Low-mass binaries in young stellar clusters: a deep near-infrared adaptive optics survey

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Abstract – Observations of different young clusters with ages ranging from 2 to 700 Myr have been performed with the adaptive optics system PUEO at CFHT to search for companions around low-mass stars ($M < 1.5 M_\odot$). Over 350 stars were observed with the high angular resolution and sensitivity provided by PUEO, leading to the detection of 60 multiple systems, with separations down to $0\farcs08$. The companion star fraction is derived in the Pleiades and in a very young cluster, IC 348; preliminary estimates are also presented for Præsepe, as well as other clusters (α Per, M 34 and Coma Berenices).

All clusters show an overall binary fraction and period distribution similar to that of main sequence binaries. This contrasts with the strong excess of binaries reported for the Taurus star-forming region. We argue that the binary fraction is established before 1 Myr in cluster evolution, and that the observed fractions are intrinsic to the clouds. Either a very rapid temporal evolution of the binary fraction occurs (on a timescale much shorter than the pre-main sequence contraction time), or the physical conditions of the parental cloud impact on the binary formation process. We find a trend for the binary fraction to be inversely correlated with the cluster density, but another physical parameter could drive both the stellar density and the binary fraction.

1 Introduction

Various studies in the last ten years have shown that binarity is a very common property of low-mass main sequence (MS) stars: about 53% of G-type stars and 42–45% of K and M dwarfs are in fact multiple (Duquennoy & Mayor, 1991; Mayor *et al.*, 1992; Fischer & Marcy, 1992). Although the binary fraction is different, the broadly peaked shape of the period distribution is very similar for all samples. This distribution is close to being log-normal, with a peak at about 30 AU for a system mass of $1 M_\odot$.

More recently, several studies have tackled the question of the frequency of binaries among young pre-main sequence (PMS) stars. The variety of the findings shows that the formation of binaries is probably not as simple and universal as one might have believed. For example, while the Orion Trapezium exhibits the same binary fraction as the MS population (Prosser *et al.*, 1994; Petr *et al.*, 1998), binaries are much more common in Taurus, where almost all stars are in multiple systems, if the period distribution is the same as on the MS (e.g., Leinert *et al.*, 1993; Ghez *et al.*, 1993).

It has been suggested that the difference between the PMS and MS populations is due to evolutionary effects (e.g., numerous binaries could be disrupted in gravitational encounters, Ghez *et al.* 1993). In this picture, the Trapezium would be an exception with its unusually low binary fraction at a very young age. Another possibility would be a tight link between the initial physical conditions in the parental cloud and the binary population properties (either the overall fraction, or the period distribution, or both). Then, the binary fraction could conceivably differ from one star-forming region (SFR) to another, depending upon environmental conditions.

To investigate the origin of these differences, we started a long-term project aimed at the determination of the number of binaries in different SFRs and young clusters, of different stellar densities and at different evolutionary stages. In order to get meaningful results, we need:

- a large sample of stars in each cluster so that the statistics are robust;
- high angular resolution imaging, in order to cover a wider range of separation, and minimizing corrections for uncompleteness;
- IR imaging, because companions are usually cooler and redder, and therefore more easily detected at IR wavelengths.

To obtain diffraction-limited images, one can use speckle interferometry and adaptive optics imaging. The latter appears well suited for our goals, since it allows a better sensitivity at large separations (beyond the seeing halo) and the observations of fainter stars, with increased efficiency compared to speckle techniques. It is also noticeable that the detection limit of faint companions is much less dependent on seeing than that of speckle surveys.

We decided to start the survey in the northern hemisphere by using the adaptive optics system on the Canada-France-Hawaii Telescope, PUEO, along with the near-infrared detectors MONICA and KIR. The observations and results are described in Sect. 2 and implications are drawn in Sect. 3. Finally, the perspectives are presented in Sect. 4.

2 Observations and results

Observations of three clusters have been completed: IC 348, Pleiades and Præsepe. The results for the Pleiades have been published by Bouvier *et al.* (1997); for Præsepe, preliminary results are presented, pending the complete analysis of the data. In Sect. 2.4, we present a progress report for three other open clusters whose observations are not fully completed yet.

2.1 Pleiades (120 Myr)

The Pleiades cluster is a well-known young open cluster, at a distance of about 130 pc (Meynet *et al.*, 1993). Companions as close as 10–12 AU ($0\farcs08$) from the primary can be detected from diffraction-limited images obtained with a 3.6-m telescope in the H band; we are thus sampling the peak of the orbital distribution of MS binaries. Applying a lithium age indicator to very low-mass stars and brown dwarfs, (Basri *et al.*, 1996; Stauffer *et al.*, 1998; Bouvier *et al.*, 1998), the age of the cluster is estimated to be about about 120 Myr. It is therefore a zero-age main sequence (ZAMS) cluster, very well suited to investigate a possible time evolution of the binary fraction between the PMS and MS stages.

The observations were taken during 4 nights in September 1996, with the MONtréal Infrared CAmera. Due to the limited field-of-view of the detector ($9'' \times 9''$) and to the observational procedure, the largest detectable separation is $7''$. We surveyed 144 Pleiades members in the central part of the cluster; all are G- and K-type proper motion members. The survey was performed in the K-band, and JHK images were obtained for all multiple systems detected in real-time, with absolute photometry in the three bands for all components. Only K photometry was obtained for the closest system (separation of $0\farcs08$). No deconvolution process was applied. A total of 27 binaries and 3 triple systems were found, but 5 of these binaries turned out to be background companions in a J–$(J-K)$ diagram. Actually, only 3 out of 8 binaries with $\Delta K > 3.5$ are physically bound pairs.

Fig. 1 presents the detection limit in this survey. It has been estimated by calculating the noise in the radial profile of a single star; the $3\,\sigma$ level is plotted along with all the observed binaries (including the background companions). The sensitivity, which is as large as $\Delta K_{lim} = 6.5$ mag for separations larger than $1''$, becomes poorer closer to the primary: $\Delta K_{\rm lim} \approx 2$ mag in the central $0\farcs3$. Consequently, some faint companions were probably missed very close to the primaries. In order to estimate the binary fraction in our sample, we therefore have to correct for uncompleteness. The method, fully described in Bouvier *et al.* (1997), consists in estimating the detection limit in several separation bins; this limit is then converted into a limiting mass-ratio using the mass-luminosity relationship from Henry & McCarthy (1993) (which applies to MS stars). Finally, it is assumed that the mass-ratio distribution observed by Duquennoy & Mayor (1991) in the solar neighbourhood for G-dwarfs binaries also applies to Pleiades binaries. Then, the limiting mass-ratio can be transformed into a fraction of missed companions. This correction

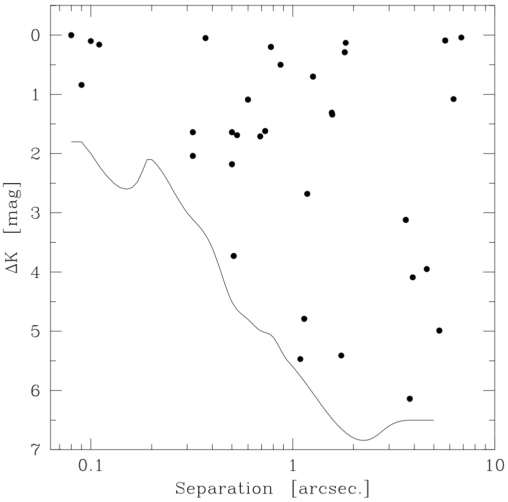

Figure 1: Observed binaries and estimated completeness limit for the Pleiades survey. The solid curve is estimated by calculating the $3\,\sigma$ noise level in the averaged radial profile of a single star. For separations smaller than 0.″3, faint companions ($\Delta K > 2$) remain undetected, and a completeness correction has to be applied (see text).

applies down to a mass-ratio of 0.1, which is the lower limit of the Duquennoy & Mayor survey. Overall, we estimate that we have missed about 13 companions in the separation range 0.″08–7″. Including this correction, the total number of companions is 40.8, leading to a total companion star fraction of $28 \pm 6\%$ in the range $\log P$ =4.2–7.1 days; this is the number of companions per target, counting twice each triple system. Over the same separation range, this fraction is $27 \pm 3\%$ for field G-dwarfs (Duquennoy & Mayor, 1991). It thus appears that there is no excess in the overall companion star fraction in the Pleiades compared to field dwarfs.

The orbital period distribution, shown in Fig. 2, allows a more detailed comparison between Pleiades binaries and the MS: the overall period distribution in Pleiades, from spectroscopic (Mermilliod *et al.*, 1992) to visual binaries (Bouvier *et al.*, 1997), agrees very well with the MS distribution, as does the overall binary frequency. Furthermore, the ratio of binaries to triple systems is about 10:1 for both the short and long period subsamples in Pleiades. On the MS, this ratio has about the same value (Duquennoy & Mayor, 1991).

2.2 IC 348 (2 Myr)

IC 348 is a very young cluster located in the Perseus molecular complex. Its distance is about 320 pc (see discussion in Herbig 1998), so we can detect companions with separations larger than about 30 AU, close to the peak of the orbital period distribution of MS dwarfs. Various studies have concluded that star formation has been going on for the last few Myrs (Lada & Lada 1995; Herbig 1998; Luhman *et al.*, in prep.). Membership has been proposed for about one hundred stars by Herbig (1998) on the basis of colour-magnitude diagrams. The median age and mass of the candidate members is 2 Myr and $0.5 M_\odot$, respectively. IC 348 mostly contains low-mass stars, and Lada & Lada (1995) concluded that the cluster density is about 500 stars/pc^3 ($220 M_\odot$/pc^3). Only one B star (BD +31^{o}643) lies in the cluster. Herbig (1998) also identified over 110 emission-line stars in the cluster; most of them are likely to be active PMS stars (about 70 of these stars are already candidate members from the colour-magnitude diagrams).

We observed 71 of Herbig's candidate members during four nights at CFHT in December 1997 with PUEO and KIR. The survey was conducted in H and, again, JHK photometry was obtained for all multiple systems detected in real-time; deconvolution has to be performed for two very close systems. The field-of-view of KIR is $36'' \times 36''$, which is not a limit for the binary separation, since confusion with background stars already occurs at smaller distances. We chose 8″ as an upper limit for bound systems, and we checked that our results are similar with a smaller value. This limit corresponds to a projected separation of $\sim$ 2500 AU.

We found 15 companions, all of them forming binary systems and no triples (Duchêne *et al.*, in prep.). The absence of triple systems can be attributed to the usually large value of the ratio of binaries to triple systems and to the fact that most triple systems are hierarchical: given the distance of the cluster, we may be missing the close companions in triple systems, which then appear as relativey wide binaries. Examples of detected binaries are presented in Fig. 3.

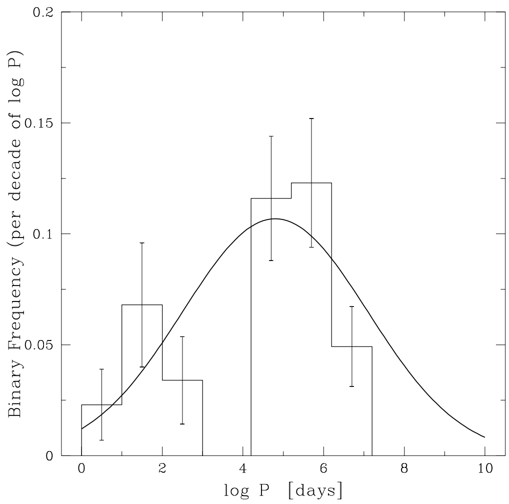

Figure 2: Orbital period distribution in the Pleiades; spectroscopic binaries are from Mermilliod *et al.* (1992) and close visual binaries from Bouvier *et al.* (1997). The solid curve is the G-type MS binary distribution from Duquennoy & Mayor (1991). Both distributions agree quite well over the whole range of orbital period.

We plot all observed companions in Fig. 4, along with the detection limit. Both noise calculation and empirical estimate of this limit are drawn. We use the histogram for the completeness correction. The widest pair with $\Delta H > 5$ mag has been observed in two bands (J and H), and this allows us to plot it in a colour-magnitude diagram. The companion appears to be a background star. We assume that the other two very faint companions are also background stars, although we lack multiwavelength images of these stars, since two populations seems to be distinguished in Fig. 4.

Strikingly, no companion is found with $2.5 < \Delta H < 5$ mag, while seven were detected in the Pleiades (only one was a background star). The reason for this difference is that the mass-luminosity relationship is much flatter for PMS objects than for MS stars. With the mass-luminosity relationship from Baraffe *et al.* (1998), we estimate that a binary with a mass-ratio of 0.1 at 2 Myr has $\Delta H \sim 3$ mag, while it has $\Delta H \sim 6$ mag on the MS. The main consequence of this is that we have missed much less low-mass companions than in Pleiades, since we reach $\Delta H = 2$ mag at least at all separations, and the $q = 0.1$ limit is reached at about 0.″3. The completeness correction indeed indicates that we might have missed only one companion over the separation range 0.″1–8″.

In the range $\log P$ =4.9–7.8 days, the companion star fraction in IC 348 is $19 \pm 5\%$. The corresponding MS value is $23 \pm 3\%$. We conclude that there is no binary excess in IC 348. The final figures are even closer to the M dwarfs ($18 \pm 6\%$, Fischer & Marcy 1992), but the difference between the G- and M-dwarfs samples is not significant. A similar trend can be observed in the orbital period distribution (Fig. 5). However, Table 1a shows that the binary fraction does not change significantly with primary mass.

	primary mass ($M_\odot$)	
	$M < 0.4$	$M \geq 0.4$
obs.	31	29
bin.	7	5

(a)

age (yr)		
$t < 10^6$	$10^6 < t < 10^{6.5}$	$t > 10^{6.5}$
21	23	15
5	3	4

(b)

ROSAT	
detec.	undetec.
33	34
7	5

(c)

$W(H\alpha)$	
emis.	abs./?
30	37
5	7

(d)

Table 1: **(a)** Evolution of the binary fraction with primary mass. **(b)** Same for primary age. **(c)** Comparison of the binary fraction for detected and undetected targets in deep *ROSAT* observations (Preibisch *et al.*, 1996). **(d)** Similar comparison with the Hα survey by Herbig (1998).

We have also tried, using the large age spread in the cluster, to search for a time evolution of the binary fraction. Although we are dealing with relatively small numbers, we do not find any significant evolution of the binary fraction with primary age (see Table 1b). This suggests that the formation of binary systems has remained

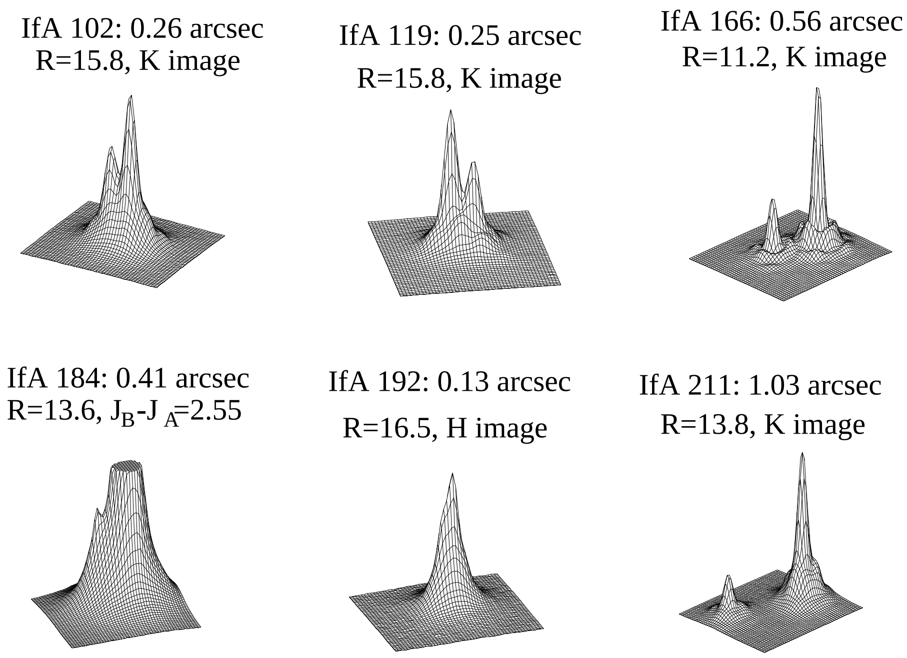

Figure 3: Examples of the detected binaries in IC 348. Each image is $1''.75 \times 1''.75$. IfA 166 and IfA 211 shows that very good corrections can be achieved on bright stars ($R > 14$): the second Airy ring is clearly detected around IfA 166; on stars brighter than $R \approx 16$, binaries with separation of about $0''.25$ are easily resolved (IfA 102 and IfA 119), while binaries with separation of $0''.13$ appear elongated and need to be deconvolved (IfA 192). Binaries with flux ratios of the order of 10 and separations smaller than $0''.5$ are hardly resolved (IfA 184).

correlated to the total formation rate at least over the last 10 Myr or so. It also means that the ages derived by Herbig are not systematically biased by binarity (since the age distributions of singles and binaries are undistinguishable).

Finally, we have compared binaries and single stars in relation with their X-ray fluxes and Hα equivalent width (see Table 1c and d). The fraction of binaries appears to be the same in the various samples, suggesting that the presence of a companion does not strongly impact upon stellar activity and accretion disks.

2.3 Præsepe (700 Myr)

Præsepe is a cluster similar to the Pleiades, though much older (about 700 Myr, Mermilliod 1981) and located at 180 pc. We observed 143 solar-type members in January 1998 at CFHT, with PUEO and KIR.

During the observations, we identified 23 multiple systems, which is comparable to the Pleiades real-time results (25 multiple systems out of 144 targets). The completeness correction has not been evaluated yet, but it is likely that it will be very similar to the Pleiades (the mass-luminosity relation from Henry & McCarthy 1993 will again be used), and we therefore do not expect any binary excess in this cluster. A complete analysis of the data is underway (Bouvier *et al.*, in prep.).

2.4 Other clusters

We have also started the observations of three other young open clusters. Observations of the 80 Myr (Prosser, 1992) α Per cluster were performed at the 88$''$ University of Hawaii telescope equipped with the UH adaptive optics system (Eislöffel *et al.*, in prep.), while M 34 (about 200 Myr, Jones & Prosser 1996) and Coma Berenices (450 Myr, Boesgaard 1989) were observed at CFHT with PUEO (Simon *et al.*, in prep.). Very preliminary analysis of these clusters indicate that our data do not contain any evidence for a strong binary excess.

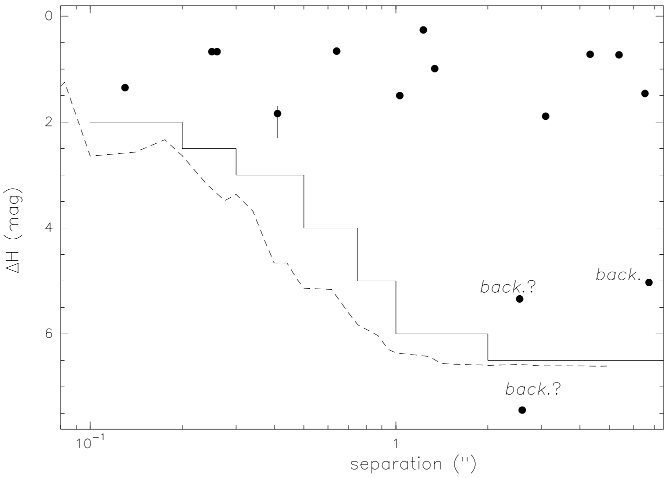

Figure 4: Detection limit in IC 348. The dashed line is a $3\,\sigma$ noise level, and the solid histogram is an empirical limit estimated by artificially adding a faint companion close to a single star. *back.* stands for companions which are probable background field stars. The PSF fitting process was highly uncertain for IfA 184, for which the error bar is plotted; in all other cases, the symbol size is larger than the uncertainties.

3 Implications

3.1 Does the binary fraction evolve with time?

The clusters we have observed all show companion star fractions similar to the MS. They are, however, quite different, especially regarding their age. Clusters are in fact found with a "normal" binary fraction at all ages, from $\sim$ 1 Myr (IC 348, Trapezium) up to ZAMS and MS clusters (Pleiades, Præsepe). Patience *et al.* (1998) recently observed the Hyades (distance 46 pc and age $\sim$ 625 Myr, Perryman *et al.* 1998) and found a marginal binary excess. Duchêne (1998), however, has shown that this was due to the method they used to estimate the completeness correction, which differs from ours. Reanalysing their data with the same approach we used for IC 348, Pleiades and Præsepe, we find that the binary fraction in their sample is in good agreement with the MS.

It thus seems very unlikely that the main parameter governing the binary fraction is the age of the cluster: the different results obtained for IC 348 and Taurus which have about the same age, for example, cannot be attributed to a time evolution. These two SFRs also contain very similar stellar populations, with no high-mass stars and comparable mass distributions (Kenyon & Hartmann, 1995; Herbig, 1998). Other evidence against significant time evolution of the binary fraction is the absence of its dependency upon the primary age in IC 348, in spite of a significant age spread.

All the clusters we have observed are quite dense, at least a few hundreds of stars/pc^3 (in Pleiades and Præsepe, the presently observed density is probably much smaller than it was at the time of their formation). The most favoured mechanism proposed to disrupt binaries is gravitational interaction with other stars; the denser the cloud, the more efficient this mechanism (e.g., Kroupa, 1995a). Therefore, in loose T associations like Taurus (which has a density of a few stars/pc^3), this mechanism may be inefficient.

All these arguments lead to the conclusion that **the binary fraction is probably established very soon in the formation history, before the first Myr**. For some reason, some clusters reach this stage with a high binary fraction and others with a low one, resulting in the difference we observe between some SFRs. In other words, binary formation appears to be linked to some intrinsic properties of the clouds and therefore varies from one SFR to another. The physical causes to these differences are explored in Sect. 3.3.

3.2 Possible changes in the orbital period distribution

The *visual* binary fraction is much higher in some SFRs like Taurus than on the MS. Does this mean that the *overall* fraction, i.e., integrated over the whole separation range of orbital period, is higher? Is it possible that these regions lack close binaries (separations smaller than $0\farcs1$)? It has been proposed by Brandner & Köhler (1998) that the separation distribution could vary between SFRs, depending on whether or not they form high-mass stars. This conclusion is however somewhat limited by small sample statistics, and by the fact that the contamination of their

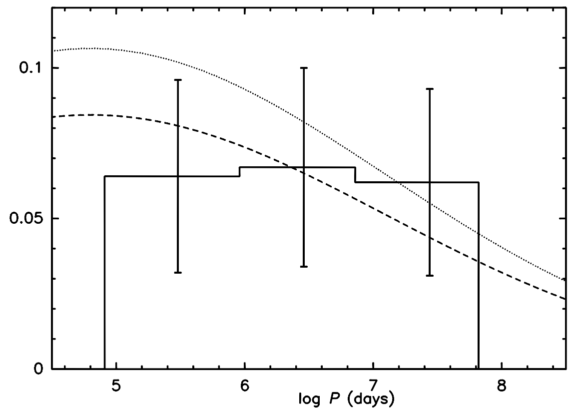

Figure 5: Orbital period distribution for IC 348 (solid histogram). The dotted and dashed curves are the G- and M-type MS binary distributions respectively (Duquennoy & Mayor, 1991; Fischer & Marcy, 1992).

samples by background stars has not been estimated (this could be another explanation for the $P_{\rm orb}$ distribution in Upper Sco B peaking at relatively wide separations).

Such a trend has not been found in any other samples: in Taurus, the excess is found down to separations of a few AU (lunar occultation observations by Richichi *et al.* 1994; Simon *et al.* 1995), and the orbital period distribution seems smooth in the Pleiades (Fig. 2). The fraction of spectroscopic binaries (with periods shorter than 100 days) in the Taurus-Auriga SFR is at least equal to that of the MS (Mathieu, 1994), suggesting that there is no significant deficiency in the number of spectroscopic binaries.

3.3 Environmental conditions and binary fraction

Let us consider all the SFRs with $t < 10^7$ yr. On the one hand, Taurus, Chamæleon and Ophiuchus show binary excesses (although they are not highly significant, Duchêne 1998 and references therein), while IC 348, the Trapezium and various Orion clusters (NGC 2024, 2068 and 2071) have binary fractions similar to the MS. One of the apparent differences between these two classes of SFRs is that the latter are all quite dense, while the former are rather loose (only a few stars/pc^3 in the Taurus aggregates or in Chamæleon). No quantitative relationship can be obtained from our data, partly because of the error bars affecting the determination of the binary fractions, and because the physical properties of the clouds are not precisely known. We only have raw estimates of the density, and the discovery of large embedded populations could modify these values. Qualitatively, however, a trend seems to emerge, which indicates that the binary fraction is inversely correlated with stellar density.

The fact that the binary fraction is established before the first Myr can have two different origins. **Either the binary fractions are different from the beginning, or this fraction evolves rapidly during the early embedded phases of the cluster history**. In the first case, the binary fraction could be driven by the gas temperature: Durisen & Sterzik (1994) have shown that current models of cloud fragmentation and disk instability both predict higher binary fractions in *cold* clouds. It is also conceivable that the initial cause of the fragmentation (depending on the equilibrium of the cloud: thermal, rotational, magnetic) could play a significant role in the binary formation rate by changing the size, mass or angular momentum of the fragments.

On the other hand, Kroupa (1995a,b) has shown that the initial dynamical evolution of a dense cluster could disrupt enough binaries to decrease the binary fraction from 100% to 50% or less in a few Myrs. He performed N-body simulations of binary clusters, without taking into account the influence of the rapid (<10 Myr) evolution of high-mass stars; this should not be, however, a major drawback of these simulations. In the case of a very dense cluster, such as the Trapezium cluster, the binary fraction could have reached the MS value before 1 Myr. Other parameters, such as the detailed orbital period and mass-ratio distributions will have to be derived from observations in order to test this class of models.

4 Conclusions

We have observed and analysed about 350 low-mass stars in three different open clusters (Pleiades, IC 348, and Præsepe) with the adaptive optics system PUEO at CFHT. We detected 60 actual companions, i.e., excluding background stars. After completeness correction, we estimate the companion star fraction in these clusters, and find it consistent with that observed in the solar neighbourhood. Preliminary results from the observations of three other clusters (α Per, M 34 and Coma Berenices) suggests that this conclusion holds for a wide range of ages.

Our results suggest that the binary fraction is established very soon after the formation process, in less than 1 Myr, and does not evolve significantly thereafter. The different binary fractions observed in different SFRs, a few Myr later, are thus intrinsic and not the result of temporal evolution during the PMS contraction phase. These differences may result from differing physical conditions in the SFRs leading to a different output of the star formation process (i.e., the fraction of binary systems relative to single stars). Alternatively, if fragmentation initially leads to the same binary fraction in all SFRs (of the order of 100%), then a very rapid evolution of the binary fraction before the stars become visible must occur. The trend that currently emerges from observations is that the binary frequency tends to be inversely correlated with the average stellar density of SFRs. Whether there is a direct link between stellar density and binary fraction (e.g., through the number of gravitational encounters) or whether both properties result from a common cause is currently unknown and will require studies of even younger embedded clusters as well as better determinations of the distribution of mass-ratios in the binary samples.

Observations with larger telescopes equipped with adaptive optics, such as the VLT, Gemini or Keck, will lead to significant improvements on the determination of both the distribution of orbital periods and mass-ratios. We will then know what is the exact difference between two star-forming regions: the overall binary fraction or the shape of period distribution. The former seems currently more likely, but the statistics needs to be ascertained and it will be very useful to detect companions as close as 5 AU at a distance of 150 pc for this purpose. The increased contrast allowed by larger telescopes will also provide a better determination of the mass-ratio distribution in binary systems.

Going further in the physics of the binary formation and early evolution will also require a better knowledge of the cluster populations: while we can currently reach accuracies of a few percent on the binary fractions, the age is only known to barely 20-30%, and the density to almost an order of magnitude.

References

Baraffe, I., Chabrier, G., Allard, F. & Hauschildt, P. H. 1998, Astron. & Astrophys. **337**, 403.

Basri, G., Marcy, G. W. & Graham, J. R. 1996, Astrophysical Journal **458**, 600.

Boesgaard, A. M. 1989, Astrophysical Journal **336**, 798.

Bouvier, J., Rigaut, F. & Nadeau, D. 1997, Astron. & Astrophys. **323**, 139.

Bouvier, J., Stauffer, J. R., Martin, E. L., Barrado Y Navascues, D., Wallace, B. & Bejar, V. J. S. 1998, Astron. & Astrophys. **336**, 490.

Brandner, W. & Köhler, R. 1998, Astrophysical Journal, Letters **499**, L79.

Duchêne, G. 1998, Astron. & Astrophys. submitted.

Duquennoy, A. & Mayor, M. 1991, Astron. & Astrophys. **248**, 485.

Durisen, R. H. & Sterzik, M. F. 1994, Astron. & Astrophys. **286**, 84.

Fischer, D. A. & Marcy, G. W. 1992, Astrophysical Journal **396**, 178.

Ghez, A. M., Neugebauer, G. & Matthews, K. 1993, Astronomical Journal **106**, 2005.

Henry, T. J. & McCarthy, Donald W., J. 1993, Astronomical Journal **106**, 773.

Herbig, G. H. 1998, Astrophysical Journal **497**, 736.

Jones, B. F. & Prosser, C. F. 1996, Astronomical Journal **111**, 1193.

Kenyon, S. J. & Hartmann, L. 1995, Astrophysical Journal, Supplement **101**, 117.

Kroupa, P. 1995a, Mon. Not. of the Royal Astron. Soc. **277**, 1491.

Kroupa, P. 1995b, Mon. Not. of the Royal Astron. Soc. **277**, 1522.

Lada, E. A. & Lada, C. J. 1995, Astronomical Journal **109**, 1682.

Leinert, C., Zinnecker, H., Weitzel, N., Christou, J., Ridgway, S. T., Jameson, R., Haas, M. & Lenzen, R. 1993, Astron. & Astrophys. **278**, 129.

Mathieu, R. D. 1994, Annual Review of Astron and Astrophys **32**, 465.

Mayor, M., Duquennoy, A., Halbwachs, J.-L. & Mermilliod, J.-C. 1992, in McAlister & Hartkopf (eds.), *Complementary approaches to double and mutiple stars research*, ASP conf. series, vol. 32, p. 73.

Mermilliod, J. C. 1981, Astron. & Astrophys. **97**, 235.

Mermilliod, J. C., Rosvick, J. M., Duquennoy, A. & Mayor, M. 1992, Astron. & Astrophys. **265**, 513.

Meynet, G., Mermilliod, J. C. & Maeder, A. 1993, Astronomy and Astrophysics, Supplement **98**, 477.

Patience, J., Ghez, A. M., Reid, I. N., Weinberger, A. J. & Matthews, K. 1998, Astronomical Journal **115**, 1972.

Perryman, M. A. C., Brown, A. G. A., Lebreton, Y., Gomez, A., Turon, C., De Strobel, G. C., Mermilliod, J. C., Robichon, N., Kovalevsky, J. *et al.* 1998, Astron. & Astrophys. **331**, 81.

Petr, M. G., Coudé Du Foresto, V., Beckwith, S. V. W., Richichi, A. & McCaughrean, M. J. 1998, Astrophysical Journal **500**, 825.

Preibisch, T., Zinnecker, H. & Herbig, G. H. 1996, Astron. & Astrophys. **310**, 456.

Prosser, C. F. 1992, Astronomical Journal **103**, 488.

Prosser, C. F., Stauffer, J. R., Hartmann, L., Soderblom, D. R., Jones, B. F., Werner, M. W. & McCaughrean, M. J. 1994, Astrophysical Journal **421**, 517.

Richichi, A., Leinert, C., Jameson, R. & Zinnecker, H. 1994, Astron. & Astrophys. **287**, 145.

Simon, M., Ghez, A. M., Leinert, C., Cassar, L., Chen, W. P., Howell, R. R., Jameson, R. F., Matthews, K., Neugebauer, G. *et al.* 1995, Astrophysical Journal **443**, 625.

Stauffer, J. R., Schultz, G. & Kirkpatrick, J. D. 1998, Astrophysical Journal, Letters **499**, L199.