New Astronomy 4 (1999) 531–542

New Astronomy

www.elsevier.nl/locate/newast

Multiplicity of the massive stars in the Orion Nebula cluster ☆

Thomas Preibisch[a,1], Yuri Balega[b], Karl-Heinz Hofmann[a], Gerd Weigelt[a], Hans Zinnecker[c]

[a] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*

[b] *Special Astrophysical Observatory, Nizhnij Arkhyz, Zelenchuk region, Karachai-Cherkesia, 357147, Russia*

[c] *Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany*

Received 2 July 1999; accepted 13 September 1999

Communicated by J. Carlstrom

Abstract

We present bispectrum speckle interferometry observations of 13 bright Orion Nebula cluster member stars of spectral type O or B. Diffraction-limited images with a resolution λ/D of 75 mas in the K'-band were obtained with the SAO 6 m telescope. In our speckle images we find 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 1/2. The distribution of mass ratios seems to be consistent with a companion mass function similar to the field IMF. Considering both, the visual and the spectroscopic companions of the 13 target stars, the total number of companions is at least 14. 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 mean number of ~ 0.5 companions per primary star found for the low-mass stars in the Orion Nebula cluster as well as in the field population. This suggests that a different mechanism is at work in the formation of high-mass multiple systems in the dense Orion Nebula cluster than for low-mass stars. © 1999 Elsevier Science B.V. All rights reserved.

PACS: 97.80.-d; 97.21.+a; 97.20.Ec; 97.10.Bt

Keywords: Techniques: interferometric; Stars: individual: Par 1993, Par 2074, Par 2271, Par 2425; Stars: binaries; Stars: pre-main sequence

1. Introduction

The Orion Nebula is an HII region on the near side of a giant molecular cloud, which contains one of the most prominent and nearby ($D \sim 450$ pc) star forming regions (for a review see Genzel & Stutzki, 1989). This star forming region contains a massive cluster of young ($\lesssim 1 \times 10^6$ yr) stars (cf. Herbig & Terndrup, 1986; McCaughrean & Stauffer, 1994; Hillenbrand, 1997), which is known as the Orion Nebula cluster (ONC). The central and most dense part of the ONC, within a few arcmin of the Trapezium system θ^1 Ori, is the Trapezium cluster (cf. Herbig & Terndrup, 1986), which thus can be considered to be the core of the more dispersed ONC. The Orion Nebula is illuminated mainly by the two most massive O-type stars θ^1 Ori C and θ^2 Ori A. The strong stellar wind and the ionizing radiation of these stars have strong effects on the surrounding cloud material. For example, they are responsible for the "proplyds", which are thought to be circumstel-

☆ Based on data collected at the SAO 6 m telescope in Russia.

[1] preib@mpifr-bonn.mpg.de

1384-1076/99/$ – see front matter

PII: S1384-1076(99)00042-1

lar disks around young stars in the process of being dissolved by the strong ionizing flux from these nearby O-stars (Bally et al. (1998); see also Richling & Yorke (1998)). There is evidence for ongoing formation of low-mass as well as high-mass stars in the Orion molecular cloud, especially near the BN/KL nebula, a region which contains deeply embedded protostars and shows evidence for very powerful outflows (cf. Schultz et al., 1999; Salas et al., 1999). This makes the Orion Nebula a perfect laboratory for observations of star formation over the full stellar mass range. As part of an OB association, the ONC does not only contain a large population of young low-mass stars (Hillenbrand (1997); see also Walter et al. (1999) for a review of the low-mass population of the Orion OB1 association in general), but also numerous intermediate- and high-mass ($M_\star \gtrsim 3\,M_\odot$) stars. Hillenbrand (1997) lists 27 O- and B-type stars as ONC members.

Most of the stars in our galaxy are in multiple systems. The binary frequency (i.e. the probability that a given object is multiple; cf. Reipurth & Zinnecker, 1993) for solar type field stars is about 50% (c.f. Duquennoy & Mayor, 1991; Fischer & Marcy, 1992) and roughly 70% for the more massive O- and B-type stars (Mason et al., 1998; Abt et al., 1990). For the specific case of the ONC, a number of searches for binaries have been performed. Abt et al. (1991) and Morrell & Levato (1991) searched for spectroscopic companions among the brightest ONC stars and found spectroscopic binary frequencies of 20% – 30%. Padgett et al. (1997) analyzed HST images of the Trapezium cluster and found 7 new visual binaries. Near-infrared speckle holographic observations of a $40'' \times 40''$ area centred on the Trapezium cluster core performed by Petr et al. (1998) revealed four new binary systems, among them the two Trapezium stars θ^1 Ori A and θ^1 Ori B. Simon et al. (1999) presented near-infrared adaptive optics observations of the Trapezium cluster core and found 17 new visual pairs with sub-arcsecond separations. In the preceding paper to this work (Weigelt et al., 1999) we have presented new near-infrared speckle images of the four Trapezium stars θ^1 Ori A, B, C, and D and detected a close companion of θ^1 Ori C.

The motivation for the survey presented in this paper is based on the following reasons: First, 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). In contrast to low- and intermediate-mass stars, high-mass stars cannot form through gravitational collapse in molecular cloud cores and subsequent accretion, 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. Our survey will help to test this prediction.

Second, a very young ($\lesssim 1$ Myr) cluster like the ONC is especially well suited for the detection of binary companions since any low- or intermediate mass companion will be still in its pre-main sequence phase and thus typically a factor of ~ 2–10 brighter than on the main sequence. This is important because it significantly decreases the enormous brightness contrast between the luminous primary star and its low-mass companion, which usually makes the detection of the companion very difficult or even impossible. The brightness contrast can be reduced even further when going from the optical to the near-infrared. For example, the optical brightness contrast between a $M_\star = 20\,M_\odot$ primary star and a $M_\star = 1\,M_\odot$ main-sequence companion is $\Delta V = 9.2$ mag, whereas the K-band brightness contrast in the case of a 0.3–1 Myr old PMS companion is only $\Delta K = 4.4$–5.4 mag.

2. Observations and data reduction

Our sample consists of 13 bright ONC members with spectral types O or B, all located within 20′ of the Trapezium. Basic information about our target stars is compiled in Table 1. The speckle interferograms were obtained with the 6 m telescope at the Special Astrophysical Observatory (SAO) in Russia in October 1997. The data were recorded through a K'-band filter with central wavelength/bandwidth of 2165 nm/328 nm. The detector used for the observations was our NICMOS-3 camera (HgCdTe array of 256^2 pixels, sensitivity from 1 to

Table 1
Target stars of this study

Par	Brun		SpT	V	K	A_V
1605	388	V372 Ori	B9.5+A0.5	7.98	6.48	1.00
1744	502	HD 36981	B5	7.89	8.22	0.06
1772	530	LP Ori	B1.5	8.47	7.52	1.47
1863	595	θ^1 Ori B	B2	7.96	6.43	1.68
1865	587	θ^1 Ori A	B0	6.73	5.65	1.89
1889	612	θ^1 Ori D	B0.5	6.71	5.69	1.79
1891	598	θ^1 Ori C	O6	5.12	4.41	1.74
1993	682	θ^2 Ori A	O9.5	5.07	4.89	1.12
2031	714	θ^2 Ori B	B1	6.41	6.32	0.73
2074	747	NU Ori	B1	6.84	5.59	2.09
2271	907	HD 37115	B6	7.00	7.12	0.30
2366	980	HD 37150	B3	6.56	7.20	0.05
2425	1018	WH 349	B6	10.64	8.15	2.67

The data are from Hillenbrand (1997) and Brown et al. (1994).

2.5 μm, frame rate 2 frames/s). The pixel size was 30.5 mas and the field of view was $\sim 8'' \times 8''$. The seeing was $1.5'' - 2''$. For each object 230 to 600 speckle interferograms were recorded with exposure times between 150 and 300 ms.

The diffraction-limited images were reconstructed using the bispectrum speckle interferometry method (Weigelt, 1977; Lohmann et al., 1983; Hofmann et al., 1995). The object visibility functions were determined with the speckle interferometry method (Labeyrie, 1970). The bispectrum of each frame consisted of 30 to 100 million elements. The resulting images have a diffraction-limited resolution of 75 mas. The geometrical calibration was based on the observations of several wide binary stars with well known relative positions. The data on their orbital motion were extracted from the Washington Double Star Catalogue. The scale calibration error is ±0.2%. The total errors (calibration plus reconstruction errors) are listed in Table 2. The flux ratios, separations and position angles of the components were derived by a least-squares fit from the measured visibility function of the object.

3. Properties of the resolved systems

3.1. Separations and flux ratios

In our speckle reconstructions we were able to resolve visual companions of 7 of the 13 target stars. Fig. 1 shows our reconstructed images of the four stars Par 1993, Par 2074, Par 2271, and Par 2425. The reconstructions of the three other resolved stars θ^1 Ori A, B, and C have already been presented in Weigelt et al. (1999). Table 2 lists the properties of all visual companions derived from our observations while Table 3 gives the detection limits for the flux ratios.

Without further information we cannot be sure that all the companions we observe actually are physically related to the respective primary stars because there might also be chance projections of unrelated stars. The probability of such a chance projection can be determined from the luminosity function of the stars in this field and the limiting magnitude of the observations as given in Table 3. According to the K-band luminosity function given by Simon et al. (1999) the probability of finding a chance projected

Table 2
Parameters of the speckle companions found in our images

Primary	Sep. [mas]	Pos. angle [deg.]	Flux ratio
Par 1863	942±20	254.4±1.0	0.30±0.02
	1023±20	249.5±1.0	0.10±0.03
Par 1865	221± 5	353.8±2.0	0.25±0.01
Par 1891	37± 6	222.0±5.0	0.32±0.03
Par 1993	383±10	291.1±1.5	0.08±0.02
Par 2074	471±17	97.7±2.0	0.03±0.02
Par 2271	889± 3	172.6±0.5	0.26±0.02
Par 2425	860± 4	307.5±1.0	0.06±0.02

Table 3
Detection limit for companions

Name	v_{min} $\rho > 150$ mas	K_{lim}	v_{min} $\rho > 300$ mas	K_{lim}
Par 1605	0.05	9.73	0.02	10.73
Par 1744	0.04	11.70	0.02	12.47
Par 1772	0.04	11.01	0.02	11.77
Par 1863	0.05	10.24	0.02	10.68
Par 1865	0.02	9.46	0.01	9.90
Par 1889	0.03	9.50	0.03	9.50
Par 1891	0.03	8.22	0.02	8.66
Par 1993	0.03	8.70	0.02	9.14
Par 2031	0.03	10.13	0.02	10.57
Par 2074	0.03	9.40	0.02	9.84
Par 2271	0.04	10.61	0.02	11.37
Par 2366	0.05	10.45	0.03	11.07
Par 2425	0.03	11.96	0.02	12.40

We list the smallest measurable flux ratio v_{min} (depending on the separation ρ) and the corresponding K-band limiting magnitude.

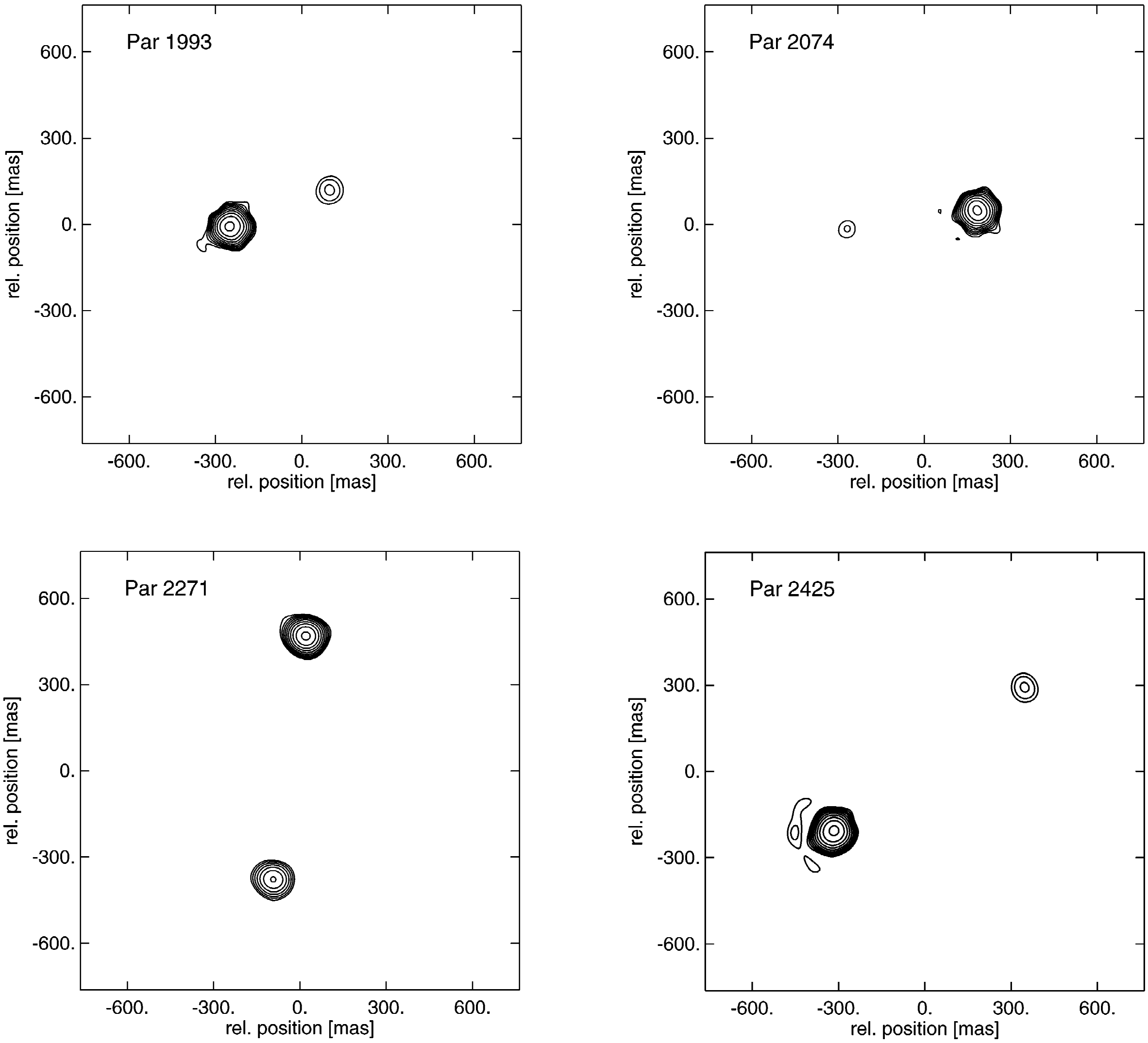

Fig. 1. Diffraction-limited images of Par 1993, Par 2074, Par 2271, and Par 2425 reconstructed by the bispectrum speckle interferometry method. The contour level intervals are 0.3 mag, down to 3.6 mag difference relative to the peak intensity. North is up and east is to the left.

star with $K \leq 9$ or $K \leq 12.5$ within $1''$ from a given position is only 0.4% or 2.4%, respectively. Thus we are confident that the visual companions we observe actually are physical companions of the massive ONC stars.

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 presumably significantly less massive than the primary stars (see discussion below). This also implies that neither the luminosity nor the reddening estimates of the primary stars, which were based on the unresolved fluxes, are significantly affected by the presence of the companions. Thus, no corrections of the primary star parameters collected from the literature are necessary.

3.2. Estimation of companion masses

The masses of the companions of the Trapezium stars have been estimated in Weigelt et al. (1999) using the observed *K*- and *H*-band flux ratios. For the other resolved systems Par 1993, Par 2074, Par 2271, and Par 2425, we cannot use the same approach since only *K*-band images have been obtained for these stars, and thus we cannot determine the $H-K$ colors of the companions. Nevertheless, we can use a similar method. From the photometric data compiled by Hillenbrand et al. (1998) and the *K*-band flux ratios derived from the speckle images we have computed the *K*-band magnitudes of the speckle companions. While these magnitudes alone are obviously not sufficient to allow a determination of the luminosities or masses of the companions, we can estimate stellar masses using the following three plausible assumptions:

(1) Extinction: We assume that the extinction to each companion is the same as to the corresponding primary. Although one might perhaps expect the companion, being a very young stellar object, to be surrounded by circumstellar material which might cause additional extinction, we believe that the strong radiation and wind of the primary star would have dispersed any diffuse material in its immediate vicinity very quickly. This effect can be nicely seen in the examples of θ^1 Ori C and θ^2 Ori A, which obviously have strong dissipative effects on the proplyds in their vicinity. The other primary stars in our sample have weaker radiation fields and winds, but the speckle companions are much closer to these stars than the proplyds to θ^1 Ori C and θ^2 Ori A and thus are most probably strongly affected by these stars too.

Even if there were some circumstellar material around some of the companions, we note that in the *K*-band the extinction is much (nearly a factor of 10) smaller than in the optical and we thus do not believe that this would alter our estimates significantly.

(2) Infrared excess: We assume that the companions do not have a strong near-infrared excess which would significantly affect their *K*-band magnitude. The justification for this assumption is the same as for the extinction given above.

(3) Stellar ages: The mean age of the ONC members is known to be $\lesssim 1$ Myr (Herbig & Terndrup, 1986; Hillenbrand, 1997). Prosser et al. (1994) found that 80% of the stars in the Trapezium cluster are less than 1 Myr old. Furthermore, there are theoretical arguments suggesting that the high-mass stars are among the yougest stars in a cluster (cf. Bonnell et al., 1998; Elmegreen, 1999). Thus, we assume that the massive stars in the ONC and their companions have ages of about 0.3 Myr.

Using the first two assumptions, we can consider the dereddened *K*-band magnitudes of the companions to be an appropriate measure of the photospheric *K*-band flux of these stars. Then, the *K*-band magnitude can be transformed into a stellar luminosity as a function of the (unknown) stellar temperature using the compilation of intrinsic $V-K$ colors and bolometric corrections of Kenyon & Hartmann (1995). The *K*-band magnitude of each star thus defines a line in the HR diagram. We now can determine an estimate for the stellar mass by looking for that point in the HR diagram (Fig. 2), where this line intersects the 0.3 Myr isochrone. We are aware that our mass estimates might be subject to serious uncertainties. In order to get a quantitative estimate of these uncertainties, we also determine the intersection of the line for each star with the main-sequence, what yields firm upper limits for the stellar masses.

3.3. Notes on individual systems

Par 1605 = V372 Ori: This star is not resolved in our images, but it is known to be a spectroscopic binary (Levato & Abt, 1976). Since both components have very similar spectral types (B9.5 and A0.5, respectively), the masses of both stars are probably quite similar, suggesting a mass ratio of ~0.9–1.0.

Par 1863 = θ^1 Ori B: This system consists of at least 5 stars: the two companions θ^1 Ori $B_{2,3}$, which have projected separations of about $1''$ from the primary θ^1 Ori B_1 are clearly resolved in our images (see fig. 2 of Weigelt et al., 1999). Simon et al. (1999) detected another faint ($\Delta K = 4.26$) component which is not visible in our images because it is just below our detection limit. Furthermore, θ^1 Ori B_1 is known to be a spectroscopic binary (Abt et al., 1991). The masses estimated for the companions 2, 3, and 4 with the method described above are $1.6\,M_\odot$, $0.7\,M_\odot$, and $0.2\,M_\odot$, respectively. The upper mass limits from the main-sequence are $<5\,M_\odot$, $<3.5\,M_\odot$, and $<2\,M_\odot$, respectively.

Par 1865 = θ^1 Ori A: The companion A_2 of the primary star θ^1 Ori A_1 (originally detected by Petr et

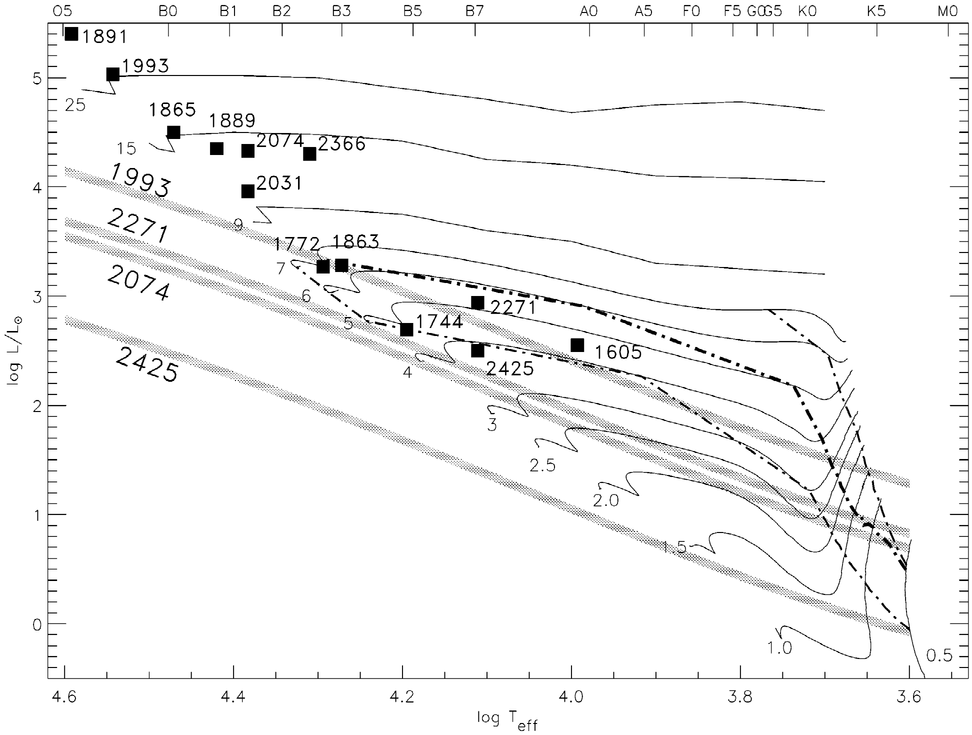

Fig. 2. HR diagram with PMS evolutionary tracks (labelled by the corresponding masses in $M_{\odot}$) from Siess et al. (1997) for $M \leq 7\,M_{\odot}$ and from Bernasconi & Maeder (1996) for $M \geq 9\,M_{\odot}$. The dashed lines show isochrones for ages of 0.1, 0.3 (thick), and 1 Myr. The positions of the primary stars of our sample are shown by the squares with the corresponding Par numbers. The thick grey lines show the range of allowed locations of the speckle companions according to the *K*-band magnitudes, as described in the text.

al., 1998) is clearly visible in our data and shown in fig. 2 of Weigelt et al. (1999), where we have estimated its mass to be $\sim 4M_{\odot}$. Furthermore, θ^1 Ori A_1 is known to be a spectroscopic binary with a companion mass of $\sim 2.6\,M_{\odot}$ (Bossi et al., 1989).

Par 1891 = θ^1 Ori C: As shown in Weigelt et al. (1999), θ^1 Ori C is resolved in our data as a close binary with a separation of only 33 mas. The estimated mass of the companion is $\sim 5\,M_{\odot}$. We note that our detection of this companion might help to understand the extreme X-ray properties of θ^1 Ori C: very strong, periodic X-ray emission was found by Gagné et al. (1997), who also noted that the fractional X-ray luminosity is at least a factor of 5 higher than that of any other O star. Although a model proposed by Babel & Montmerle (1997), which explains the intense X-ray emission by shocks in a magnetically confined wind, can account for the unusual X-ray properties of θ^1 Ori C, we note that the companion might contribute a significant, perhaps even dominant fraction of the observed X-ray emission. If the companion is in a similar evolutionary stage as the very young intermediate-mass star EC 95 in the Serpens star forming region (Preibisch, 1999), it also might be an extremely strong X-ray source like EC 95.

Par 1993 = θ^2 Ori A: The companion of θ^2 Ori A is clearly visible in our images. Our method for estimating masses gives no unique result in this case, since the companion's line in the HR diagram intersects the 0.3 Myr isochrone near a mass of $\sim 7\,M_{\odot}$ as well as near $M \sim 3\,M_{\odot}$. We prefer the former value. The intersection with the main sequence gives an upper limit for the mass of $< 8\,M_{\odot}$. The primary star is known to be a spectroscopic binary with an estimated mass ratio of ~ 0.35 (Abt et al., 1991).

Par 2074 = NU Ori: Our estimate for the mass of

Table 4
Summary of all known companions of the observed stars

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

References: 1: this work; 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).

the companion is $\sim 1\,M_\odot$ with an upper limit of $<4\,M_\odot$. The primary star is known to be a spectroscopic binary with an estimated mass ratio of ~ 0.19 (Abt et al., 1991).

Par 2271 = HD 37115: Our estimate for the mass of the companion is $\sim 1.5\,M_\odot$ with an upper limit of $<5\,M_\odot$.

Par 2425 = Bruns 1018: For the companion we estimate a mass of $\sim 0.15\,M_\odot$ (this time using the low-mass stellar tracks of D'Antona & Mazzitelli (1994) since the Siess et al. (1997) tracks do not extend to such low masses). The upper mass limit from the main-sequence is $<1.4\,M_\odot$.

Par 1744, Par 1772, Par 1889, Par 2031, and Par 2366: We find no indication for companions of these stars. We also could not find any information about spectroscopic companions in the literature.

A summary is given in Table 4.

4. Multiplicity of the massive stars in the Orion nebula cluster

4.1. The distribution of mass ratios

The distribution of mass ratios in binary systems can provide important information on the formation

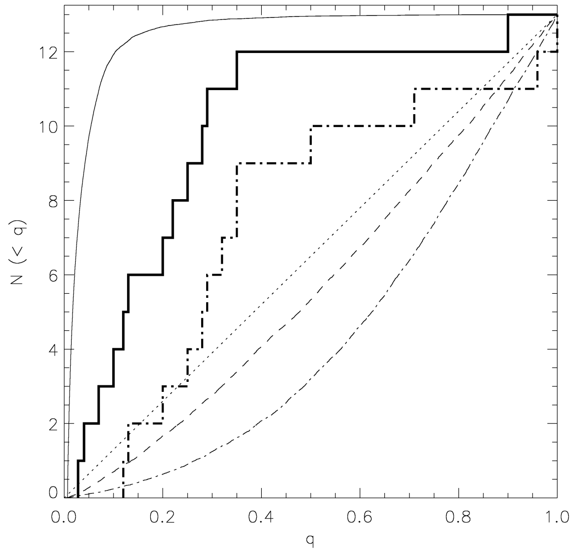

Fig. 3. Distribution function of observed mass ratios of the ONC multiple systems (thick solid line) compared to the four model functions discussed in the text: (a) Scalo (1998) IMF (thin solid line), (b) flat mass ratio distribution (thin dotted line) (c) (dashed line); (d): (thin dashed-dotted line). The thick dashed-dotted line shows the distribution function based on the upper mass limits.

mechanism of multiple systems. While the mass ratio distribution for low-mass binaries is rather well known to be consistent with the field IMF, several very different distributions have been proposed for the mass ratios in high-mass binary systems. For example, Mason et al. (1998) suggested that the distribution might be consistent with the field IMF (i.e. the preponderant majority of the companions being low-mass stars) as well as with a flat distribution of mass ratios, while other studies suggested distributions which more or less strongly favour relatively massive companions (e.g. Abt & Levy, 1978; Garmany et al., 1980). Thus, we will compare our empiric mass ratio distribution for the ONC stars to a wide range of different models:

(a) a companion mass function corresponding to the field IMF (cf. Scalo, 1998) with the probability density $f(M_c) = dN/dM_c$ of the form

$$f(M_c) \propto \begin{cases} M_c^{-1.2} & \text{for} \quad 0.1 < M_c/M_\odot < 1 \\ M_c^{-2.7} & \text{for} \quad 1 < M_c/M_\odot < 10 \\ M_c^{-2.3} & \text{for} \quad 10 < M_c/M_\odot < 100 \end{cases}$$

(b) a flat distribution of mass ratios $q := M_c/M_p$, i.e.

$$f(q) = \text{const.} \quad \text{for} \quad 0.1\,\mathrm{M}_\odot < \mathrm{M}_c < \mathrm{M}_p$$

(c) a distribution that slightly favours massive companions

$$f(q) \propto q^{0.25} \quad \text{for} \quad 0.1\,M_\odot < M_c < M_p$$

as derived by Abt & Levy (1978) for a sample of early B-type stars.

(d) a distribution of mass ratios which strongly favours systems with (nearly) equal masses. Here we consider the findings of the binary survey among O-type stars performed by Garmany et al. (1980), which can be roughly approximated by a Gaussian distribution with a mean mass ratio of $\langle q \rangle = 1$ and a width of $\sigma \approx 0.45$ for $0.1\,M_\odot < M_c < M_p$.

We have simulated the distributions (a) to (d) using 10 000 random realizations for each of these models. The primary mass was set to $15\,M_\odot$, representative of the range of primary masses in our sample[2]. As can be seen in Fig. 3, the observed distribution function systematically lies above the simulated distribution functions for models (b), (c), and (d). We have to take into account that our sample has an observational bias against systems with low q, corresponding to a large brightness contrast in the speckle images, which thus are hard or even impossible to detect. This means that, most probably, there are more, still undetected systems with $q \lesssim 0.1$. The inclusion of these presumably undetected systems would make the empirical distribution function even steeper in the low-q part, i.e. would shift it closer towards the IMF model function (a) and even further away from functions (b), (c), and (d). 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 IMF model (a). A Kolmogorov-Smirnow two-sample test (this is a nonparametric test yielding the probability that two samples are drawn from the same population; cf. Babu & Feigelson, 1996) demonstrates this: the test gives a probability of $P = 9 \times 10^{-4}$ for the flat mass distribution (model b), $P = 2 \times 10^{-5}$ for model (c), and $P = 1 \times 10^{-7}$ for model (d). This means that each of these three models can be rejected at a very high ($>99.9\%$) confidence level.

As stated above, the accuracy of our mass estimates is not very high. We thus have to check to what extent these uncertainties might affect our conclusions. For this, we also have constructed the distribution function of mass ratios based on the upper mass limits as derived above. This ‘‘upper-limit-distribution’’ function, shown as the thick dashed-dotted line in Fig. 3, might eventually appear to be consistent with the flat mass ratio distribution model (b), for which the Kolmogorov-Smirnow test gives $P < 0.132$, but it is still not consistent with the other two models (c) and (d) for which we find $P < 10^{-3}$ and $P < 4.4 \times 10^{-4}$, respectively. Thus we conclude that any mass function favouring high mass ratios seems to be definitely excluded by our data. Furthermore, we once again emphasize that most probably there are undetected faint low-q companions, which are missing in our distribution functions. Thus it seems very likely that even the flat mass ratio distribution model is not consistent with the data.

4.2. The binary frequency

Several recent studies (Petr et al., 1998; Simon et al., 1999) have concordantly found that the binary frequency of the low-mass stars in the ONC is comparable to that of solar type field stars, which is about 50%, with a median number of about 0.5 companions per primary (c.f. Duquennoy & Mayor, 1991; Fischer & Marcy, 1992).

In order to estimate the true degree of multiplicity in our sample and to compare it to other samples, we have to correct for undetected companions. It is obvious that our data do not allow us to detect all multiple systems; we can only detect those systems which are wide enough and for which the flux ratio is not too low. In order to determine the correction factor for the extrapolation from the number of detected companions to the true number of companions, one needs to know the mass distribution of the companions and the distribution of separations. Both distributions, however, are not well known for young

[2] We have repeated these simulations with primary masses of $10\,M_\odot$ and $20\,M_\odot$ and found no significant changes.

massive stars and thus we have to work with reasonable assumptions. The best available data set on the multiplicity of normal stars seems to be the unbiased sample of solar-type field stars of Duquennoy & Mayor (1991). In that study the distribution of orbital periods was found to be well described by the formula

$$f(\log P) \propto \exp\left[\frac{-(\log P - \langle \log P \rangle)^2}{2\sigma^2}\right], \quad (1)$$

with $\langle \log P \rangle = 4.8$ and $\sigma = 2.3$, and P in days. We are aware that our sample of massive stars does not necessarily share these properties of solar-mass stars, but we note that Abt (1983) concluded that neither the binary frequency nor the period distribution seem to vary strongly from G-type to B-type stars. Also, we note that the distribution of periods for O-type binaries (cf. fig. 1 in Mason et al., 1998) might well be consistent with this formula, if one takes biases due to selection effects into account.

In order to estimate the fraction of undetected binary systems, we have performed simulations of companions as follows: we assume a primary mass of $15\,M_\odot$ and randomly draw 30 000 companion masses according to either the Scalo (1998) field IMF (model a) or the flat mass distribution (model b), with the restriction that the companion mass must not exceed the primary mass. We then use the PMS evolutionary tracks for the age of 0.3 Myr to determine the luminosity and temperature of each star according to its mass. This allows us to determine the K-band magnitude of each star via a bolometric correction taken from Kenyon & Hartmann (1995) and to determine the corresponding flux ratio between the primary star and the companion. We note that in some cases (if the companion has a mass only slightly lower than the primary) the companion can be brighter in the K-band than the primary. In these cases, the flux ratio was inverted, since it is not relevant here which of the stars is brighter. Then, for each of the simulated systems we randomly draw a value for the orbital period from distribution (1). Using Kepler's law with the appropriate system mass, we computed the corresponding separation ρ assuming a distance of 450 pc and a correction factor 0.95 for the transformation of the semimajor axis to the projected separation (cf. Leinert et al., 1997).

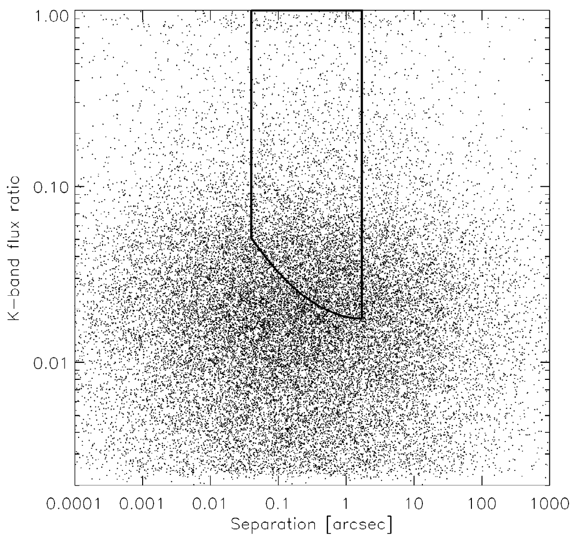

Fig. 4. Results of the simulations for the case of companions from the Scalo (1998) field IMF (model a). The simulated systems are shown as dots. The area delimited by the thick line marks the region of systems detectable in our observations.

The simulation results for the case of the Scalo (1998) field IMF are shown in Fig. 4. In this figure we have marked the region in the flux-ratio versus separation space, which contains the binary system we would be able to resolve in our data. The boundaries of this area are defined by our minimal detectable separation of ~33 mas, the maximum separation of 1.75″ (given by the 3.5″ × 3.5″ field of our images which we inspected for companions), and the minimum detectable flux-ratio as a function of the separation (cf. Table 3). 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 ~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. We note that these results do not strongly depend on the assumed primary mass: we have repeated these simulations, assuming primary masses of $10\,M_\odot$ and $20\,M_\odot$ instead of $15\,M_\odot$ above, and found that the fractions of detectable systems vary only very slightly, not more than 2–3%.

Since we find visual companions to 7 of the 13 target stars, i.e. an apparent binary frequency of (54±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).

4.3. Discussion of the observed multiplicity

Finally, we look for relations between the observed multiplicity and several parameters. We emphasize that, due to the quite limited size of our sample, we are necessarily dealing with small-number statistics. Also, one should keep in mind that, most probably, there are many still undetected companions, and thus our current sample of companions probably only represents ''the tip of the iceberg''. With these caveats in mind, we can nevertheless start to explore potential relations.

4.3.1. Multiplicity versus spectral type

A strong trend for a higher degree of multiplicity among the stars of very early spectral type as compared to the later type stars has been found by Abt et al. (1991) and Morrell & Levato (1991): most of the spectroscopic binaries in the ONC are among the stars earlier than B3, and much less frequent among the later B- and the A-type stars. A similar trend is apparent in our sample, as can be seen in Fig. 5 in the upper left plot. The average number of

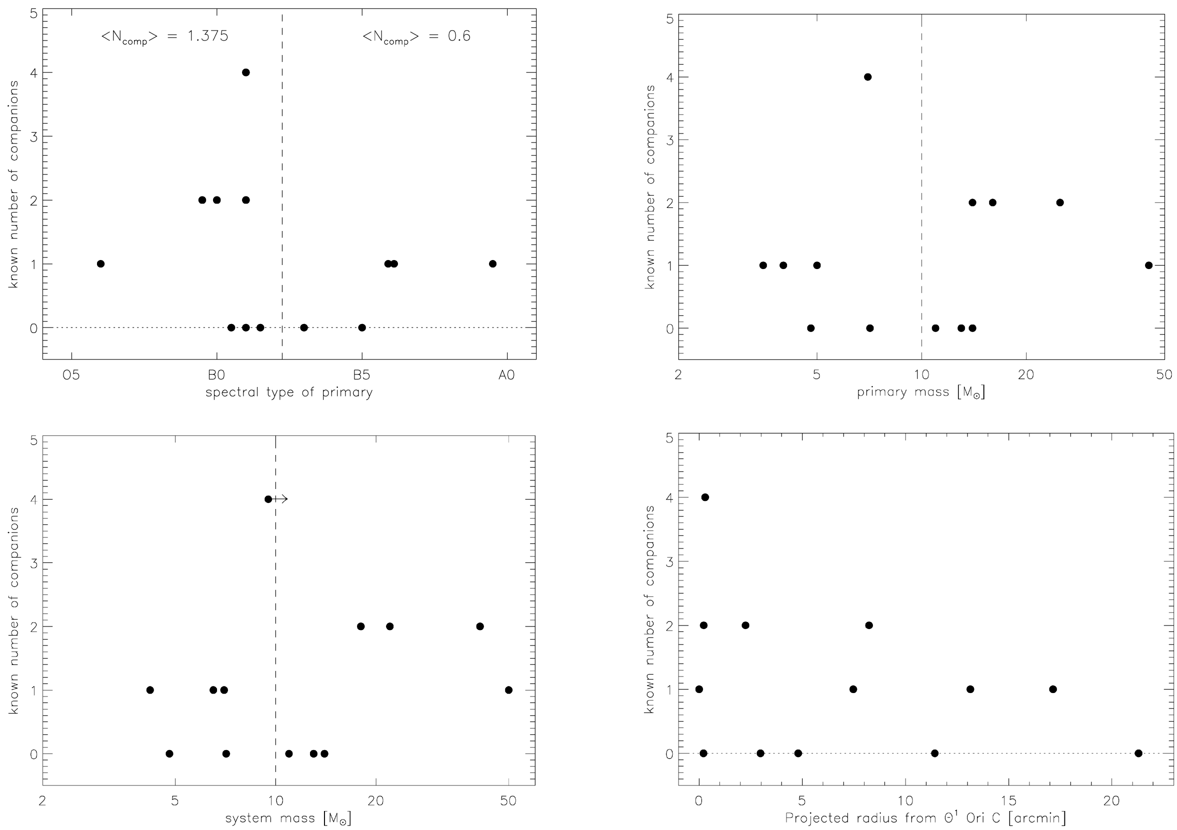

Fig. 5. The known number of companions is plotted against the spectral type of the primary, the primary mass, the total system mass and the projected distance from the center of the ONC.

known (visual & spectroscopic) companions per primary is 2.3 times 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).

4.3.2. Multiplicity versus primary- or system-mass

As discussed in the introduction, it has been suggested that stars with masses above $\sim 10\,M_\odot$ form through collisions of intermediate-mass protostars, and thus multiple systems should be very common amongst these stars (cf. Bonnell et al., 1998). In the upper right plot of Fig. 5 we have plotted the known number of companions as a function of the primary mass in each system. No significant difference can be seen between the mean number of known companions to the primaries with masses above $10\,M_\odot$ as compared to the primaries with lower masses.

If we use the total mass of all members in each system[3] instead of the primary mass (Fig. 5, lower left plot), we find that the mean number of known components for the $M_{sys} > 10\,M_\odot$ systems is about twice as high as for the $M_{sys} < 10\,M_\odot$ systems. Also, we note that all triple and higher order systems are found among the $M_{sys} > 10\,M_\odot$ systems.

4.3.3. Multiplicity versus location

The lower right plot in Fig. 5 indicates that there might be a trend of decreasing multiplicity from the center of the ONC towards the outer regions. However, one has to be aware that the current locations of the stars are not necessarily close to their birth places. With typical velocities of 2 km/sec, the stars can easily move some 5′ within 0.3 Myr.

5. 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. This finding suggests different formation mechanisms for the high-mass and low-mass multiple systems. The stars of spectral type earlier than B3 display a higher degree of multiplicity than the later type stars. Also, the multiplicity of the stars near the center of the cluster seems to be higher than that of the stars in the outer parts of the ONC. The nature of our results seems to support the idea that high-mass ($M > 10\,M_\odot$) stars form through collisions of protostars.

[3]Note that the inclusion of the unknown mass of the spectroscopic companion to θ^1 Ori B would raise the system mass of Par 1863 above $10\,M_\odot$.

Acknowledgements

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

Abt, H.A., 1983, ARA&A, 21, 343.
Abt, H.A. & Levy, S.G., 1978, ApJS, 36, 241.
Abt, H.A., Gomez, A.E., & Levy, S.G., 1990, ApJS, 74, 551.
Abt, H.A., Wang, R., & Cardona, O., 1991, ApJ, 367, 155.
Babel, J. & Montmerle, T., 1997, ApJ, 485, L29.
Babu, G.J. & Feigelson, E.D., 1996, Astrostatistics, Chapman & Hall, London.
Bally, J., Sutherland, R.S., Devine, D., & Johnstone, D., 1998, AJ, 116, 293.
Bernasconi, P.A. & Maeder, A., 1996, A&A, 307, 829.
Bonnell, I.A., Bate, M.R., & Zinnecker, H., 1998, MNRAS, 298, 93.
Bossi, M., Gaspani, A., Scardia, M., & Tadini, M., 1989, A&A, 222, 117.
Brown, A.G.A., de Geus, E.J., & de Zeeuw, P.T., 1994, A&A, 289, 101.
D'Antona, F. & Mazzitelli, I., 1994, ApJS, 90, 467.
Duquennoy, A. & Mayor, M., 1991, A&A, 248, 485.
Elmegreen, B.G., 1999, ApJ, 515, 323.
Fischer, D.A. & Marcy, G.W., 1992, ApJ, 396, 178.
Gagné, M., Caillault, J.-P., Stauffer, J.R., & Linsky, J.L., 1997, ApJ, 478, L87.
Garmany, C.D., Conti, P.S., & Massey, P., 1980, ApJ, 242, 1063.
Genzel, R. & Stutzki, J., 1989, ARA&A, 27, 41.
Herbig, G.H. & Terndrup, D.M., 1986, ApJ, 307, 609.
Hillenbrand, L.A., 1997, AJ, 113, 1733.
Hillenbrand, L.A., Strom, S.E., et al., 1998, AJ, 116, 1816.
Hofmann, K.-H., Seggewiss, W., Weigelt, G., 1995, A&A, 300, 403.
Kenyon, S.J. & Hartmann, L., 1995, ApJS, 101, 117.
Labeyrie, C.D., 1970, A&A, 6, 85.
Leinert, Ch., Richichi, A., & Haas, M., 1997, A&A, 318, 472.
Levato, H. & Abt, H.A., 1976, PASP, 88, 712.

Lohmann, A.W., Weigelt, G., & Wirnitzer, B., 1983, Appl. Opt., 22, 4028.
Mason, B.D., Gies, D.R., Hartkopf, W.I., et al., 1998, AJ, 115, 821.
McCaughrean, M.J. & Stauffer, J.R., 1994, AJ, 108, 1382.
Morrell, N. & Levato, H., 1991, ApJS, 75, 965.
Padgett, D.L., Strom, S.E., & Ghez, A., 1997, ApJ, 477, 705.
Petr, M.G., Du Foresto, V., & Beckwith, S.V.W., 1998, ApJ, 500, 825.
Preibisch, Th., 1999, A&A, 345, 583.
Prosser, C.F., Stauffer, J.R., Hartmann, L., Soderblom, D.R., Jones, B.F., Werner, M.W., & McCaughrean, M.J., 1994, ApJ, 421, 517.
Reipurth, B. & Zinnecker, H., 1993, A&A, 278, 81.
Richling, S. & Yorke, H.W., 1998, A&A, 340, 508.
Salas, L., Rosado, M., Cruz-Gonzales, I., et al., 1999, ApJ, 511, 822.
Scalo, J., 1998, in: Gilmore, G., Howell D., (Eds.), The Stellar Initial Mass Function, ASPC, Vol. 142, p. 201.
Schultz, A.S.B., Colgan, S.W.J., Erickson, E.F., et al., 1999, ApJ, 511, 282.
Siess, L., Forestini, M., & Dougados, C., 1997, A&A, 324, 556.
Simon, M., Close, L.M., & Beck, T.L., 1999, AJ, 117, 1375.
Stahler, S.W., Palla, F., & Ho, P.T.P., 1999, in: Mannings, V., Boss, A., Russel S., (Eds.), Protostars and Planets IV, University of Arizona Press, in press.
Walter, F.M., Alcalá, J.M., Neuhäuser, R., Sterzik, M., & Wolk, S.J., 1999, in: Mannings, V., Boss, A., Russel S., (Eds.), Protostars and Planets IV, University of Arizona Press, in press.
Weigelt, G., 1977, Opt. Commun., 21, 55.
Weigelt, G., Balega, Y., Preibisch, Th., Schertl, D., Schöller, M., & Zinnecker, H., 1999, A&A, 347, L15.
Yorke, H.W. & Krügel, E., 1977, A&A, 54, 183.