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Optical spectroscopy of XMEGA targets in the Carina Nebula – III. The multiple system Tr 16-104 (≡CPD −59° 2603)

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ABSTRACT

We discuss the orbital elements of the multiple system Tr 16-104 which is usually believed to be a member of the open cluster Trumpler 16 in the Carina complex. We show that Tr 16-104 could be a hierarchical triple system consisting of a short-period (2.15 d) eclipsing O7 V + O9.5 V binary bound to a B0.2 IV star. Our preliminary orbital solution of the third body indicates that the B star most probably describes an eccentric orbit with a period of ~285 or ~1341 d around the close binary. Folding photometric data from the literature with our new ephemerides, we find that the light curve of the close binary exhibits rather narrow eclipses indicating that the two O stars must be well inside their Roche lobes. Our analysis of the photometric data yields a lower limit on the inclination of the orbit of the close binary of $i \geq 77°$. The stellar radii and luminosities of the O7 V and O9.5 V stars are significantly smaller than expected for stars of this spectral type. Our results suggest that Tr 16-104 lies at a distance of the order of 2.5 kpc and support a fainter absolute magnitude for zero-age main-sequence O stars than usually adopted. We find that the dynamical configuration of Tr 16-104 corresponds to a hierarchical system that should remain stable provided that it suffers no strong perturbation. Finally, we also report long-term temporal variations of high-velocity interstellar Ca II absorptions in the line of sight towards Tr 16-104.

Key words: binaries: close – binaries: spectroscopic – stars: early-type – stars: fundamental parameters – stars: individual: Tr 16-104 – open clusters and associations: individual: Trumpler 16.

1 INTRODUCTION

The study of spectroscopic binary systems in open stellar clusters with well-determined age and distance constitutes an elegant means to constrain the fundamental properties of the binary components and to evaluate the time-scales of tidal circularization. This is especially true for early-type binaries in the youngest open clusters. In principle, the very young Trumpler 16 cluster in the Carina region [log (age) = 6.5, Massey & Johnson 1993] could be one of the best places in our Galaxy to study the multiplicity of massive stars. A previous study of the duplicity in Tr 16 (Levato et al. 1991) revealed the presence of at least five O-type spectroscopic binaries with orbital periods shorter than seven days. Using spectrograms of 43 Å mm^{-1} dispersion, Levato et al. found rather large eccentricities ($e \geq 0.16$) even for the shortest orbital periods. However, higher spectral resolution is required to ascertain the orbital elements of these systems and this is especially true for those systems classified as single-lined spectroscopic binaries (SB1s) where the apparent eccentricity could result from the blend of the spectral lines of the individual components.

Tr 16-104 (≡CPD −59° 2603, Feinstein, Marraco & Muzzio 1973) is a multiple system in the Tr 16 cluster. Walborn (1973) determined an O7 V ((f)) spectral classification for the composite spectrum and suspected multiplicity for this star. Levato et al. (1991) classified Tr 16-104 as a short-period SB1 binary. Their preliminary orbital solution yields an orbital period of 1.81 d, an eccentricity of 0.16 and a semi-amplitude $K = 160$ km s^{-1}.

Howarth et al. (1997) studied the only two *IUE* spectra of this

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system and found three peaks in their cross-correlation function. According to Howarth et al., only peak A (the most prominent one) had changed its position between the two *IUE* exposures. These authors suggested therefore that star A could be the SB1 binary component that had been studied by Levato et al. (1991) while the other two peaks would not be associated with the binary. This would bring the number of stars in the system to at least four. More recently, a preliminary SB2 orbital solution for Tr 16-104 was proposed by Solivella & Niemela (1999) who derived a period of 2.15291 d from the radial velocities of the He II λ 4686 line as measured on medium resolution spectra.

Besides our will to investigate the multiplicity of Tr 16-104, our observing campaign was motivated by the fact that this system was also observed with the *ROSAT* satellite as part of the XMEGA campaign (http://lheawww.gsfc.nasa.gov/users/corcoran/xmega/xmega.html) to study the X-ray properties of early-type stars (Corcoran, Pittard & Marchenko 1999). Since the *ROSAT* observations could have revealed an excess X-ray emission arising in a wind interaction zone, new accurate ephemerides were needed to fully interpret the X-ray data. In the present paper, we discuss a large set of medium and high resolution optical spectra and we show that Tr 16-104 could actually be a hierarchical triple system consisting of a short period eclipsing O7 V + O9.5 V binary revolving around a third component of spectral type B0.2 IV.

The paper is organized as follows. In Section 2, we present our observations and the properties of the spectrum of Tr 16-104 are discussed in Section 3. Section 4 deals with the orbital solutions of this multiple system and the light curve is analysed in Section 5. The fundamental parameters of the components and the multiplicity of Tr 16-104 are discussed in Section 6. Finally our conclusions are outlined in Section 7.

2 OBSERVATIONS

Blue–violet and yellow medium-resolution spectra of Tr 16-104 were gathered during several observing runs in 1995, 1996 and 1997 with the ESO 1.5-m telescope equipped with a Boller & Chivens (B&C) Cassegrain spectrograph. The data were obtained with a holographic grating (2400 line mm^{-1}) providing a reciprocal dispersion of 32.6 Å mm^{-1}. The detector used in 1995 was a Ford Aerospace 2048L UV-coated CCD with a pixel size of 15 μm, whereas in 1996 and 1997 we used a thinned, UV flooded Loral-Lesser CCD. The slit width was set to 220 μm corresponding to 2 arcsec on the sky. The spectral resolution as measured on the helium–argon calibration spectra is 1.2 Å. Our blue–violet data cover the wavelength ranges 3800–4750 Å (1995 March) and 3850–4800 Å (1996 May and 1997 March). The yellow setting covers the range 5400–6200 Å (1995 March). Part of the B&C data are affected by a strange fringing pattern (Turatto, Tighe & Castillo 1997) that occurs over the wavelength range 4050–4250 Å in the present instrument configuration. Given the variability of the fringing pattern and in order to avoid amplification of the fringes in the stellar spectra, the data were not flat-fielded. All the reductions were performed using the MIDAS software developed at ESO.

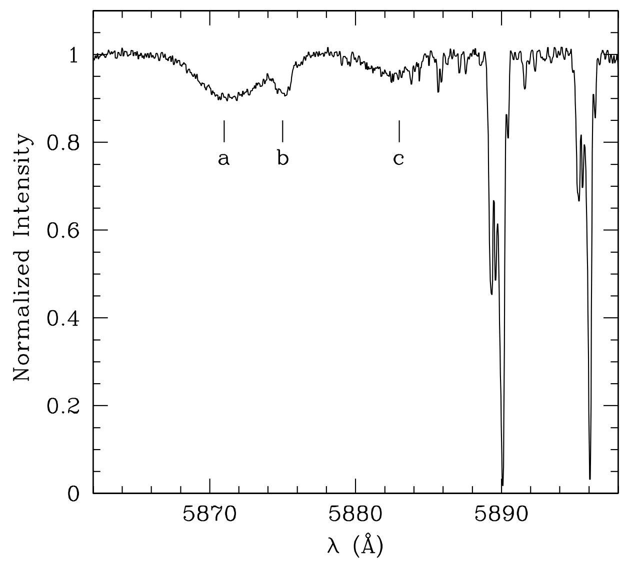

Figure 1. FEROS spectrum of Tr 16-104 around the He I λ 5876 line as observed on HJD 245 1299.602. Note also the very complex structure of the interstellar Na I profiles.

19 CCD echelle spectra were obtained at the Complejo Astronómico El Leoncito (CASLEO),[1] Argentina during five different observing runs between 1997 February and 2001 March. We used the 2.15-m Jorge Sahade Telescope and the modified REOSC SEL[2] Cassegrain spectrograph equipped with a Tek 1024×1024 pixel CCD as detector. These spectra cover an approximate wavelength range from 3500 to 6000 Å, at a reciprocal dispersion of 0.17 Å pixel^{-1} at 4500 Å. All the data obtained at CASLEO were reduced and analysed using IRAF[3] routines.

During three observing runs in 1999 April–May, end of 1999 May and 2000 May, a set of echelle spectra was taken with the Fiber-fed Extended Range Optical Spectrograph (FEROS, Kaufer et al. 1999) attached to the ESO 1.5-m telescope at La Silla. 37 orders corresponding to a wavelength domain from 3650 to 9200 Å were observed. The spectral resolving power of the FEROS instrument is 48 000. The detector was an EEV CCD with 2048×4096 pixels of 15×15 μm. We used the FEROS context working under the MIDAS environment to reduce the FEROS echelle spectra.

3 THE SPECTRUM OF TR 16-104

Our medium- and high-resolution spectra of Tr 16-104 clearly reveal the spectral signature of at least three stellar components. These are best seen in the profiles of the He I absorption lines (Fig. 1). The absorptions of two of the three components are quite broad and their wavelengths change rather quickly as a result of their orbital motion. On the contrary, the lines of the third component are rather narrow and their radial velocity evolves only very slowly. We also notice a fourth, very narrow (FWHM ~0.23 Å) absorption component of the He I λ 3889 line at a fairly constant radial velocity of $\sim -33 \pm 1$ km s^{-1}. On some of our spectra, a similar feature can be seen in the He I λ 5876 line. This fourth component is most likely of interstellar origin. In fact, interstellar He I λ 3889 absorption at this radial velocity is a common feature in the spectra of early-type stars in the Carina complex (Walborn & Hesser 1975).

In the following, we call component 'a' the star that displays the broadest and strongest absorption lines (see Fig. 1). In particular, component 'a' has the strongest He II absorption lines and is the

[1] CASLEO is operated under agreement between CONICET and the National Universities of La Plata, Córdoba and San Juan.

[2] Spectrograph Echelle Liège (jointly built by REOSC and Liège Observatory and on long-term loan from the latter).

[3] IRAF is distributed by NOAO, operated by AURA, Inc., under agreement with NSF.

Table 1. FWHM of the He I λ 5876 lines of the various components of the Tr 16-104 system. The third column provides the most likely cross-reference with the identifications proposed by Howarth et al. (1997). The last column lists the rotational velocities of the three components as derived by Howarth et al.

Component	$\overline{\mathrm{FWHM}}$ (He I λ 5876) (Å)	Cross-ID	$v_e \sin i$ (km s^{-1})
a	5.0 ± 0.4	A	164
b	1.2 ± 0.2	B	59
c	4.0 ± 0.4	C	111

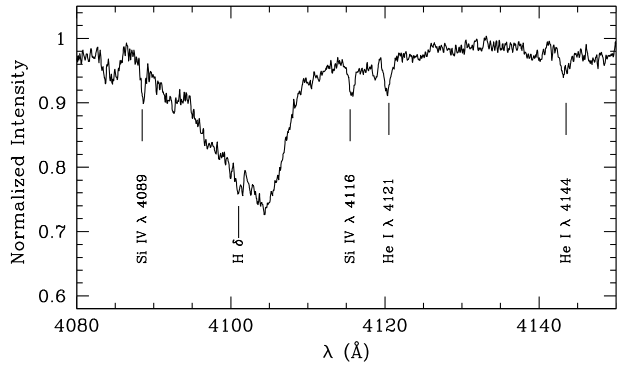

Figure 2. FEROS spectrum of Tr 16-104 in the region around the Hδ line as observed on HJD 245 1300.608. The figure illustrates the relative strengths of the lines of the B0.2–0.5 component that are used for the luminosity classification of this star (see text).

only star in the system that shows C IV $\lambda\lambda$ 5801, 5812 in absorption. A broad and very weak C III λ 5696 emission line appears also to be associated with star ‘a’.

In addition to the sharp prominent He I absorption lines, the spectrum of component ‘b’ displays also narrow absorptions of He II λ 4686 as well as many metal lines (e.g. O II $\lambda\lambda$ 4070, 4072, 4075, 4415, 4417, 4699; Si III $\lambda\lambda$ 4552, 4568; Si IV λ 4089, …).

Star ‘c’ displays broad absorption lines. While the He I lines have strengths comparable to those of star ‘a’, the He II lines are considerably weaker and we see no trace of C IV lines associated with this star. Comparing our observations with the relative intensities and the widths of the UV lines reported by Howarth et al. (1997), it seems reasonable to cross-identify the components A = a, B = b and C = c (see Table 1).

3.1 Spectral classification

We have measured the equivalent widths (EWs) of the O-star classification lines He I λ 4471 and He II λ 4542 on those high resolution spectra where they are best separated. Using the Conti (1973b) and Mathys (1988) classification scheme, we find that the primary (i.e. the more massive star, ‘a’) is of spectral type O7–7.5 ($\log W' = \log \mathrm{EW}(\mathrm{He\,I}\lambda 4471) - \log \mathrm{EW}(\mathrm{He\,II}\lambda 4542) = -0.1$ to $+0.06$), whilst the secondary (‘c’) yields $\log W' = 0.42$–0.72, corresponding to a spectral type O9.5–9.7. Our data reveal no trace of the very weak N III emission reported by Walborn (1973). Therefore we cannot confirm the O ((f)) classification of Tr 16-104. It seems likely that the continuum between the absorption features of the triple spectrum had been mistaken for weak emission in the past.

Finally, the Si IV λ 4089 and Si III λ 4552 lines in the spectrum of component ‘b’ have comparable strengths and the He II λ 4686 line is seen in absorption. According to the criteria of Walborn & Fitzpatrick (1990), these spectral features correspond to a B0.2–0.5 spectral type.

From the dilution of the absorption lines in Tr 16-104 compared to the line strength in the spectra of single stars of the same spectral type, we can infer a very rough estimate of the relative contributions of the various stars in the system to its total optical luminosity (see e.g. Rauw et al. 2000). Assuming that stars ‘a’ and ‘c’ have normal He abundances, we compare the observed equivalent widths of the He I $\lambda\lambda$ 4026, 4471 and He II λ 4542 lines to the average EWs of these lines in the spectra of O7 and O9.5 stars as tabulated by Conti & Alschuler (1971) and Conti (1973a). In this way, we obtain $l_a = L_a/L_{tot} \simeq 0.64$ and $l_c = L_c/L_{tot} \simeq 0.29$ in the blue–violet part of the spectrum for orbital phases outside photometric eclipse (see below).

Similarly, using the typical equivalent widths of spectral lines in B-type stars as listed by Didelon (1982), we obtain $l_b = L_b/L_{tot} \simeq 0.15$. Of course, the sum of the relative contributions should not exceed 1.0 and if we normalize our results hereabove, we derive $l_a \simeq 0.59$, $l_b \simeq 0.14$ and $l_c \simeq 0.27$.

From the strengths of the cross-correlation peaks, Howarth et al. (1997) derived raw magnitude differences of 1.2 and 1.3 between the A–B and A–C components respectively. The results of Howarth et al. yield $l_a = 0.61$, $l_b = 0.20$ and $l_c = 0.19$ in the *IUE* spectral range. Given the uncertainties and the different spectral domains, the numbers inferred from both methods (Howarth et al.’s technique and ours) are in fair agreement with each other.

We can use the $\log W'' = \log \mathrm{EW}(\mathrm{Si\,IV}\lambda 4089) - \log \mathrm{EW}(\mathrm{He\,I}\lambda 4144)$ criterion proposed by Conti & Alschuler (1971) to determine the luminosity of the O7 component. From our FEROS spectra, we find that $\mathrm{EW}(\mathrm{Si\,IV}\lambda 4089) \simeq 0.16$ Å and $\mathrm{EW}(\mathrm{He\,I}\lambda 4144) \leq 0.15$ Å yielding $\log W'' \geq 0.03$. According to Conti & Alschuler (1971), this corresponds to a main-sequence classification, though the fact that we are dealing with a lower limit on W'' leaves some ambiguity between luminosity classes V and III. The strength of the He II λ 4686 absorption and the ratio of He I λ 4388/He II λ 4542 (Walborn & Fitzpatrick 1990) do not allow us to discriminate between luminosity classes V and III either, though they are slightly more consistent with a main-sequence classification. Walborn (1980) pointed out that the strength of the C III λ 5696 emission line in the spectrum of O7–O8 stars increases with luminosity. Therefore, the weak (EW $\simeq$ 0.1 Å) C III λ 5696 emission associated with star ‘a’ is also marginally more consistent with a main-sequence classification of this star.

We use the Mathys (1988) criterion ($\log W^+ = \log \mathrm{EW}(\mathrm{He\,I}\lambda 4388) + \log \mathrm{EW}(\mathrm{He\,II}\lambda 4686)$) for the luminosity classification of the O9.5 secondary (i.e. star ‘c’). This criterion yields $\log W^+ = 4.23 - 2 \log l_c$. Inserting the above estimates of $l_c = 0.20$–0.27, we obtain $\log W^+ = 5.37$–5.63 corresponding to a main-sequence star ($\log W^+ > 5.35$, Mathys 1988) though again we cannot completely rule out a luminosity III classification from this result. We emphasize that the primary/secondary optical luminosity ratio clearly indicates that the primary and the secondary should be of the same luminosity class.

From the relative strengths of the Si IV $\lambda\lambda$ 4089, 4116 and He I $\lambda\lambda$ 4121, 4144 lines (Fig. 2) in the spectrum of component ‘b’, we infer a luminosity class IV (Walborn & Fitzpatrick 1990) for this star, though we cannot rule out a luminosity class III. Again the relative luminosity of the ‘b’ component implies that this star is most likely of a similar luminosity class than the components of the short-period binary.

In summary, the short-period binary most probably consists of an O7 primary and an O9.5 secondary, whilst the third component is of spectral type B0.2–0.5. The spectroscopic luminosity ratios indicate that all three stars should belong to the same luminosity class. Though some of the criteria yield somewhat ambiguous results, it seems that the stars are of main-sequence luminosity class (we shall return to this point in Section 6.1).

Though the equivalent widths of the absorption lines of the close binary display some variations, we could not find any significant phase-locked variations that might be related to the so-called ‘Struve–Sahade’ effect (e.g. Stickland 1997). The only possible exception is the He I λ 4471 line that appears stronger in the primary spectrum around orbital phases when the star is approaching, while the EW of the secondary’s line does not vary.

3.2 The interstellar absorption lines

The spectrum of Tr 16-104 displays very prominent and complex interstellar absorption lines of Ca II and Na I (see Figs 1 and 3). In the Ca II H and K lines, the strongest absorption features have radial velocities of −216, −34, −18, +5, +25 and $+100\,\mathrm{km\,s^{-1}}$. The same structures are found in the Na I D1 and D2 lines although the visibility of the fainter higher velocity (−216 and $+100\,\mathrm{km\,s^{-1}}$) components is hampered by the telluric absorption lines. The RVs of the strongest components are in good agreement with those of the double-peaked nebular [O III] $\lambda\lambda$ 4959, 5007 lines (−29, $+8\,\mathrm{km\,s^{-1}}$). The optical and UV interstellar absorption spectrum towards Tr 16-104 has been extensively studied by Walborn (1982), Walborn et al. (1998) and Danks et al. (2001) and we refer to their analyses for further details. Nevertheless, we emphasize that the Ca II profiles in our spectra are slightly different from those published by Walborn (1982). The most outstanding difference concerns the absorption component at $+100\,\mathrm{km\,s^{-1}}$ which appears much stronger in our spectra than in the data of Walborn (1982). Though the variability of interstellar absorptions is an a priori unexpected feature, this is not the first time that such a phenomenon is reported for Tr 16-104. In fact, Danks et al. (2001) recently analysed high-resolution *HST*–STIS observations of the interstellar Mg I and Mg II lines towards Tr 16-104 taken 22 months apart and discovered temporal variations in five distinct interstellar velocity components. These authors suggest that the high-velocity interstellar features are produced through the interaction of the stellar winds with dense surrounding material. In this context, we note that we find no significant variability on the time-scales of the orbital periods of the close binary or of the third component that could indicate an origin of the variations in changing lines of sight to the binary components at different phases.

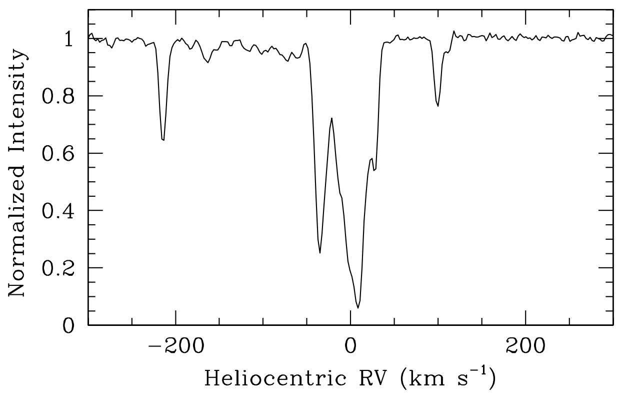

Figure 3. Mean FEROS spectrum of Tr 16-104 around the Ca II K line. Note the complex structure of the line and the sharp component at RV = $+100\,\mathrm{km\,s^{-1}}$ that was only marginally present in the data of Walborn (1982).

4 ORBITAL SOLUTIONS

The radial velocities of the three stellar components in Tr 16-104 were measured by fitting simultaneously up to three Gaussians to the observed line profiles. Because of the varying strength of the different line components (see below), good fits could only be

Table 2. Journal of our spectroscopic observations of Tr 16-104. For each component we list the radial velocity (RV in $\mathrm{km\,s^{-1}}$) as well as the number of spectral lines (n) used to determine these RVs. The last column specifies the instrument used to collect the spectrum: B&C = Boller & Chivens at the 1.5 m ESO, R = REOSC at CASLEO, F = FEROS at the 1.5 m ESO.

HJD	‘a’		‘b’		‘c’		Inst.
−244 0000	RV	n	RV	n	RV	n	
9805.723	−111.1	3	−65.9	1	266.3	3	B&C
9805.799	−104.5	2			233.9	1	B&C
9808.727	229.4	3	−67.5	1	−328.6	1	B&C
9808.787	218.7	3	−68.0	1	−330.5	1	B&C
9808.853	219.9	3	−71.2	1	−307.5	1	B&C
9809.739	−221.9	2	−70.5	1	354.1	1	B&C
10205.696	−212.5	3	27.2	3	260.1	3	B&C
10206.718	74.0	3	34.1	2	−265.5	3	B&C
10207.691	−113.6	1	49.3	2	34.3	1	B&C
10208.688	23.3	3	38.7	2	−182.8	2	B&C
10209.696	5.7	1	24.2	3	−140.9	3	B&C
10210.681	−46.2	1	41.6	2	231.1	2	B&C
10211.552	95.5	2			−280.9	2	B&C
10505.675	−3.0	4	6.0	10	−87.0	4	R
10507.770	−59.0	4	5.0	16	103.0	2	R
10508.648	177.0	12	15.0	5	−247.0	4	R
10534.712	62.9	1					B&C
10535.717	−53.3	3			−173.0	3	B&C
10536.679	149.7	3	36.4	3	−235.4	3	B&C
10537.708	−169.8	4			223.5	4	B&C
10538.747	162.2	3	25.6	3	−292.3	3	B&C
10539.729	−180.7	3			298.5	3	B&C
10841.769	143.0	7	−13.0	6	−204.0	4	R
10844.832	−75.0	3	−18.0	11	83.0	3	R
10846.814	120.0	7	−20.0	9	−124.0	1	R
10851.799	−229.0	7	−3.0	2	322.0	2	R
11209.828	137.0	12	−56.0	9	−156.0	2	R
11210.822	−77.0	4	−55.0	15	72.0	10	R
11211.856	13.0	4	−50.0	9	76.0	3	R
11216.719	234.0	10	−52.0	8	−321.0	6	R
11217.845	−178.0	9	−57.0	8	344.0	5	R
11218.705	230.0	12	−59.0	8	−294.0	5	R
11299.602	−201.6	9	−27.7	14	340.2	10	F
11300.608	222.9	10	−30.6	14	−309.1	7	F
11301.584	−182.7	7	−30.0	13	292.3	8	F
11302.627	193.1	11	−26.6	14	−264.5	8	F
11304.585	98.7	6	−26.4	11	−157.0	3	F
11327.576	−217.9	9	−3.4	15	332.8	8	F
11615.749	−141.0	5	36.0	6	202.0	6	R
11619.507	178.0	5	44.0	5	−280.0	5	R
11620.516	−198.0	12	21.0	6	251.0	6	R
11669.598	−146.4	6	24.4	11	203.2	5	F
11670.556	98.3	9	23.7	13	−109.3	4	F
11671.609	−91.8	6	21.2	11	122.5	4	F
11672.545	−25.5	3	21.2	9	68.3	2	F
11673.543	96.5	5	22.4	11	−67.6	2	F
11969.548	−78.0	5	−5.0	5	97.0	5	R
11970.583	153.0	5	6.0	4	−133.0	5	R
11971.541	−150.0	5	−5.0	4	240.0	5	R

achieved when the depths and widths of the Gaussians were allowed to vary. The formal errors on the central wavelengths of these Gaussian fits in the FEROS spectra are about 4 km s^{-1} for the SB2 components and 2 km s^{-1} for the third star, whilst these formal errors are about three times larger for the lower resolution B&C data. For the O-star lines, we adopted the effective wavelengths from Underhill (1995). For component 'b', the radial velocities of the metal lines provide an independent check of the results of the multiple Gaussian fit used to deblend the He I lines. The radial velocities of the three components are listed in Table 2.

4.1 The orbital periods

We performed a period search on the radial velocity differences (primary – secondary) using the trial period technique of Lafler & Kinman (1965). Since we expect the systemic velocity of the close binary to vary owing to the influence of the third star, these RV differences are better suited for the purpose of period determinations than the actual RVs of the individual components. In fact, the RV differences are not sensitive to possible temporal changes of the systemic velocity γ. The results are listed in Tables 3 and 4. The Lafler & Kinman method yields two minima at ν_2 and $\nu_1 = 0.5 \times \nu_2$. While the FWHM of the dip at ν_2 is roughly equal to the natural width (4.6×10^{-4} d^{-1}) of the peak set by the sampling of our RV time series, we notice that the dip at ν_1 has a FWHM about half this value. Therefore, ν_1 is clearly a classical sub-harmonic artefact of the ν_2 frequency.

The most likely orbital period of the close binary turns out to be 2.15294 d. The natural width of the peak set by the sampling of our time series amounts to 0.00214 d. Assuming that the actual uncertainty equals about one tenth of the natural width, we find that the orbital period would be equal to 2.15294 ± 0.00021 d. Our value is in excellent agreement with the one obtained by Solivella & Niemela (1999) but it is different from the 1.81-d period suggested by Levato et al. (1991). The latter discrepancy is most probably a result of the severe one-day aliasing that affected the Levato et al. data set.

We have applied the 'generalized spectrogram' Fourier method introduced by Heck, Manfroid & Mersch (1985), see also the appendix in Gosset et al. (2001). The strongest peak in the periodogram of the time series of the $RV_a - RV_c$ differences was found at $\nu'_2 = 0.46449$ d^{-1} corresponding to a period of 2.15290 d in excellent agreement with the result above. In the following, we will adopt an orbital period for the close binary of $P^{in}_{orb} = 2.15287$ d, which is slightly different from the best-fitting period derived hereabove, but which lies well within the error bar and provides the best agreement between our spectroscopic data and photometric data from the literature (see Section 5).

Table 2 clearly reveals that the radial velocity of the third component of Tr 16-104 varies slowly as a function of time. We have therefore searched the time series of the RVs of star 'b' for a long term periodicity. The results are also indicated in Tables 3 and 4. The most likely frequencies found with the Lafler & Kinman (1965) technique are ν_3 and $\nu_4 \sim 5 \times \nu_3$ corresponding to periods of respectively 1408.5 ± 91.6 d and 281.7 ± 3.6 d. Again, the quoted uncertainties correspond to one tenth of the natural width. We caution that our data do not allow us to discriminate between the ν_3 and ν_4 frequencies since both dips have a FWHM consistent with the natural width set by the time series (see also Section 4.2). However, our data set covers only about 1.5 cycle of the ν_3 frequency and the existence of a true 1408 d 'periodicity' is thus quite uncertain. Using the Fourier method of Heck et al. (1985) and Gosset et al. (2001), the most prominent peaks appear at frequencies of $\nu'_3 = 0.000746$ d^{-1} and $\nu'_4 = 0.003508$ d^{-1} that differ by less than one tenth of the natural width from ν_3 and ν_4 respectively. We find also a strong one-day alias of ν'_3 at ν'_5. The periods corresponding to ν'_3 and ν'_4 are 1340.5 ± 83.0 and 285.1 ± 3.8 d respectively. In the following, we will focus on the periods derived from the Fourier analysis.

There are two possible explanations for the RV variations of the third component: either the B0.2 star belongs to a rather wide binary that lies along the line of sight towards the close binary or alternatively it is physically connected to the close binary and is revolving around the centre of mass of a genuine triple system. We will address this question in the following subsection.

Table 3. Results of the period search using the Lafler & Kinman technique. Θ_{LK} corresponds to the value of the criterion defined by Lafler & Kinman (1965) normalized to 1.0. The first two periods refer to the time series of the RV differences between the two components of the close binary, whilst the other two periods correspond to the analysis of the RVs of the third component.

	ν (d^{-1})	Θ_{LK}	P (days)	Data set
ν_1	0.23224	0.0935	4.30589	$RV_a - RV_c$
ν_2	0.46448	0.0494	2.15294	
ν_3	0.000710	0.0864	1408.5	RV_b
ν_4	0.003550	0.0898	281.7	

Table 4. Same as Table 3, but using the Fourier method of Heck et al. (1985) and Gosset et al. (2001). A is the amplitude of the RV curve (in km s^{-1}) corresponding to the peaks in the periodogram.

	ν (d^{-1})	A	P (d)	Data set
ν'_2	0.46449	524.8	2.15290	$RV_a - RV_c$
ν'_3	0.000746	48.8	1340.5	RV_b
ν'_4	0.003508	49.3	285.1	
ν'_5	0.999332	49.9	1.00067	

4.2 Mass ratios and orbital solutions

An orthogonal regression method applied to the RV data of the 'a' and 'c' components yields a mass-ratio of $m_c/m_a = 0.65 \pm 0.03$ (1σ). Since the systemic velocity of the close binary could change as a function of time (if the binary is physically connected to the B0.2–0.5 star), the value of m_c/m_a derived hereabove is strictly valid only if our observations provide a sufficient sampling of the orbital period of the third star.

Before we turn to the orbital solution of the close binary system, let us first consider the issue of the connection between the close binary and star 'b'. To this aim, we computed

$$v_a + \frac{m_c}{m_a} v_c = \gamma_a + \frac{m_c}{m_a} \gamma_c$$

as a function of time. Here, γ_a and γ_c stand for the *apparent systemic velocities* as derived from the measured RVs of the 'a' and 'c' components respectively. The quantity $v_a + (m_c/m_a) v_c$ provides a direct measure of any time variation of the systemic velocity of the close binary and allows us to test whether or not

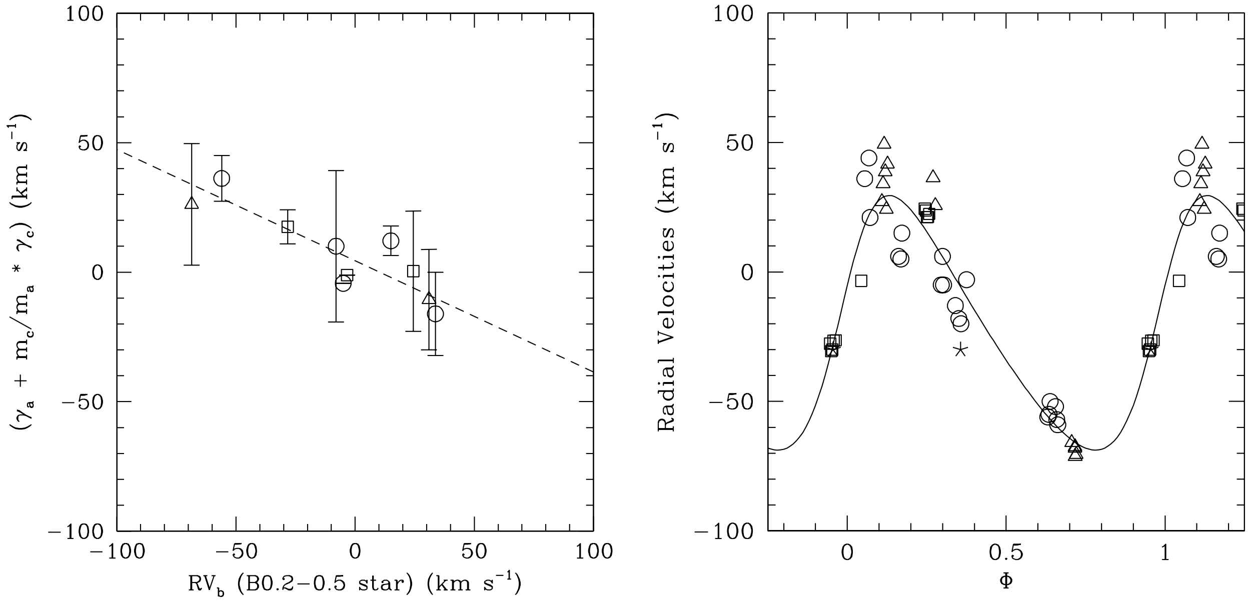

Figure 4. Left: plot of the systemic velocity $\gamma_a + \frac{m_c}{m_a}\gamma_c$ as a function of the RV of the third star. The data points are average values over an observing run. Triangles, circles and squares stand for data obtained respectively with the B&C, REOSC and FEROS instruments. Right: radial velocities of the third component as a function of phase, adopting a period of 285.1 d and assuming $T_0^{\rm out} = 2450174.6$. The continuous line corresponds to the eccentric solution described below (Table 6). The symbols have the same meaning as in the left panel except for the asterisks that indicate rough estimates of the RV of the third component as derived from the cross-correlation functions of Howarth et al. (1997).

Table 5. Orbital solutions derived from the radial velocities of the components of the close binary ('a' + 'c'). The adopted orbital period is $P_{\rm orb}^{\rm in} = 2.15287$ d. Columns 2 and 3 yield the orbital elements derived from a least squares fit, without any a priori correction of the systemic velocity, whereas the last two columns list the orbital parameters obtained from a fit where the RVs have been corrected for the variations of the systemic velocity. The radii of the Roche lobes ($R_{\rm RL}$) are computed using the formula of Eggleton (1983).

	No correction		Corrected γ	
	Primary	Secondary	Primary	Secondary
γ (km s^{-1})	4.0 ± 4.6	-3.2 ± 5.9	-1.5 ± 3.9	-6.7 ± 5.1
K (km s^{-1})	215.3 ± 5.5	331.8 ± 8.4	212.9 ± 5.0	332.8 ± 7.8
$T_0^{\rm in}$ (JD–2450000)	1621.967 ± 0.008		1621.973 ± 0.006	
$a \sin i$ (R$_\odot$)	9.2 ± 0.1	14.1 ± 0.4	9.1 ± 0.1	14.2 ± 0.2
$m \sin^3 i$ (M$_\odot$)	22.2 ± 1.4	14.4 ± 0.9	22.1 ± 1.3	14.1 ± 0.8
$R_{\rm RL}/a_{\rm tot}$	0.417 ± 0.003	0.342 ± 0.003	0.418 ± 0.002	0.341 ± 0.002
$\overline{\lvert O - C \rvert}$ (km s^{-1})	23.1		20.5	

these variations are anti-correlated with the RV variations of the B0.2–0.5 star. Since the error bars on the individual data points are rather large, we averaged the results obtained during a given observing run. To further reduce the errors, we only included RV measurements of the close binary obtained near quadrature. Though the errors are still quite large, Fig. 4 reveals that the systemic velocity varies indeed roughly in anti-correlation with the velocity of the third star indicating that we are probably dealing with a genuine triple system. The dashed line in Fig. 4 yields the best-fitting orthogonal regression to the data excluding the B&C measurement that deviates the most from the general trend. If $\gamma_a = \gamma_c$, then our best-fitting relation corresponds to $(m_a + m_c)/m_b \simeq 3.8$. We caution that the latter result should be regarded only as a rough estimate of the actual mass ratio because of the rather large uncertainties on the radial velocity of the centre of mass of the close binary.

Coming back to the close binary and assuming that its orbit is circular, we obtain the orbital elements listed in Table 5 and the solution shown in Fig. 5. $T_0^{\rm in}$ corresponds to the conjunction with the most massive star (component 'a') being behind its companion. Our first solution was obtained without any correction for the changing systemic velocity. The corresponding orbital elements are in excellent agreement with the preliminary SB2 solution of Solivella & Niemela (1999). Part of the scatter around the orbital solution could result from the use of varying samples of lines from night to night (owing to the various spectral ranges observed). In fact, absorption lines in O-star spectra often show different systemic velocities because they form at different depths in an expanding atmosphere and this could introduce some scatter in the average RVs.

Since Levato et al. (1991) quoted an eccentricity of $e = 0.16 \pm 0.1$ for their SB1 orbit of Tr 16-104, we have also tested the assumption of an elliptical orbit, though the short orbital period seems to rule this out a priori. An eccentric orbital solution for the close binary yields $e = 0.02 \pm 0.02$ (1σ) which is clearly consistent with $e = 0$. The eccentric solution does not provide any improvement of the quality of the fit either. We conclude therefore that the orbit of the close binary system is indeed circular.

The eccentricity found by Levato et al. (1991) was most likely an artefact due to the fact that these authors did not resolve the spectral signatures of the three components of Tr 16-104. This result is not only important for the study of Tr 16-104 as an individual system, but is also relevant for the issue of the ($\log P_{\rm orb}, e$) diagram for OB stars in very young open clusters (e.g. Mermilliod 1996; Mason et al. 1998) and of the determination of the cut-off period below which most orbits are circular due to tidal circularization.

Using the least squares fit between the systemic velocity of the short period binary and the velocity of component 'b', we have also computed an orbital solution where the radial velocities of components 'a' and 'c' have been corrected for the variations of the 'instantaneous' systemic velocity. The results are also listed in Table 5. We see that the corresponding parameters are in excellent agreement with those obtained for the RV solution without correction for the γ velocity variations.

We note that the minimum masses of the two components are quite large which is a good indication that the orbital inclination must be large. In fact, if we compare the values of $m \sin^3 i$ of the primary and secondary components to the 'typical' masses of O7 V and O9.5 V stars as listed by Howarth & Prinja (1989), we derive an orbital inclination of 58° and 62° respectively. Therefore, it seems likely that the close binary system could display photometric eclipses.

Our data do not allow us to decide which of the two frequencies ν'_3 or ν'_4 provides the best estimate of the orbital period $P_{\rm orb}^{\rm out}$ of the B0.2–0.5 star. While the 1340.5-d period corresponds to a rather asymmetrical ($e \sim 0.37$) radial velocity curve, the 285.1-d period yields a moderate eccentricity of 0.25. We have computed preliminary orbital solutions for both periods which are given in Table 6. We caution however that the scatter around the best-fitting solutions remains quite large (compared to the amplitude K) and we have no means to chose definitively between the two possible orbital periods. One notices that the systemic velocity derived for the third component in the case of the 285.1-d period is in excellent agreement with the mean heliocentric radial velocity ($-23.5\ \mathrm{km\ s^{-1}}$) of stars in Tr 16 as derived by Levato et al. (1991).

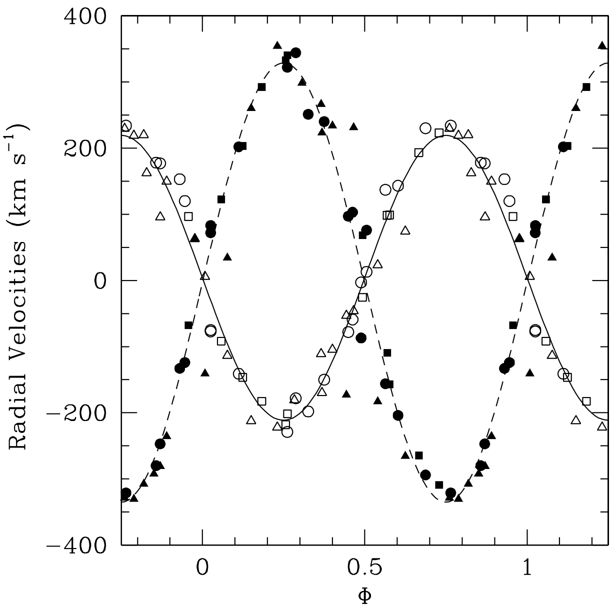

Figure 5. Orbital solution ($e = 0.0$) of the close binary for $P_{\rm orb}^{\rm in} = 2.15287$ days without correction of the systemic velocity. The symbols have the same meaning as in Fig. 4. Open and filled symbols stand for the primary (i.e. star 'a') and secondary (i.e. star 'c') respectively, while the solid and dashed lines show the corresponding best fitting solutions.

5 PHOTOMETRIC VARIABILITY

Inspection of our spectra reveals that the intensities of the lines of the B0.2–0.5 star vary as a function of time. We have measured the EWs of the least blended absorption lines of this star and plotted them as a function of the orbital phase of the close binary system. The result for the Si III λ 4552 and Si III λ 4568 lines is shown in Fig. 6. Though the typical errors of the EW measurements are of

Table 6. Orbital solution from the RVs of the B0.2–0.5-type star (component 'b') in the spectrum of Tr 16-104 assuming a period of 285.1 or 1340.5 days. $T_0^{\rm out}$ denotes the time of periastron passage and ω the longitude of periastron. $X_0^{\rm min}$ indicates the value of the stability criterion of Eggleton & Kiseleva (1995), see Section 6.3.

$P_{\rm orb}^{\rm out}$ (d)	285.1	1340.5
γ (km s^{-1})	-23.2 ± 1.5	-8.7 ± 1.5
K (km s^{-1})	49.1 ± 2.7	46.4 ± 1.7
e	0.25 ± 0.05	0.37 ± 0.04
ω (°)	287.0 ± 19.6	238.3 ± 8.1
$T_0^{\rm out}$ (JD–2450000)	174.6 ± 12.5	1264.8 ± 18.2
$a \sin i$ (R$_\odot$)	267.5	1129.6
$a \sin i$ (AU)	1.25	5.27
$f(m)$ (M$_\odot$)	3.20	11.2
$\overline{\lvert O - C \rvert}$ km s^{-1}	8.5	6.6
$X_0^{\rm min}$	29.7	35.4

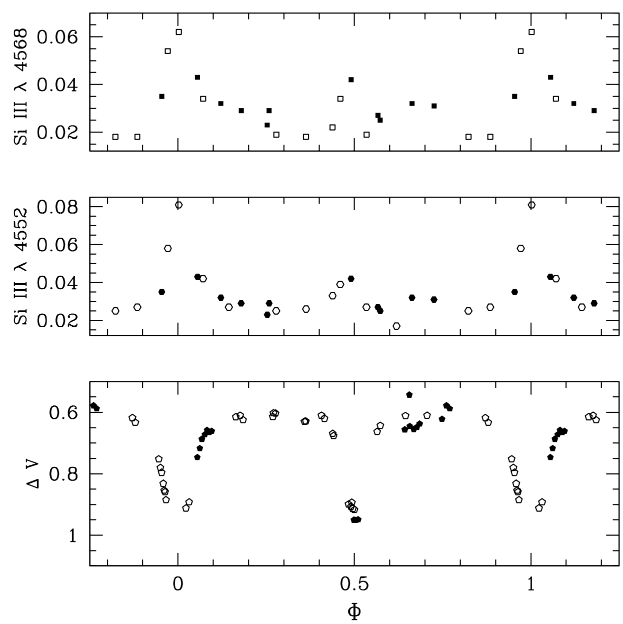

Figure 6. Top and middle panels: EWs (in Å) of two rather unblended absorption lines of component 'b' in the spectrum of Tr 16-104 as a function of the orbital phase of the close binary. Open and filled symbols stand for the EWs measured on the B&C and FEROS spectra respectively. Lower panel: V-band light curve of Tr 16-104 as derived from the data of Antokhin & Cherepashchuk (1993) assuming an orbital period of 2.15287 days. The photometric data are given as differential magnitudes with respect to HDE 303308. The open and filled symbols in the V light curve stand for the 1980 and 1991 data respectively.

the order of 0.005 Å near maximum EW and about twice as large near minimum EW, we see a clear increase of the EWs at phases around 0.0 and 0.5, i.e. around conjunction of the close binary system. The most straightforward interpretation of this phenomenon is that the continuum light of the close binary (and hence the dilution of the B0.2–0.5 star's lines) is reduced at these phases because of photometric eclipses.

Antokhin & Cherepashchuk (1993) presented *UBV* photometry of a set of stars in the Carina complex including Tr 16-104. These data were gathered in 1980 and 1991 at the Siding Spring Observatory. The authors reported photometric variability of Tr 16-104 between two light levels with the brightness changes occurring over rather short time-scales. Antokhin & Cherepashchuk were not aware of the multiplicity of this system and although they considered the possibility of an eclipsing binary, they found it rather unlikely since the radii of the binary components had to be very small.

We have folded the data of Antokhin & Cherepashchuk (1993) using the 2.15290-d period derived from our RV time series. The resulting light curve displays two rather narrow eclipses around the conjunction phases. We find a slight shift in phase between the eclipses and the conjunctions ($\Delta\Phi \simeq 0.044$) for this value of the period. This shift is extremely small given that half of the photometric data were taken about 15 yr (i.e. more than 2500 cycles!) before our spectroscopic data were obtained. From the preliminary orbital solution of the third component and assuming that star 'b' is indeed bound to the close binary, we find that the changes in the projected distance result in a light time effect with a peak-to-peak amplitude of about 1400 s at most (for $P_{\rm orb}^{\rm out} = 1340.5$ d). This translates into a phase shift for the minima of the eclipsing binary of 0.007. Therefore, we can safely rule out the light time effect as the origin of the $\Delta\Phi \simeq 0.044$ phase difference. The most likely reason for this shift is therefore a small error on the orbital period. Unfortunately a period search on the photometric time series is not very helpful in this case because of the huge number of aliases that have the same importance. We found however that a period of 2.15287 d allows us to simultaneously fit the light curve and the RV solution and we therefore used this period to derive the ephemerides of the close binary in Section 4.2. The *V* light curve obtained by folding the Antokhin & Cherepashchuk (1993) data according to the ephemeris

$$\mathrm{HJD}(\Phi = 0) = 245\,1621.973 + 2.152\,87E$$

is shown in Figs 6 and 7. We estimated the typical uncertainties from the 1σ dispersion of the differential magnitudes of HD 93204 with respect to HDE 303308 as observed by Antokhin & Cherepashchuk. In this way, we obtain estimates of the uncertainties on the individual data points of $(\sigma_U, \sigma_B, \sigma_V) = (0.033, 0.022, 0.020)$ and (0.051, 0.044, 0.046) for the 1980 and 1991 data respectively.

Although the light curve is somewhat sparse, we can nevertheless use it to derive constraints on the physical parameters of the components of the close binary in Tr 16-104. In fact, we notice that the eclipses are rather narrow and there is no evidence for a strong phase-locked photometric variability outside the eclipses unlike what would be expected for a contact or semi-detached binary. This is strong evidence that both components of the close binary should have rather spherical shapes and must be well inside their Roche lobes.

From the light curve, we find that the full width of both eclipses is about 0.164 in phase. At the 'first contact' (i.e. when the projections of the stars on the plane of the sky touch for the first time), the projected separation of the centres of the stars is equal to the sum of their radii. If the stars are indeed spherical, this condition can be expressed by the relation

$$R_{\rm a} + R_{\rm c} = a_{\rm tot}(1 - \sin^2 i \cos^2\theta_1)^{1/2}$$

where θ_1 is the position angle (with respect to conjunction) of the stars at first contact. The *UBV* light curves yield $\theta_1 \simeq 29\overset{\circ}{.}5$. From our orbital solution, we obtain

$$R_{\rm a} + R_{\rm c} = 23.3(1 - 0.758\sin^2 i)^{1/2}(\sin i)^{-1}$$

where the radii are given in $\mathrm{R}_\odot$. This relation expresses a model-independent constraint on the absolute dimensions of the stars. However, we caution that this is only valid if the stars have a roughly spherical shape, i.e. if they are well inside their Roche lobes (which seems to be the case for the components of the close binary in Tr 16-104).

Assuming that stars 'a' and 'c' were in synchronous rotation, the projected rotational velocities derived by Howarth et al. (1997), yield $R_a/R_c = 1.48$, $R_a \sin i = 6.96\,\mathrm{R}_\odot$ and $R_c \sin i = 4.71\,\mathrm{R}_\odot$. Comparison of the latter values with the first contact relation requires a rather large inclination of $\sim 83\overset{\circ}{.}8$ and hence very small radii. If we assume that the ratio of the radii of the components is indeed given by $R_a/R_c = 1.48$, we find that the first contact relation yields a radius of the secondary that is always smaller than the radius of its Roche lobe provided that $i \gtrsim 37\overset{\circ}{.}5$, whereas the primary is only inside its Roche lobe for $i \gtrsim 55\overset{\circ}{.}3$ (see Fig. 8). The validity of the first contact relation is thus restricted to $i > 55°$. For inclinations between 55° and 90°, the sum of the radii varies between 19.9 and $11.5\,\mathrm{R}_\odot$. This result clearly demonstrates that the components of the close binary must be on the main sequence, in very good agreement with our luminosity classification hereabove.

To proceed one step further, we have calculated a grid of synthetic light curves using the numerical code of Antokhina

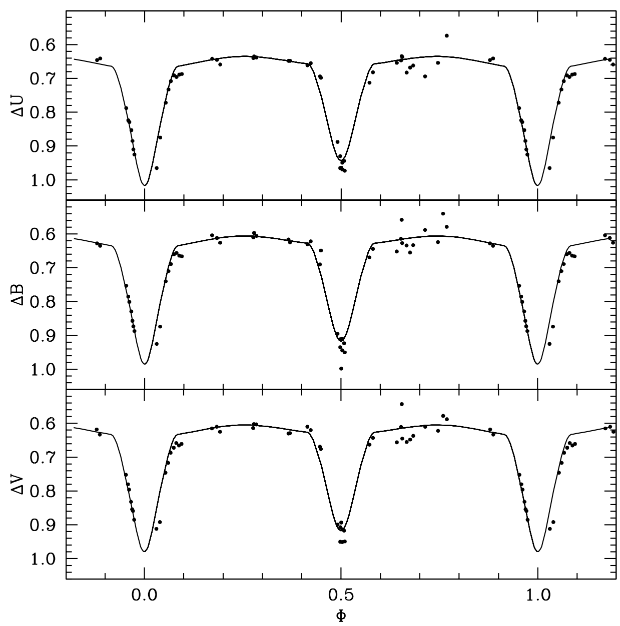

Figure 7. Best fitting synthetic light curves for $i = 82\overset{\circ}{.}5$ compared to the *UBV* photometric data of Antokhin & Cherepashchuk (1993).

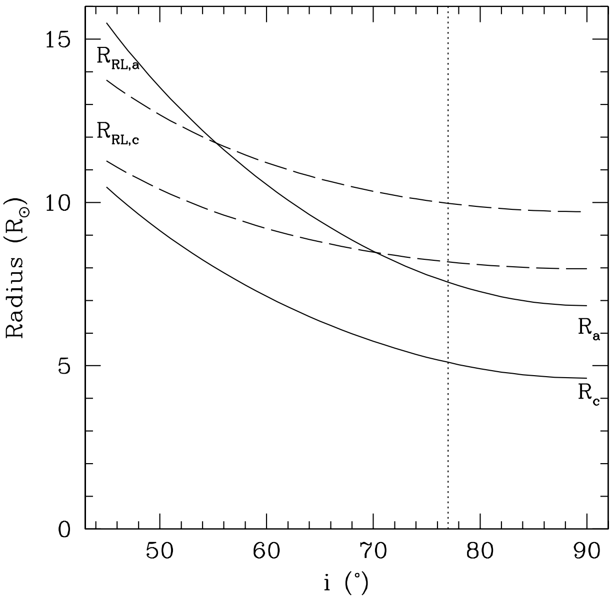

Figure 8. Constraints on the radii and the inclination of the close binary system in Tr 16-104 as derived from the first contact relation. The continuous lines yield the radii of the O7 V primary and the O9.5 V secondary assuming $R_a/R_c = 1.48$, whilst the dashed lines indicate the radii of the Roche lobe of the primary and secondary as calculated from our orbital solution (Table 5). The dotted vertical line corresponds to the minimum inclination of the orbit as derived from our best fitting models of the light curve (see text).

Table 7. Absolute parameters of the O7 V + O9.5 V close binary in Tr 16-104 as derived from the best fitting light curve model at $i = 82\overset{\circ}{.}5$. The third light contribution was assumed to be $l_b = 0.14$ in all three filters. R stands for the mean radius (slightly larger than the polar radius, R^p) of the star.

	Primary	Secondary	
T_{eff} (K)	37500	32750	adopted
i	$82\overset{\circ}{.}5$		
m ($M_\odot$)	22.7	14.5	
μ	0.75 ± 0.10	0.65 ± 0.07	
R ($R_\odot$)	7.11 ± 0.94	4.93 ± 0.53	
$v_e \sin i$ (km s^{-1})	166	115	
$\log(L_{bol}/L_\odot)$	4.96	4.41	
M_{bol}	−7.65	−6.27	

(1988) (see also Antokhina et al. 2000). Adopting the calibration of Humphreys & McElroy (1984), we fixed the effective temperatures of the primary and the secondary at $T^a_{eff} = 37500$ K and $T^c_{eff} = 32750$ K respectively. Assuming a typical uncertainty of half a spectral type, these effective temperatures should be accurate within about 1500 K for the primary and 1250 K for the secondary. We further assumed that the stars are in synchronous rotation and we adopted a third light contribution of $l_b = 0.14$. The albedo ($A^a = A^c = 1.0$, Wilson 1994) and gravity darkening coefficients ($\beta^a = \beta^c = 0.25$, von Zeipel 1924) were fixed and we adopted a square-root limb darkening law (Diaz-Cordovés & Giménez 1992) with the corresponding coefficients taken from the work of van Hamme (1993). Finally, the orbital parameters were taken from our corrected-γ orbital solution in Table 5. Therefore, the only remaining free parameters are the orbital inclination i and the Roche lobe filling factors[4] of the two stars μ_a and μ_c.

In our grid of models, we generated theoretical *UBV* light curves for $i \in [50°, 90°]$ with a step $\Delta i = 2°$ up to $i = 78°$ and $\Delta i = 0\overset{\circ}{.}5$ between $i = 78°$ and $i = 90°$. The Roche lobe filling factors were varied in the range $\mu_a, \mu_c \in [0.1, 1.0]$ with $\Delta\mu = 0.05$. The synthetic light curves in all three filters were compared to the observations of Antokhin & Cherepashchuk (1993). We find that the best-fitting models with $i \gtrsim 79°$ have almost identical χ^2-values. At the 99 per cent confidence level, all values of the inclination in the range $i \in [77°, 90°]$ are acceptable. We remind the reader that these results were obtained under a number of assumptions (e.g. synchronous rotation, adopted effective temperatures) and depend also on the actual value of the third light contribution. Some additional uncertainties might result from the poor phase coverage of the observed light curve around the primary minimum. However, the conclusion that the orbital inclination must be larger than $\sim 75°$ is quite robust. In fact, below this inclination, the synthetic light curves predict that the bulk of the photometric variability should be owing to the ellipticity of the components rather than to genuine eclipses and this is clearly not the case for the close binary in Tr 16-104. We will discuss the implications of these results in Section 6.1.

The lowest χ^2 value was obtained for $i = 82\overset{\circ}{.}5$, $\mu_a = 0.75$ and $\mu_c = 0.65$. The corresponding absolute parameters of the close binary are listed in Table 7 and the model light curves are shown in Fig. 7. We emphasize the almost perfect agreement between the projected rotational velocities derived from our best-fitting light curve model and those measured by Howarth et al. (1997) and listed in Table 1 above.

6 DISCUSSION

6.1 Fundamental parameters

Several authors obtained photometric measurements of Tr 16-104 (Antokhin & Cherepashchuk 1993; Massey & Johnson 1993; Kaltcheva & Georgiev 1993). In the Antokhin & Cherepashchuk (1993) data, the differential magnitude of Tr 16-104 outside eclipse with respect to HDE 303308 is $\Delta V \simeq 0.64$. From the results of Massey & Johnson (1993), we derive a differential magnitude of 0.63, whereas the photometry of Kaltcheva & Georgiev (1993) yields $\Delta V = 0.74$. Therefore, it seems likely that the data of Kaltcheva & Georgiev were affected by the eclipse of the close binary. In the following, we adopt a V magnitude of 8.82 as obtained by Massey & Johnson. Splitting the total brightness of the system according to the spectroscopic brightness ratios derived hereabove, we infer magnitudes of $m^a_V = 9.39$, $m^b_V = 10.95$ and $m^c_V = 10.24$. The distance of the Tr 16 cluster remains a controversial issue. Using *UBV* photometry, Massey & Johnson (1993) obtained a distance modulus of $DM = 12.49 \pm 0.09$. On the other hand, Kaltcheva & Georgiev (1993) derived the distance of individual stars in Tr 16 from the relation between the Strömgren β index and the absolute magnitude M_V (Balona & Shobbrook 1984). Assuming a normal extinction law, these authors found a large dispersion in the distance moduli that might reflect a real range in distance. Since the line of sight towards Tr 16 is almost parallel to the molecular cloud ridge in the Carina spiral arm, Kaltcheva &

[4] The Roche lobe filling factor $\mu = R^p/R^p_{RL}$ corresponds to the ratio between the actual polar radius and the polar radius for complete filling of the Roche lobe (see Antokhina 1988).

Georgiev question the existence of an open cluster and suggest that the stars could rather lie along an extended star formation region which is projected on a small area on the sky. For Tr 16-104, Kaltcheva & Georgiev (1993) derived $DM = 13.24$ from their Strömgren photometry. However, as pointed out hereabove, the data of Kaltcheva & Georgiev were most probably obtained during an eclipse of the close binary and it is not clear how this affects the strength of the Hβ line and the corresponding β index.

As a first step, we assume that the distance modulus of Tr 16-104 amounts to 12.49 as suggested by Massey & Johnson (1993). Accounting for a colour excess $E(B-V) = 0.43$, we obtain absolute visual magnitudes of $M_V^{\rm a} = -4.5$, $M_V^{\rm b} = -2.9$ and $M_V^{\rm c} = -3.6$. Components 'a' and 'c' are about 0.5 mag fainter than expected for a typical O7 V and O9.5 V star (see e.g. Humphreys & McElroy 1984). An even larger discrepancy (~1.5 mag) holds for the B0.2-0.5 IV star. Of course, the most straightforward solution to this problem would be to adopt a larger distance modulus than suggested by Massey & Johnson (1993). As a second step we could therefore adopt the distance modulus $DM = 13.24$ as derived by Kaltcheva & Georgiev (1993). In this way, we obtain absolute visual magnitudes of $M_V^{\rm a} = -5.2$, $M_V^{\rm b} = -3.7$ and $M_V^{\rm c} = -4.4$, slightly brighter than for typical stars of the same spectral type. However, such a large distance leads to a large discrepancy with the results of our light-curve analysis (see below).

Alternatively there could be a problem with the absolute magnitude–spectral type calibration. Lamers et al. (1997) discussed the absolute visual magnitude of a sample of OB V-III stars as determined from the parallaxes measured by *Hipparcos*. Slowly rotating stars (i.e. $v_{\rm e} \sin i < 100\,{\rm km\,s^{-1}}$) were found to be fainter by up to 1.5 mag than the standard M_V-spectral type relation, whereas the differences were much smaller for rapid rotators of the same spectral type. Lamers et al. (1997) attributed this phenomenon to the influence of rotation on the assignment of the luminosity class. In the case of the O7 V and O9.5 V stars in Tr 16-104, we are dealing with rather fast rotators (in the terminology of Lamers et al. 1997) and we expect therefore a priori that this effect should be small. However, the influence of rotation could be considerably larger for the B0.2–0.5 IV component ($v_{\rm e} \sin i = 59\,{\rm km\,s^{-1}}$) and this could probably account for part of the larger discrepancy found for this star. In fact, comparing the absolute magnitude of star 'b' to the *Hipparcos* absolute magnitude of ϕ^1 Ori (B0.2 IV, $v_{\rm e} \sin i = 39\,{\rm km\,s^{-1}}$, $M_V = -3.39$, Lamers et al. 1997), the discrepancy is reduced to about 0.5 mag which is pretty much the same value than for the other components of Tr 16-104.

Now, a more serious dilemma arises if we compare the bolometric luminosities derived from our light curve analysis with those obtained for the two values of the distance modulus and adopting the bolometric corrections of Humphreys & McElroy (1984). In fact, the bolometric luminosities of the O7V and O9.5V stars corresponding to the Massey & Johnson (1993) distance modulus would be $\log L_{\rm bol}^{\rm a}/{\rm L}_\odot = 5.14$ and $\log L_{\rm bol}^{\rm c}/{\rm L}_\odot = 4.64$. These values are about 50 per cent larger than those derived from the light curve analysis (Table 7). Of course, adopting the Kaltcheva & Georgiev (1993) distance will increase this discrepancy to about a factor 3. If the bolometric corrections are correct, then the luminosities derived from our light curve analysis suggest a distance of about 2.5 kpc for Tr 16-104, in agreement with the recent determination of the distance of the eclipsing binary Tr 16-1 (≡CPD −59° 2628) by Freyhammer et al. (2001). In this context, we emphasize that the complex structure of the interstellar absorption lines in the spectrum of Tr 16-104 demonstrates that the star is either behind or immersed in the region where the interstellar lines originate. The fact that we observe interstellar He I absorptions further indicates that this star is inside a hot gas bubble. Therefore Tr 16-104 must be at the same distance as most of the stars of the Tr 16 cluster. Walborn (1995) pointed out that the distance determinations of the open clusters in the Car OB1 association are in fact very sensitive to the assumption on the ratio R of total-to-selective extinction. Indeed, the results of Walborn (1995) indicate that for $R = 3$ and 4, the distance of Tr 16-104 would be respectively 2.8 and 2.25 kpc. Walborn (1995) further noted that the inclusion of a number of main-sequence O and B stars, that might be closer to the ZAMS – and hence less luminous – than the 'typical' calibrators, could artificially raise the distance modulus as determined by Massey & Johnson (1993). Finally it is worth mentioning that a spectroscopic study of the Homunculus Nebula by Davidson et al. (2001) yielded a distance of 2250 ± 180 pc for η Car which is believed to be associated with Tr 16.

The low luminosities of the stars as inferred from the light curve stem from the fact that the radii of the O7V and O9.5V components that we derived in Section 5 are surprisingly small. As stated above, the values of the Roche lobe filling factors inferred from the light curve analysis depend on several assumptions that are difficult to check. Nevertheless, the rather large orbital inclination ($i \gtrsim 77°$ at the 99 per cent confidence level) and the first contact relation (see Fig. 8) obviously imply radii and luminosities that are certainly much smaller than the 'typical' values listed by Howarth & Prinja (1989) or than the radii inferred from the analysis of a sample of interacting (and probably more evolved) O-star binaries (Harries, Hilditch & Hill 1998). In this context, it is interesting to point out that the analyses of the light curves of HD 93205 (Antokhina et al. 2000), ι Orionis (Marchenko et al. 2000) and Tr 16-1 (Freyhammer et al. 2001) also yield radii that are comparatively small for the spectral types and luminosity classes inferred from the spectroscopic data. The light variations in HD 93205 and ι Ori are due to the changing shapes of the stars during the eccentric orbit rather than to geometric eclipses and the uncertainties on the orbital inclination and hence on the radii are thus somewhat larger than in our case. Tr 16-1, on the other side, was found to be an eclipsing binary system consisting of an O9.5 V primary and a B0 V secondary and the parameters of the O9.5 V star in Tr 16-1 as derived by Freyhammer et al. (2001) are in excellent agreement with those of the O9.5 V secondary in Tr 16-104 (star 'c'). Our results for the close binary in Tr 16-104 as well as the results of Freyhammer et al. (2001) suggest therefore that the luminosities of main-sequence O-stars in very young clusters such as Tr 16 could be systematically smaller than usually believed. These results are in line with the conclusions of Lamers et al. (1997) and cast some doubt on distance determinations using the 'standard' M_V – spectral type calibration. In this context, we point out that Walborn & Blades (1997) reported the existence of a number of subluminous so-called O Vz stars among the youngest objects of the 30 Doradus complex. The O Vz stars stand out through a very strong He II λ 4686 absorption line and Walborn & Blades (1997) suggested that they are nearer to the ZAMS than more luminous 'typical' O V stars.

6.2 X-ray data

So far, Tr 16-104 has not been detected at X-ray energies. Seward & Chlebowski (1982) only quoted an upper limit of 0.23×10^{-3} count s^{-1} on the *EINSTEIN*-HRI count rate. The XMEGA observation (rh202331) provides the deepest *ROSAT*-HRI pointing on the Carina region including Tr 16-104. We have analysed these data with the XSELECT software (v1.4b). Inside a radius of 40 arcsec around the position of Tr 16-104, we obtain a net background-corrected HRI count rate of $\sim 1.55 \times 10^{-3}$ count s^{-1} which corresponds to a marginal detection against the strong diffuse X-ray emission from the Carina Nebula. Assuming a thermal plasma model (Raymond & Smith 1977) of temperature $kT = 0.5$ keV and adopting the interstellar H I column density of $N_H = 2.9 \times 10^{21}$ cm^{-2} (Diplas & Savage 1994), we derive a dereddened flux of 9.5×10^{-14} erg cm^{-2} s^{-1} in the 0.5–2.0 keV energy range. Adopting a distance of 2.5 kpc (see Section 6.1), we infer $L_x = 7.0 \times 10^{31}$ erg s^{-1}. Using the bolometric luminosities derived from our light curve solution yields $\log L_x/L_{bol} = -6.85$. The latter value is in excellent agreement with the predicted ratio $\log L_x/L_{bol} = -6.90$ between the sum of the individual X-ray luminosities of components 'a' and 'c' compared to the sum of their bolometric luminosities. The theoretical X-ray luminosities of star 'a' and 'c' were derived from the empirical $\log L_x/L_{bol}$ relation for single OB stars proposed by Berghöfer et al. (1997). Therefore, we conclude that there is no indication of any significant X-ray emission that could be attributed to a colliding wind interaction in Tr 16-104, but this is not surprising for a close binary consisting of two main-sequence stars (Chlebowski & Garmany 1991).

6.3 The multiplicity of Tr 16-104

Let us briefly return to the cross-identification of the optical and UV components of the system. Extrapolating our ephemerides back to the epoch of the *IUE* observations, we obtain predicted radial velocities of $\mathrm{RV_a} = 206$ km s^{-1} and $\mathrm{RV_c} = -331$ km s^{-1} for SWP7022 (JD 244 4174.737, $\Phi = 0.787$) as well as $\mathrm{RV_a} = 151$ km s^{-1} and $\mathrm{RV_c} = -244$ km s^{-1} for SWP7988 (JD 244 4289.024, $\Phi = 0.873$). Comparing these results with the cross-correlation functions of Howarth et al. (1997) (see their fig. 2), we find that the RVs of their component 'A' is in good agreement with our component 'a', whereas we find a rough agreement between our component 'c' and star 'C' in the Howarth et al. naming. The RVs of star 'B' are also in rough agreement with those expected from our preliminary ephemerides of star 'b' (see Fig. 4). A slight discrepancy is not surprising given the preliminary nature of the orbital solution and the large uncertainties on the orbital period of this star. All in all, the comparison between our ephemerides and the *IUE* data further confirms our cross-identification initially based on the relative widths and strengths of the lines (Section 3).

Our data discussed here provide some evidence that the third component is physically related to the system. In fact, the radial velocity of star 'b' varies with a 'period' of 285.1 or 1340.5 d. Though we cannot completely rule out that Tr 16-104 could be a quadruple (or line of sight binary + binary) system consisting of an SB2 binary ('a' + 'c') with an orbital period of 2.15 d and an SB1 ('b' + ?) with a longer period, the fact that the variations of the close binary's γ systemic velocity are essentially anti-correlated with those of the third component indicates that Tr 16-104 is most probably a hierarchical triple system. The mass of star 'b' inferred from this anti-correlation and the best-fitting parameters of the close binary (Table 7) would be $9.8\,\mathrm{M_\odot}$. We emphasize that we found no spectral indication of any additional component in our present data.

So far there are only a few other examples of hierarchical multiple systems containing early-type stars. HD 167971 consists of a close O-type eclipsing binary ($P^{\rm in}_{\rm orb} = 3.3$ d) and a third more distant Of companion that dominates the optical and UV spectrum and could actually be a line-of-sight object (Leitherer et al. 1987).

Niemela, Seggewiss & Moffat (2001) found that Sk-67° 18 in the LMC is a multiple system harbouring at least two pairs of short-period binaries (an O3f* + O binary with $P_{\rm orb} = 2.001$ d and another system with $P_{\rm orb} = 19.3$ d). However, the physical connection between these binaries is not clear and they could just lie along the same line of sight.

SZ Cam (Lorenz, Mayer & Drechsel 1998; Harries et al. 1998) consists of an O9 IV+B0.5 V eclipsing binary ($P^{\rm in}_{\rm orb} = 2.7$ d) that is physically bound ($P^{\rm out}_{\rm orb} \sim 50$–60 yr) to a third component which is itself a short-period SB1 binary. A visual companion (which is also a binary) seems also related to the system, bringing the total number of stars in this system to six.

The τ CMa system (van Leeuwen & van Genderen 1997) is slightly more similar to Tr 16-104. This system consists of a close eclipsing binary ($P^{\rm in}_{\rm orb} = 1.3$ d) connected in an eccentric orbit ($e = 0.3$, $P^{\rm out}_{\rm orb} = 155$ d) to a third component. However, the fundamental parameters of the stars in τ CMa are rather poorly constrained since this system remains so far an SB1 binary with no indication of the spectral signature of the other two stars.

IU Aur is believed to be a genuine triple system consisting of a semi-detached B0.5+B0.5 binary with a period of 1.9 d and a gravitationally bound tertiary with a period of $P^{\rm out}_{\rm orb} = 294$ d. However, the third component has been resolved by speckle interferometry (Mason et al. 1998) and this suggests that the system might actually be quadruple (see Harries et al. 1998). Therefore, the properties of Tr 16-104 (eclipsing 'SB3' system) make this system a rather unique example of its kind that deserves more studies (especially long-term monitoring of the third component).

N-body simulations indicate that hierarchical triple systems and double binaries can be produced by collisions of hard binaries in open clusters (e.g. Leonard & Duncan 1990; Kiseleva et al. 1996), although clusters consisting of a large number of stars have an aversion to forming triple systems (Leonard & Duncan 1990). Kaltcheva & Georgiev (1993) argued that the stars in Tr 16 are not members of a real open cluster but belong rather to a huge stellar complex seen in projection on the line of sight. As pointed out in Section 6.1, the distance towards Tr 16-104 is most probably significantly smaller than the value suggested by Kaltcheva & Georgiev and the interstellar spectrum suggests that Tr 16-104 is located at the same distance as most of the stars of Tr 16. Alternatively, it could be that Tr 16-104 came out of a small compact cluster or that the third component was formed from the outer circumstellar envelope of the protostellar cloud of the close binary.

Hierarchical triple systems may be quite stable for significant times if the external perturbations are small. According to Eggleton & Kiseleva (1995), hierarchical systems are stable provided that their configuration is such that $P^{\rm out}_{\rm orb}/P^{\rm in}_{\rm orb} \geq X^{\rm min}_0$ where $X^{\rm min}_0$ is a function of the mass ratios $q_{\rm in} = m_{\rm a}/m_{\rm c}$ and $q_{\rm out} = (m_{\rm a} + m_{\rm c})/m_{\rm b}$ and the eccentricities of the inner and outer orbits. Substituting our orbital parameters of Tr 16-104 into the stability criterion of Eggleton & Kiseleva (1995), we obtain the results listed in Table 6. Obviously a system such as Tr 16-104 with $P^{\rm out}_{\rm orb}/P^{\rm in}_{\rm orb} \simeq 132 \gg X^{\rm min}_0 = 29.7$ (assuming an outer orbital period of 285.1 d) or $P^{\rm out}_{\rm orb}/P^{\rm in}_{\rm orb} \simeq 623 \gg X^{\rm min}_0 = 35.4$ (assuming an outer orbital period of 1340.5 d) should form a stable configuration.

7 CONCLUSIONS

We have shown that Tr 16-104 could be a rather rare case of a hierarchical triple system consisting of an eclipsing binary bound to a third component in a slightly eccentric orbit. This system offers an interesting opportunity for studying the fundamental parameters of unevolved early-type main-sequence stars. In fact, we have shown that the components of the close binary must be well inside their Roche lobes and therefore, their parameters are most probably not yet affected by evolution through mass transfer. Our analysis of the photometric data yields a lower limit on the inclination of the orbital plane of the close binary of $i \geq 77°$. The corresponding stellar radii and luminosities are significantly smaller than usually believed for stars of the same spectral type. This conclusion points towards a problem in the absolute magnitude versus spectral type calibration for O-stars and accurate distance determinations from future astrometric observations (e.g. with ESA's planned *GAIA* satellite) should help to clarify this situation. Our results suggest that Tr 16-104 (and probably also the Tr 16 cluster) lies at a distance of the order of 2.5 kpc i.e. slightly closer than the mean distance of Tr 16 as suggested by Massey & Johnson (1993). The triple system Tr 16-104 could either have emerged from a single protostellar cloud or alternatively it could have been formed by the collision of a hard binary either with a single star or with another binary in the Tr 16 open cluster. In the latter case, the fourth star would probably have been dynamically ejected from the system (Leonard & Duncan 1990).

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