MULTIPLICITY OF THE MASSIVE STARS IN THE ORION NEBULA CLUSTER AND IMPLICATIONS ON THEIR FORMATION MECHANISM

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Abstract

We present the results of a bispectrum speckle interferometric survey for binaries among the massive stars in the Orion Nebula cluster. Observations of 13 bright cluster members of spectral type O or B reveal 8 visual companions in total. Using the flux ratios of the resolved systems to estimate the masses of the companions, we find that the systems generally have mass ratios below 0.5. Extrapolation with correction for the unresolved systems suggests that there are at least 1.5 companions per primary star on average. This number is clearly higher than the corresponding number for low-mass primaries, suggesting that a different mechanism is at work in the formation of high-mass multiple systems than for low-mass multiple systems.

Key words: Stars: formation – Stars: binaries – Stars: pre-main sequence

1. Introduction

The knowledge of the multiplicity of very young massive stars can provide important information on their formation mechanism, which is still not well understood (cf. Stahler et al. 1999). High-mass stars probably cannot form through gravitational collapse in molecular cloud cores and subsequent accretion like the low-mass stars, because as soon as the stellar core reaches a mass of $\sim 10\,M_\odot$, the radiation pressure on the infalling dust halts the accretion and thus limits the mass (Yorke & Krügel 1977). Bonnell et al. (1998) suggested that high-mass stars form through accretion-induced collisions of protostars in the dense central regions of forming stellar clusters. Their theory predicts that multiple systems should be very common amongst the massive stars, due to frequent tidal encounters.

We have performed a survey for binaries among the massive stars in the very young Orion Nebula cluster (cf. Herbig & Terndrup 1986; Hillenbrand 1997), which can help to test this prediction.

2. Observations

Our sample consists of 13 bright ONC members with spectral types O or B, all located within 20′ of the Trapezium (cf. Table 1). The speckle interferograms were obtained with the 6 m telescope at the Special Astrophysical Observatory (SAO) in Russia in October 1997. We obtained data in the near-infrared H- and K-bands. The diffraction-limited images were reconstructed using the bispectrum speckle interferometry method (Weigelt et al. 1977; Lohmann et al. 1983; Hofmann et al. 1995).

Table 1. Target stars of our survey.

Par #	Brun #	other name	spectral type	V [mag]
1605	388	V372 Ori	B9.5+A0.5	7.98
1744	502	HD 36981	B5	7.89
1772	530	LP Ori	B1.5	8.47
1863	595	θ^1 Ori B	B2	7.96
1865	587	θ^1 Ori A	B0	6.73
1889	612	θ^1 Ori D	B0.5	6.71
1891	598	θ^1 Ori C	O6	5.12
1993	682	θ^2 Ori A	O9.5	5.07
2031	714	θ^2 Ori B	B1	6.41
2074	747	NU Ori	B1	6.84
2271	907	HD 37115	B6	7.00
2366	980	HD 37150	B3	6.56
2425	1018	WH 349	B6	10.64

3. Results

In our speckle reconstructions we were able to resolve visual companions of 7 of the 13 target stars. Figure 1 shows our reconstructed images of the resolved systems. Interestingly, in all resolved systems the K-band flux ratios are quite small, i.e. less than 1/3. This suggests that all these visual companions are much less luminous and thus less massive than the primary stars

3.1. Estimation of companion masses

We have estimated the masses of the companion stars in the resolved systems from the observed K- and H-band flux ratios in our images. These flux ratios, together with the assumption that the companions are very young pre-main sequence stars, can be used to estimate their location in the HRD, what then allows to determine stellar masses by comparison with pre-main sequence tracks. All details of this method can be found in Weigelt et al. (1999) and Preibisch et al. (2000). Since the masses estimated in

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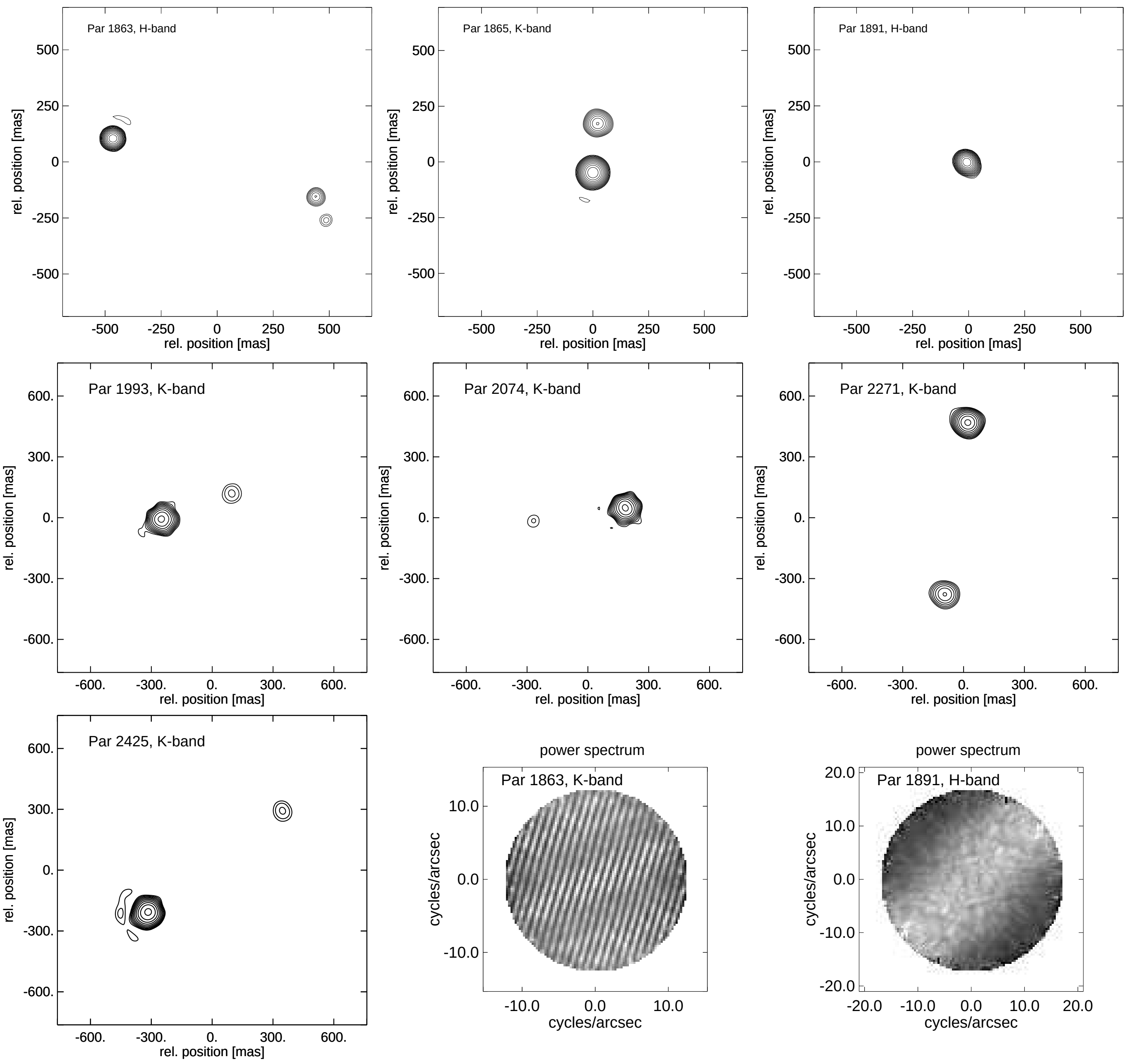

Figure 1. Diffraction-limited images of the resolved systems, reconstructed by the bispectrum speckle interferometry method. The contour level intervals are 0.3 mag, down to 3.6 mag difference relative to the peak intensity. North is up and east is to the left. The two plots in the lowest row show reconstructed power spectra of Par 1863 and Par 1891.

this way might be subject to significant uncertainties, we have also determined firm upper limits for the companion masses by assuming the companions to be main-sequence stars. From the companion masses we have computed the mass-ratios $q := M_c/M_p$, which are listed in Table 2; the upper limits to the mass-ratios are added in brackets.

3.2. The distribution of mass ratios

In Fig. 2 we compare our empiric mass ratio distribution for the ONC stars to several different model distributions: **(a)** to a companion mass function corresponding to the Scalo (1998) field IMF, **(b)** to a flat companion mass function (i.e. all companion masses are equally likely), **(c)** to a distribution that slightly favours massive companions, and **(d)** to a distribution that strongly favours systems with (nearly) equal masses. All details about this distributions can be found in Preibisch et al. (2000).

The observed distribution function for the stars in our sample systematically lies above the simulated distribution functions for models (b), (c), and (d). If we take into account our observational bias against systems with low

Table 2. Summary of all known companions of the observed stars. References: 1: Preibisch et al. (2000); 2: Weigelt et al. (1999); 3: Petr et al. (1998); 4: Bossi et al. (1989); 5: Simon et al. (1999); 6: Abt et al. (1991); 7: Levato & Abt (1976)

Prim. Par	M_p $[M_\odot]$	Comp	ρ [AU]	q	Ref
1605-1	3.5	-2 (spec)		$\sim 0.9-1.0$	7
1863-1	7	-2 (vis)	430	$\sim 0.22\,(<0.71)$	1,2
		-3 (vis)	460	$\sim 0.10\,(<0.50)$	1,2
		-4 (vis)	260	$\sim 0.03\,(<0.29)$	1,5
		-5 (spec)	0.13		6
1865-1	16	-2 (vis)	100	~ 0.25	2,3
		-3 (spec)	1	~ 0.13	4
1891-1	45	-2 (vis)	16	~ 0.12	2
1993-1	25	-2 (vis)	173	$\sim 0.28\,(<0.32)$	1
		-3 (spec)	0.47	~ 0.35	6
2074-1	14	-2 (vis)	214	$\sim 0.07\,(<0.28)$	1
		-3 (spec)	0.35	~ 0.2	6
2271-1	5	-2 (vis)	400	$\sim 0.29\,(<0.96)$	1
2425-1	4	-2 (vis)	388	$\sim 0.04\,(<0.35)$	1

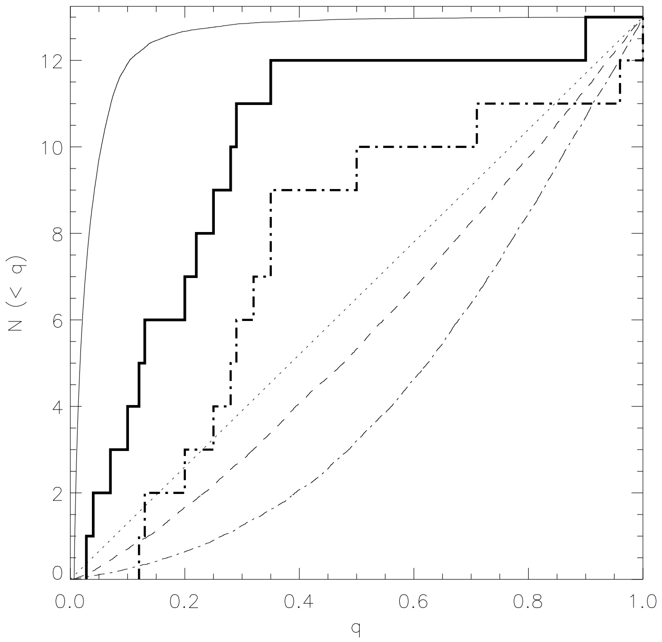

Figure 2. Distribution function of observed mass ratios of the ONC multiple systems (thick solid line) compared to the four model functions discussed in the text: (a): Scalo (1998) field IMF (thin solid line); (b): flat mass ratio distribution (thin dotted line); (c): massive companions slightly favoured (dashed line); (d): systems with equal masses strongly favoured (thin dashed-dotted line). The thick dashed-dotted line shows the observed distribution function based on the upper mass limits for the companions.

mass ratios, which are hard to detect due to contrast problems, the true mass ratio distribution must be even steeper in the low-q part. Thus it seems very likely that the true distribution of mass ratios in our sample is not consistent with any of the models (b), (c), or (d), but might in principle be consistent with the field IMF model (a).

3.3. The binary frequency

It is obvious that our data do not allow us to detect all multiple systems; we can only see those systems which are wide enough and for which the flux ratio is not too low. In order to correct for this effect, we have performed numerous simulations of multiple systems to estimate the fraction of undetected binary systems. We assume that the distribution of orbital periods is the same as found by Duquennoy & Mayor (1994). For the companions we consider either a mass function according the the Scalo (1998) field IMF (model a), or the flat mass distribution (model b). All details of our simulations are described in Preibisch et al. (2000).

The simulation results for the case of the Scalo (1998) field IMF are shown in Fig. 3. In this figure we have marked the region in the flux-ratio versus separation space, which contains those simulated binary system we would be able to resolve in our data. The boundaries of this area are defined by our minimal detectable separation of $\sim$ 33 mas, the maximum separation of $1.75''$ (given by the $3.5'' \times 3.5''$ field of our images which we inspected for companions), and the minimum detectable flux-ratio as a function of the separation. The fraction of binaries which would be detectable in our data can now easily be determined by counting the number of simulated systems within this area. We find that the detectable fractions are 15% and 40% for the Scalo (1998) field IMF and the flat mass ratio distribution, respectively. Thus, we conclude that a detectable fraction of $\sim$ 40% certainly is a conservative upper limit, i.e. that the correction factor to extrapolate from the detected companions to the full population of companions is at least $\sim$ 2.5.

Since we find visual companions to 7 of the 13 target stars, i.e. see an apparent binary frequency of $(54 \pm 14)\%$, the true binary frequency must be very close to 100%. Given the number of 8 detected visual companions, the true number of companions is $\gtrsim$ 20, suggesting a mean number of $\gtrsim$ 1.5 companions per primary star. This is clearly higher than the corresponding number for the low-mass stars in the Orion nebula cluster and the field star population ($\sim$ 0.5 companions per primary star on average; cf. Duquennoy & Mayor 1994; Petr et al. 1998; Simon et al. 1999).

3.4. Multiplicity versus spectral type

A trend for a higher degree of multiplicity among the stars of very early spectral type as compared to the later type stars is apparent in our sample, as can be seen in Fig. 4. The average number of known (visual & spectroscopic) companions per primary is 2.3 times higher among the primaries with spectral type earlier than B3 (11 known

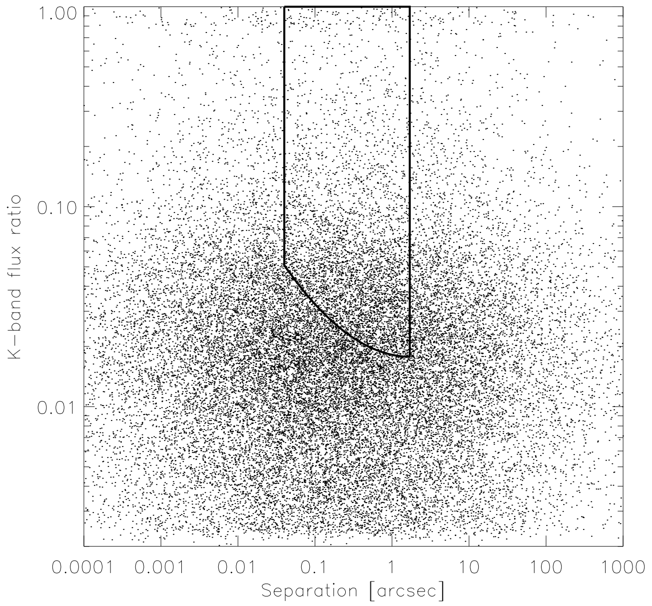

Figure 3. Results of the simulations for the case of companions from the Scalo (1998) field IMF (model a). Each simulated system is shown as a dot in the separation – flux ratio space. The area delimited by the thick line marks the region of systems detectable in our data.

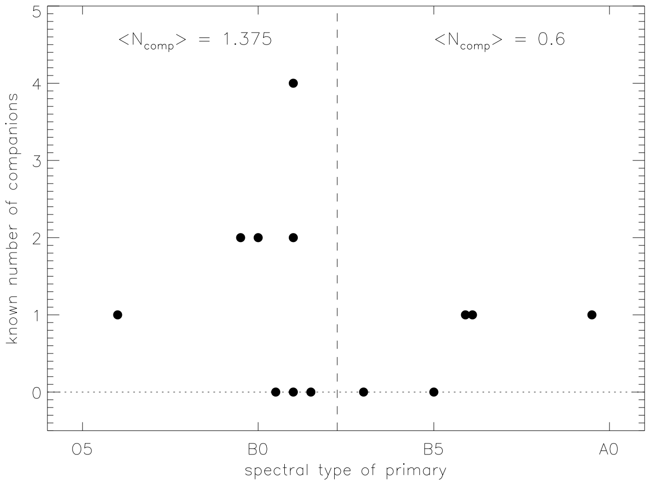

Figure 4. The known number of companions is plotted against the spectral type of the primary.

companions to 8 primaries) than among the later type primaries (3 known companions to 5 primaries).

4. Conclusions

Our data show that the multiplicity of the massive stars in the ONC is quite high ($\gtrsim$ 1.5 companions per primary star on average, after correction for unresolved systems) and significantly ($\sim 3\times$) higher than among low-mass stars. The stars of spectral type earlier than B3 display a higher degree of multiplicity than the later type stars. These findings suggests different formation mechanisms for the high-mass and low-mass multiple systems. The nature of our results seems to support the idea that high-mass ($M > 10\,M_\odot$) stars form through collisions of protostars.

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