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Dynamical detection of three triple stellar systems in open clusters

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ABSTRACT

We present a kinematic analysis of three triple stellar systems belonging to two open clusters: CPD−60°961 and HD 66137 in NGC 2516, and HD 315031 in NGC 6530. All three systems are hierarchical triples with a close binary bound to a third body in a wider orbit, whose presence is detected through velocity variations of the close binary barycentre. Orbital parameters are derived from radial velocity curves. Absolute parameters for all stars are estimated assuming cluster membership. Some dynamical and evolutionary aspects of these systems are discussed, particularly the possible influence of Kozai cycles. The two systems of NGC 2516 have similar orbital configurations with inner periods of 11.23 and 8.70 d and outer periods of 9.79 and 9.24 yr. The young system HD 315031 in the cluster NGC 6530 has an inner binary with a period of 1.37 d and a very eccentric ($e = 0.85$) outer orbit with a period of 483 d. We report also radial velocity measurements of the components of the visual binary CPD−60°944 in NGC 2516. Including results from previous works, this cluster would harbour five hierarchical triples. Possible dynamical evolutionary scenarios are discussed. Long-term radial velocity monitoring is highlighted as strategy for the detection of subsystems with intermediate separations, which are hard to cover with normal spectroscopic studies or visual techniques.

Key words: binaries: spectroscopic – stars: chemically peculiar – open clusters and associations: individual: NGC 2516 – open clusters and associations: individual: NGC 6530.

1 INTRODUCTION

The frequency and the observed properties of multiple systems constitute key evidence for models of stellar formation and evolution. Presently, our statistical knowledge of early-type high-order multiple systems is insufficient for a useful test of theoretical models. In fact, in most of the catalogued multiple systems, the hierarchical configuration, the physical link between the companions, and even the number of stellar components has not been reliably established. Indeed, in our spectroscopic study of stellar components in 30 early-type multiples (Veramendi & González 2014), we found that a significant fraction of the systems have a number of components that is different from previously known.

Early-type multiple stars are also crucial for the understanding of B and A-type chemically peculiar stars, whose physics is not completely understood. On the one hand, peculiar stars that occur in multiple systems and clusters may be assigned an age, which makes it possible to approach the time development of chemical peculiarities (Bailey, Landstreet & Bagnulo 2014). The study of the companions gives eventually the opportunity to know the original composition of the peculiar star. On the other hand, statistically some types of chemical peculiarities appear predominantly in binary or multiple stars. This is the case of HgMn stars for example, whose multiplicity frequency might be as high as 90 per cent (Schöller et al. 2010). Finally, there is observational evidence suggesting that stellar companions might influence the generation of surface regions with abnormal composition (Hubrig et al. 2006, 2012; Makaganiuk et al. 2011).

Open clusters provide large samples of coeval stellar objects. However, the studies of multiplicity in open clusters are surprisingly scattered in the literature (Duchêne & Kraus 2013). Searches for spectroscopic and visual binaries have been carried out only in the nearest associations (Taurus-Aurigae, the Hyades, Praesepe, and the Pleiades), for which frequencies and some properties of multiple systems have been derived. Currently, hydrodynamic simulations of cluster formation (Bate 2012) predict fractions of multiplicity increasing with the stellar mass, with values in agreement with the observational results for solar- or low-mass stars, including very low mass objects.

According to Leigh & Sills (2011), dynamical encounters involving triple systems should be common in open clusters and they would significantly contribute to the population of blue stragglers. Leigh & Geller (2013) confirmed these predictions considering the

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fractions of binaries and triples empirically determined in Taurus-Aurigae, the Hyades, Praesepe, and the Pleiades. These authors concluded that in such clusters encounters involving triple systems are as frequent as, or even more, than encounters involving single stars and binaries. These results suggest that models of open cluster evolution should include high-order multiples in their initial population and allow these systems to evolve dynamically through the cluster evolution and to influence the dynamical evolution of the latter through energy exchange (Leigh & Geller 2013). From the observational point of view, these results highlight the need for a more detailed knowledge of the binary and especially triple population in clusters (Leigh & Sills 2011).

The detection and exhaustive characterization of hierarchical multiples represent an observational challenge, since different instrumental techniques have to be combined to cover all the range of separation between the components of subsystems, which span several orders of magnitudes from a few solar radii to thousands of astronomical units. Spectroscopy is the main tool for studying binary subsystems with periods shorter than tens or a few hundreds of days, while astrometric techniques and high-resolution imaging are used for the widest systems. Particularly tough is the intermediate range of separations, with periods of the order of a few thousands of days ($a \sim 10$ au). In this paper, we report the discovery of triple systems through the detection of long-period variations in the centre-of-mass velocity of spectroscopic binaries, demonstrating the usefulness of long-term spectroscopic monitoring for the study of this intermediate range of separation.

In the long-term spectroscopic survey of stars in open clusters carried out at ICATE (Levato et al. 2004) several new spectroscopic binaries have been discovered. Eventually, some of the systems showed run-to-run variations of the barycentric velocity and from then on were monitored until the whole cycle of those slow variations was covered.

The cluster NGC 2516 is particularly interesting for its content of binary and peculiar stars. Early spectroscopic works of this cluster reported about 10 chemically peculiar late-B and early-A type stars (Abt & Morgan 1969; Dachs 1972; Hartoog 1976) and 9 single-lined spectroscopic binaries (Abt & Levy 1972; Gieseking & Karimie 1982). However, only a few of these objects have been studied subsequently and good quality orbits have been published for only two of them: the eclipsing binary V392 Car (Debernardi & North 2001) and HD 65949 (Cowley et al. 2010). On the other hand, González & Lapasset (2000) reported three new double-lined spectroscopic binaries (SB2s) and one radial velocity (RV) variable (CPD−60°944A). The stars studied in this paper, HD 66137 and CPD−60°961 (stars 19 and 2 in the cluster numbering by Cox 1955), are two of these three SB2s. The third one is HD66066A, a short period binary studied by González & Lapasset (2003), who mentioned that would be a triple star, since it has a visual companion to which it could be dynamically bound (Dachs & Kabus 1989). On the other hand, no spectroscopic study of stars HD 66137 and CPD−60°961 has been published since they were reported as binaries, although preliminary results of the present investigation, were presented by Veramendi & González (2010). In addition to these two objects, in this paper we present a few observations of CPD−60°944A, the star reported as variable in González & Lapasset (2000), confirming its binary nature. Since this star has (at least) one visual companion (Dachs & Kabus 1989) this would be also a multiple star.

HD 315031 is an early-B type star member of the young open cluster NGC 6530. It was studied by González & Lapasset (2003), who measured the RV of both components using two-dimensional cross-correlations (Zucker & Mazeh 1994), and determined the spectroscopic orbit. Already in that first study, the measurements from different runs were found to be inconsistent with a constant binary centre-of-mass velocity, which was interpreted as due to the presence of a third body. However, the available data were not sufficient to secure the period of the outer orbit.

In Sections 2 and 3 we describe the orbital analysis and derive physical properties of the systems studied. In Section 4, we discuss some dynamical and evolutionary aspects. Finally, our main conclusions are summarized in Section 5.

2 OBSERVATIONS AND ORBITAL ANALYSIS

In this paper, we analyse spectroscopic observations taken over 15 years with the 2.15 m telescope and the REOSC echelle spectrograph at Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina. The spectra cover the wavelength range 3700–5900 Å with a resolving power $R = 13\,300$. The spectra were reduced by using standard procedures with the NOAO/IRAF package. In the case of HD 315031 our analysis includes remeasurement of most of the spectra of González & Lapasset (2003).

Our spectra show, in principle, two sets of spectral lines belonging to the companions of the close binary system. We will identify these stars with letters A and B, A being the most massive of this pair. The third companion in the outer orbit will be called star C, regardless of its mass. We applied the spectral separation method by González & Levato (2006) to measure RVs and reconstruct the spectra of both visible stellar components. For the cross-correlations used by this method in the RV calculation, standard templates taken from the Pollux data base (Palacios et al. 2010) were used. Table 1 (available electronically) lists all measured RVs for the three spectroscopic binaries. Columns 3 and 4 are orbital phases for the inner and outer orbits, calculated from the time of periastron passage. In the case of the inner orbit of HD 315031, which is circular, the phase origin is at the primary conjunction. Columns 5 to 8 list the measured RVs and their errors. Columns 9 and 10 are the calculated velocities for the two close binary companions with respect to its barycentre, while the last column lists the calculated RV for the barycentre of the binary, $V_{\rm o}$.

RV data were fitted with a double Keplerian orbit. In this scheme, the two visible components are assumed to move in a two mass points orbit whose centre of mass follows in turn a Keplerian orbit. In the orbital phase calculation, observation times are corrected by the light-time effect due to the variation of the distance between the close binary and the observer. To find the best solution our orbit fitting program seeks in the parameter space the minimum of the quantity χ^2. Consequently, data points are weighted according to their formal measurement errors. The parameter errors are calculated considering the parameter variation for an increment $\Delta\chi^2 = 1$ while all remaining parameters are allowed to vary to minimize χ^2, taking into account in this way correlations between parameters. In this manner, we fitted simultaneously 12 orbital parameters: the six elements of the inner orbit (orbital period P, time of periastron passage T_π, RV amplitudes $K_{\rm A}$ and $K_{\rm B}$, argument of periastron ω, and eccentricity e) and six parameters for the outer orbit that the binary barycentre describes around the centre of mass of the whole triple system (systemic velocity $\gamma_{\rm o}$, period $P_{\rm o}$, time of periastron passage $T_{\pi,\,{\rm o}}$, RV amplitude $K_{\rm o}$, argument of periastron $\omega_{\rm o}$, and eccentricity $e_{\rm o}$). Table 2 lists the orbital parameters for the three systems including, in addition to the mentioned orbital elements, the time of primary conjunction $T_{\rm I}$, projected orbital semi-axis $a\sin i$, and minimum masses $M\sin^3 i$. Note that the subindex 'o' does not

Table 1. Radial velocities. This is a sample of the full table.

Object	HJD	ϕ	ϕ_o	V_A km s^{-1}	err$_A$ km s^{-1}	V_B km s^{-1}	err$_B$ km s^{-1}	$(V_A - V_o)_{cal}$ km s^{-1}	$(V_B - V_o)_{cal}$ km s^{-1}	V_o km s^{-1}
CPD−60°961	2451 587.7233	0.9437	0.4843	16.4	0.6	39.6	0.6	−9.7	14.0	26.8
CPD−60°961	2451 590.6421	0.2035	0.4851	47.1	0.6	−5.3	0.7	21.4	−30.8	26.8
CPD−60°961	2451 939.7566	0.2838	0.5819	46.9	0.5	−1.2	0.5	19.4	−28.0	26.6
CPD−60°961	2452 270.7007	0.7465	0.6736	6.3	0.8	56.0	1.1	−20.6	29.7	26.2
CPD−60°961	2452 271.7615	0.8409	0.6739	5.1	0.8	54.6	0.9	−20.3	29.3	26.1
–										

Table 2. Orbital parameters. Parameters with subindex 'o' refer to the outer orbit described by the barycentre of the spectroscopic binary. The last three rows show the number of observations and the rms of the residuals.

Parameter	Units	CPD−60°961	HD 66137	HD 315031
P	d	11.23259 ± 0.00013	8.70355 ± 0.00004	1.377436 ± 0.000003
T_I	d	2 454 705.43 ± 0.04	2 454 446.884 ± 0.014	2 454 484.623 ± 0.005
T_π	d	2 454 688.55 ± 0.13	2454448.142 ± 0.017	–
K_A	km s^{-1}	21.4 ± 0.3	64.4 ± 0.7	66.2 ± 1.1
K_B	km s^{-1}	30.9 ± 0.3	64.7 ± 0.6	89.0 ± 1.6
ω		4.70 ± 0.07	3.236 ± 0.014	–
e		0.124 ± 0.009	0.380 ± 0.005	0.00
q		0.694 ± 0.013	0.995 ± 0.013	0.744 ± 0.018
$a_A \sin i$	$R_\odot$	4.72 ± 0.07	10.24 ± 0.10	1.80 ± 0.03
$a_B \sin i$	$R_\odot$	6.80 ± 0.07	10.29 ± 0.10	2.42 ± 0.04
$a \sin i$	$R_\odot$	11.52 ± 0.10	20.53 ± 0.14	4.22 ± 0.05
$M_A \sin^3 i$	$M_\odot$	0.096 ± 0.003	0.769 ± 0.016	0.306 ± 0.012
$M_B \sin^3 i$	$M_\odot$	0.067 ± 0.002	0.765 ± 0.016	0.228 ± 0.008
γ_o	km s^{-1}	24.54 ± 0.19	24.64 ± 0.24	6.8 ± 0.8
P_o	d	3575 ± 65	3376 ± 39	482.9 ± 0.5
$T_{I,o}$	d	2 456 385 ± 55	2 456 138 ± 46	2 454 513 ± 13
$T_{\pi,o}$	d	2 460 611 ± 148	2 454 865 ± 125	2 455 339 ± 2
K_o	km s^{-1}	4.2 ± 0.4	10.1 ± 0.4	37.6 ± 1.6
ω_o		3.2 ± 0.2	5.4 ± 0.3	5.15 ± 0.13
e_o		0.47 ± 0.06	0.17 ± 0.03	0.85 ± 0.03
$a_o \sin i_o$	$R_\odot$	258 ± 21	660 ± 24	190 ± 10
n		34	36	71
σ_A	km s^{-1}	0.58	1.17	4.4
σ_B	km s^{-1}	0.61	1.23	7.7

correspond to the orbit of star C but to the observed movement of the barycentre of the spectroscopic binary. In particular, the semi-axis of the outer relative orbit is $a_{out} = a_o \cdot (M_A + M_B + M_C)/M_C$. For notation simplicity in the parameters of the inner binary concerning both components (P, e, ω, q, etc.) we use no subindex.

For both triples of NGC 2516, CPD−60°961 and HD 66137, cluster membership is confirmed kinematically by the agreement between barycentric velocity of the two triples and the cluster velocity: 22.0 km s^{-1}(González & Lapasset 2000) and 23.08 km s^{-1}(Mermilliod, Mayor & Udry 2008).

RV curves are shown in Figs 1, 2, and 3. In these figures, upper panels show the velocity of the spectroscopic binary companions with respect to the barycentric velocity of the binary, while the lower panels show the velocity variations of the binary barycentre.

3 PHYSICAL PARAMETERS

Cluster membership allows us to know the age of these multiple systems and to estimate absolute stellar parameters from their position in the cluster colour–magnitude diagram. Nevertheless, the third body might contribute significantly to the integrated light of the system, making these calculations less reliable. Therefore, we adopted primarily estimated masses from the spectral types. Using line ratios measured in the separated spectra, we determined spectral types for the six studied stars. We then derived temperatures using the Schmidt-Kaler (1982) calibration and estimated masses and other parameters interpolating in the isochrone corresponding to the cluster age in the stellar model grids of the Geneva group (Ekström et al. 2012; Mowlavi et al. 2012; Georgy et al. 2013). Uncertainties in these parameters were estimated from the range of spectral types considered compatible with the observed spectrum.

We used the spectroscopic parameters of the outer orbit and the estimated masses of the visible companions to derive a lower limit to the mass of the third body. Combining the expression for the RV semi-amplitude of the wide orbit:

$$K_o = \frac{2\pi a_o}{P_o} \frac{\sin i_o}{\sqrt{1 - e_o^2}} \leq \frac{2\pi a_o}{P_o \sqrt{1 - e_o^2}},$$

with the Kepler equation for the outer orbit we obtain

$$\frac{M_C}{(M_A + M_B + M_C)^{2/3}} = \frac{K_o P_o^{1/3} \sqrt{1 - e_o^2}}{(2\pi G)^{1/3} \sin i_o} \geq \frac{K_o P_o^{1/3} \sqrt{1 - e_o^2}}{(2\pi G)^{1/3}}. \quad (1)$$

On the other hand, when it was possible we estimated an upper limit to M_C considering the intensity that its spectral lines would

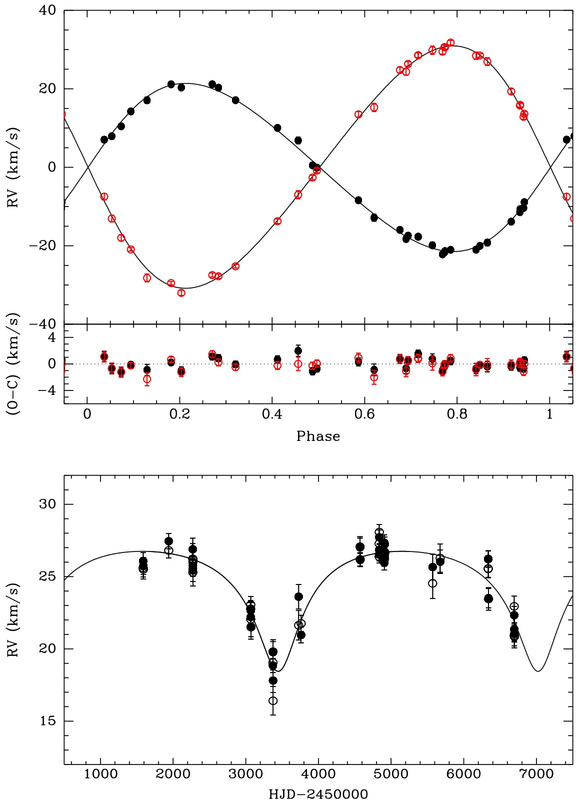

Figure 1. RV curves of CPD−60°961. The upper panel shows the RV curves of the inner binary over the 11.23 d period. At the bottom of the same panel, the residuals observed-minus-calculated are plotted. The lower panel shows the longer time variation of the centre-of-mass velocity. The filled (open) circles correspond to the primary (secondary) star.

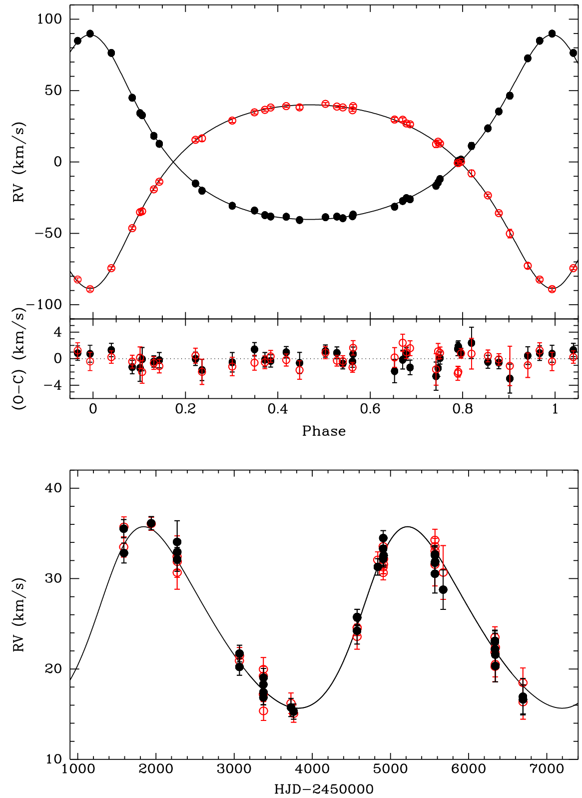

Figure 2. RV curves of HD 66137. The upper panel shows the RV curves of the inner binary. At the bottom of the same panel, the residuals observed-minus-calculated are plotted. The lower panel shows the time variation of the centre-of-mass velocity. The filled (open) circles correspond to the primary (secondary) star.

have in the spectrum. This upper limit to M_C was used to obtain a lower limit to the outer orbit inclination i_o using equation (1). Obtaining at least rough estimates for the masses of all three stars, allow us to get, in combination with the spectroscopic parameters, information about the mutual inclination between the inner and the outer orbits. In fact, the mutual inclination between both orbital planes (i_m) is given by

$$\cos(i_m) = \cos(i)\cos(i_o) + \sin(i)\sin(i_o)\cos(\Delta\Omega),$$

where $\Delta\Omega$ is the angle between the lines of nodes of the two orbits. Therefore,

$$\cos(i_m) \le \cos(i - i_o),$$

and finally, taking into account that both i_m and $|i - i_o|$ are in the interval $(0, \pi)$, we obtain

$$i_m \ge |i - i_o| \,.$$

In short, from estimates of stellar masses it is possible to obtain a lower limit for the inclination between inner and outer orbits, which is an important parameter for the dynamics of the triple. In Table 3, we summarize these results, which are discussed for each system in the following sections.

3.1 CPD−60°961

For the components of this spectroscopic binary, we derived spectral types B9 V and A4 V. In our spectra, both stars have sharp lines (full width at half-maximum of about 25 km s^{-1}) with rotational velocity too low to be measured with our spectral resolution. As already noted in the preliminary work by Veramendi & González (2010), star A shows a peculiar spectrum with a notable λ3984 Hg II line and other lines typical of HgMn stars (strong Y II, Sr II, P II, and Pt II). However, strikingly, Mn II lines are not present. We analysed 884 wavelength measurements by the method of wavelength coincidence statistics and the results show very low probability for the presence of Mn. P II is clearly present but not Ga II. Highly significant results were obtained for Sr II, Y II, and Pt II. Interestingly, the presence of several lanthanide spectra is very likely, particularly lines of Nd III and Pr III. All these characteristics, which altogether are not typical of any group of peculiar stars, resemble the spectrum of the unique star HD 65949 studied by Cowley et al. (2006, 2010), which is also a spectroscopic binary of the same cluster NGC 2516.

From the spectral types, we estimated temperatures $T_{\rm eff}$(A) = 10 500 ± 1000 K and $T_{\rm eff}$(B) = 8 450 ± 250 K. We then interpolated in the Geneva model grid to find stellar models that are consistent with the temperature estimates, the spectroscopic mass ratio, and the cluster age. We adopted for the cluster log(age) = 8.0–8.3, which is a conservative range consistent with the published values: 8.04 (Dachs & Kabus 1989), 8.15 (Meynet, Mermilliod & Maeder 1993), 8.2 ± 0.1 (Sung et al. 2002). We obtained masses $M_A = 2.6 \pm 0.4$ M$_\odot$ and $M_B = 1.8 \pm 0.2$ M$_\odot$, and visual absolute magnitudes M_V(A) = 0.9 ± 0.5 mag and M_V(B) = 2.3 ± 0.2 mag. The comparison of these masses with the spectroscopic parameters gives a low orbital inclination ($i = 19.^\circ5 \pm 1.^\circ0$) and for M_C a lower limit of 0.8 M$_\odot$. An upper limit can be established considering that there is no trace of its lines in the spectrum. Assuming that this third

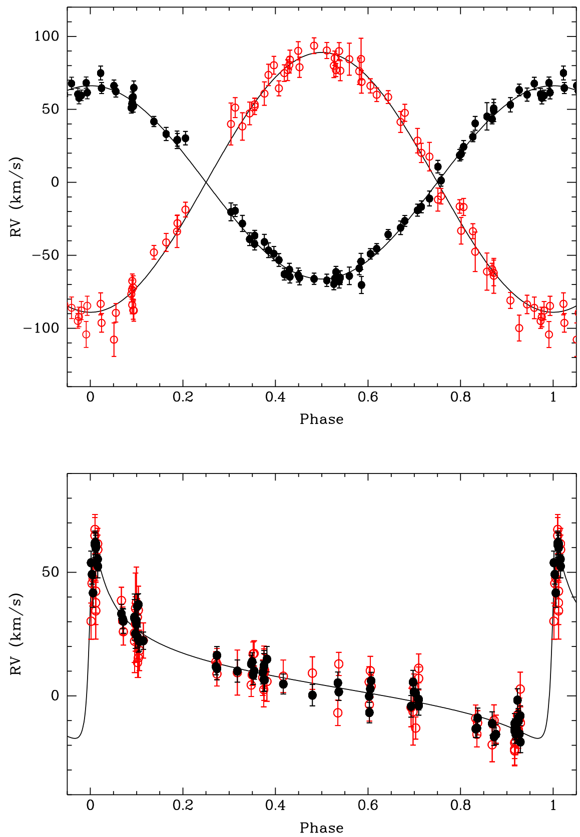

Figure 3. RV curves of HD 315031. The upper panel shows the RV curves of the inner binary. At the bottom of the same panel, the residuals observed-minus-calculated are plotted. The lower panel shows the time variation of the centre-of-mass velocity. The filled (open) circles correspond to the primary (secondary) star.

Table 3. Estimated absolute masses and inferred orbital inclinations.

Parameter	Units	CPD−60°961	HD 66137	HD 315031
$T_{\rm eff}(A)$	K	10 500 ± 1000	10 100 ± 900	28 000 ± 2000
$T_{\rm eff}(B)$	K	8450 ± 250	10 100 ± 900	25 400 ± 2000
$M_{\rm A}$	$M_\odot$	2.6 ± 0.4	2.3 ± 0.3	12.9 ± 1.5
$M_{\rm B}$	$M_\odot$	1.8 ± 0.2	2.3 ± 0.3	9.6 ± 1.1
i	°	19.5 ± 1.0	43.5 ± 2.6	16.7 ± 0.6
$M_{\rm C}{}^a$	$M_\odot$	>0.8	>2.6	>7.0
$M_{\rm C}{}^b$	$M_\odot$	<1.6	∼3.2 ± 0.5	<10
$i_{\rm o}$	°	$\gtrsim 72$	∼77 ± 7	$\gtrsim 75$
$i_{\rm m}$	°	$\gtrsim 52$	$\gtrsim 34$	$\gtrsim 58$

[a]Lower limit from the spectroscopic mass function.
[b]Estimated from detection/non-detection of lines in the spectrum.

body is a main-sequence star, we estimate that its relative flux is at least 30 per cent lower than the flux of the secondary star, even if its lines were rotationally broadened. Therefore, $M_{\rm C}$ is expected to be less than about 1.6 $M_\odot$.

Assuming an absolute magnitude corresponding to a star of 0.8–1.6 $M_\odot$ for component C, we obtained an integrated absolute magnitude for the system of about $M_{\rm V}({\rm ABC}) = +0.6 \pm 0.4$ mag, which corresponds to an apparent distance modulus $V - M_{\rm V} = 8.2 \pm 0.4$ mag. This value is consistent with the photometric values determined for the cluster by Dachs & Kabus (1989, 8.54 mag), Sung, Chun & Bessell (2000, 8.12 mag), Terndrup et al. (2002, 8.30 mag), and Loktin, Matkin & Gerasimenko (1994, 8.19), as well as the one derived from the *Hipparcos* parallaxes ($V_{\rm o} - M_{\rm V} = 7.70 \pm 0.16$ mag; Robichon et al. 1999).

Approximate values for the orbital inclination of both the inner and outer orbits can be derived if the masses of the three stars are estimated. For the inner orbit we obtained $i \approx 19\overset{\circ}{.}5$. For the outer orbit, assuming an upper limit of 1.6 $M_\odot$ for star C, we calculated a lower limit $i_{\rm o} \gtrsim 72°$. Therefore, the mutual inclination of the inner and outer orbits is $i_{\rm m} \gtrsim 52°$.

Dynamically, the system contains a close binary with two stars about 2.6 and 1.8 $M_\odot$ in an orbit with a semi-axis of about 35 $R_\odot$ and moderate eccentricity. This close pair is bound to a third star, less massive, orbiting in an eccentric orbit with a semi-axis of about 8 au. The triple is markedly hierarchical with a semi-axis ratio of ∼50.

3.2 HD 66137

The spectral morphology of components A and B is very similar to each other: both have spectral type B9–A0 V and low rotational velocity. Their temperatures would be approximately 9700 ± 400 K, which in the cluster isochrone corresponds to a mass of 2.3 ± 0.3 $M_\odot$ and an absolute visual magnitude of 1.35 ± 0.45 mag. The lower limit for the mass of star C is high. Using equation (1) we deduced that star C contains at least 35–37 per cent of the total mass of the triple, being probably the most massive star of the three. Likewise, the intensity of spectral lines of the two visible components suggests that the flux contribution of star C is considerable. Indeed, the equivalent width of all spectral lines in stars A and B are smaller than expected for stars of the same spectral type by a factor 0.3–0.4. In absence of a third light, this factor would be 0.5 for both stars. Therefore, all three stars seem to have comparable brightness.

The lines of star C are in fact present in the spectrum, but pass unnoticed due to its high rotation. In order to make its spectrum more visible, we built the grey-scale image shown in Fig. 4, in which all observed spectra [excluding a few low signal-to-noise (S/N) spectra] are stacked ordered by orbital phase. Besides the sharp lines of the spectroscopic binary, which nicely trace its orbital motion, broad spectral lines are visible as shadows at the position of lines He I λ4471 and Mg II λ4481. A few other similar broad lines can be distinguished in the spectrum, including He I lines at λλ4089, 4144, 4388, He I–Fe II blends at λ4922–24 and λ5016–18, and the Si II doublet λ4128–30. Since He I λ4471 and Mg II λ4481 have similar intensity, we estimate a spectral type B7–B8 for star C, somewhat earlier than its companions. Its rotational velocity is of the order of 200–250 km s^{-1}. If these broad lines belong indeed to the same object that is responsible for the barycentric movement of the close binary, its RV is expected to vary with a semi-amplitude

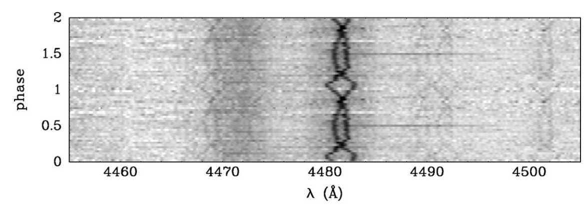

Figure 4. Stacked spectra of HD 66137 ordered by orbital phase. Shadows at λλ4471 and 4481 are broad spectral lines belonging to the fast rotating star C. Several sharp lines of the close binary are visible: the strong line Mg II 4481 and weak lines of Ti II (4468 and 4501) and Fe II (4489 and 4491).

of the order of 10 km s^{-1}. These variations, however, are very hard to measure with such shallow and broad lines.

The integrated magnitude of the triple allows us to make an estimate of the mass of star C. From the apparent magnitude of the triple ($V = 7.85$; Dachs & Kabus 1989), the apparent distance modulus, and the estimated magnitudes of the components of the inner binary, we obtain for star C an absolute magnitude $M_{\rm V}({\rm C}) \approx +0.2$ mag, which corresponds to a mass $M_{\rm C} \sim 3.2$ M$_\odot$. From the estimated mass of star C we derived $i_{\rm o} \approx 77° \pm 7°$ and a lower limit $i_{\rm m} \gtrsim 34°$ for the mutual inclination of the orbits, although considering the uncertainties in $i_{\rm o}$ and i this lower limit might be as low as 24°.

In short, this triple is structured in two hierarchical levels. The outer binary subsystem has a period of 9.2 yr and a semi-axis of about 8–9 au. The less massive component of this subsystem is a 3 M$_\odot$ star, while the primary is a close binary of 8.7 d period with twin components of about 2.3 M$_\odot$.

3.3 HD 315031

We determined for the visible components of this system's spectral types B0.5 IV–V and B1 V, which correspond to temperatures $T_{\rm eff,\,A} = 28\,000 \pm 2000$ K and $T_{\rm eff,\,B} = 25\,400 \pm 2000$ K, according to the Schmidt-Kaler (1982) calibration. The low values of the spectroscopic minimum masses in comparison with the masses corresponding to the spectral types, indicate a low orbital inclination.

The eccentricity of the orbit is indistinguishable from zero, as is expected as a consequence of tidal friction for a binary with a period as short as this ($P = 1.377$ d). Hence, in the final calculation of the orbital parameters we fixed the eccentricity at zero. Furthermore, both stellar components are expected to rotate synchronously with the orbital motion, since the time-scale for synchronization is shorter than for circularization. Under this hypothesis, the projected radii can be calculated from the projected rotational velocities. We determined $v \sin i$ by applying the method by Díaz et al. (2011) on the reconstructed spectra of stars A and B. We obtained $v_{\rm A} \sin i = 48 \pm 4$ km s^{-1} and $v_{\rm B} \sin i = 42 \pm 4$, from which we calculated $R_{\rm A} \sin i = 1.31 \pm 0.11$ R$_\odot$ and $R_{\rm B} \sin i = 1.14 \pm 0.12$ R$_\odot$. Even though the orbital inclination is in principle unknown, the projected radius can be combined with the minimum mass obtained from the orbital analysis to get the mean stellar densities:

$$\left(\frac{\rho}{\rho_\odot}\right)_j = 0.01343 \left[\frac{K_{\rm A} + K_{\rm B}}{(v \sin i)_j}\right]^3 \cdot \frac{q^{j-1}}{P^2\,(1+q)}, \qquad (2)$$

where $j = 1$ ($j = 2$) for star A (B), the period is in days, and the numerical constant is $(1\,{\rm R}_\odot/1\,{\rm au})^3 \cdot (1\,{\rm yr}/1\,{\rm d})^2$.

Using this equation we obtained: $\rho_{\rm A} = 0.137 \pm 0.035\,\rho_\odot$ and $\rho_{\rm B} = 0.137 \pm 0.035\,\rho_\odot$. These values correspond to stars very close of the zero-age main sequence. Fig. 5 shows the position of both companions in the colour–magnitude diagram. The coloured regions mark the stellar models that are consistent with all observational information, essentially spectroscopic mass ratio, densities, and temperatures.

In short, this binary is formed by two unevolved main-sequence stars of 12.9 ± 1.5 and 9.6 ± 1.1 M$_\odot$ with radii of about 4.6 ± 0.4 and 3.9 ± 0.3 R$_\odot$, corresponding to an age of about 1 Myr. The inclination of the orbit is about 16°.7. The spectroscopic minimum mass for the third star is a fraction 0.24 ± 0.01 of the total mass. This value corresponds to 0.7–0.8 times the mass of star B. Considering that the lines of star C are not clearly visible in the spectrum, its mass should be close to this lower limit. Even if it is a fast rotator, a conservative higher limit for its mass would be 9–10 M$_\odot$.

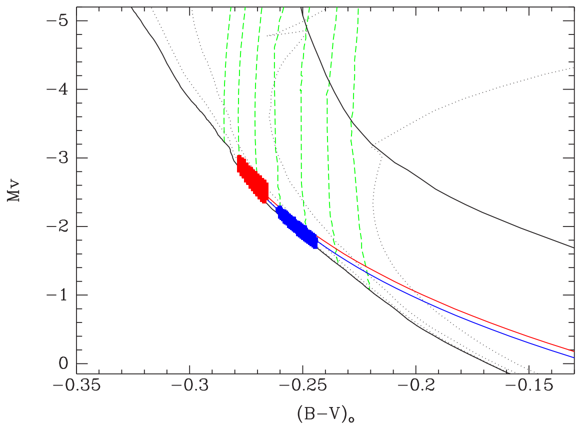

Figure 5. Position of the stellar components of HD 315031 in the colour–magnitude diagram. The black heavy lines are the zero-age and terminal-age main sequences; dotted lines are the isochrones $\log \tau = 6.0$, 6.5, 7.0, and 7.5; dashed lines are isotherms from 20 000 K (right) to 32 000 K (left); thin continuous lines are curves corresponding to densities $\rho = 0.137$ and $0.152\,\rho_\odot$. The grey (red and blue in the colour version) areas mark the stellar models compatible with the observed temperatures and densities.

The integrated absolute visual magnitude derived from the estimated stellar parameters is in agreement with the cluster membership. Although NGC 6530 has been subject of several photometric studies, the distance to this cluster is not well known. Published values for the distance modulus range from $V_0 - M_{\rm V} \approx 11.3$ to 10.5 (Sung et al. 2000; Prisinzano et al. 2005; Arias et al. 2006), while the $E(B-V)$ reddening value would be between 0.20 and 0.35 mag. The disagreement between different authors or even different star samples within the same work, might be related to variable extinction, an abnormal extinction law, or the existence of several stellar groups at different distances (Arias et al. 2006). The location of this triple in the cluster colour–magnitude diagram corresponds to $M_{\rm V} \approx -2.9$ for $V_0 - M_{\rm V} = 10.5$, $E(B-V) = 0.2$ and $M_{\rm V} \approx -4.1$ for $V_0 - M_{\rm V} = 11.25$, $E(B-V) = 0.35$. Our estimated absolute parameters correspond to an integrated absolute magnitude of the binary HD 315031AB of $M_{\rm V} = -3.16 \pm 0.25$. Assuming $M_{\rm C}$ is in the range 7–10 M$_\odot$, the total absolute magnitude of the triple would be $M_{\rm V} \approx -3.4$, which is consistent with the cluster distance.

The total mass A+B+C is of the order of 31 M$_\odot$, and therefore the outer orbital semi-axis is about 800 $R_\odot$. However, since the orbit is very eccentric, at periastron the third star is at only 120 $R_\odot$ from the close binary. This distance is about eight times larger than the separation of the companions of the inner pair. The high inclination of the outer orbit and low inclination of the inner orbit ($i \approx 17°$) assure a high relative inclination of the two orbital planes ($i_{\rm m} \gtrsim 58°$).

4 DISCUSSION

4.1 Detection of long period spectroscopic subsystems

We reported in this paper, the dynamical discovery of two triples in the cluster NGC 2516 with outer periods between 9 and 10 yr. Our time baseline was long enough to cover in both cases about one and a half orbital cycles of the outer subsystems. At the distance of the cluster (380 pc), the projected semi-axis of the outer subsystems in angular units is, in both triples, about 20–25 mas. This separation range is still out of the reach of visual techniques like speckle interferometry or adaptive optic imaging, showing the difficulty

Table 4. Radial velocities of visual pair CPD−60°944AB. Uncertainties are about 1.2 km s^{-1} for component A and 0.9 km s^{-1} for component B.

CPD−60°944A		CPD−60°944B	
HJD	RV km s^{-1}	HJD	RV km s^{-1}
2 451 590.6287	22.7	2 453 761.7224	24.3
2 451 592.7282	24.3	2 454 835.6489	23.9
2 451 939.7416	18.7	2 454 905.5928	23.9
2 452 270.7174	9.8	2 454 907.5665	23.3
2 454 905.5859	28.3	2 455 566.6242	24.2
2 455 572.6178	9.8	2 455 572.6046	23.2
2 456 695.7500	22.8	2 455 674.5250	23.7
		2 456 695.7389	22.8
		2 456 696.6007	21.8

of a complete multiplicity survey, covering all separation ranges. Even in close well-studied clusters like the Pleiades and Praesepe our knowledge of multiplicity at intermediate separations (5–15 au) is presently very poor (Leigh & Geller 2013). Interestingly, the semi-axis of the outer orbit for our two triples of NGC 2516 are in the middle of this separation range, showing the importance of long time-baseline RV monitoring in multiplicity surveys.

Most long-period spectroscopic binaries in open clusters have been discovered by studies focused on late-type stars, like the systematic survey of giant stars of Mermilliod & Mayor (1989) (see also Mermilliod et al. 2007). The small-amplitude velocity variations of wide binaries are easier to detect in late-type stars where higher precision can be reached in RV measurements. By contrast, our knowledge of early-type wide binary systems is much poorer, as is evident from the content of the Ninth Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2009). Among the 254 binaries with periods above 3000 d in this catalogue, 231 are late-type (F–M) dwarfs or giants, while only 14 binaries have A-type primaries and nine have spectral types O or B. Binaries and multiples with periods of several years are virtually impossible to discover in fast rotating early-type stars. However, errors of 1 km s^{-1}can be obtained in O–B–A stars of low $v \sin i$, and the monitoring such objects, particularly in young clusters, would alleviate the lack of statistical information on massive long period spectroscopic binaries.

4.2 Triple stars of NGC 2516

In this section we show, through the analysis of published and new information, that the cluster NGC 2516 would contain five hierarchical triples among its early-type main-sequence stars. The two triple systems detected dynamically in this paper are hierarchical with similar orbital configuration: an outer subsystem with a semi-axis of about 8 au and an inner subsystem with $a \approx 30\ \mathrm{R}_\odot$. However, in the triple CPD−60°961 the most distant star (component C) is the least massive of the three, while in HD 66137 it is the most massive.

Additionally, we present here spectroscopic material for one visual-spectroscopic triple. The visual binary CPD−60°944AB is very probably a physical pair (Dachs & Kabus 1989), and its primary was reported as RV variable by González & Lapasset (2000) on the basis of two RV measurements. We present in Table 4 velocity measurements obtained in the last years for both visual companions. These observations definitely confirm the binarity of the visual primary. The available observations, however, are not sufficient to fit the orbit reliably. We found two possible orbits with periods of 121.6 and 182.5 d and eccentricity $e \approx 0.4$ in both cases. A notable fact of this triple is that both visible components are chemically peculiar. CPD−60°944A was reported as B8pSi by Hartoog (1976). In our spectra Si II is clearly enhanced, Cr II appears weak, and Eu II lines at λλ 4130, 4205, and 4436 Å are clearly visible. Wavelength coincidence statistics showed that several other rare earth elements are also present. With a wavelength tolerance of 0.06 Å, highly significant results were obtained for ions Si II, Ca II, Ti II, Fe II, Pr II, Nd III, Eu II, and Ho II. At somewhat lower confidence level Cr II, Nd II, Dy II, and Er III would be also present. Even though significance levels change slightly using different tolerance values or line lists, the presence of at least three lanthanide (Eu, Dy, Ho) is a robust result.

On the other hand, CPD−60°944B, classified as B9.5IVp(Si) by Dachs & Kabus (1989), is in fact a HgMn star, which exhibits strong lines of Hg II, Mn II, P II, Ga II, and Xe II. This system, therefore, would be one of the few known multiple system formed by peculiar stars of different type.

A fourth triple would be HD 65949, a chemically peculiar single-lined spectroscopic binary studied by Cowley et al. (2010), who detected a small variation in the centre-of-mass velocity, which was interpreted as due to the presence of a third body. The chemical pattern of this star is not typical of any group of peculiar stars, presenting several lines typical of HgMn stars, but lacking Mn lines. Strikingly, this morphology is very similar to the primary of CPD−60°961, one of the triples analysed in this paper.

Finally, the short period spectroscopic binary HD 66066A (González & Lapasset 2003) has a visual companion that could be dynamically bound (Dachs & Kabus 1989), being therefore also a hierarchical triple.

4.3 Dynamical evolution of the observed triples

We will comment in this section about three aspects of the system dynamics: tidal effects in the close binary, orbital stability of the triple, and the possible occurrence of Kozai oscillations. In close binaries, tidal interaction in combination with energy dissipation mechanisms (radiative damping in the case of early-type stars) tends to synchronize stellar rotation with orbital motion and circularize the orbit (Zahn 1977; Hut 1981). In order to estimate the circularization time-scales of the close pair in our triples we used the binary evolution code developed by Hurley, Tout & Pols (2002).[1] Inner binaries in both triple systems of NGC 2516 have periods long enough for circularization not to be reached until after the end of the main sequence. By contrast, HD 315031 would have been circularized in about 1.0–1.5 Myr, which is comparable with the cluster age.

According to Mardling & Aarseth (2001), a triple or higher order star system is stable if the periastron distance of the third star ($r_\pi^{\rm out}$) and the inner semi-axis (a) orbits obey the criterion

$$\frac{r_\pi^{\rm out}}{a} > 2.8 \left[(1+q_{\rm out})\cdot\frac{1+e_{\rm o}}{(1-e_{\rm o})^{1/2}}\right]^{2/5}\cdot\left(1-0.3\frac{i}{\pi}\right),$$

which as a function of the spectroscopic parameter $a_{\rm o}$ can be written as

$$\frac{a_{\rm o}}{a} > 2.8\,\frac{q_{\rm out}}{(1+q_{\rm out})^{3/5}}\cdot\frac{(1+e_{\rm o})^{2/5}}{(1-e_{\rm o})^{6/5}}\cdot\left(1-0.3\frac{i}{\pi}\right).$$

For the three triples studied here this relation is satisfied. In the two triples of NGC 2516 the estimated semi-axis ratio is at least

[1] Publicly available at http://astronomy.swin.edu.au/~jhurley/.

10 times larger than this minimum value for stability, while in the more eccentric system HD 315031 the observed value would be about twice the limit value.

In a hierarchical triple system, both the eccentricity of the inner binary and the mutual inclination execute periodic oscillations known as Kozai cycles (Kozai 1962; Harrington 1968; Ford, Kozinsky & Rasio 2000). The amplitude of the eccentricity variations are significant when the relative inclination between the orbits is higher than $\arcsin(\sqrt{2/5}) = 39\overset{\circ}{.}2$, being maximum when orbital planes are perpendicular to each other. On the other hand, the eccentricity amplitude does not depend on either the mass of the third body or the outer semi-axis. The duration of the Kozai cycle, however, does depend on the outer period and the mass of the distant star. In practice, tidal effects between the companions of the inner binary, rotational deformation of the stars, or relativistic terms can detune the Kozai effect in systems with large outer-to-inner semi-axis ratio. According to Makarov & Eggleton (2009) the Kozai cycling is suppressed if $P_{\rm o}({\rm yr}) \gtrsim [{\rm P(days)}]^{1.4}$. In the three analysed systems the outer period is lower than this limit.

The period of Kozai cycles is given approximately by (Ford et al. 2000; Mazeh & Shaham 1979)

$$P_{\rm e} \approx \beta \frac{P}{q_{\rm out}} \left(\frac{a_{\rm ou}}{a_{\rm in}}\right)^3 (1 - e_{\rm o}^2)^{3/2}, \quad (3)$$

where β is a factor of order unity that depends on the initial values for mutual inclination, eccentricity, and argument of periastron of the inner orbit. For the two triples of NGC 2516 the periods of the eccentricity oscillations, which depend mainly on orbital periods P and $P_{\rm o}$, are similar to each other: $\sim$8–14 × 10^3 yr for CPD−60°961 and $\sim$8–10 × 10^3 yr for HD 66137. These values are much shorter than the time-scales for tidal effects or nuclear evolution. The short time-scale for the variation of orbital elements and the high mutual inclination ($i_{\rm m} \gtrsim 52°$, see Section 3.1) assure that the Kozai mechanism would be working efficiently in CPD−60°961. The maximum eccentricity, which is a function of orbital inclination (Kinoshita & Nakai 1999), would be $e_{\rm max} \gtrsim 0.60$. In the case of HD 66137 the lower limit for the mutual inclination ($\gtrsim$34°) is slightly lower than the critical value, so the occurrence of Kozai cycles in this system is not certain, although probable. In fact, in both triples, mutual inclinations above 80°–85° are still compatible with the spectroscopic parameters. If high eccentricity configurations take place periodically, the inner orbit could have been (or is being) shrunk by tidal interactions. However, if during the eccentricity cycles the maximum values are not very high ($e_{\rm max} \lesssim 0.7$), then strong binary interactions (tidal circularization, mass transfer) would not take place before the end of the main-sequence stage.

If the inner orbit is not dynamically modified, in both triples the primary star will overflow its Roche lobe during giant branch ascent before the core He burning, giving place to case B mass transfer.

HD 315031 has a very eccentric outer subsystem ($e_{\rm o} = 0.85$) and a very close inner subsystem ($P = 1.38$ d). The angular momentum exchange between the inner binary and a third body in hierarchical triple systems has been proposed to play a key role in formation of short-period binaries (Tokovinin 1997). Statistics of binary and triples among solar-type stars supports this scenario (Tokovinin et al. 2006). Even though the mutual inclination of the inner and outer orbits is high, we consider unlikely that the inner binary has reduced its size through the combination of Kozai cycles and tidal friction. The reason is that the high eccentricity of the outer orbit (which remains constant in Kozai cycles), leaves little room for the size or the original inner orbit. For example, for an inner orbit with $P \sim 6$ d the system would not be stable. A possible explanation is that the present configuration is not the result of the isolated evolution of the triple system, but the outcome of the dynamical decay of a higher order multiple system. In fact, dynamical simulations of small N clusters produce frequently triples with relatively small period ratio and high outer eccentricity (Sterzik & Tokovinin 2002), as is the case of HD 315031.

This system is expected to experience mass transfer during the main sequence (case A mass transfer). In fact, the primary Roche lobe radius is currently $\sim$6 $R_{\odot}$, while the terminal-age main-sequence radius for a star with the primary mass is close to 12 $R_{\odot}$. According to Hurley's evolutionary code, the secondary star will become a blue straggler star at about 14 Myr.

5 SUMMARY AND CONCLUSIONS

The long-term spectroscopic monitoring of three double-lined spectroscopic binaries members of two open clusters, led to the discovery of the triple nature of these systems. All three systems are hierarchical with a close pair and a third object in a wide orbit. The ratio of the semi-axis of the outer and inner orbits are larger than 50, while the period ratio is larger than 350.

Besides the two triples of NGC 2516 analysed in detail in this paper (CPD−60°961 and HD 66137), spectroscopic data for the visual-spectroscopic triple CPD−60°944 of the same cluster are reported. NGC 2516 harbours five known hierarchical triples with inner binaries in the spectroscopic separation range, with periods between 1.7 and a few hundred days. Three of these systems contain at least one chemically peculiar star.

The triple HD 66137 (and probably also CPD−60°961) in NGC 2516 might be experiencing Kozai cycles with inner eccentricity oscillating in time-scales of $\sim 10^4$yr. However, the orbits of the inner binaries have not been circularized yet. Without a precise knowledge of the mutual inclination between the inner and outer orbit, it is not clear if significant tidal effects are taking place at epochs of high inner eccentricity. If the eccentricity remains lower than $\sim$0.7, strong tidal interaction is not expected until the end of the main sequence. Even without orbit shrinking, the inner binaries of both systems would experience case-B mass transfer, giving origin eventually to exotic objects.

On the other hand, HD 315031 contains a short-period massive binary and a third star orbiting in a very eccentric orbit. Due to the proximity of the third star at periastron the inner binary cannot have evolved from a significantly wider orbit. We speculate therefore that the present configuration is the result of a dynamical decay of a non-hierarchical multiple. The inner binary is expected to suffer mass transfer during the main-sequence stage and the secondary star will become a cluster blue straggler star.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Radial velocities (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu1257/-/DC1).

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