in Taurus (99.5% confidence level), where the overall binary fraction is $\sim 90\%$ provided that the period distribution shape is the same as the MS. Actually, the binary fraction given in Table 1 is comparable to the *overall* estimated *csf* in the MS stars ($\sim 61 \pm 7\%$, DM). On the other hand, all studies of the Orion clusters (Trapezium, NGC 2024, 2068 and 2071) converge to a “normal” binary fraction. In the other SFRs, no obvious excess can be detected, with the exception of Ophiuchus which is discussed below. Although all data have been carefully analyzed, no definitive conclusions can be drawn. Angular resolution still has to be improved to increase the number of companions. The use of larger telescopes equipped with adaptive optics, however, will not solve the main problem. The low significance of the results is tightly linked to the small sample sizes: except for the Trapezium cluster, there are always less than 150 targets. Until an important embedded population is found and surveyed, it will be very difficult to increase our confidence in these results.

Reipurth & Zinnecker (1993) first proposed that there are more binaries in PMS stars than in the MS. The excess they find is not highly significant (about 1.5σ), but they use direct imaging, without high angular resolution. Their sample consists mainly in Ophiuchus, Chameleon and Lupus (213 out of 238 targets); here, combining these three regions, the excess represents a factor of 1.5, significant at the 2.6σ level (*i.e.*, a probability of 99% for these clusters to have a binary fraction different from the MS). Although each individual cluster does not contain enough stars, this is an evidence that other SFRs than Taurus have binary excesses. Actually, Ophiuchus and Chameleon both seem to have excesses comparable to Taurus. If one excludes Simon et al. (1995) data concerning Ophiuchus (see below), the excess becomes a factor of 1.6, and the significance is increased to the 2.9σ level.

Simon et al. (1995) do not find a binary excess in Ophiuchus, while in Taurus, they end with a result similar to Table 1. They

point out the fact that they give only a lower limit to the actual binary fraction, and the difference they find seems to vanish in Table 1 after averaging with the results of Ghez et al. (1993). The main difference between Simon et al. survey and all other study of Ophiuchus is that the former is sensitive to closer separations, thanks to a lunar occultation technique. This could reveal a trend for Ophiuchus to lack very close binaries ($\rho < 0.1''$, below the limit of Ghez et al. 1993 survey). However, Simon et al. find 31% of their companions below $0.1''$ in Ophiuchus and 27% in Taurus. Of course, these numbers suffer from poor statistics, but there is no evidence for a difference in the period distributions in their study. Another possibility to explain the results of Simon et al. is the difference in flux ratios in Ophiuchus and Taurus. From Ghez et al. (1993), it appears that 73% of the binaries in Taurus have $\Delta K < 1.5$ mag, while only 23% in Ophiuchus have such flux ratios (the median flux ratios in both samples are respectively $\Delta K \sim 0.8$ and ~ 1.6 mag). From a χ^2 test, the probability that the two samples are drawn randomly from the same distribution is smaller than 0.5%. The median dynamic range in Simon et al. survey is $\Delta K \sim 1.7$ mag, and it is plausible that they do not find a binary excess in Ophiuchus because they miss faint companions. The problem is then to understand why the flux ratios are different in Ophiuchus and Taurus SFRs.

The *ROSAT* population is not easy to handle: as already proposed by Köhler & Leinert (1998), the “X-sources” in Taurus are probably related to the molecular cloud since the binary excess, although not statistically significant, is rather similar to the other sources; this argument, however, is given *a fortiori*, and thus it is not very compelling. The resulting excess (a factor of 1.6) is significant at the 2.9σ confidence level. On the other hand, in Chameleon, the X-ray selected population and the rest of the cloud are different at the 1.2σ level. This is in agreement with Brandner et al. (1996), who find a 2σ difference. However, they consider it as similar and average the two results. It seems more likely that the *ROSAT* population is not entirely related to the SFR, as proposed by Neuhäuser & Brandner (1998), who find that 6 out of 7 stars observed with *HIPPARCOS* are foreground stars. In Scorpius-Lupus, finally, the excess is large, although not very significant. It is interesting to notice that, in the separation range $0.8\text{--}3''$, Brandner et al. (1996) find a very large excess in Upper-Scorpius B and a MS result in Upper-Scorpius A (which are two parts of the same SFR with different ages); the average of these two values leads to the observed excess. With high angular resolution, Brandner & Köhler (1998) proposed that the period distributions are different in the two subclusters.

In older clusters (120 and 600 Myr respectively for the Pleiades and the Hyades), no strong binary excess is detected; the excess reported by Patience et al. (1998) is due to the large correction they evaluated (see Sect. 3.7).

4.2. Implications for binary formation

As explained in Sect. 4.1, Taurus is probably not the only SFR with a large binary excess in the separation range $\approx 10\text{--}2000$ AU. Ophiuchus and Chameleon have probably similar excesses, although the results are less significant than in Taurus. On the

other hand, several very young clusters (Trapezium, NGC clusters in Orion) do not have such features. It can thus be excluded that *all* SFR have very high binary fractions at the beginning of the star formation stage: the possibility of a time evolution for all PMS associations is very unlikely, at least after ~ 1 Myr, the typical age of these SFR.

All the regions with a binary excess (Taurus, Chameleon, Ophiuchus) are loose associations: all dense clusters have binary fractions compatible with the MS. Unless the majority of the solar neighbourhood stars were formed in Taurus-like associations, it appears that the binary fraction does not evolve from the T Tauri phase to the MS. This is an evidence for the low impact of gravitational encounters in *dense* clusters after 1 Myr or so, and it is very unlikely that such interactions can affect the binary fraction in loose SFR. Furthermore, as the ratio of binaries to triple systems in PMS and MS are similar (DM, Leinert et al. 1993), it seems that disruption of high order multiples due to unstable orbits are quite rare too.

It is still unclear whether the *total binary fraction* is higher in dense clusters or if the *period distribution* is different, with more visual binaries and an overall fraction similar to the MS. In Taurus, however, the latter seems unlikely, as the number of spectroscopic binaries is not extremely low (Mathieu 1994). In any case, it seems that the binary fraction in the range $\approx 10 - 2000$ AU is established very soon in the history of star formation, probably before ~ 1 Myr. Kroupa (1995) has shown, with N -body simulations, that wide binaries may be massively disrupted in a time shorter than a few Myr, provided it is extremely dense in its very first stages (it would require $n \sim 10^5$ stars/pc³). Bate et al. (1998) find a weak evidence that wide binaries ($a \gtrsim 400$ AU) may have actually been disrupted in the Trapezium cluster. At smaller separations, however, it seems that no disruption has occurred. It is possible that all SFR start their evolution with a high binary fraction and that the dense clusters disrupt most of the widest pairs. However, it appears unlikely because no excess is found in Trapezium down to ~ 50 AU, while it should still exist at such small separations. Furthermore, the proportion of circumstellar disks is very high in the Trapezium (Hillenbrand et al. 1998), implying that the number of encounters is not very high.

It is also possible that the binary fraction is established during the formation process, without any later disruption. Durisen & Sterzik (1994) have pointed out that a natural prediction of both cloud and disk fragmentation models is that the binary fraction is higher in colder SFR. If the Trapezium and similar clusters had a high initial gas temperature, it could explain the large excess of loose associations with regard to the MS. On the other hand, Durisen et al. (in prep.) show that the cloud temperature could also influence the orbital period distribution. This could account for the results of Brandner & Köhler (1998) who present evidence that the peak of the orbital period distribution changes with the physical conditions of the parent cloud; their numbers, however, are very small, and their results need to be ascertained.

5. Conclusion

I developed a method with consistent corrections for incompleteness and selection biases to clarify the issue of the possible binary excess in SFRs. Reanalyzing all published PMS binary surveys, it appears that some previous conclusions have to be revisited, although the major ones hold (Taurus and Ophiuchus SFR show binary excess, while Orion and zero-age MS clusters do not). The following conclusions are reached here:

- the Taurus members have a significant binary excess (2.8σ), with $\sim 95\%$ of stars being multiple systems if the orbital period distribution has the same shape as the MS binaries. I also report astrometry and near-infrared photometry for four new subseconds companions.
- combining Ophiuchus, Chameleon and Lupus, the excess is significant at the 2.6σ confidence level at least, which increases the confidence in the result initially pointed out by Reipurth & Zinnecker (1993). It also appears that the binary infrared flux ratios are larger (towards fainter companions) in Ophiuchus than in Taurus.
- all the Orion clusters, as well as the Pleiades and the Hyades, have binary fractions similar to the MS.
- unlike in Taurus, there is no evidence from binarity that the *ROSAT* populations in Chameleon and Lupus are linked to the clouds.

It is not currently possible to discriminate between a difference in the overall binary fraction or in the orbital period distribution, though the former appears more likely. The use of larger telescopes with adaptive optics will be needed to settle this issue. Also, to confirm and increase the confidence level of the binary excesses in Ophiuchus or Chameleon, it will be necessary to survey a sample at least twice as large as the current known population.

Acknowledgements. I wish to thank J. Bouvier, F. Ménard, J.-L. Moïnin, M. Bate and M. Simon for fruitful discussions and comments on early versions of this work. I also thank Ch. Leinert for his prompt and helpful referee report.

Appendix A: cluster distances and separation range of the different surveys

The distances assumed to convert angular to linear separations are presented in Table 1. These values are not very accurate (the uncertainties are probably about 20%), but they are not extremely important values, since the period distribution is rather flat and, thus, a simple shift in the integration limits does not change dramatically the results. Concerning the *ROSAT* populations, I first assumed that they are linked to the SFRs, as proposed by Guillout et al. 1998, although this is still unclear.

More critical are the separation ranges in which each study was performed (Table A1). When the technique is simple imaging (without high angular resolution), I choose the worst value of the seeing as the lower limit, so that all stars were observed under better or equivalent conditions. For speckle surveys, it is

Table A1. Separation range for each study. “diff”: diffraction limit; “sens”: limit for homogeneous sensitivity; “seeing”: worse seeing value; “fov”: instrument field-of-view; “back”: limit for small background stars contamination. References are the same as in Table 1.

Ref.	sep. range (″)	lower limit	upper limit
1	0.13–13.0	diff	back
2	0.1–1.8	sens	fov
3	0.02–10.0	sens	back
4	1.0–12.0	seeing	back
5	0.1–1.0	sens	back
6	0.14–0.5	diff	back
7	0.3–2.3	sens	back
8	0.1–1.2	sens	fov
–	1.2–12.0	seeing	back
9	0.8–3.0	seeing	back
10	0.13–13.0	diff	back
11	0.08–7.0	diff	fov
12	0.1–1.07	sens	fov

possible to choose a lower limit such that the sensitivity is almost constant for larger separations without losing too much companions; furthermore, the scatter in the individual sensitivities is so large that it is impossible to apply a uniform correction to the whole sample. Adaptive optics studies, on the other hand, are diffraction-limited and very uniform in sensitivity, but the sensitivity increases gradually up to roughly $1''$, and it is not interesting to use this wide lower limit; I just kept the diffraction limit, although I acknowledge that a few companions may have been missed. The dynamic range, however, is usually about 2 mag around the first Airy ring; the majority of the close companions are thus detected at near-infrared wavelength. Binary separations can be limited either by the instrument field-of-view or by the need to avoid background contamination (this is discussed in each study), the latter being a problematic issue.

Appendix B: new companions in Taurus

On December 11 and 18, 1997, near-infrared images of Taurus binaries from Leinert et al. (1993) and Reipurth & Zinnecker (1993) samples were taken at CFHT, using the adaptive optics system and the new near-infrared camera, KIR. While obtaining *JHK* photometry of already known multiple systems, five new companions were discovered in binary and triple systems. I report in Table B1 the astrometry and relative photometry; all details will be published in a forthcoming paper (Monin et al., in prep.). The uncertainties for the astrometry are smaller than 2% for the separation and 0.5° for the position angle (measured eastwards from the North); the relative photometry is accurate to about 0.05 mag in each band.

The status of the faint star close to HBC 358 is not addressed here, although at this separation, the probability that this is a background projected companion is low (the fact that the flux

Table B1. Astrometry and relative photometry for the 4 new subarc-second companions in Taurus. Astrometry and photometry for HBC 358 C are with regard to HBC 358 Aa (brightest component in *JHK*).

primary	sep. (″)	PA ($^\circ$)	ΔJ	ΔH	ΔK
UX Tau B	0.138	303.9	0.29	0.28	0.27
J 4872 A	0.175	76.4	0.26	0.16	0.14
Haro 6-37 A	0.333	181.2	1.78	1.67	1.57
HBC 358 A	0.150	334.0	0.06	0.07	0.09
HBC 358 C	3.15	331.2	4.35	4.33	4.49

ratio decreases with increasing wavelength, however, could be an evidence for its background location). Given the flux ratio, anyway, it has not been included in this paper.

References

- Baraffe I., Chabrier G., Allard F., Hauschildt P., 1998, *A&A* 327, 1054
 Bate M., Clarke C., McCaughrean M., 1998, *MNRAS* 297, 1163
 Bouvier J., Rigaut F., Nadeau D., 1997, *A&A* 323, 139
 Brandner W., Alcalá J., Kunkel M., Moneti A., Zinnecker H., 1996, *A&A* 307, 121
 Brandner W., Köhler R., 1998, *ApJ* 499, L79
 Chini R., 1981, *A&A* 99, 346
 Duquennoy, Mayor, 1991, *A&A* 248, 485
 Durisen R., Sterzik M., 1994, *A&A* 286, 84
 Elias J., 1978, *ApJ* 224, 453
 Ghez A., Neugebauer G., Matthews K., *AJ* 106, 2005
 Ghez A., McCarthy D., Patience J., Beck T., 1997, *ApJ* 481, 378
 Gizis J., Reid I., 1995, *AJ* 110, 1248
 Guillout P., Sterzik M., Schmitt J., et al., 1998, *A&A* 334, 540
 Henry T., McCarthy D., 1993, *AJ* 106, 773
 Hillenbrand L., Strom S., Calvet N., et al., 1998, *AJ* 116, 1816
 Hughes J., Hartigan P., 1992, *AJ* 104, 680
 Köhler R., Leinert Ch., 1998, *A&A* 331, 977
 Krautter J., 1991, In: Reipurth (ed.) Low mass star formation in southern molecular clouds. ESO scientific report No. 11, 127
 Kroupa P., 1995, *MNRAS* 277, 1522
 Leinert Ch., Zinnecker H., Weitzel N., et al., 1993, *A&A* 278, 129
 Marraco H., Rydgren A., 1981, *AJ* 86, 62
 Mathieu R., 1994, *ARA&A* 32, 465
 Neuhäuser R., Brandner W., 1998, *A&A* 330, L29
 Padgett D., Strom S., Ghez A., 1997, *ApJ* 477, 705
 Patience J., Ghez A., Reid I., Weinberger A., Matthews K., 1998, *AJ* 115, 1972
 Perryman M., Brown A., Lebreton Y., et al., 1998, *A&A* 331, 81
 Petr M., Coudé du Foresto V., Beckwith S., Richichi A., McCaughrean M., 1998, *ApJ* 500, 825
 Prosser C., Stauffer J., Hartmann L., et al., 1994, *ApJ* 421, 517
 Reipurth B., Zinnecker H., 1993, *A&A* 278, 81
 Richichi A., Leinert Ch., Jameson R., Zinnecker H., 1994, *A&A* 287, 145
 Schwartz R., 1991, In: Reipurth (ed.) Low mass star formation in southern molecular clouds. ESO scientific report No. 11, 93
 Simon M., Ghez A., Leinert Ch., et al., 1995, *ApJ* 443, 625
 Stapelfeldt K., Krist J., Ménard F., et al., 1998, *ApJ* 502, L65