High-order multiplicity of PMS stars: results from a VLT/NACO survey

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Summary. We report on our survey for high-order multiplicity among wide visual Pre-Main Sequence (PMS) binaries conducted with NACO at the VLT. The sample comprises 55 T Tauri systems from various star-forming regions. Of these systems, 8 are found to be triple and 7 quadruple. The corresponding degree of multiplicity among binaries (number of triples and quadruples divided by the number of systems) is 27.3 ±7.0% in the projected separation range $0\farcs07$-$12''$, with the largest contribution from the Taurus cloud. The observed frequency agrees with results from previous multiplicity surveys within the uncertainties, but seems lower than current predictions from numerical simulations of multiple star formation. CTTS-WTTS type statistics among the components of multiple systems is such that half of the systems have mixed-types (i.e. at least one component with a different type), and close pairs are predominantly WTTS pairs. The degree of multiplicity may be higher if we could include spectroscopic components.

1 Observation and Data Reduction

Observations were carried out during two periods. A first set of 37 objects was observed from October 22^{th} 2002 to March 26^{th} 2003 while observations of another 21 systems were conducted from April 4^{th} 2004 to June 17^{th} 2004 (Table 1). A report about the first data set has already been published in [1]. Each object of the first set was observed through the three narrow-band filters Brγ (2.166 μm, 0.023 μm width), H_2 (2.122 μm, 0.022 μm width), and [FeII] (1.644 μm, 0.018 μm width). Objects of the second set were observed only through the [FeII] filter. The combination of natural guide star magnitude and seeing lead to AO-corrections with typical Strehl ratios of $\sim$30% in Brγ, which provides mainly diffraction-limited cores. Data reduction was performed in the usual way: sky subtraction, flat-fielding, bad-pixels and cosmics corrections.

2 Results

All candidate triples/quadruples of our survey are shown in Fig. 1.

Table 1. Observed sample of wide PMS binaries.

Name	R.A.	Decl.	Cloud	Dist.	V	K	Obs. date
	[J2000.0]			[pc]	[mag]	[mag]	[UT]
LkHα 262/263	02 56 08.4	+ 20 03 40	MBM 12	275	14.6	9.5	2002 Nov 14
J 4872	04 25 17.6	+ 26 17 51	Taurus	142	13.0	8.6	2002 Nov 13
FV Tau	04 26 53.6	+ 26 06 55	Taurus	142	15.4	7.4	2002 Nov 13
UX Tau	04 30 04.0	+ 18 13 49	Taurus	142	10.7	7.6	2002 Oct 22
DK Tau	04 30 44.3	+ 26 01 25	Taurus	142	12.6	7.1	2002 Nov 13
HK Tau	04 31 50.6	+ 24 24 18	Taurus	142	15.0	8.6	2003 Feb 17
LkHα 266	04 31 57.8	+ 18 21 37	Taurus	142	14.6	8.5	2002 Oct 22
GG Tau	04 32 30.3	+ 17 31 41	Taurus	142	12.3	7.4	2002 Oct 22
UZ Tau	04 32 43.0	+ 25 52 32	Taurus	142	12.9	7.4	2002 Nov 14
HN Tau	04 33 39.3	+ 17 51 53	Taurus	142	13.7	8.4	2003 Feb 18
IT Tau	04 34 13.9	+ 26 11 42	Taurus	142	14.9	13.7	2003 Feb 19
L1642-1	04 35 02.3	− 14 13 41	L1642	100	13.7	7.7	2003 Feb 20
RW Aur	05 07 49.6	+ 30 24 05	Auriga	142	10.3	7.0	2002 Nov 17
CO Ori	05 27 38.3	+ 11 25 39	Orion	460	10.6	6.5	2002 Nov 13
AR Ori	05 35 54.1	− 05 04 14	Orion	460	13.9	9.8	2003 Feb 19
LkHα 336	05 54 20.1	+ 01 42 56	L1622	460	14.4	9.2	2003 Feb 19
CGHα 5/6	07 31 37.4	− 47 00 22	Gum Neb.	450	14.2	9.1	2002 Dec 23
PHα 14	08 08 33.8	− 36 08 10	Gum Neb.	450	15.8	10.3	2002 Dec 23
PHα 30	08 12 05.6	− 35 31 45	Gum Neb.	450	15.1	12.2	2003 Jan 17
vBH 16	08 27 39.0	− 51 09 50	Gum Neb.	450	15.6	9.3	2003 Jan 27
PHα 51	08 15 55.3	− 35 57 58	Gum Neb.	450	15.9	11.1	2003 Jan 23
HD 76534	08 55 08.7	− 43 28 00	DC164.3+1.5	830	8.0	7.8	2003 Jan 20
SX Cha	10 55 59.9	− 77 24 41	Cha I	160	14.7	8.7	2003 Jan 22
Sz 15	11 05 41.5	− 77 54 44	Cha I	160	...	10.6	2003 Jan 22
ESO Hα 281	11 07 04.0	− 76 31 45	Cha I	160	...	9.7	2003 Jan 22
Sz 19	11 07 20.7	− 77 38 07	Cha I	160	10.9	6.2	2003 Jan 20
VV Cha	11 07 28.4	− 76 52 12	Cha I	160	14.8	9.5	2003 Feb 19
VW Cha	11 08 01.8	− 77 42 29	Cha I	160	12.6	7.0	2003 Feb 20
Glass I	11 08 15.4	− 77 33 54	Cha I	160	13.3	6.9	2003 Feb 20
CoD −29 8887	11 09 14.0	− 30 01 39	TW Hya	50	11.1	6.7	2003 Jan 20
Sz 30	11 09 12.3	− 77 29 12	Cha I	160	13.2	9.0	2003 Jan 20
Hen 3-600	11 10 28.9	− 37 32 05	TW Hya	50	12.1	6.8	2003 Feb 20
Sz 41	11 12 24.5	− 76 37 06	Cha I	160	11.6	8.0	2003 Jan 22
CV Cha	11 12 27.8	− 76 44 22	Cha I	160	11.0	6.9	2003 Jan 20
Sz 48	13 00 53.2	− 77 09 10	Cha II	178	...	9.5	2004 Apr 06
BK Cha	13 07 09.3	− 77 30 24	Cha II	178	15.2-16.5	8.4	2004 Apr 03
Sz 60	13 07 23.4	− 77 37 23	Cha II	178	...	9.5	2004 Apr 05
Sz 62	13 09 50.7	− 77 57 24	Cha II	178	15.6	9.1	2003 Jan 22
Herschel 4636	13 57 44.1	− 39 58 45	NGC 5367	630	9.7	7.2	2003 Jan 20
ESO Hα 283	15 00 29.6	− 63 09 46	Circinus	700	...	10.3	2003 Mar 26
Sz 65	15 39 27.7	− 34 46 17	Lupus I	190	12.7	8.0	2004 Apr 06
Sz 68	15 45 12.9	− 34 17 31	Lupus I	190	10.4	6.5	2004 Apr 06
HO Lup	16 07 00.6	− 39 02 19	Lupus III	190	13.0	8.6	2004 Apr 06
Sz 101	16 08 28.4	− 39 05 32	Lupus III	190	15.5	9.4	2004 Apr 10
Sz 108	16 08 42.7	− 39 06 18	Lupus III	190	13.1	8.8	2004 Apr 10
Sz 120	16 10 10.6	− 40 07 44	Lupus III	190	7.1	6.2	2004 Apr 10
WSB 3	16 18 49.5	− 26 32 53	Ophiuchus	160	...	9.3	2004 May 01
WSB 11	16 21 57.3	− 22 38 16	Ophiuchus	160	18.5	10.1	2004 Jun 18
WSB 20	16 25 10.5	− 23 19 14	Ophiuchus	160	13.4	7.5	2004 May 01
WSB 28	16 26 20.7	− 24 08 48	Ophiuchus	160	...	9.5	2004 May 01
SR 24	16 26 58.8	− 24 45 37	Ophiuchus	160	...	7.1	2004 May 01
Elias 2-30	16 27 10.2	− 24 19 16	Ophiuchus	160	14.1	6.7	2004 May 01
WSB 46	16 27 15.1	− 24 51 39	Ophiuchus	160	...	9.4	2004 May 01
Haro 1-14c	16 31 04.4	− 24 04 32	Ophiuchus	160	12.7	7.8	2004 May 01
ROX 43	16 31 20.1	− 24 30 05	Ophiuchus	160	10.6	6.7	2004 May 04
Elias 2-49	16 40 17.9	− 23 53 45	Ophiuchus	160	8.9	5.5	2004 May 01
HBC 652	16 48 18.0	− 14 11 15	L162	160	13.5	7.5	2004 May 01
B59-1	17 11 03.9	− 27 22 57	B59	160	...	8.1	2004 May 01

2.1 Chance projections

In order to discriminate systems whose components are gravitationally bound from those that are only the result of chance projection, we used two approaches. The first one is a statistical approach which consists of estimating the probability that the companions we found are physically bound to their primary based on the local surface density of background/foreground sources in each field. The details of the method are reported in Correia et al. [2]. We found that all but three of the companions detected in our survey have probabilities for chance projection well below the 1% level. This means that most are very likely bound to their systems, although considering probabilities to individual sources is known to be prone to errors (see e.g. [3] for a discussion). The candidate companions (ESO Hα 283 C, ESO Hα 283 D, and PHα 30 C) show a non-negligible probability of being chance projections, with probabilities of 2.9%, 37%, and 8.8%, respectively. The second approach is an attempt to determine the nature of the new or so far unconfirmed candidate companions through the use of a color-color J-H/H-K diagram and has already been shown [1]. Although spectroscopy and common proper-motion

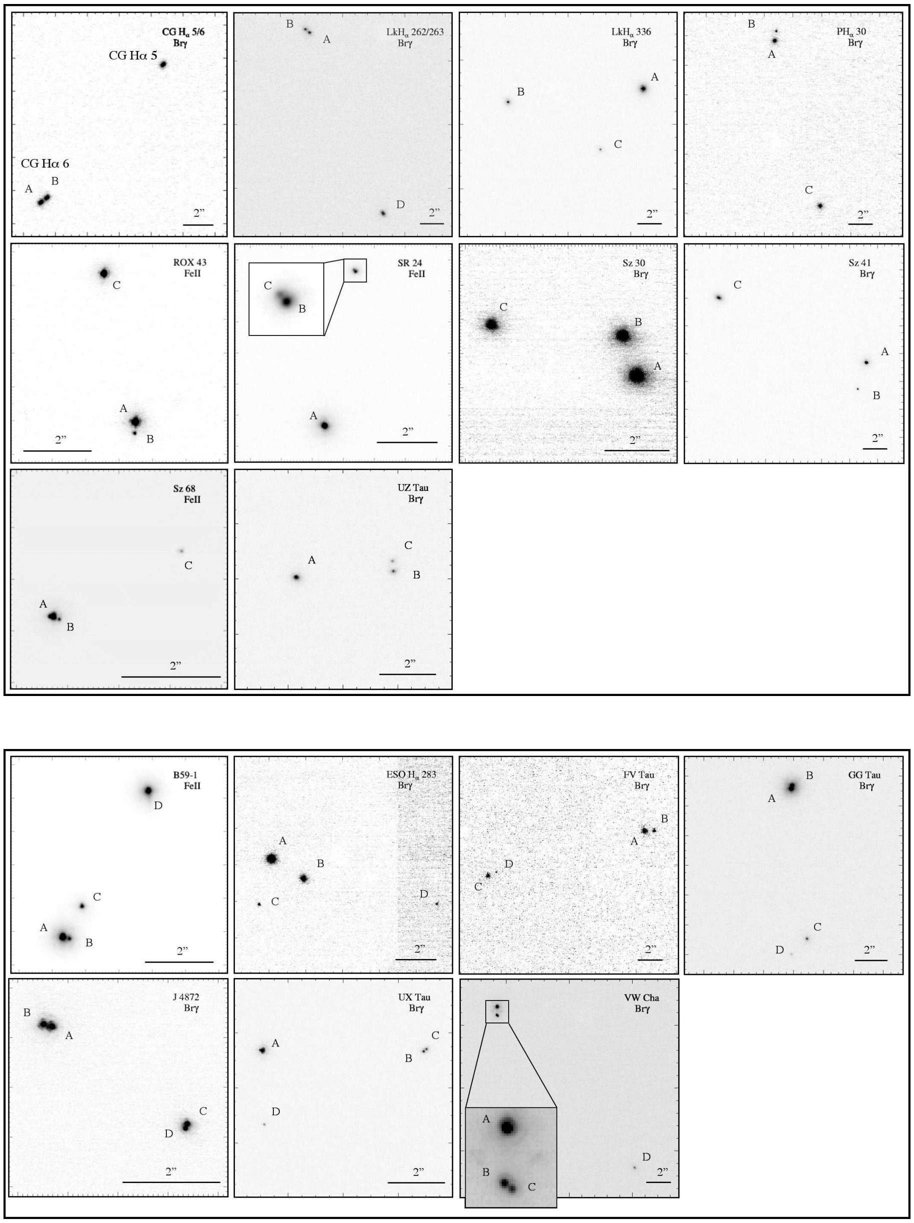

Fig. 1. Apparent triple (upper panel) and apparent quadruple (lower panel) systems detected in our VLT/NACO survey, showing the adopted nomenclature. North is up, east is left.

evidence are necessary in order to unambiguously identify any chance projection, we conclude from the above analysis that PHα 30 C, ESO Hα 283 C and ESO Hα 283 D are consistent with being projected background stars. We will not consider further these companion candidates in our analysis.

2.2 Multiplicity statistics

Among the 58 wide binaries surveyed, two are Herbig Ae/Be binary stars (HD 76534 and Herschel 4636) and one is likely to be a foreground (older) object (Sz 15). We excluded these systems from the statistics and take into account an additional faint companion known from other studies but undetected here for sensitivity reasons (LkHα 262/263C that was found recently as an edge-on disk [4]). We have thus 40 binaries, 8 triples and 7 quadruples. We did not attempt to correct for incompleteness. Therefore, the number of triple/quadruple systems identified should be considered as lower limits, given our sensitivity limits (discussion in [2]).

In order to characterize the multiplicity, we here define a quantity that we call *degree of multiplicity per wide binary* (or a multiplicity frequency per wide binary, MF/wB) :

$$MF/wB = \frac{T + Q + ...}{wB + T + Q + ...}, \qquad (1)$$

where wB represents the number of wide binaries (with projected component separations typically $\gtrsim 1''$), T the number of triples and Q the number of quadruples. This quantity here equals 27.3 ±7.0%.

The question that arises naturally is the one about the multiplicity frequency in different clouds, although the latter is of lower statistical significance than that of the total sample. The cloud with the highest value is Taur-Aur (5 triples-quadruples/10 wide binaries, MF/wB=50 ±22%), followed by Cha I (3/10, MF/wB=30 ±17%) and Ophiuchus (2/10, MF/wB=20 ±14%).

We considered a distance-limited sample in order to ensure a similar range of linear projected separations probed. Limiting ourselves to only the wide binaries of the sample at distance 140-190pc (i.e. for which multiples have companions in the separation range 10/14 AU - 1700/2300 AU corresponding to a projected separation between $0''\!.07$ and $12''$), one obtains MF/wB=28.6 ±8.3% (30 binaries, 6 triples, 6 quadruples).

Comparison with previous multiplicity surveys

We compared our result with the proportion of triples/quadruples found in previous multiplicity surveys with similar separation range and sensitivity. These are the studies by Leinert et al. [5] and Köhler & Leinert [6] in Tau-Aur, Ghez et al. [7] in Chamaeleon, Lupus and CrA, and Köhler et al. [8] in the Scorpius-Centaurus OB association. We based this comparison on the multiplicity frequency per wide binary, as defined above (Eq.1), including in these surveys only binaries with separations larger than about 1″ (i.e. ∼140 AU). On our side, we had to restrict the separation range to the resolution achieved by those surveys (i.e. typically ∼0.″1-12″ at 140 pc that is ∼14-1700 AU). This means that, when considering the systems from the distance-limited sample as defined above, we had to discard two companions (VW Cha C and SR 24 C, with projected separations 0.″11 and 0.″08, respectively), ending up with MF/wB=26.2 ±7.9% (31 binaries, 6 triples, 5 quadruples). The result, as summarized in Table 2, is that our newly derived multiplicity agrees with the previous surveys, within the uncertainties.

Comparison with theory

There is a probable overabundance of high-order multiples produced by the current simulations of star formation with respect to current observations. Direct comparison is not possible since theoretical multiplicity frequencies include both, all the binaries with separations $<$ 140 AU, down to $\sim$ 3-5 AU, and wider high-order companions (with separations $\gtrsim$ 2000 AU), unlike the observations. However, we assumed here that the corrections to be applied in order to obtain MF/wB in the same separation range are minor [2]. In the following, we summarize the theoretical studies used for the comparison.

Sterzik & Durisen [9] performed few-body cluster decay simulations. Although that study neglected the effect of remnant molecular gas and disk accretion and treated only the process of dynamical evolution of young small N-body clusters, it yields highly significant and robust statistics since a large number of realizations (10 000) has been computed. A degree of multiplicity of 34% was found. Delgado-Donate et al. [10] modeled the dynamical decay of a large number (a hundred) of small-N (N=5) star-forming clusters including the effects of competitive accretion and dynamical evolution through 3D hydrodynamical simulations with a ∼1AU spatial resolution, and found a rather high multiplicity frequency close to 50%. A similar high frequency of multiple systems was the outcome of two other recent and more sophisticated hydrodynamical simulations. Delgado-Donate et al. [11] simulated the fragmentation of 10 small-scale turbulent molecular clouds and their subsequent dynamical evolution, including this time the effect of accretion disks into the evolution of multiples. Goodwin et al. [12] followed the collapse and fragmentation of 20 dense star-forming cores with a low-level of turbulence. In both cases a high frequency of high-order multiples was obtained (Table 2).

3 CTTS vs WTTS companion statistics

We performed a compilation of T Tauri types for both individual components and pairs of the triple/quadruple systems from the available literature [2]. It turns out that, among the systems with CTTS/WTTS information for each component (8 systems), one half are systems of mixed type (i.e. at least

Table 2. Comparison of the multiplicity frequency per wide binary (MF/wB) of our work with those derived from previous multiplicity surveys among T Tauri stars in the same separation range ∼14-1700 AU, and with recent numerical simulations (bottom part).

Reference	cloud	MF/wB
This work	several	$26.2 \pm 7.9\%$
Leinert et al. (1993)	Tau-Aur	$18.5 \pm 8.3\%$
Koehler et al. (1998)	Tau-Aur	$41.2 \pm 15.6\%$
Ghez et al. (1997)	Cha/Lup/CrA	$13.6 \pm 7.9\%$
Koehler et al. (2000)	Sco-Cen OB assoc.	$26.1 \pm 10.6\%$
Sterzik & Durisen (2003)		34%
Delgado-Donate et al. (2003)		49.8%
Delgado-Donate et al. (2004)		$38.9 \pm 14.7\%$
Goodwin et al. (2004)		$56.3 \pm 18.8\%$

one component with a different type). This is quite in contrast with what is known for binaries (e.g. [13, 14]). Another interesting point is that close pairs are usually non-accreting in these systems. In fact, here almost all pairs with separations $\lesssim 0\farcs3$ (∼50 AU) are WTTS-WTTS pairs. There are two important exceptions : GG Tau AB and UZ Tau BC. However, GG Tau AB is known to be surrounded by a massive circumbinary disk for resplenishment.

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