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Early-type stars in the young open cluster IC 1805

I. The SB2 system BD+60° 497 and the probably single stars BD+60° 501 and BD+60° 513*

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Abstract. We investigate the multiplicity of three O-type stars in the very young open cluster IC 1805. All our targets were previously considered as spectroscopic binaries, but no orbital solution was available for any of them. Our results confirm the binarity of BD+60° 497 and we provide the very first orbital solution for this double-lined spectroscopic binary. This is only the second O-star binary in IC 1805, and the first SB2 system, for which an orbital solution is now available. BD+60° 497 has an orbital period of 3.96 days and consists of an evolved O6.5 V((f)) primary and an O8.5-9.5 V((f)) secondary with minimum masses of $m_1 \sin^3 i = 13.9\ M_\odot$ and $m_2 \sin^3 i = 10.9\ M_\odot$. The observed primary/secondary mass ratio (1.28) appears lower than expected from a comparison with single star evolutionary models (1.60−1.74). For the other two stars, BD+60° 501 and BD+60° 513, we find no significant radial velocity variations, suggesting that they are most probably single. Although a fraction of binaries among the early-type stars of IC 1805 as high as 80% has been advocated in the literature, our results suggest that this number might be overestimated.

Key words. stars: binaries: spectroscopic – stars: early-type – stars: fundamental parameters – stars: individual: BD+60° 497 – stars: individual: BD+60° 501 – stars: individual: BD+60° 513

1. Introduction

Studying early-type binaries in very young open clusters has the potential to provide important information on many fundamental problems of stellar astrophysics including the star and cluster formation processes, dynamical interactions in clusters and stellar evolution in general. This is especially crucial for the still poorly understood formation of the most massive stars. Unfortunately, our present knowledge of the binary properties of massive stars is still fragmentary (Mermilliod 1996). For many binaries reliable orbital solutions are still lacking and the binarity of the majority of the early-type stars has simply never been investigated.

Several years ago, our group started an investigation of a number of early-type binaries in the open clusters Trumpler 16 and NGC 6231 in the southern hemisphere. Our extensive observing campaigns already led to the discovery of several triple systems and allowed us to considerable improve the orbital solutions for a number of binaries (Rauw et al. 2000, 2001; Morrell et al. 2001; Sana et al. 2001, 2003; Albacete Colombo et al. 2002). In this context, we have also undertaken a spectroscopic monitoring of the most massive members of the IC 1805 cluster in the northern hemisphere.

IC 1805 is a rich cluster in the core of the Cas OB6 association which in turn is embedded in the molecular cloud W 4 in the Perseus spiral arm of our Galaxy. All in all, the cluster harbors about forty early-type stars from spectral type O4 through B2 (Shi & Hu 1999) and their energetic winds have created a "galactic chimney" – i.e. a cone-shaped cavity in the interstellar medium – that allows efficient transport of hot gas from the galactic disk into the halo (Normandeau et al. 1996).

Among the 10 O-stars in IC 1805, García & Mermilliod (2001, see also Ishida 1970) estimated an extremely high binary frequency of 80%. However, to date, an orbital solution is available for only one of them: HD 15558 (O5 III(f)). HD 15558 is the optically brightest star in the cluster. It is an eccentric single-line binary (SB1) system with an orbital period of 440 days, the longest of any known O-star binary (Garmany & Massey 1981).

In this paper, we present the first double-line (SB2) orbital solution for another O-type binary (BD+60° 497 = LSI +61 274) in IC 1805. Although, Underhill (1967) and Walborn (1973) already reported the presence of a secondary spectrum in their observations of BD+60° 497, no detailed investigation of this system has apparently ever been performed. Underhill (1967) further noted that Trumpler (1930)

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had suspected BD+60° 497 to be an SB1 with an orbital period of 25.48 days.

We also analyse the spectra and radial velocities of two other O-type stars in IC 1805: BD+60° 501 (=LSI +61 282) and BD+60° 513 (=LSI +61 296) for which we find no evidence of binarity in contradiction with previous reports of radial velocity changes for the former and apparent double lines for the latter (Underhill 1967). Our results on the earliest O-type stars in this cluster will be the subject of a forthcoming paper.

In Sect. 2, we present our new data on the program stars and we derive their spectral classification. The orbital solution of BD+60° 497 and the radial velocities of the other two targets are discussed in Sect. 3 whilst the fundamental parameters of the BD+60° 497 system are the subject of Sect. 4. Section 5 presents a brief discussion of the *ROSAT* X-ray observations of our program stars and finally, our conclusions are given in Sect. 6.

2. Spectral classification

2.1. Observations and data reduction

Spectroscopic observations were collected during several observing campaigns in 2002 and 2003 at the Observatoire de Haute-Provence (OHP). We used the Aurélie spectrograph attached to the 1.52 m telescope. The detector was a 2048 × 1024 CCD EEV 42-20#3, with a pixel size of 13.5 μm squared. Our spectra cover the wavelength range from 4455 to 4905 Å with a reciprocal dispersion of 16 Å mm^{-1}. Depending on the atmospheric conditions, the exposure times were of order 30 to 45 min (respectively 45 to 60 min.) for BD+60° 497 and BD+60° 501 (respectively BD+60° 513). The mean signal to noise ratio of individual spectra is about 200−300 in the continuum.

The data were reduced using the MIDAS software developed at ESO. For each observation, the Aurélie CCD data consist of five images of the object's spectrum obtained by means of a Bowen image slicer (see Gillet et al. 1994). These five images were treated individually, i.e. they were bias-subtracted, flat-fielded and extracted. After removing the cosmic ray events from the individual images, we combined them into a weigthed average. The resulting spectrum was wavelength-calibrated using a Th-Ar comparison exposure taken shortly before or after the observation on the sky. Finally, the spectra were normalized using properly chosen continuum windows.

2.2. BD+60° 497

The blue spectra of BD+60° 497 are dominated by He I, He II and the Hβ absorption lines of the primary. Weak metal lines due to C III, N III, O II, Mg II, Si III and Si IV are also present. Their changing wavelengths indicate that they mainly follow the orbital motion of the primary. The secondary spectrum is seen in the He I absorption lines. The visibility of the secondary lines changes with orbital phase (see Fig. 1 and below).

Several authors provided spectral classifications for BD+60° 497: O7 (Underhill 1967), O6 V(n) (Walborn 1973), O7 V (Mathys 1989), O7 V((f)) (Massey et al. 1995) and O7 V (Shi & Hu 1999). It should be noted that these results are in fair agreement with each other whilst older classifications included early B-types (see Ishida 1970, and references therein). Ishida (1970) suggested that the spread in older spectral types (from B3 to O7) might indicate a possible change of some spectral features. However, this is not confirmed by the more recent results (including our own data).

In order to determine the spectral type of both components of BD+60° 497, we deblended the classification lines by simultaneously fitting two Gaussian profiles. The average equivalenth width (*EW*) of the He I λ4471 line in the spectrum of the primary (resp. secondary) determined in this way amounts to 0.34 ± 0.02 Å (resp. 0.22 ± 0.03 Å). For the He II λ4542 line the situation is less clear: due to the stronger intensity contrast between the primary and secondary in this line, it was only at a few phases that we were able to deblend the lines. For the primary (resp. secondary) we find EW = 0.54 Å (resp. 0.08 Å) for this line. Due to the orbital variation of the secondary line strength (see below) and the fact that we could only deblend this line at phases when the secondary is approaching, the *EW* of the secondary line could be a lower limit. The equivalent width ratio of the He I λ4471 and He II λ4542 classification lines places the primary of BD+60° 497 right at the border between spectral type O6 and O6.5 (Conti 1973b), whilst the secondary would be of spectral type O9−9.5 (or of somewhat earlier spectral type if the measured *EW* of He II λ4542 is indeed a lower limit). We have also compared the blue spectrum of BD+60° 497 to the atlas of Walborn & Fitzpatrick (1990). The primary's spectrum is intermediate between those of HD 101190 of type O6 V((f)) and HD 93146 of type O6.5 V((f)), but slightly closer to the latter. For the secondary, comparison with the spectra provided by Walborn & Fitzpatrick suggests that this star should have a spectral type later than about O8.5.

The He II λ4686 absorption line is in rather strong absorption in the spectrum of BD+60° 497, suggesting a main sequence luminosity class for both stars (see however also Sect. 4 below). We note the presence of a very weak N III λ4641 emission line. The line roughly moves in phase with the primary component though with a reduced radial velocity (*RV*) amplitude. We further note that the width of the line changes as a function of phase. At some phases near ϕ = 0.25, the line deblends into two components suggesting that the reduced *RV* amplitude and the changing width are due to a blend between two emission lines associated with both components. This means that both stars probably have this line in weak emission in their spectrum.

In summary, we thus classify the primary and secondary of BD+60° 497 as O6.5 V((f)) and O8.5−9.5 V((f)) respectively.

Finally, let us briefly turn to the apparent change in the strength of the secondary's absorption lines as a function of orbital phase. Though in the mean spectra displayed in Fig. 1 the He I λ4713 line doubles its *EW* between approaching and receding quadrature, we must note that the effect is much less clear cut in the He I λ4471 line and moreover, the dispersion of the *EW* of He I λ4713 measured on individual spectra at

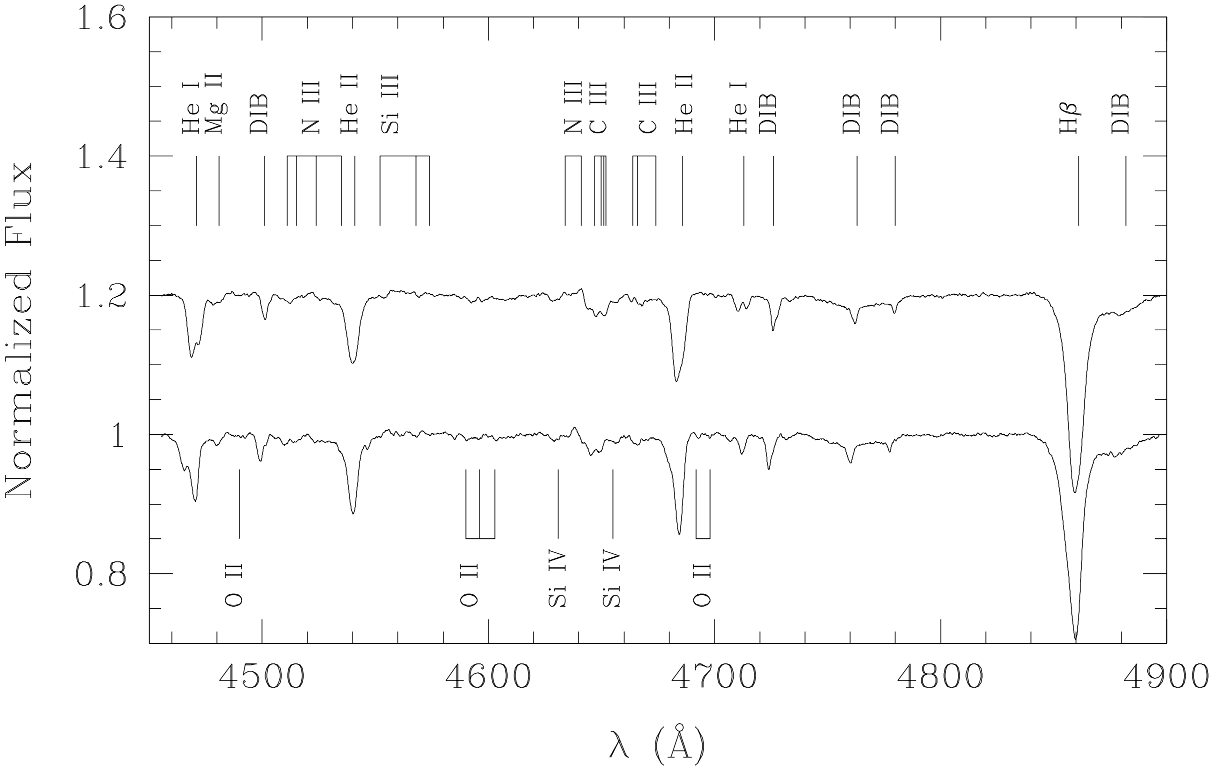

Fig. 1. Average spectrum of BD+60° 497 as observed around the phases of quadrature. The average spectrum around phases 0.65−0.85 is shifted vertically by 0.2 units with respect to the average spectrum around phases 0.1−0.35. The most prominent stellar features as well as the diffuse interstellar bands (DIBs) are identified. Note the aspect of the He I λ 4471 and λ 4713 lines that reveal clearly the signature of the secondary star. The relative importance of the secondary lines varies between the two quadratures (see text).

similar orbital phases is uncomfortably large. If real, the effect seen in Fig. 1 is such that the secondary's lines appear stronger at phases when the secondary is moving away from us compared to their intensity at approaching phases. This is the opposite situation of the so-called "Struve-Sahade" effect (SSe) which is defined as the apparent strengthening of the secondary lines at those orbital phases when the secondary is approaching and the corresponding weakening of its lines when it is receding (see e.g. Bagnuolo et al. 1999). BD+60° 497 is not the only binary where such an opposite SSe is seen. In fact, a similar behaviour was reported by Howarth et al. (1997) for HD 100213 (O7.5 V + O9.5 V).

2.3. BD+60° 501

The blue spectrum of BD+60° 501 is very similar to that of BD+60° 497 except for sharper and somewhat deeper absorptions (see Fig. 2). No indication of a secondary spectrum is found. The average *EW*s of the He I λ 4471 and He II λ 4542 classification lines are 0.57 ± 0.02 Å and 0.68 ± 0.04 Å respectively (in good agreement with the values quoted by Mathys 1989). According to the criterion provided by Conti (1973b), the ratio of these equivalent widths indicates an O7 classification. This result is confirmed by a comparison with the spectral atlas of Walborn & Fitzpatrick (1990). The strong He II λ 4686 absorption further indicates a main sequence luminosity class. Finally, we note some evidence of a very weak N III λ 4641 emission. In summary we thus assign an O7 V((f)) spectral type to BD+60° 501.

The spectral types given in the literature range from O6.5 V (Underhill 1967; Ishida 1970; Conti & Alschuler 1971) to O7 V (Walborn 1973; Mathys 1989; Shi & Hu 1999) and O7 V((f)) (Massey et al. 1995). Our result appears thus fully consistent with these classifications.

2.4. BD+60° 513

The spectrum of BD+60° 513 is similar to that of BD+60° 501 except for the much broader lines in the former (see Fig. 2). This is not unexpected since the projected rotational velocity is significantly larger for BD+60° 513 ($v \sin i \sim 300\,\mathrm{km\,s^{-1}}$) than for BD+60° 501 ($v \sin i \sim 200\,\mathrm{km\,s^{-1}}$; see Mathys 1987; Conti & Ebbets 1977). We note that the absorption lines in the spectrum of BD+60° 513 display some low-level profile variability, but no obvious indication of a secondary spectrum is found (see below). The average *EW*s of the He I λ 4471 and He II λ 4542 lines are 0.61 ± 0.04 Å and 0.56 ± 0.02 Å respectively. These values and the strength of the He II λ 4686 absorption yield an O7.5 V classification (Conti 1973b; Walborn & Fitzpatrick 1990). Again, the possibility of a very weak N III λ 4634-41 emission, finally leads to an O7.5 V((f)) spectral type for BD+60° 513.

The spectral types quoted in the literature include O7 V (Shi & Hu 1999), O7 Vn (Walborn 1973), O7.5 V (Mathys 1989; Conti & Ebbets 1977), O8 V((f)) (Massey et al. 1995),

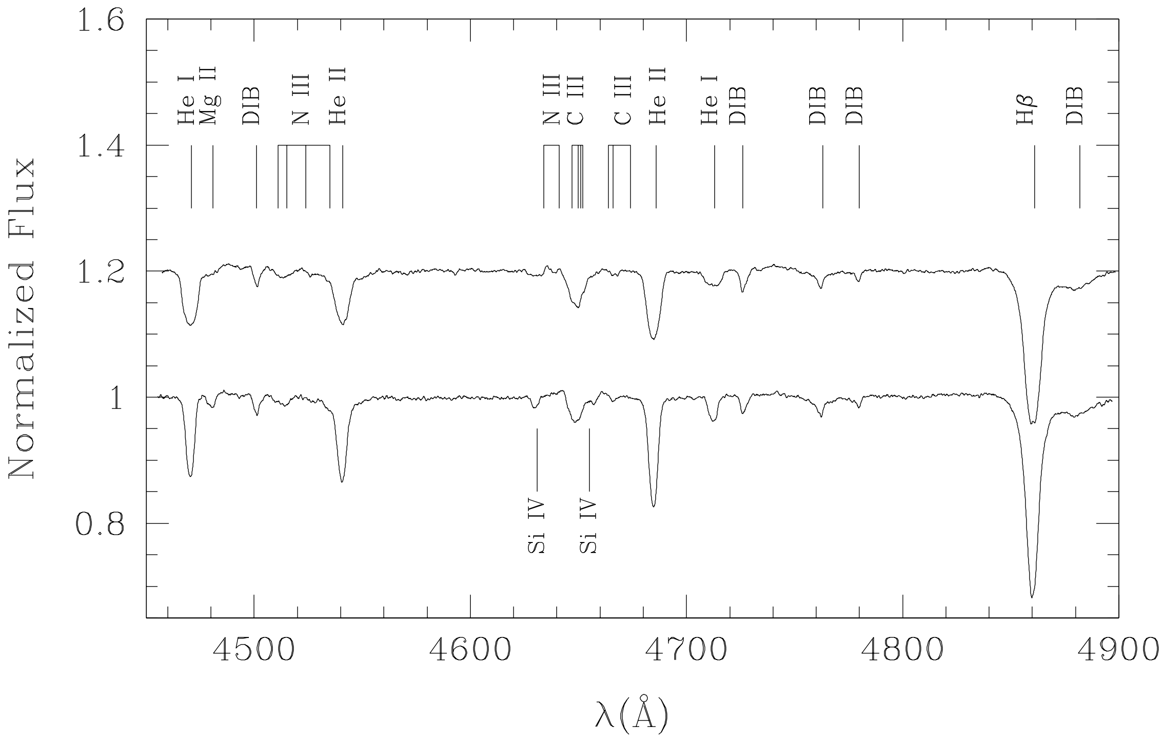

Fig. 2. Average spectra of BD+60° 501 (*bottom*) and BD+60° 513 (shifted vertically by 0.2 units). The lines of BD+60° 513 are significantly broader than those of BD+60° 501 (see text).

O9 V (Ishida 1970) and B0 (Underhill 1967). This rather wide range of spectral types most probably results from the difficulties related to the broad lines of this star and possibly some confusion problems between BD+60° 513 and BD+60° 512 in older studies (as pointed out by Conti & Leep 1974 and Mathys 1987).

3. Radial velocities and orbital solutions

3.1. BD+60° 497

Radial velocities of the components of BD+60° 497 were determined from simultaneous fits of several Gaussian profiles and through cross-correlation with a template spectrum. The results of both techniques generally agree within the uncertainties. Most lines of the binary components remain blended over large parts of the orbital cycle and the intensities of the secondary's lines change as a function of the orbital phase (Fig. 1). The secondary's signature is best seen in the He I λ 4471 and λ 4713 lines as well as, at some orbital phases, in Mg II λ 4481. These three absorptions provide therefore the best lines to derive the radial velocities (*RV*s) of the binary components. We adopt the rest wavelengths for these lines from Underhill (1994) and the resulting *RV*s (determined by means of simultaneous Gaussian fitting) are listed in Table 1. For most measurements the typical uncertainties are of order 10−15 km s^{-1}. About twice as large uncertainties affect the data points indicated by a colon in Table 1.

We applied the generalized spectrogram technique of Heck et al. (1985; see also Gosset et al. 2001) and the trial method of Lafler & Kinman (1965) to the timeseries of our $RV_1 - RV_2$ data. Both methods consistently yield 3.96 days as the best estimate for the orbital period. This result was confirmed by a 2D period search technique (see e.g. Rauw et al. 2003) applied to the line profile changes in the spectrum of BD+60° 497. Assuming that the uncertainty on the corresponding frequency amounts to one tenth of the width of the peak in the periodogram, we estimate an uncertainty of 0.09 day on the orbital period. Our orbital period is clearly at odds with the much longer value (25.48 days) suggested by Trumpler (1930, as reported by Underhill 1967). In the following we adopt 3.96 days as the orbital period of BD+60° 497.

A circular orbital solution of BD+60° 497 yields a mass ratio $q = m_1/m_2 = 1.28$ and the minimum masses of the stars are found to be $m_1 \sin^3 i = 13.9\,M_\odot$ and $m_2 \sin^3 i = 10.9\,M_\odot$ for the primary and the secondary respectively. The systemic velocities obtained for each component are in broad agreement with each other and with the mean radial velocity of other IC 1805 cluster members (see Underhill 1967 and the cases of BD+60° 501 and BD+60° 513 below). Allowing for an eccentric orbital solution yields $e = 0.14 \pm 0.14$. Given the large errors on the eccentricity and though we cannot completely rule out a small eccentricity, in the following we assume $e = 0.0$.

3.2. BD+60° 501

We measured the *RV*s of the He I λ 4471, He II $\lambda\lambda$ 4542, 4686 and Hβ lines in the spectra of BD+60° 501 by fitting Gaussians. These fits are of good quality and the position of the line centre is determined with an accuracy of about 1−2 km s^{-1}. The resulting mean *RV*s are listed in Table 3. Again, the rest wavelengths were adopted from Underhill (1994).

Table 1. Radial velocities of BD+60° 497 as derived from our Aurélie spectra. The orbital phases are computed with respect to HJD 2 452 935.977 with a period of 3.96 days (see Table 2).

HJD−2 450 000	ϕ	RV_1 (km s^{-1})	RV_2 (km s^{-1})
2520.644	0.118	−151.1	94.4:
2523.600	0.864	76.3	−285.2:
2524.552	0.105	−142.0:	91.9:
2527.555	0.863	92.0	−286.1
2528.533	0.110	−158.7:	77.0:
2529.562	0.370	−156.9	74.0
2531.543	0.870	91.1	−264.6
2532.534	0.120	−179.1	79.9
2533.638	0.399	−146.6	44.4
2916.583	0.103	−185.9	108.5
2918.667	0.629	50.0:	−210.6:
2919.632	0.872	78.4	−203.8
2922.677	0.641	74.3	−176.1
2925.665	0.396	−155.8:	−16.3:
2928.641	0.147	−236.3	118.0
2934.545	0.638	67.4	−189.4

Table 2. Orbital solution for BD+60° 497 assuming a circular orbit. T_0 refers to the time of conjunction with the primary being behind. γ, K and $a\ \sin i$ denote respectively the systemic velocity, the amplitude of the radial velocity curve and the projected separation between the centre of the star and the centre of mass of the binary system. $R_{\rm RL}$ stands for the radius of a sphere with a volume equal to that of the Roche lobe computed according to the formula of Eggleton (1983).

	Primary	Secondary
P(days)	3.96 (fixed)	
e	0.0 (adopted)	
T_0(HJD-2 450 000)	2935.977 ± 0.152	
γ (km s^{-1})	−53.7 ± 9.2	−68.9 ± 11.9
K (km s^{-1})	171.9 ± 11.9	220.6 ± 14.9
$a \sin i$ ($R_\odot$)	13.4 ± 0.9	17.3 ± 1.7
$q = m_1/m_2$	1.28 ± 0.12	
$m \sin^3 i$ ($M_\odot$)	13.9 ± 2.5	10.9 ± 2.0
$R_{\rm RL}\ \sin i$ ($R_\odot$)	12.3 ± 0.8	11.0 ± 0.7

We find no significant variations neither over the data taken in September 2002 nor between the September 2002 and the October 2003 campaigns. This suggests that the star has a constant radial velocity over time scales of days, weeks and probably years. This result is at odds with the SB1 status (with an orbital period of 3.69 days) that Trumpler assigned to this system (see Underhill 1967). Underhill (1967) measured *RV*s of +1 and −57 km s^{-1} on two spectra taken two years apart. We note however that the velocities of the interstellar Ca II K-line reported by Underhill for these spectra also differ by as much as 39 km s^{-1}, confirming the caveat given by Underhill that the accuracy of her *RV*s was not very high.

Finally, in order to search for low level line profile variability – that could be due e.g. to non-radial pulsations, wind structures or binary effects – we have computed the time variance spectrum (TVS, Fullerton et al. 1996) of our entire data set over the spectral range 4460 to 4890 Å. The TVS hardly exceeds the expected level due to normalization errors and the S/N ratio of the data. Therefore, we conclude that no significant line profile variability is present in our data of BD+60° 501.

In summary, the *RV*s of BD+60° 501 as well as the lack of profile variability suggest that this is a single O7 V((f)) star.

Table 3. Radial velocities of BD+60° 501 as derived from our Aurélie spectra (see text).

HJD−2 450 000	RV (km s^{-1})
2518.633	−54.1
2520.611	−49.5
2524.527	−44.8
2527.617	−48.5
2531.572	−51.3
2532.573	−50.3
2533.602	−49.6
2919.602	−50.6
2922.588	−50.3
Mean	−49.9 ± 2.5

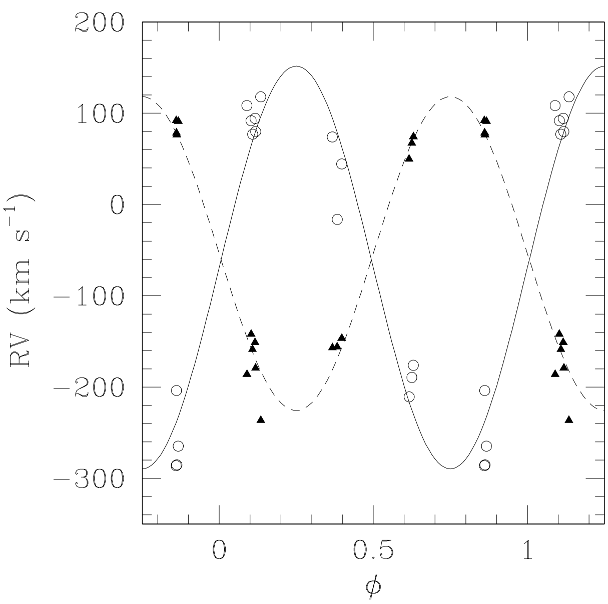

Fig. 3. Radial velocity curve of the BD+60° 497 binary system as derived from the He I $\lambda\lambda$4471, 4713 and Mg II λ4481 absorption lines (see Table 1). Filled triangles and open circles stand for the primary and secondary *RV*s respectively. The circular orbital solution of Table 2 is shown by the solid and dashed lines.

Table 4. Same as Table 3 but for BD+60° 513.

HJD−2 450 000	*RV* (km s^{-1})
2520.569	−59.2
2524.609	−57.5
2527.662	−55.8
2529.602	−43.3
2531.612	−36.4
2532.619	−37.5
2533.580	−39.1
2918.631	−28.8:
2922.633	−48.9
2934.664	−36.8
Mean	−44.3 ± 10.5

3.3. BD+60° 513

Following the same procedure as for BD+60° 501 we measured the *RV*s of the He I λ4471, He II $\lambda\lambda$4542, 4686 and Hβ lines in the spectra of BD+60° 513 by fitting Gaussians. Due to the much broader line profiles in the spectrum of BD+60° 513, these fits are however of much poorer quality than in the case of BD+60° 501 (this is especially true for He I λ4471 and He II λ4542) leading to uncertainties of ~10 km s^{-1} on the line centroids. The mean *RV*s of BD+60° 513 are provided in Table 4.

Though the *RV*s show a much wider spread than in the case of BD+60° 501, they do not reveal a clear binary behaviour. Actually, the ~10 km s^{-1} dispersion in our *RV* data most probably reflects the difficulties related to the broadening of the lines and their distortion due to the profile variability (essentially for Hβ), whilst the star likely has a roughly constant radial velocity.

Most importantly, we do not detect any evidence for double lines contrary to the results of Trumpler reported by Underhill (1967). Underhill measured *RV*s of +27 and −63 km s^{-1} on two spectra separated by one year. The same remarks as for BD+60° 501 hold for these *RV*s especially as a result of the difficulties related to the line broadening.

An alternative possibility to explain the line broadening and the lack of significant *RV* changes with a binary scenario would be to assume that we observed the binary at phases between quadrature and conjunction, when the lines of the individual components are still blended. In this case, the shape of the lines (i.e. the lack of an obvious blue/red asymmetry in any of the stronger lines) would suggest that the putative binary components have to be of the same spectral type. BD+60° 513 would therefore consist of two roughly identical O7.5 V stars. It seems however rather unlikely that all our observations sample a unique orbital phase (unless the orbital period would be very long). Therefore, because of the orbital motion, we would expect the *RV* separation of both stars and hence the width of the various absorption lines to change. This is not the case in our data.

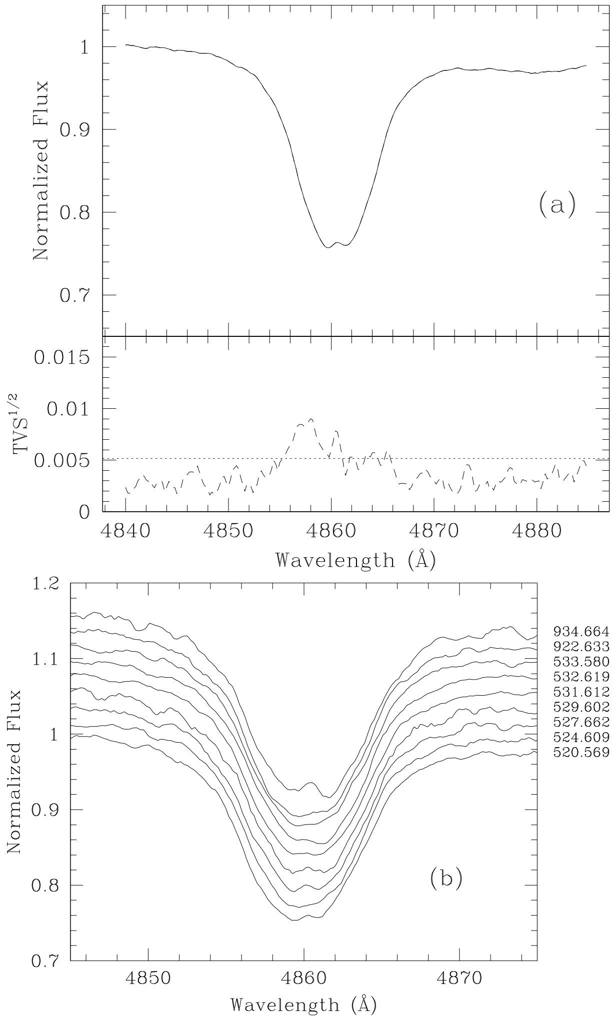

Fig. 4. Variability of the Hβ line in the spectrum of BD+60° 513. Panel **a)** yields the mean profile over our entire data set along with the square root of the TVS. The dotted line on the TVS$^{1/2}$ plot illustrates the thresholds for variations significant at the 99% level. Panel **b)** illustrates the variations of the Hβ profile as a function of time. The heliocentric Julian days are given in the format HJD−2 452 000 on the right of each spectrum. Note that the weak central emission peak in the core of the Hβ absorption is due to the contamination by the nebular emission from the IC 1805 nebula.

As mentioned above, there is some low-level line profile variability in the spectrum of BD+60° 513. In order to quantify this variability, we have computed the time variance spectrum over the entire spectral range from 4460 to 4890 Å as well as for individual lines. The TVS yields the most significant detection of variability in the blue wing of the Hβ line (see Fig. 4). The existence of this variability turns out to be robust in the sense that it remains if we omit individual spectra (one at the time) and reapply our analysis to the remaining time series. A 2D Fourier analysis (see e.g. Rauw et al. 2003) suggests time scales of 1.4 or 3.5 days for this variability. The former "period" is too short to be due to an orbital motion (there would not be enough room for a pair of O7.5 V stars in such a system). The 3.5 days period would not suffer from this problem. However, as stated above, for a short orbital period our data set would sample very different orbital phases and we would thus expect to see variations of the apparent line widths, which we do not observe here. We note that the presence of other strong peaks in the 2D periodograms suggests that the line profile variability could occur over significantly longer or shorter time scales (depending on the choice of the right alias). Unfortunately, our time series does not allow to properly investigate profile variability on these time scales.

In summary, the *RV*s of BD+60° 513 as well as the lack of line width changes suggest that this is a rather rapidly rotating single O7.5 V((f)) star. The low-level profile variability of the Hβ line could be due to non-radial pulsations maybe occuring on a time scale too short to be sampled by our data set. In fact, the rather low mass loss rate (2.8×10^{-7} $M_\odot$ yr^{-1}) inferred by Llorente de Andrés et al. (1982) suggests that the stellar wind density might be too low to trigger an appreciable variability in optical lines.

4. Fundamental parameters of BD+60° 497

Moffat & Vogt (1974) quote a V magnitude of 8.84 and a $B-V$ colour of 0.51 for BD+60° 497 (their star # 27011). On the other hand, Reed (1998) presents a compilation of *UBV* measurements from different bibliographic sources (see references in Reed 1998) that yield V in the range 8.76 to 8.80 and a $B-V$ colour of 0.57. Massey et al. (1995) finally quote $V = 8.85$ and $B-V = 0.54$. In the following we adopt an average value of $V = 8.80$ and $B-V = 0.57$. The latter value yields $E(B-V) \simeq 0.90$. Using near infrared photometry, Sagar & Qian (1990) showed that $R_V = 3.0$ should be appropriate for BD+60° 497. We thus obtain an extinction of $A_{\rm V} \simeq 2.70$ in excellent agreement with the value (2.73 ± 0.05) that Sagar & Qian independently derived from their IR photometry.

Using photometry and spectroscopy of a large set of cluster members, Massey et al. (1995) inferred a distance modulus of $DM = 11.85 \pm 0.08$ and an age of 1−3 Myr for IC 1805. They also derived a mean colour excess $\overline{E(B-V)} = 0.87 \pm 0.02$ with a spread in colour excess from 0.68 to 1.29. The distance is in good agreement with the result ($DM = 11.9 \pm 0.1$) of Guetter & Vrba (1989). Therefore, we obtain an absolute V magnitude of $M_V = -5.75 \pm 0.12$ for the BD+60° 497 binary.

In order to position the components of BD+60° 497 in the Hertzsprung-Russell diagram, we need to derive the bolometric luminosity of the individual components. To do so, we first infer their relative brightness in the blue spectral range by comparing the measured *EW*s of the two components of the He I λ4471 line to the mean *EW* of this line in the spectra of single stars of same spectral type. The latter were evaluated from the compilation of *EW*s provided by Conti & Alschuler (1971) and Conti (1973a). In this way, we find that the primary must be about three times brighter than the secondary in the optical spectral range: $M_{V,1} - M_{V,2} \sim -1.14 \pm 0.16$. Combining this result with the absolute magnitude of the binary system inferred above yields $M_{V,1} = -5.42 \pm 0.13$ and $M_{V,2} = -4.28 \pm 0.17$. Finally, adopting the bolometric corrections from Humphreys & McElroy (1984), we obtain bolometric luminosities of $\log L_{\rm bol,1}/L_\odot = 5.55 \pm 0.05$ and $\log L_{\rm bol,2}/L_\odot = 4.94 \pm 0.07$ for the primary and secondary respectively.

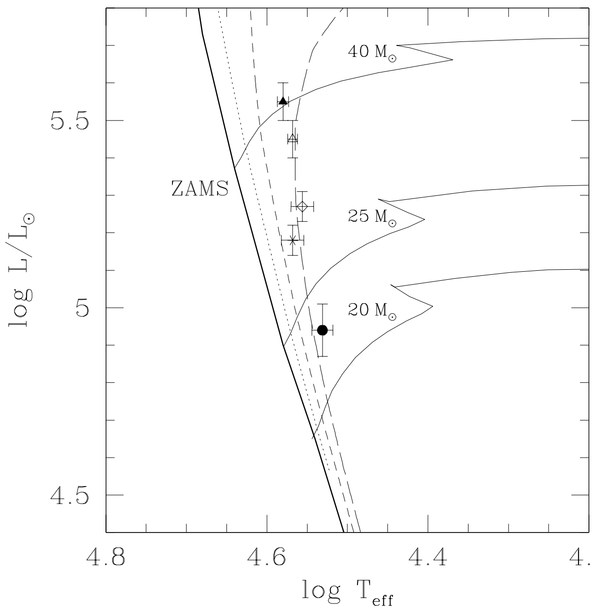

Fig. 5. Position of the primary (filled and open triangle respectively for a bolometric correction for luminosity class V or III) and secondary (filled circle) of BD+60° 497 in the Hertzsprung-Russell diagram. The evolutionary tracks for single stars of initial mass 20, 25 and 40 $M_\odot$ as well as the isochrones corresponding to ages of 1, 2 and 3 Myr are from Schaller et al. (1992) for solar metallicity. The locations of BD+60° 501 and BD+60° 513 are indicated by the star and open diamond respectively.

Following the temperature scale of main sequence O-type stars proposed by Martins et al. (2002), the effective temperature of the primary and secondary should be respectively $(38\,000 \pm 500)$ K and $(34\,000 \pm 1000)$ K. The location of the two components in the H-R diagram is illustrated in Fig. 5. Both stars appear to have evolved off the zero age main sequence (ZAMS). More precisely, whilst the absolute magnitude and the bolometric luminosity that we derived for the secondary are in good agreement with typical values of late O main sequence stars (see e.g. Howarth & Prinja 1989), the parameters of the primary are intermediate between those of a main sequence and a giant O6.5 star. Therefore, we may wonder whether it would not be more appropriate to use a luminosity class III bolometric correction for the primary. If we do so, we obtain $\log L_{\rm bol,1}/L_\odot = 5.45 \pm 0.05$ and $T_{\rm eff,1} = (37\,000 \pm 500)$ K. The corresponding position for the primary is also shown in Fig. 5.

In Fig. 5 we compare the properties of the components of BD+60° 497 to the single star evolutionary models of Schaller et al. (1992). We find that the primary lies almost exactly on the 40 $M_\odot$ initial mass evolutionary track, whilst the secondary lies between the tracks for an initial mass of 20 and 25 $M_\odot$. A crude interpolation between the various models yields evolutionary masses of $M_1 = (39.6 \pm 2.5)\,M_\odot$ and $M_2 = (22.7 \pm 1.0)\,M_\odot$ for the primary (adopting the main sequence bolometric correction) and secondary respectively. The corresponding evolutionary mass ratio (1.74 ± 0.13) of the system appears thus significantly larger than the observed mass ratio of 1.28 ± 0.12. This discrepancy (although slightly less severe) subsists if we adopt instead the luminosity class III bolometric correction for the primary ($M_1 = (36.3 \pm 1.5)\ M_\odot$; $M_1/M_2 = 1.60 \pm 0.10$).

The evolutionary tracks of Schaller et al. (1992) account for the effect of mass loss but do not include rotational mixing. Meynet & Maeder (2000) quantified the importance of rotation on the output of stellar evolution models at solar metallicity. As a consequence of rotational mixing, fast rotators appear more luminous than non-rotating stars of the same mass. However in the region of the H-R diagram where the components of BD+60° 497 are located (i.e. near the main sequence), this effect should have a rather modest impact on the stellar luminosity (≤ 0.1 in $\log L_{\rm bol}/L_\odot$ according to Fig. 8 of Meynet & Maeder 2000), probably not sufficient to reconcile the mass ratio estimated from the single star evolutionary tracks with the observed mass ratio, especially since the primary absorption lines do not reveal evidence for an exceptionally large rotational velocity.

These problems in the comparison of massive binaries to single star evolutionary theories are actually not new. Penny et al. (1996) already described the same sort of conflicts for binary systems where one component is suspected to currently undergo Roche lobe overflow (RLOF). These authors suggested that during case A RLOF, the mass-losing star is apparently hotter and more luminous than its mass would predict. Could this imply that the primary in BD+60° 497 is currently losing mass through RLOF?

From the luminosities and temperatures derived above we can estimate the radii of the two components to be (13.6 ± 0.9) $R_\odot$ and (8.5 ± 0.8) $R_\odot$ for the primary[1] and secondary respectively. Whilst the secondary probably fits well inside its critical volume, the primary component might fill its Roche lobe if the inclination is as large as 65° (or 74° for the giant parameters). BD+60° 497 is not known to display eclipses that might help to constrain the orbital inclination. Halbedel (1986) monitored BD+60° 497 over 43 night as one of two comparison stars during her observing campaign on BD+60° 562. The differential photometry failed to reveal significant variability of the program star or the comparison stars. Although for a short orbital period that close to an integer number of days the orbital cycle could under some circumstances be poorly sampled, it appears unlikely that BD+60° 497 displays strong variability attributable to photometric eclipses. We further checked this on the data of the Northern Sky Variability Survey (NSVS[2], Woźniak et al. 2004). The NSVS contains time series of data obtained in a single unfiltered photometric band with the Robotic Optical Transient Search Experiment. Though these data indicate a dispersion of 0.018 mag for BD+60° 497, they fail to reveal phase-locked variations attributable to eclipses or ellipsoidal variations. The lack of eclipses yields the condition $a \cos i \geq R_1 + R_2$. Substituting the numerical values from Table 2 and the radii of the components, we obtain $i \leq (54 \pm 2.5)°$ (or $i \leq (55 \pm 2.5)°$ for the giant parameters). For these values of the inclination, the Roche lobe radii (computed from the results in Table 2) would be sufficiently large so that none of the stars should be filling its Roche lobe. Moreover, though a direct comparison with binary evolutionary models is always tricky (due to the huge parameter space to explore), we note that models predict a rather complex behaviour for the evolutionary tracks during RLOF (e.g. de Loore & Vanbeveren 1994; Wellstein et al. 2001) and an overluminosity of the mass losing star during RLOF does not seem to be a general feature.

We thus conclude that there is no indication at present that the primary in BD+60° 497 is undergoing Roche lobe overflow. Alternatively, we caution that the numerical results obtained in this section (including the evolutionary masses) rest upon the various calibrations that we adopted. Recent results suggest that the effective temperature scale of mid-O stars might have to be revised downwards by as much as 6000 K (Bianchi & Garcia 2002) compared to the calibration of Martins et al. (2002) and this could of course impact on the properties derived in this section and account for some of the discrepancy between the observed and evolutionary mass ratios.

Using the same calibrations as above, we have also plotted the locations of BD+60° 501 and BD+60° 513 in the H-R diagram. For BD+60° 501, we infer on average $V = 9.58 \pm 0.03$ and $B - V = 0.46 \pm 0.01$ (Massey et al. 1995; Reed 1998). With $R_V = 3.0$, we thus obtain $A_{\rm V} \simeq 2.34$ in good agreement with the value (2.24 ± 0.18) of Sagar & Qian (1990). The absolute V magnitude and bolometric luminosity of BD+60° 501 thus become $M_V = -4.61 \pm 0.11$ and $\log L_{\rm bol}/L_\odot = 5.18 \pm 0.04$, whilst the effective temperature of an O7 V star should be (37 000 ± 500) K according to Martins et al. (2002). For BD+60° 513, we obtain in a similar fashion $V = 9.40 \pm 0.01$ and $B - V = 0.49 \pm 0.01$. From these values we derive $M_V = -4.88 \pm 0.11$ and $\log L_{\rm bol}/L_\odot = 5.27 \pm 0.04$ and the effective temperature is estimated as (36 000 ± 500) K. It can be noted from Fig. 5 that the location of these stars in the H-R diagram is in good agreement with the 1–3 Myr age of the cluster as determined by Massey et al. (1995).

5. *ROSAT* data

O-type stars are rather soft intrinsic X-ray emitters with luminosities that roughly follow an empirical relation between $L_{\rm X}$ and $L_{\rm bol}$ (see Berghöfer et al. 1997 and references therein). Due to an excess X-ray emission produced in the wind interaction zone, some binary systems display an X-ray luminosity above the level expected from this empirical relation. X-ray observations therefore have the potential to provide some additional hints on the multiplicity of early-type stars.

IC 1805 was observed for 8.8 ks with the PSPC instrument onboard the *ROSAT* satellite on 22–23 August 1992 (sequence number rp201263n00). We have extracted these data from the LEDAS archive and processed them using the XSELECT and XSPEC softwares. BD+60° 497 and BD+60° 501 are clearly detected with net (i.e. background corrected) count rates of $(4.6 \pm 1.3) \times 10^{-3}$ and $(6.4 \pm 1.1) \times 10^{-3}$ cts s^{-1}. BD+60° 513 is not detected in this observation and a save upper limit on its net count rate (determined from the count rate of the faintest source detected in this field) is $\sim 2 \times 10^{-3}$ cts s^{-1}.

[1] If we adopt the luminosity III bolometric correction for the primary, the radius becomes (12.8 ± 0.8) $R_\odot$.

[2] The NSVS was created jointly by the Los Alamos National Laboratory and the University of Michigan and was funded by the US Department of Energy, NASA and the NSF.

Although the X-ray spectra of BD+60° 497 and BD+60° 501 are of poor quality, we managed to fit them with an absorbed `mekal` optically thin thermal plasma model (Mewe et al. 1985).

For BD+60° 497 we fixed the neutral hydrogen column density at the interstellar value of $N_{\rm H}^{\rm ISM} = 0.52 \times 10^{22}$ cm^{-2} and we obtained a best fitting temperature $kT = 0.34^{+.43}_{-.14}$ keV with a flux of 4.2×10^{-14} erg cm^{-2} s^{-1} in the energy band 0.1−2.0 keV. The corresponding dereddened X-ray flux over the same energy range is 3.6×10^{-13} erg cm^{-2} s^{-1}. Adopting a distance of 2.3 kpc (see above), we obtain an X-ray luminosity of $L_{\rm X} = 2.4 \times 10^{32}$ erg s^{-1} in the 0.1−2.0 keV domain. From the empirical $L_{\rm X}/L_{\rm bol}$ relation of Berghöfer et al. (1997) and the bolometric luminosities of the individual binary components derived hereabove, we expect an X-ray luminosity of the binary of 2.6×10^{32} erg s^{-1} in excellent agreement with the value derived from the *ROSAT* data. Therefore, we conclude that BD+60° 497 does not display any excess X-ray emission that could be attributed to a wind interaction in the binary.

For BD+60° 501 the hydrogen column density was fixed at $N_{\rm H}^{\rm ISM} = 0.45 \times 10^{22}$ cm^{-2} and the best fitting temperature was found at $kT = 0.93^{+.75}_{-.59}$ keV. The corresponding observed and unabsorbed fluxes are 4.6×10^{-14} and 1.8×10^{-13} erg cm^{-2} s^{-1} in the 0.1−2.0 keV band. This corresponds to an X-ray luminosity of $L_{\rm X} = 1.1 \times 10^{32}$ erg s^{-1}. Again this value is in good agreement with the empirical $L_{\rm X}/L_{\rm bol}$ relation of Berghöfer et al. (1997) from which we expect an X-ray luminosity of 0.8×10^{32} erg s^{-1}. On the other hand, given the bolometric luminosity of BD+60° 513 estimated above, the non-detection of the latter in the *ROSAT* data is somewhat surprising. We note that this non-detection – and consequently the lack of an X-ray luminosity excess – provides further evidence against a close binary scenario for BD+60° 513. In fact, the O7 V + O7 V binary HD 159176 displays an X-ray excess of about a factor 7 (De Becker et al. 2004) and one would expect a very similar result if BD+60° 513 were an O7.5 V + O7.5 V binary.

In summary, the *ROSAT* data do not provide any evidence for multiplicity of BD+60° 501 or BD+60° 513.

6. Summary and conclusions

Using a set of spectroscopic data we have investigated the multiplicity of three mid-O (O6−8.5) stars in the very young open cluster IC 1805. We have found that BD+60° 497 is an SB2 system consisting of an O6.5 V((f)) primary and an O8.5-9.5 V((f)) secondary. From the radial velocities of its components, we have inferred an orbital period of 3.96 ± 0.09 days and we have presented the very first orbital solution for this system. The mass ratio of the binary 1.28 ± 0.12 is smaller than the value expected from a comparison with single star evolutionary tracks. We suggest that this discrepancy stems mainly from the uncertainties that affect the current calibrations of O-star temperatures, bolometric corrections and luminosities.

The other two targets of our present study, BD+60° 501 and BD+60° 513, do not display significant radial velocity changes, suggesting that these are probably single stars. This is in contradiction with previous reports of these stars showing *RV* changes or double lines.

So far, the only confirmed spectroscopic binaries in IC 1805 are the SB1 system HD 15558 (Garmany & Massey 1981) and the SB2 system BD+60° 497 studied in the present paper. The stars investigated here provide a complete sample of mid-O type stars in IC 1805. The fraction of confirmed binaries in this mass range is thus 1/3. Our results imply therefore that the lower limit[3] on the binary fraction among the early-type stars of IC 1805 is reduced to 60% rather than the 80% quoted by Ishida (1970) and García & Mermilliod (2001) who included BD+60° 501 and BD+60° 513 in their census of massive binary stars in IC 1805. Therefore the binary fraction in this cluster appears less extreme than previously thought. Additional data on the earliest O-type stars (HD 15558, HD 15570 and HD 15629) of IC 1805 are currently being analysed and will help to further constrain the binary fraction among O-type stars in this cluster. This will be the subject of a forthcoming paper (De Becker et al. in preparation).

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[3] This fraction is a lower limit since we cannot rule out the existence of binaries seen under a low inclination (thus preventing us from detecting any *RV* changes).

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