NIR interferometric observations of massive hierarchical triple systems: Tr16-104 and HD150136

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Abstract: we report on an observational astrometric study of the orbit of the tertiary stars in two massive hierarchical triple systems. The work is complemented by radial velocity data with the aim of deriving the full 3D orbit and constraints on the orbital planes. This is the first report of the tertiary star's detection for Tr16-104. The work is a natural extension of the search for binaries among massive O-stars. The basic motivation of the study of hierarchical triple systems is the determination of the masses of the individual components and the derivation of the relative orientation of the two orbital planes, with the ultimate aim of understanding the related star formation processes.

Tr16-104

Introduction

Tr16-104 (numbering from Feinstein et al., 1973, also CPD-59°2603, V572 Car) is a massive O star located in the Trumpler 16 open cluster in the Carina region. An O7V spectral type was attributed by Walborn (1973). It was recognized to be a radial-velocity (RV) variable by Levato et al. (1991) and a photometric variable by Antokhin & Cherepashchuk (1993). A first SB2 solution with a period of 2.15287d was presented by Solivella & Niemela (1999). Analyzing Short-Wavelength High-Resolution spectra from the IUE facility, Howarth et al. (1997) discovered that the Tr16-104 spectrum was actually triple and composed of two broad line systems and a weak narrower one as illustrated in Fig.1 for the visible domain.

As shown by Rauw et al. (2001), the two systems of broad lines were issued from a primary star of spectral type O7V and from a secondary of spectral type O9.5V, both constituting the 2.15287d SB2 system. The latter was actually exhibiting eclipses. Additional data acquired by Fernández-Lajús et al. (2004) suggest that the system is well detached and has eclipses of depths 0.42 and 0.31 mag.

The third spectrum features rather narrow lines and corresponds to a spectral type B0.2-0.5 of luminosity class IV or V. Rauw et al. (2001) deduced from the dilution of the lines that the primary was contributing in the visible to 59%, the secondary to 27% and the third object to 14% of the total light. These authors also demonstrated that the centre of mass of the P+S system was varying in anti-correlation with the RV of the third object that can thus be considered as the tertiary (T) in a hierarchical triple system (SB3). Two values were suggested for the period of the outer system (P+S versus T): 285.1d and 1340.5d; the two values were strong one-year aliases of each other and cannot be disentangled on the basis of the existing data. Deducing from the eclipses an inclination of the inner system (P+S) of 82.5°, they derived masses of M_P=22.7 M_{sol}, M_S=14.5 M_{sol} and M_T=9.8 M_{sol}.

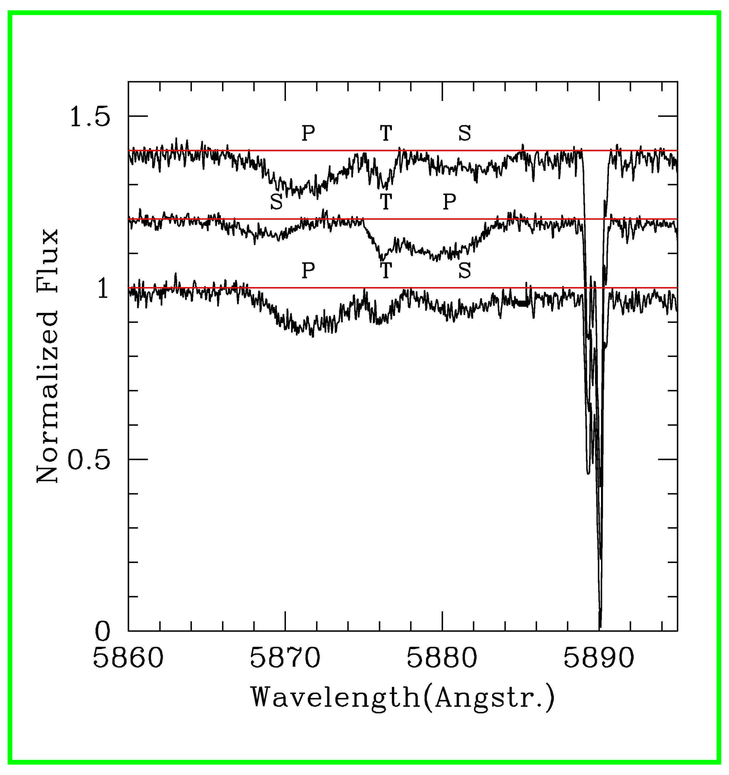

Figure 1: The normalized spectrum of Tr16-104 in the neighbourhood of the HeI λ5876 line. We present three spectra acquired on three successive nights in 2003 (bottom to top); they are shifted up by convenience. The presence of three components is clear. The spectral lines are attributed to the Primary, Secondary or Tertiary object as labelled.

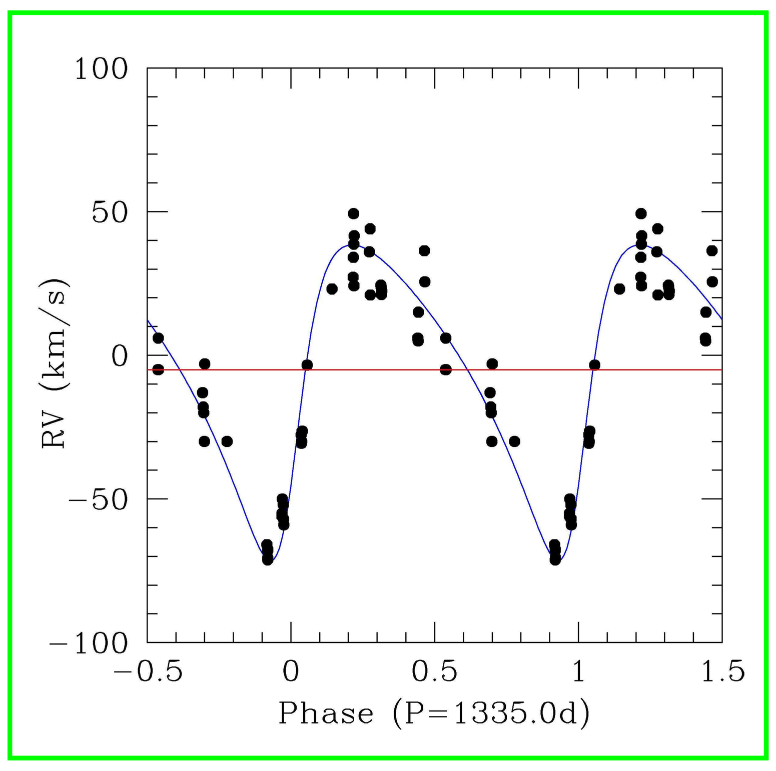

Figure 2: Plot of the RV curve of the Tertiary as a function of phase as computed according to the period P=1335.0d. Phase zero corresponds to the time of passage at periastron. The continuous blue curve represents the prediction of the model for the parameters given in Table 1.

A radial velocity study

To the data analyzed by Rauw et al. (2001), we added three nights (May 2003, PI: P. Maxted, obs. JS) of intense observations of Tr16-104 spectrum with the FEROS spectrograph attached to the ESO/MPG 2.2m telescope at La Silla. Since we are here mainly interested in the outer system, we used this dataset to derive the RV of the tertiary object. This extends the database by two years and could help in addressing the long-term behaviour. On each spectrum, we measured the positions of some 40 lines belonging to the tertiary star. These lines were stable in position over the run and, from all the lines, we derived a mean RV of 23.1 km/s. This point has been added to the dataset of Rauw et al. (2001) and the whole was submitted to a detailed period search. The Fourier spectrum is indeed dominated by two peaks of almost identical height. One corresponds to the 285.1d period, the other to a larger period that we found to be at 1315.8d. The latter is not significantly different from the one reported by Rauw et al. (2001). Being aliases, the two peaks cannot be disentangled and will remain so as long as no much denser monitoring is performed. In Fig.2 we show the phase diagram corresponding to the outer RV-orbit of the tertiary in the case of the long period. A similar diagram for the short period is to be found in Rauw et al. (2001). We also fitted an orbital model to these data and its RV curve prediction is also given in the figure. The model is not significantly different from the one fitted by Rauw et al. (2001) underlining the stability of the solution. Our values for the parameters are given in Table 1. It is interesting to notice that the eccentricity is not strongly constrained and, even if the best value is 0.4, it could range from 0.37 to almost 0.6. Clearly the old B&C data are strongly dispersed and should be replaced by new more accurate ones. We adopt here the value for a_T sin i of 1329.6 R_{sol}.

First interferometric detection of the tertiary in Tr16-104

Although Tr16-104 is at the limit of the possibilities of the current interferometric instruments, we considered this object as very interesting and anticipated that the tertiary object could be astrometrically separated from the P+S system. We previously performed a similar work for HD150136. The interest of the interferometric observations is to separate the tertiary object T from the P+S inner system. We then monitor the object to obtain a relative astrometric orbit tracing the outer system. This result, linked to RV measurements, allows us to derive the inclination of the outer orbit and thus to derive the masses separately for the three objects in the SB3 system. In addition the relative orientation of the two orbital planes becomes accessible and these characteristics are useful for testing various formation scenarii of these hierarchical triple systems. Despite this interest, up to now no astrometric companion has been reported for Tr16-104 (Mason et al. 2009; Nelan et al. 2004).

Interferometric measurements of Tr16-104 were obtained on 29-12-2013 and on 24-02-2014 using the PIONIER four beam combiner (Le Bouquin et al. 2011) at the four Auxiliary Telescopes of the ESO VLTI (Haguenauer et al. 2010). The data were reduced with the pndrs package (Le Bouquin et al. 2011). The data analysis closely follows the procedure used in the Southern Massive Star at High angular resolution survey (SMaSH+, Sana et al. submitted) which uniformly analyzes PIONIER observations of a sample of over 100 O-type stars. Tr16-104, which is not part of the survey, was clearly resolved at two epochs with a separation of about 3.5 milli-arcsec (mas). Only a marginal rotation of the binary axis could be detected over the 57 days baseline of our PIONIER observations.

Figure 3 shows the reduced H-band visibilities and closure phases, and the best fit with a two-point-like-object model. The chi-square maps demonstrate that the two-object solution is very robust and unambiguous, as the observed chi-square minimum is well defined and unique. The relative position of the companion compared to the main target is characterized by the parameters reported in Table 2. The flux ratio is of course in the H-band.

Considering the flux ratio and separation, the detection is very unlikely to be a chance alignment. To verify this point, we queried the 2MASS catalog over a large region of 2 arcmin (120 arcseconds) around the target to guess the local density of infrared sources. We found ~5 sources with the flux of the detected companion, or brighter. Considering that the observed separation is only 4 mas, the false alarm probability is less than 10^{-6}. We conclude that our newly detected companion is most probably physically bound to Tr16-104. Further discussion can be found in the next section.

Table 1: Derived spectroscopic parameters (period, RV of the centre of mass, RV semi-amplitude, longitude of periastron, eccentricity, time of passage at periastron, projected semi-major axis) for the tertiary in the outer system.

P=1335.0 d
γ = -5 km/s
K = 55 km/s
ω_T = 238.3°
e = 0.4
T_0 = 2451251.64 d
a_T sin i = 1329.6 R_{sol}

Table 2: Results of the PIONIER observations fitted by a two-point-like source model. First and second columns are the normal and Julian dates of observations; δE is the separation along the right ascension (α cos δ), δN along the declination (δ); ρ is the radial separation, θ the azimut (0° is North), r is the brightness ratio and $\chi^2_{red.}$ is the reduced chi-square of the fit.

Date	JD 2400000+	δE (mas)	δN (mas)	ρ (mas)	θ (degree)	r	$\chi^2_{red.}$
29-12-2013	56655.839	2.12±0.19	-3.01±0.11	3.68	144.8	0.26	0.4
24-02-2014	56712.745	2.44±0.53	-2.41±0.31	3.43	134.7	0.26	0.8

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Discussion and conclusion

Although the argument based on the neighbourhood seems to support the association of the detected companion with the tertiary, some aspects need to be further investigated and additional support remains necessary. According to the deduced relative luminosity reported by Rauw et al. (2001), the brightness ratio $l_T/(l_P+l_S)$=0.16 in the visible domain. The one observed by PIONIER is 0.26 in the H-band. Apparently, we have to deal with a possible discrepancy. The flux distribution with wavelength of the three stars have different slopes and this could explain part of the difference but not the majority of it. On the opposite hand, the discrepancy could be explained by the fact that the inner system P+S is eclipsing. Its short period is not known accurately enough to be extrapolated over the 10 years separating the PIONIER observations from the other ones such that we could only conjecture that some eclipse took place during the PIONIER observations. The depths of 0.31 and 0.42 mag. of the eclipses are sufficient to boost the luminosity ratio T/(P+S) to 0.22-0.26 .

If the small value of the outer period is selected, we are facing two problems. Firstly, over the 56.906 day baseline separating the two PIONIER observations, the binary axis is observed to rotate by 10.1°. Within such a time interval (0.2 in phase), the 285.1d model predicts a difference in true anomaly that amounts to 72° for a circular orbit, ~50° for an eccentric e=0.25 orbit around apastron and ~35° for an eccentric e=0.6 orbit around apastron. Therefore, such an orbit is hardly compatible with the interferometric observations. If we want to reduce the 35° angle to render it compatible with the observed 10.1°, we have to invoke an additional rotation of the orbital plane (e.g. due to inclination). However, this would imply a projection angle larger than 73° (if less than 90°) which is not compatible with the expected inclination that is supposed to be around 30°-50° (120°-140°) according to the masses derived by Rauw et al. (2001). Secondly, the a_T sin i (projected semi-major axis) reported by Rauw et al (2001) is 267.5 R_{sol} and corresponds to a semi-major axis of 275.7 R_{sol} for an inclination of 76° and to 535.0 R_{sol} for an inclination of 30°. If we conservatively multiply the semi-major axis by 1+e and by 1.26 (to get the system a), we obtain respectively 435.4 R_{sol} and 844.7 R_{sol}. Admitting that Tr16-104 is at the distance of 2.5 kpc, the projected separation on the sky does not exceed 2 mas which is also in contradiction with the observed separation of the order of 3.5 mas. To explain the observed separation, we have to decrease the distance by a factor of two which is not affordable. Therefore the short candidate period for the outer system seems unlikely. The projected rotation of the binary axis of 10.1° better corresponds to a period beyond 1000d which pinpoints to the alternative candidate value of 1335.0d. The difference between the relative positions P+S versus T over the two observations is still too marginal to draw definitive conclusions and further observations are clearly necessary, both interferometric and spectroscopic.

Adopting the ephemerides agreeing with the radial velocity curve of Fig.2, we tried to include the PIONIER data to further constrain the orbit with the 1335.0d period. Admitting that the true rotation of the binary axis is in agreement with the one suggested by the observations, we note that the astrometric orbit is clockwise and then the inclination is larger than 90°. Figure 4 presents a candidate astrometric orbit adopting an inclination of 143° and a Ω_{asc} = 100°.

Clearly, an orbit compatible with the interferometric and the spectroscopic data could be found giving strong support to the P=1335.0d period. Therefore, we consider that we have presented here the very first detection of the tertiary component in the triple system Tr16-104.

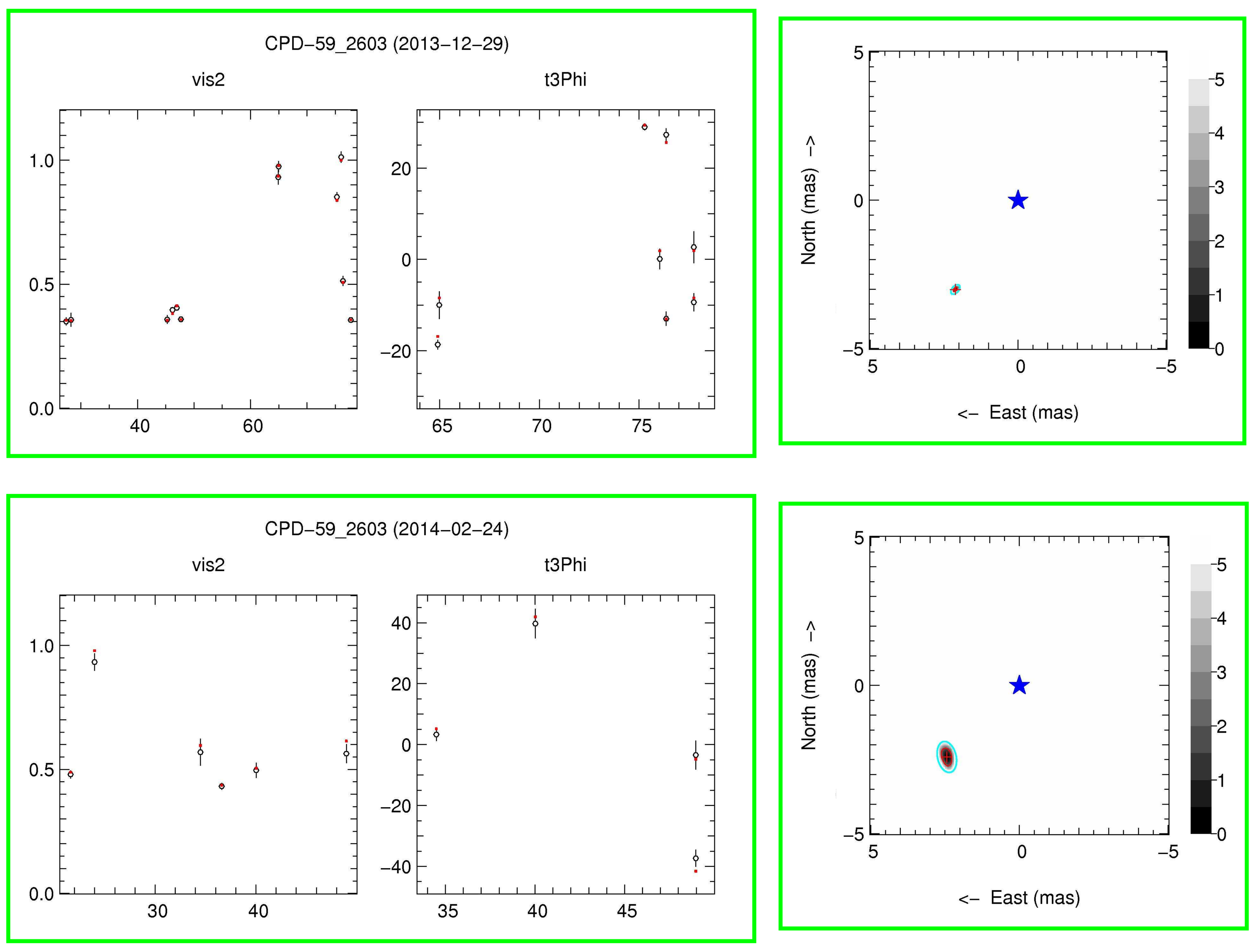

Figure 3: Calibrated visibilities (vis2, left panel) and closure phases (t3Phi, middle panel) overlaid with the best two-point-like source model (in red) for the December 2013 (upper row) and for the February 2014 (lower row) PIONIER observations. The right panel exhibits the chi-square map in the vicinity of the best fit solution giving the relative position of the Tertiary around the P+S inner system. The solution is very robust and unambiguous and the chi-square minimum is well-defined and unique. The 3σ astrometric uncertainty is approximated with the ellipse shown in cyan in the chi-square map (right panel).

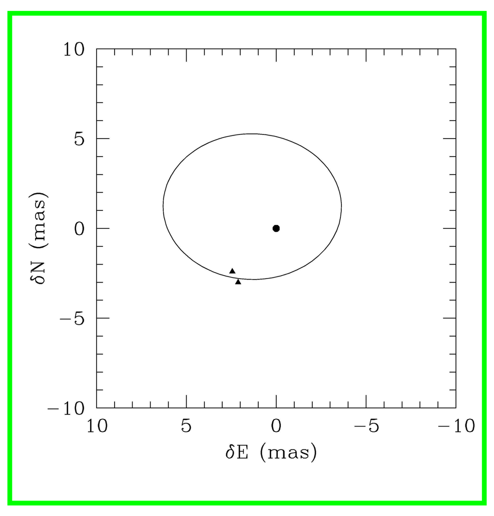

Figure 4: Relative positions of the Tertiary (triangles) with respect to the P+S inner system (circle). The projected ellipse represents an astrometric model compatible with the radial velocity study. This suggests that the detected astrometric companion can be identified with the T object in the spectrum. A value for the inclination of 143° and an Ω_{asc} of 100° were estimated.

HD150136

Another hierarchical triple system under study: HD150136

HD150136 is another example of such massive hierarchical triple systems, it totals some 130 M_{sol} . It is composed of an inner O3+O5.5 system on a 2.67d orbit. This binary is a strong X-ray emitter (see Leyder and Pollock, this colloquium). This inner system constitutes an SB3 with an O6.5 companion on an orbit characterized by a 3000d period. The whole system is known to be a non-thermal radio emitter. The spectroscopic study of the triple system has been published in Mahy et al. (2012). The first interferometric detection of the tertiary was reported in Sana et al. (2013). Since this detection, we continue to monitor the astrometric orbit. The first related results were published in Gosset et al. (2013). The next periastron of the outer system is occurring in 2015 and at that time we will hopefully have covered half of the total astrometric orbit. The parameters for HD150136 can be found in the references mentioned above. Figure 5 exhibits the status of the monitoring.

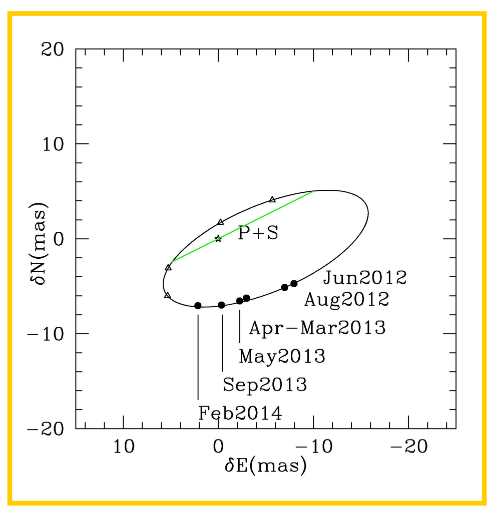

Figure 5: Illustration of the results of our interferometric observations obtained so far on HD150136. The currently most probable orbit (relative position of the tertiary star) is represented by the solid ellipse. The existing observations we acquired have been plotted and labelled with the date of the observations (filled circles).The four triangles present the foreseen positions for Sep2014, Feb2015, Jun2015 and Sep2015 (left to right, respectively). The straight line crossing P+S represents the line of nodes. The periastron passage is mid-2015.

The orientation of the orbits in massive triple systems

We have demonstrated here that the relative orientation of the two orbits in Tr16-104 implies the lack of coplanarity. We arrive at the same conclusion after the study of HD150136. If we also consider the case of HD152246 recently studied by Naseri et al. (submitted), we note that coplanarity does not seem to be the rule. We intend to increase the sample in the future.

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