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The formation and evolution of binary systems

III. Low-mass binaries in the Praesepe cluster*

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Abstract. With the aim of investigating the binary population of the 700 Myr old Praesepe cluster, we have observed 149 G and K-type cluster members using adaptive optics. We detected 26 binary systems with an angular separation ranging from less than 0.08 to 3.3 arcsec (15–600 AU). After correcting for detection biases, we derive a binary frequency (BF) in the log P (days) range from 4.4 to 6.9 of 25.3 ± 5.4%, which is similar to that of field G-type dwarfs (23.8%, Duquennoy & Mayor 1991). This result, complemented by similar ones obtained for the 2 Myr old star forming cluster IC 348 (Paper II) and the 120 Myr old Pleiades open cluster (Paper I), indicates that the fraction of long-period binaries does not significantly evolve over the lifetime of galactic open clusters. We compare the distribution of cluster binaries to the binary populations of star forming regions, most notably Orion and Taurus, to critically review current ideas regarding the binary formation process. We conclude that it is still unclear whether the lower binary fraction observed in young clusters compared to T associations is purely the result of the early dynamical disruption of primordial binaries in dense clusters or whether it reflects intrinsically different modes of star formation in clusters and associations. We also note that if Taurus binaries result from the dynamical decay of small-N protostellar aggregates, one would predict the existence of a yet to be found *dispersed* population of mostly single substellar objects in the Taurus cloud.

Key words. stars: binaries: close – stars: formation – stars: low-mass, brown dwarfs – galaxy: open clusters and associations: individual: Praesepe, M 44

1. Introduction

Binary and multiple systems provide a fossil record of the star formation process. In the last decade, studies of various galactic populations (field stars, open clusters, star forming regions) have led to the conclusion that most solar-type stars occur in binary systems rather than in isolation (e.g., Duquennoy & Mayor 1991; Mathieu et al. 2000). Hence, the most common output of protostellar collapse appears to be the formation of multiple systems. Beyond this indisputable observational result, the way stellar systems form remains an important issue (Bodenheimer et al. 2000), and so a robust determination of the detailed properties of binary stars, e.g., the distributions in their orbital periods, mass-ratios, and orbital eccentricities, is critically needed to guide theoretical models (Clarke et al. 2001; Ghez 2001).

Equally important in order to get clues to the star formation process is to determine whether the properties of binaries depend upon the environment in which they form, and whether these properties evolve over time or, on the contrary, remain stable during pre-main sequence and main sequence evolution; that is, are the statistical properties of binary populations universal and do they unambiguously reflect the processes which gave them birth, or do they vary both over time and from place to place in the solar neighbourhood? In order to address these issues, multiple systems have to be sampled and characterized in various types of environments and in stellar populations that have reached different stages of evolution.

A number of studies have been devoted to these issues. Large scale searches for binaries have been completed

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* Based on observations obtained at the Canada-France-Hawaii Telescope.

among low-mass field dwarfs (Duquennoy & Mayor 1991; Fisher & Marcy 1992; Tokovinin 1992), T Tauri stars in young stellar associations (e.g., Leinert et al. 1993; Ghez et al. 1993; Simon et al. 1995) and low-mass stars in young clusters (e.g., Bouvier et al. 1997; Duchêne et al. 1998; Patience et al. 1998; Mermilliod & Mayor 1999). The results indicate that in most surveyed regions the low-mass stars exhibit a similar fraction of close visual binaries with semi-major axes between a few tens to about 1000 AU (see Duchêne 1999 for a summary). There are, however, two notable exceptions. First, the Taurus star-forming association appears to contain about twice as many binaries as are present in the field (Leinert et al. 1993; Ghez et al. 1993). Second, there is a marked deficit of wide binaries, with semi-major axes in the range from 1000 to 5000 AU, in the Orion cluster as compared to the field binary population (Scally et al. 1999).

One of the difficulties in interpreting these results is that the various studies were performed with different techniques, thus introducing different observing biases (see Duchêne 1999). Motivated by the need to obtain homogeneous data sets for close visual binaries, especially in cluster environments whose study has been somewhat neglected compared to star forming regions and field populations, we have started high angular resolution surveys of low-mass stars in nearby young clusters. For this project, we have selected a number of clusters having ages in the range from 2 Myr to 700 Myr, in order to investigate any evolution of the binary content with time. The first 2 papers of this series reported on the results obtained for the ∼100 Myr Pleiades cluster (Bouvier et al. 1997, Paper I), the ∼2 Myr IC 348 cluster (Duchêne et al. 1999, Paper II), while preliminary results for the ∼80 Myr Alpha Per cluster have been reported by Eislöffel et al. (2001).

We report here the results obtained on the binary population of the 700 Myr old Praesepe cluster from high angular resolution observations of 149 low mass cluster members. Section 2 describes our data aquisition and analysis techniques, which are similar to those used in Papers I and II. The binary frequency among the low-mass stars in Praesepe and the binary properties of the cluster are derived in Sect. 3. Combining these data with those available in the literature for other young clusters, star forming associations, and the field, we discuss in Sect. 4 the implications of the trends (or lack of) observed in binary frequency as a function of time and environmental conditions for the binary formation process.

2. Observations and data analysis

The sample was primarily drawn from the proper motion study of Praesepe candidate members by Jones & Stauffer (1991, hereafter JS91). From this catalogue, we first selected 70 candidates in a $B-V$ range between 0.52 and 1.4 which had a proper motion membership probability larger than 90%. These candidates were observed in February and December, 1997. For another observing session in January 1998, 53 additional candidates were selected from JS91 in the same $B-V$ range, which had a proper motion membership probability larger than 75% and visual photometry consistent with membership in a (V, $B-V$) color-magnitude diagram. We completed our sample with 26 additional candidates having both radial velocities and photometry consistent with Praesepe membership, which were selected from Mermilliod's Open Clusters Database (WEBDA, Mermilliod 1999) and amongst Praesepe halo candidates (Mermilliod et al. 1990).

A total of 149 Praesepe G and K dwarfs were thus observed in 1997 and 1998 at the Canada-France-Hawaii Telescope with the adaptive optics system PUEO (Rigaut et al. 1998). The IR camera was MONICA (Nadeau et al. 1994) in Feb. 1997 and KIR (Doyon et al. 1998) in Dec. 1997 and Jan. 1998, which provide a field of view of 9″ and 36″, respectively. We used the same aquisition procedure for all runs. The targets were observed successively in four quadrants of the camera, for a total integration time of typically 60 s; the 4 exposures were subsequently registered and added to produce a final image that was properly sky subtracted and flat-field corrected. The primaries were first observed in either the H or K band, depending on the atmospheric turbulence conditions, in order to optimize the adaptive correction. Whenever a binary was detected in real-time, it was observed in at least one other filter in order to subsequently check the membership of the companion in a color-magnitude diagram. During each run, the images produced by the adaptive optics system were diffraction-limited in the H and K bands, providing a spatial resolution of 0.09″ and 0.13″ *FWHM*, respectively.

Aperture photometry was performed using IRAF/APPHOT and calibrated using several UKIRT Faint Standards observed during the 3 runs. The photometric accuracy is of order of 0.05 mag in the *JHK* bands. Table 1 lists the near infrared magnitudes of non resolved primaries while those of Praesepe binaries are listed in Table 2. For the binaries, differential photometry was obtained by fitting a template PSF simultaneously to the primary and the companion within IRAF/DAOPHOT. The PSF was provided by unresolved Praesepe stars that were observed just before and/or just after the exposure on the binary. Several PSF templates were used for each binary, thus providing an estimate of the photometric error. Typically, the differential photometry is accurate to within 0.02 mag, but the error may be larger for binaries with a separation close to the resolution limit or for companions close to the detection limit. The magnitude difference between the companion and the primary was combined with the aperture photometry of the system to provide the magnitude of each component.

The separation and position angle were derived from the photocenter of the components in the image as provided by the PSF fitting algorithm. The plate scale and orientation of the detector were calibrated by observing IDS astrometric standards (Van Dessel & Sinachopoulos 1993) during each run. The rms error is typically 5 mas on the separation and 0.1° on the position angle.

Table 1. Photometry of non resolved Praesepe primaries[1].

BDA	Filt	Mag	Run	BDA	Filt	Mag	Run	BDA	Filt	Mag	Run	BDA	Filt	Mag	Run
9	K	9.51	Jan. 98	23	K	9.64	Feb. 97	30	K	9.75	Jan. 98	48	K	10.17	Jan. 98
49	H	9.27	Jan. 98	58	K	9.64	Feb. 97	70	H	10.08	Dec. 97	127	H	9.41	Jan. 98
141	H	10.27	Dec. 97	162	H	9.15	Feb. 97	172	K	10.34	Jan. 98	181	H	9.04	Jan. 98
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

[1] Full Table 1 is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/375/989`

Table 2. Astrometric and photometric properties of Praesepe binaries.

BDA	KW[a]	VL[b]	JS[c]	V	$B-V$	*sep* $''$	PA $^\circ$	$J_{\rm AB}$	$H_{\rm AB}$	$K_{\rm AB}$	ΔJ	ΔH	ΔK	q	Notes
79	79	572	211	12.10	0.91	0.174	73.5	10.40	9.98	9.83		1.40	1.58	0.64	1
90	90	598	222	10.89	0.70	0.184	27.4		9.20	9.14		0.90	1.02	0.75	1
100	100	621	228	10.55	0.58	1.03	97.3	9.53	9.22	9.25		6.20	5.70	0.11	
164	164	789	279	11.31	0.70	0.256	18.4			9.60			2.76	0.42	
198	198	870	306	12.62	0.97	1.153	354.48	10.82	10.37	10.25	2.64	2.50	2.35	0.47	
275	275	993		9.96	0.58	0.21	90.4†	8.83	8.60	8.54	0.03	−0.02	0.02	1.0	1
287	287	1014		10.37	0.59	1.798	24.84	9.46	9.07	9.15	5.63	5.31	5.13	0.15	2
297	297	1033	362	11.64	0.86	0.126	188.3		9.49	9.40		0.61	0.56	0.83	3
322	322	1070	375	10.87	0.68	<0.09	∼150		9.20	9.14			∼0.5	0.8	4
334	334	1091	387	11.01	0.72	0.091	44.9	9.56	9.20		1.14	0.85		0.77	1
365	365	1142	407	10.18	0.65	0.373	109.27	8.86	8.52		0.87	0.83		0.79	5
401AB	401	1214	436	12.97	1.00	1.688	239.56	10.77	10.23	10.15	2.51	2.41	2.30	0.43	
401AC*	401	1214	436	12.97	1.00	1.776	286.69	10.77	10.23	10.15		6.1	5.4	0.10	
466**	466	1345	486	10.99	0.65	2.184	304.97	9.71			4.48	4.12	3.87	0.26	
488	488	1399	509	11.43	0.73	1.263	198.1		9.76	9.73		4.91	4.65	0.17	
495	495	1416	515	9.97	0.66	0.072	159.3†	9.66	9.35			0.03		0.99	6
533	533	237	122	11.59	0.90	0.124	16.2		9.54			0.25		0.93	7
540	540	387	167	11.03	0.69	3.35	233.59	9.69	9.33	9.29	6.12	5.88	5.67	0.11	8
809			194	13.04	1.13	1.737	325.96	10.99	10.44	10.32	1.62	1.49	1.35	0.66	
901			354	13.82	1.39§	2.428	191.7		10.66	10.52		0.34	0.31	0.92	
1184		184	102	11.85	0.79	1.285	151.95		9.85	9.73		2.50	2.43	0.48	9
1452		452	186	13.87	1.32§	0.390	130.9		10.80	10.68		2.78	2.62	0.38	
1995		995	350	12.97	1.21	0.337	289.49	10.71	10.11	10.01	0.18	0.11	0.18	0.73	
2029		1029	359	12.90	1.04	0.520	204.9		10.46	10.38		3.94	3.78	0.23	
2085		1085	383	12.89	1.10§	0.642	186.9		10.54	10.44		4.00	3.79	0.22	
2418		1418	516	13.67	1.18	0.394	221.5		10.84	10.65		3.1	3.16	0.32	
2692		1692	588	10.92	0.72	0.405	234.6		9.17	9.13		0.50	0.61	0.85	
3231			231	13.31	1.39§	0.168	172.0†		10.26	10.16		0.13	0.09	0.97	

[a] Klein-Wassink (1927), [b] Vanderlinden (1933), [c] Jones & Stauffer (1991).
§ Photographic magnitudes.
† Within 3σ photometric errors, the PA could be 180° away from the listed value.
* BDA 401C is a probably a field object.
** Due to non-photometric conditions, only differential photometry was obtained in the H and K bands.

Notes: [1] Photometric binary; [2] SB1, $P = 7635$ d; [3] SB1, long period; [4] SB1, $P > 10\,000$ d; [5] Triple, A: SB1O, B: single; [6] Triple, A: single, B: SB2; [7] SB2, long period; [8] SB1, $P = 1149$ d; [9] SB1, $P = 1.23$ d.

3. Results

We detected 26 binaries and one triple system having separations less than 7″ among 149 Praesepe G and K dwarfs. Table 2 provides their names and cross-identifications, visual photometry, and indicates whether they were previously known as either photometric or spectroscopic binaries.

3.1. Comparison with previous work

Of the 26 binaries reported here, eight were previously known as spectroscopic binary (SB) systems (Mermilliod & Mayor 1999): three long-period SBs (BDA 297, 322, 533) are resolved here with a projected separation of 23 AU or less, while three others have too short a period to be resolved (BDA 287, 540, 1184) and so the

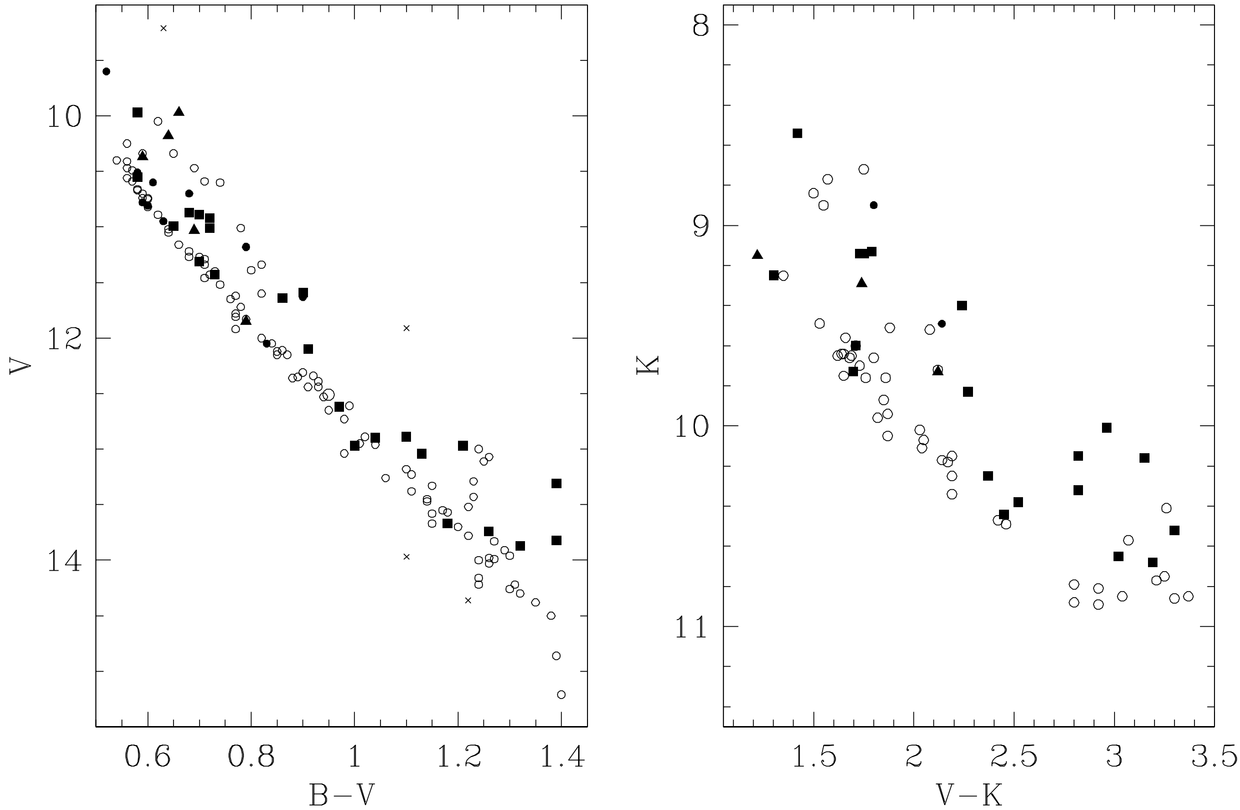

Fig. 1. Color-magnitude diagrams (CMD) for low-mass Praesepe members. The (V, $B-V$) CMD (*left panel*) contains the whole sample observed with PUEO, while the (K, $V-K$) one (*right panel*) contains only a subset of it since some primaries were not observed in the K-band. Symbols are as follows: *filled squares*: binary systems resolved with PUEO, *filled dots*: known spectroscopic binaries, *filled triangles*: triple systems resolved by PUEO, *open circles*: "single stars", *crosses*: suspected non members. Several systems resolved in the near-infrared appear to be single in the visible.

companion reported here makes them triple systems. The two remaining systems, BDA 365 and BDA 495, are known to be spectroscopic triples (Mermilliod et al. 1994). They both consist of a long-period binary with one of the components itself being a short-period binary. Both objects are spatially resolved here, and, given their angular separations and spectroscopic orbits, it is likely that we resolved the widest binary pair of these systems.

Figure 1 shows a (V, $B-V$) color-magnitude diagram (CMD) for the whole sample of G and K Praesepe members observed in this survey. The different symbols indicate previously known spectroscopic binaries, visual binaries detected here by adaptive optics, and "single" stars. Not surprisingly, the sample contains a number of (presumably short-period) SBs located on the main and binary sequences of the cluster that are not resolved by adaptive optics. More interestingly, about 15 objects that are not detected as binaries, either from spectroscopy or adaptive optics, lie more than 0.5 mag above the main sequence of the cluster and must therefore be nearly equal-mass binary systems. In order to escape detection, these systems must have an orbital period in the range from about 3×10^3 to 3×10^4 days, i.e., a semi-major axis in the range from about 4 to 15 AU. Finally, although many of the binaries that are resolved in the present study are displaced above the main sequence as expected, about a third of them are located on the cluster main sequence and were not previously detected as binaries through photometry. BDA 1184 (the triangle at $V = 11.85$, $B-V = 0.79$) is the most extreme case: it appears to be a single star but is in fact a triple system, a short-period spectroscopic binary and a wider companion at $1\farcs28$. This simply means that many faint and red companions are hidden in visible light and are too light-weight to show up in radial-velocity observations.

A (K, $V-K$) CMD, also shown in Fig. 1, is more appropriate to detect very red companions photometrically. In this diagram, BDA 1184 shows a vertical displacement of 0.42 mag. Another example, BDA 2418, which lies right on the single star sequence in the (V, $B-V$) plane, already shows a displacement of 0.15 mag in (I, $V-I$) and 0.35 mag in (K, $V-K$). However, the star BDA 287, another triple system, is still located on the single star sequence even in (K, $V-K$), because the K magnitude difference is 5.13.

To conclude this section, the common use of (V, $B-V$) colour-magnitude diagram to study binarity in open clusters from photometric data is not a good choice or strategy. (I, $V-I$) planes are certainly better and JHK observations provide still much more information on faint red companions. Observations through the $BVIK$ filters would therefore permit the detection of a wealth of new binary candidates, which would raise the binary frequency to values that are probably more realistic. However, direct observations are still needed to detect systems with large magnitude differences or with a multiplicity of order higher than 2.

3.2. Binary frequency and orbital period distribution

Table 2 also lists the astrometric and infrared properties of the systems and their components. Although BDA 322 is clearly elongated on the images, its separation is too small for deriving precise astrometric and photometric properties, and so we list only approximate values in Table 2. The masses of the individual binary components and the resulting mass ratios, $q = M_2/M_1$, were derived from the *JHK* photometry of the components using the mass-magnitude relationships from Baraffe et al. (1998) models, assuming an age of 0.7 Gyr and a distance modulus for Praesepe of $(m - M) = 6.28$ ($d = 180$ pc, Robichon et al. 1999). For the primaries or secondaries that are themselves unresolved spectroscopic binaries, this method would overestimate their mass by up to about 20% for equal-brightness components.

In order to ascertain photometric membership, we plotted the primaries and secondaries in various *JHK* color-magnitude diagrams, comparing their location in these diagrams with the 700 Myr isochrone from Baraffe et al. (1998). The primaries and secondaries are all consistent with being Praesepe members within the photometric errors. However, the third component of the BDA 401 system, BDA 401C, lies far away from the isochrone and is probably a field object. We therefore ignore it in the following discussion and consider BDA 401 to be a double. Finally, a few binaries were observed at only one wavelength, but these systems are so tight that their binary nature is not in serious doubt.

That we find only one chance projection at a distance of less than 7″ in a sample of 149 stars is consistent with the 2 MASS Point Source Catalogue Statistics, which predict about 1200 objects per square degree down to a magnitude of $K = 15$ in the direction of Praesepe. This translates into ∼0.015 objects within a 7″ radius and leads to an estimate of 2 chance projections in the present sample.

In order to estimate the binary frequency among the Praesepe G and K dwarfs, a correction factor has to be applied to the number of systems actually detected to account for the detection limit of our survey. The largest magnitude difference we are able to detect between the secondary and the primary is shown in Fig. 2 as a function of angular separation. At separations close to the diffraction limit, the detection of faint companions is limited by the constrast against the bright primary while, at large separations, the detection is background limited. We therefore proceed to derive a correction factor in various separation bins as follows.

In each bin, we convert the maximum reachable contrast between the secondary and the primary, $\Delta m_{\rm max}$, into

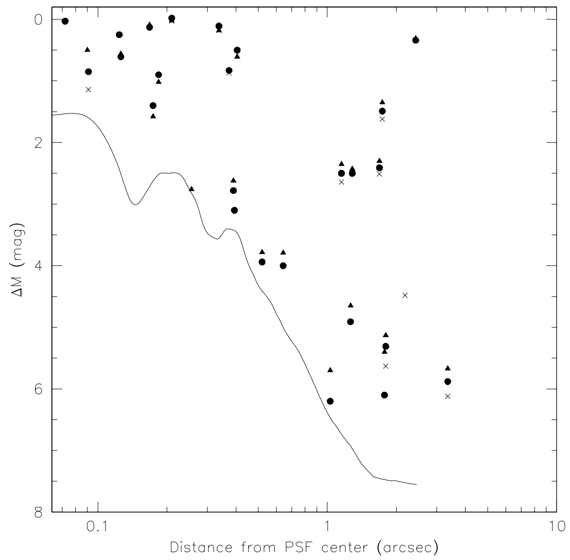

Fig. 2. Limit of detection for faint companions. The location of resolved Praesepe binaries in this diagram is indicated (crosses: ΔJ, filled dots: ΔH, filled triangles: ΔK). The curve indicates the maximum magnitude difference detectable on AO images at any distance from the center of the primary. It was derived by computing the 5σ noise level on radial profiles of unresolved Praesepe primaries. By adding artificial companions to the primaries on the images, we empirically verified that this curve corresponds to the limit of detectability of faint and/or close companions.

a minimum mass ratio $q_{\rm min}$ using the mass-magnitude relationship from the Baraffe et al. (1998) models. We assume that the mass-ratio distribution of the Praesepe binaries is the same as that of the field G dwarfs derived by Duquennoy & Mayor (1991, DM91). This assumption is consistent with the mass ratio distribution derived for our binary sample. While the overall q–distribution is rather flat (see Table 2), restricting the analysis to the separation range where we can detect all companions down to $q = 0.1$ ($sep \geq 0.8''$, see Table 3) so that we can compare to DM91, we count 10 companions. Mass ratios in this small subsample range from 0.11 to 0.92, with a mean of 0.38. In DM91 survey, for binaries with periods longer than 10^4 days, the average mass ratio is 0.40. Both results are very similar, though ours admitedly relies on only a few systems. The fraction of missed companions is then found by integrating DM91's mass-ratio distribution between $q = 0.1$ and $q = q_{\rm min}$. We finally apply this correction factor to the number of detected binaries to obtain the total number of systems with mass-ratios larger than 0.1 in this separation range. The 1σ uncertainties on BF in each $\log P$ bin correspond to Poisson noise, i.e., $\sigma = \sqrt{N_{\rm d}} \times (1 + N_{\rm u}/N_{\rm d})$, where $N_{\rm d}$ and $N_{\rm u}$ are the number of detected and missed systems, respectively (see Table 3).

In order to establish the distribution of orbital periods, i.e., the frequency of binary systems in each $\log P$ bin, we convert the intervals of projected separation into bins of orbital periods. Angular separations ρ are statistically corrected for projection effects to yield the semi-major axis

Table 3. Binary frequency (see text).

$\log P_{\rm orb}$	4.4–4.9	4.9–5.4	5.4–5.9	5.9–6.4	6.4–6.9	days
Semi-major axis	18–39	39–86	86–183	183–394	394–852	AU
Sep. range	0.08–0.17	0.17–0.38	0.38–0.81	0.81–1.74	1.74–3.76	$''$
$\Delta m_{\rm max}$	2.2	3.0	4.5	6.7	7.2	mag
$q_{\rm min}$	0.50	0.40	0.20	<0.1	<0.1	
$N_{\rm detect.}$ $[q_{\rm min}, 1.0]$	4	6	5	6	4	
$N_{\rm undetect.}[0.1, q_{\rm min}]$	6.4	5.4	0.95	0	0	
$N_{\rm tot}$	10.4	11.4	5.95	6	4	
B.F. Praesepe (rms)	7.0 (3.5)	7.7 (3.1)	4.0 (1.8)	4.0 (1.6)	2.6 (1.3)	%
B.F field G dwarfs	5.4	5.3	5.0	4.5	3.9	%
$\log P_{\rm orb} = 4.4$–6.9	**B.F. Praesepe:** 25.3 ± 5.4%			**B.F. field:** 23.8%		

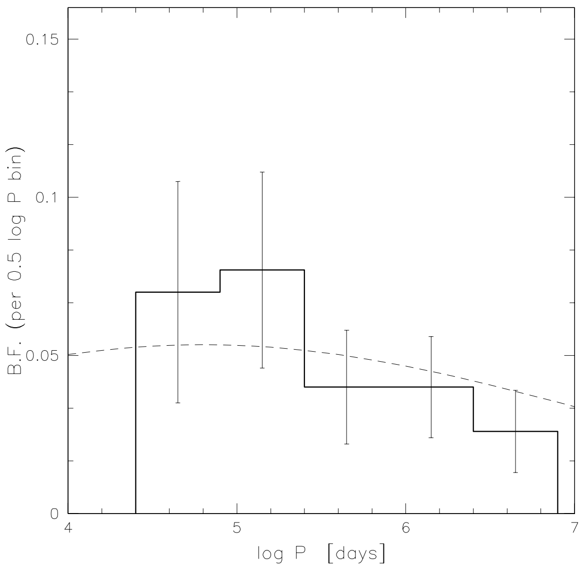

Fig. 3. Distribution of orbital periods for Praesepe binaries (histogram). The error bars represent Poisson noise (see text). The dashed curve is the orbital period distribution of field G dwarf binaries as derived by DM91.

according to: $\log a = \log(\rho \times d) + 0.1$ (DM91), where $d = 180$ pc is the distance to the Praesepe cluster. Kepler's 3rd law with an average mass of 1.3 $M_\odot$ for the system yields the corresponding range of orbital periods (see Table 3).

The last lines of Table 3 list and also Fig. 3 illustrates the derived frequency of Praesepe low-mass binaries in each $\log P$ bin between 4.4 and 6.9 (P in days), as compared to the frequency of G dwarf binaries over the same separation range[1]. Even though the statistical uncertainties in each bin are somewhat large, especially at the shortest orbital periods where the incompleteness correction is significant, the overall binary frequency appears to be very similar among the solar-type Praesepe stars and the field G dwarfs, amounting to 25.3 ± 5.5% and 23.8%, respectively, for the 4.4–6.9 range in $\log P$. Restricting the comparison to the range of orbital periods not affected by detection biases ($\log P$ from 5.4 to 6.9), the BF amounts to $10.7 \pm 2.6\%$ for Praesepe stars compared to 13.4% for field dwarfs. We thus conclude that the frequency of long period binaries among Praesepe G and K stars is indistinguishable from that measured among the G field dwarfs by DM91. This conclusion seems to apply to short-period systems as well ($\log P \leq 4.0$) as Mermilliod's & Mayor's (1999) investigation of spectroscopic binaries in the Praesepe cluster yields $BF = 25 \pm 5\%$, as compared to 21% for field dwarfs.

Praesepe has nearly the same age as the Hyades cluster. Unfortunately, comparison of the BF between the two clusters is limited by the fact that there is only a slight overlap in the separation ranges covered by Patience et al.'s (1998) survey in the Hyades and ours in Praesepe. In the 15–50 AU common range of semi-major axes, we detect 8 companions, i.e. an observed companion fraction of $5.3 \pm 1.9\%$. In the same separation range, Patience et al. (1998) detected 9 companions, out of which 3 would not have been detected in our survey given their flux ratios. This amounts to a companion star fraction of $3.7 \pm 1.5\%$, less than 1σ lower than our Praesepe estimate. Thus, within this restricted range of orbital periods, we do not find any significant difference between Hyades and Praesepe binary fraction, though this conclusion is obviously based on small number statistics.

4. Discussion

In this section, we first briefly review current observational results on the statistics of binary frequency in young clusters and associations, including results from both this and previous papers of this series and other published work. The comparative analysis of the properties of binary populations in different environments and at various evolutionary stages provides constraints on binary formation models, which are discussed below with the emphasis on the difficulties that are encountered by the various formation scenarios. The discussion is restricted to visual ($a \sim 20$–1000 AU), low-mass binaries ($\sim$0.5–1.1 $M_\odot$) that are resolved by high angular resolution techniques.

[1] As in our previous paper on the Pleiades (Bouvier et al. 1997), we define the binary frequency, B. F., as the number of binary orbits divided by the number of primaries in the sample. This is equivalent to the companion star fraction, $csf = (B + 2T)/(S + B + T)$, where S, B, and T are single, binary, and triple systems, respectively.

4.1. Binary statistics in clusters and associations

The three young clusters we surveyed for low-mass binaries, IC 348 (~2 Myr, Duchêne et al. 1999), the Pleiades (120 Myr, Bouvier et al. 1997), and Praesepe (700 Myr), have been observed with the same instrumentation, thus resulting in similar detection biases. Moreover, the results have been analyzed in a consistent way, in particular with regard to the incompleteness corrections. The three clusters are found to exhibit identical binary frequencies over the $\log P$ range ~4.5–7.0, $<BF> \sim 0.25 \pm 0.05$, which is also consistent with the BF measured for solar-type field dwarfs in the same range of orbital periods ($BF \sim 0.24$, DM91). Similar results have been obtained for other clusters, Orion (~2 Myr, Prosser et al. 1994; Petr et al. 1998; Simon et al. 1999), Alpha Persei (~80 Myr, Eislöffel et al. 1999), and the Hyades (~600 Myr, Patience et al. 1998) – all of which exhibit a low-mass BF in a restricted $\log P$ range that is consistent with the field dwarf BF when the results are analyzed in a uniform way (see Duchêne 1999).

Since the ages of these clusters cover a huge range from 2 to 700 Myr, the results suggest that low-mass binaries are formed at a very early stage of cluster evolution (at an age ≤1 Myr) and that the binary fraction does not evolve much thereafter until the cluster eventually dissolves into the field (≃1 Gyr). The lack of a significant evolution of the binary population during the secular dynamical evolution of a cluster is consistent with recent numerical simulations (e.g. Kroupa 2000).

Note, however, that this conclusion may not hold for more massive and/or spectroscopic binaries. Abt & Willmarth (1999) have reported marginal evidence for a BF that increases with a cluster's age, from the Orion Nebula Cluster to Praesepe, for spectroscopic binaries with A-type primaries. They interpret this trend as the possible signature of binary formation by capture in evolving clusters and/or preferential escape of single stars during the secular dynamical evolution of clusters (de la Fuente Marcos 1997). No such trend is seen for low-mass wide binaries.

Another general result is that pairs of nearly coeval clusters (e.g., IC348 and Orion, Alpha Persei and the Pleiades, Praesepe and the Hyades) not only exhibit similar fractions of low-mass visual binaries over the separation range probed by adaptive optics and speckle techniques (~20–1000 AU), but the distribution of orbital periods is consistent as well, with admittedly large uncertainties in the shape of the $\log P$ distribution (see Fig. 3). These similarities suggest that either all these clusters were formed under very similar conditions and have evolved in the same way, or else the binary content of clusters and their properties depend only weakly on initial conditions.

In marked contrast with the results obtained for cluster binaries, the binary frequency in low-density star forming associations, most notably the Taurus-Auriga cloud, is higher by a factor of about 2 than that observed in both clusters and field solar-type stars (Leinert et al. 1993; Ghez et al. 1993). Ghez (2001) also reported a significant difference between the $\log P$ distributions of binaries in clusters and those in associations, the latter harbouring a larger fraction of wider binaries than the former.

The different properties of binary populations in clusters and associations can be a signature of different formation mechanisms in these environments (e.g., Durisen & Sterzik 1995). Alternatively, if one assumes a universal formation mechanism that yields the same initial BF in clusters and associations, the observed differences could reflect dynamical processes acting very early-on, such as the rapid disruption of wide primordial binaries in clusters through gravitational encounters (e.g. Kroupa et al. 1995). We discuss these two possibilities in turn below.

4.2. A universal mechanism for binary formation?

Among the various possible ways of forming low-mass binaries, tidal capture has been shown to be inefficient even in the densest protostellar clusters (Clarke & Pringle 1991; Kroupa 1995; Clarke 2001) and fission of massive protostars or protostellar disks, which could conceivably yield the tightest binaries, seems to be prevented by the development of bar-like instabilities (Durisen et al. 1986; Bate 1998). Therefore, multiple fragmentation during protostellar collapse appears today to be the most promising mechanism for creating wide multiple systems (Bodenheimer 2001).

Recent collapse calculations indicate that the likely output of multiple fragmentation is the formation of small-N protostellar aggregates, where $N \simeq 3$–10 (e.g., Burkert et al. 1997; Klessen & Burkert 2000). These aggregates experience rapid dynamical decay and eventually leave a bound binary system, while other fragments are dynamically ejected mostly as single remnants (e.g., McDonald & Clarke 1993, 1995; Sterzik & Durisen 1998). Since few-body interactions occur on a small scale within protostellar aggregates ($r \sim$ a few 100 AU) and on a very short time scale (~10^4 yr), the resulting primordial binary fraction is not expected to depend strongly upon the global properties of the star forming region.

The fraction of primordial binaries that results from the dynamical decay of protostellar aggregates is usually identified with the high BF observed in loose associations like Taurus. Then, the lower BF measured in clusters is thought to result from the rapid disruption of primordial binaries, through destructive gravitational encounters that occur on a time scale of less than 1 Myr (e.g., Kroupa et al. 1999). Since the rate of gravitational encounters scales with the local stellar density, this scenario conceivably accounts for the observed trend of lower binary fractions in denser star forming regions (Patience & Duchêne 2001), and it is further supported by the paucity of wide binaries observed in the ONC (Scally et al. 1999) and, more generally, in young open clusters (Ghez 2001).

This mode of binary formation is not exempt from difficulties, however. One issue is whether the Taurus binaries can be regarded as representative of a universal population of primordial binaries. The frequency of primordial binaries that is expected from the decay of small-N aggregates is of order of $BF_{\rm p} \simeq 1 / (N{-}1)$, i.e., at most 50% for $N = 3$. This is significantly lower than the BF measured in the Taurus association, which amounts to $\geq$80% for stars in the mass range $\sim$0.3–1.2 $M_\odot$, with little dependence on the primary mass (Leinert et al. 1993). This discrepancy could be solved if single fragments that were dynamically ejected from protostellar aggregates had escaped from their birth place. With typical ejection velocities of 3–4 km s^{-1} (Sterzik & Durisen 1995), they would be located a few parsecs away from their birth site at an age of 2 Myr, i.e., a few degrees away from the Taurus stellar groups (Gomez et al. 1995). A widely distributed population of X-ray emitting T Tauri stars has been detected with ROSAT over the Taurus cloud (Wichmann et al. 1996, 2000; Frink et al. 1997), but these stars do not seem to be preferentially single (Köhler & Leinert 1998), as would be expected if they were escapers.

An intriguing possibility is that the ejected fragments are very low mass, indeed substellar, objects (Sterzik & Durisen 1999; Clarke & Reipurth 2001) that might so far have escaped detection in the Taurus cloud. Although the search for brown dwarfs in Taurus has been somewhat disappointing (Luhman 2000), it has only concentrated on very limited areas centered on the small Taurus stellar groups. A widely distributed population of (single) substellar objects over the Taurus cloud could reconcile the high BF frequency measured for Taurus *stars* with the lower BF expected from the decay of small-N aggregates, which includes both stellar and substellar fragments. In support of this hypothesis, we note that current determinations of the substellar IMF do indicate that isolated brown dwarfs are numerous in clusters (e.g. Luhman et al. 2000; Moraux et al. 2001) and appear to be preferentially single objects (Martín et al. 1999). If originally ejected from small-N aggregates, substellar fragments may be more easily retained in the deep potential well of dense clusters than in loose associations (de la Fuente Marcos & de la Fuente Marcos 2000), which might explain why they have not been found in the central regions of Taurus.

Another aspect of the models that is challenged by the observations is whether the lower BF of clusters compared to associations can be understood as the mere result of the disruption of primordial binaries. Models that describe the dynamical evolution of primordial binaries in young clusters, starting from an initial distribution similar to the one observed in Taurus, show that the destruction rate of wide primordial binaries ($\log P \sim$ 5–7) is a sensitive function of the initial stellar density (e.g., Kroupa 1995; Kroupa et al. 2000). Yet, all clusters studied so far appear to harbour the same BF to within a few percent in this $\log P$ range. The lack of dispersion in the BF measured for clusters is then surprising, given that it is unlikely all clusters surveyed so far have formed with precisely similar densities. For instance, the stellar density in the Trapezium cluster is of order of 5×10^4 pc^{-3} (McCaughrean & Stauffer 1994) whereas, at a similar age, it is about 5×10^3 pc^{-3} in IC 348 (Herbig 1998). If gravitational encounters leading to the disruption of primordial binaries are the dominant mechanism that yields a lower BF in clusters, one would expect to observe somewhat different binary fractions between clusters themselves.

Hence, while scenarios of binary formation and evolution that assume an initially large fraction of primordial binaries in all star forming regions, followed by a rapid erosion of the binary population in dense clusters, have recently become quite popular, it remains to be seen whether the difficulties outlined above can be solved.

4.3. Do local conditions impact on the binary formation process?

As an alternative to a universal formation mechanism, it is probably too early yet to rule out binary and, indeed, single star formation as the direct outcome of cloud collapse and fragmentation, without going through the transient episode of small-N protostellar aggregates. Unfortunately, the theory and simulations of fragmentation are not yet predictive enough, and the final product of protostellar collapse can depend sensitively on initial conditions (see Bodenheimer et al. 2000 for a review), e.g., the radial density profile of the parental cloud (Burkert et al. 1997), its temperature (Sterzik & Durisen 1995), turbulence (Klein 2001), the magnetic field (Boss 2001), etc. The large scale environment, such as cloud-cloud collisions, or other external impulsive processes, such as supernova blasts, may also impact on the fragmentation process (Whitworth 2001). Hence, one might expect that different initial conditions in star forming regions lead to significant variations in the properties of the young stellar populations they harbour.

Since the initial conditions that led to star formation in a given molecular cloud are usually poorly known, it is somewhat difficult to constrain this alternative mode of binary and single stars formation with current observations. As noted above, however, one of the striking results of the recent binary surveys is the quasi-universality of the BF in clusters, which all appear to harbour the same fraction of solar-type, wide ($sep \geq 20$ AU) binaries to within the statistical uncertainties. This suggests that the fragmentation process, if directly responsible for the formation of binary systems, might not be as sensitive to local conditions as numerical simulations tend to indicate. On the other hand, while the results for cluster binaries are homogeneous and similar to those obtained for the field binary population, the much larger BF observed in the Taurus cloud would seem to suggest that gross variations in the local conditions do impact on the fragmentation process.

In this respect, it is interesting to note that binary frequency is not the only difference that exists between the stellar populations of the Orion cluster and Taurus association. Significant differences have also been found in the distribution of stellar angular momentum among their low-mass T Tauri stars (Clarke & Bouvier 2000), and in the distribution of their stellar masses, with Taurus harbouring apparently both fewer high-mass stars and fewer very-low mass objects than Orion (Hartmann& Kenyon 1995; Luhman 2000). It is tempting to think that the differences observed in the fundamental properties (mass and angular momentum distributions, binary frequency) of the Orion and Taurus populations are causally related and point to a common origin that reflects intrinsically different modes of star formation in clusters and in associations (e.g., Myers 1998; Williams et al. 2000; Motte & André 2001).

5. Conclusion

From an adaptive optics imaging survey of 149 G and K-type primaries of the Praesepe cluster, we find that solar-type cluster members harbour the same proportion of close visual binaries as do G-type field dwarfs. Long lived open clusters, such as Praesepe, probably started their evolution as extremely dense protostellar clusters. Yet, only about 10% of the field population is thought to result from the dissipation of such rich clusters. At the other extreme, Taurus-like regions of distributed star formation have very low star forming efficiencies. Hence, as recently advocated by Adams & Myers (2001), most field stars must have been born in stellar groups which dissipate in a few million years, corresponding to initial conditions somewhat intermediate between dense protostellar clusters destined to become young open clusters and loose associations. The very similar binary fraction measured for solar-type stars in young open clusters (Praesepe, Pleiades, Alpha Per) and in the field thus suggest that the formation and evolution of low-mass binaries are not very sensitive to local conditions.

The main limitation of studies like the present one which aim at constraining the star formation process through the investigation of young binaries is that they have been mostly concerned with low-mass systems so far and somewhat neglected higher mass binaries (see, however, Preibisch et al. 1999; Garcìa & Mermilliod 2001; Duchêne et al. 2001). If multiple fragmentation of collapsing clouds is the dominant mode for the formation of multiple stellar systems, the mass distribution of fragments in small protostellar groups may largely determine the resulting binary frequency for a given primary mass. For instance, we argued above that the high *BF* observed for T Tauri stars in Taurus might merely be the result of neglecting a putative population of single brown dwarfs distributed over the cloud. In regions where high mass stars are formed, such as in Orion, more single ejected fragments would be of solar mass or so, thus resulting in a lower binary fraction among low mass stars. The investigation of such causal relationships between the fundamental properties of young stars, e.g., between binary fraction and the mass function, requires the consideration of the whole stellar population of the star forming region with a complete census of multiple systems at all primary masses, which is not available today for any star forming region.

A promising new way to better understand the formation of multiple systems is to investigate, in different environments, extremely young stellar objects still embedded in their natal cloud at the end of the protostellar collapse. The high degree of multiplicity of such Class 0 and Class I "protostellar" sources starts to be revealed from high angular resolution studies in the millimeter range (Looney et al. 2000). The advent of adaptive optics systems equipped with near-IR wavefront sensors on large telescopes will now open the way to large scale surveys of embedded protobinaries with a tenfold increase in angular resolution compared to current millimeter studies, reaching separations as small as a few astronomical units. Such studies will provide unprecedented details on the fragmentation process at a very early stage of evolution of young systems, before any significant dynamical evolution of protostellar systems has occurred.

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