Multiplicity of the young O- and B-type stars in the Orion Nebula cluster

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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.

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 the following 13 bright ONC members with spectral types O or B, all located within 20′ of the Trapezium: Par 1605 (V372 Ori), Par 1744 (HD 36981), Par 1772 (LP Ori), Par 1863 (θ^1Ori B), Par 1865 (θ^1Ori A), Par 1889 (θ^1Ori D), Par 1891 (θ^1Ori C), Par 1993 (θ^2Ori A), Par 2031 (θ^2Ori B), Par 2074 (NU Ori), Par 2271 (HD 37115), Par 2366 (HD 37150), Par 2425 (WH 349).

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)).

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. (1999). Since the masses estimated in 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 1; the upper limits to the mass-ratios are added in brackets.

Table 1: Summary of all known companions of the observed stars. References: 1: Preibisch et al. (1999); 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

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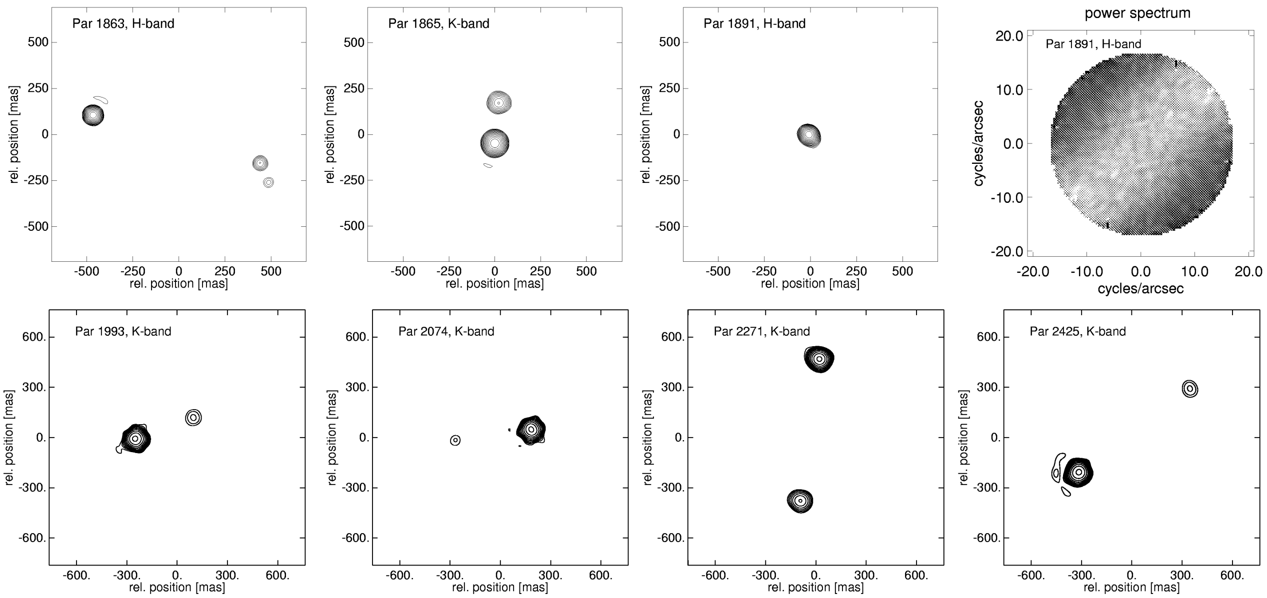

Fig. 1.— Diffraction-limited images of the resolved systems, reconstructed by the bispectrum speckle interferometry method. The contour level intervals are 0.3 mag, down to 3.6 mag difference relative to the peak intensity. North is up and east is to the left. The plot in the upper right corner shows the reconstructed power spectrum of Par 1891.

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. (1999).

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 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. (1999).

We can resolve binary systems with a minimum separation of ~ 33 mas, a maximum separation of $1.75''$ (given by the $3.5'' \times 3.5''$ field of our images which we inspected for companions), and a minimum detectable flux-ratio of about 0.02. The fraction of binaries which would be detectable in our data can easily be determined by counting the number of simulated systems that satisfy these conditions. 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 ~ 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 (~ 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. 3. The average number of known (visual & spectroscopic) companions per primary is 2.3 times

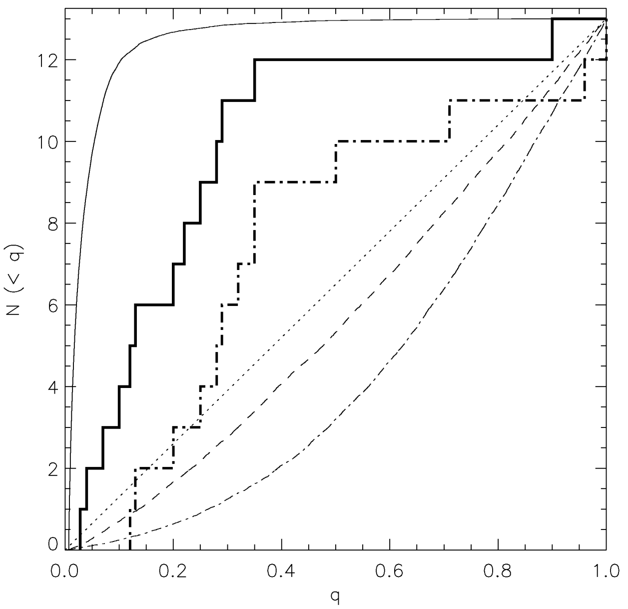

Fig. 2.— Distribution function of observed mass ratios of the ONC multiple systems (thick solid line) compared to the four model functions discussed in the text: (a): Scalo (1998) field IMF (thin solid line); (b): flat mass ratio distribution (thin dotted line); (c): massive companions slightly favoured (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.

higher among the primaries with spectral type earlier than B3 (11 known 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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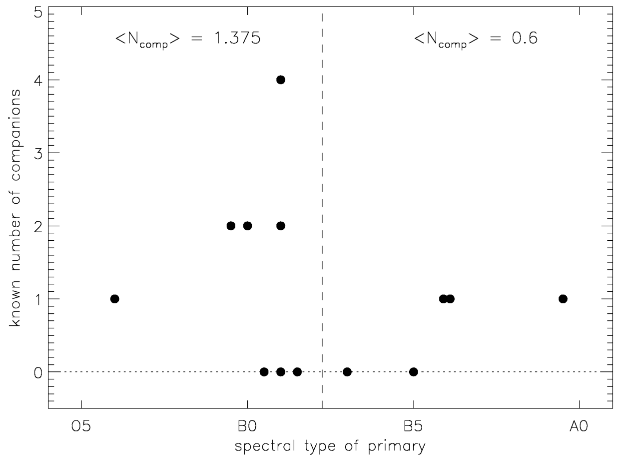

Fig. 3.— The known number of companions is plotted against the spectral type of the primary.

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