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Wide binary stars with non-coeval components

Abstract: We have estimated masses of components of visual binaries from their spectral classification. We have selected pairs, where the less massive component looks more evolved. Spectral observations of some of such pairs were made, and at least one pair, HD 156331, was confirmed to have components of different age. Since mass exchange is excluded in wide binaries, it means that HD 156331 can be formed by the capture.

Keywords: Binary Stars, Stellar Mass

1 Introduction

The formation of binary stars basically follows two scenarios: fission of rotating molecular gas clouds during gravitational collapse, and inelastic collisions of stars during the formation of young star clusters (Tutukov & Cherepashchuk 2020). A capture of a component from the field stars is not ruled out in principle either, although it should be relatively rare. Capture occurs when two stars pass close to each other in the presence of a scattering medium that can take in excess kinetic energy, to leave the two stars bound. This medium could be a third star, a circumstellar disk, or the stars themselves, if the collision is close enough to cause the tides to rise and fall. Capture in the presence of a third body and "tidal capture" requires a high stellar density, which is atypical for field stars.

Capture in the presence of a stellar disk may play some role in the formation of wide systems, because the capture cross section has to be on the order of the size of the disk and thus lead to the formation of systems with large semi-axes about 100 AU. Clarke & Pringle (1991) considered the possibility of a large, massive protostellar accretion disk playing a role in the formation of binary stars by enabling the capture of a passing star within a dense star-forming region. It was found that capture rates are too low to play a major role in all known star-forming environments, particularly when the probability of prior disc dispersal by the more frequent high-velocity interactions is taken into account.

An indicator of the capture could be the difference in the ages of the components. It is evident, in particular, that in evolutionary wide systems (i.e., systems with no matter transfer between components today or in the past) with components of the same age, a less massive component cannot appear to be more evolved.

Our previous attempt to find pairs with non-coeval components was based on estimating the durations of preMS and MS stages for stars of different masses. In particular, we looked for wide pairs where a very low-mass secondary component (with mass $m_2$ and duration of preMS stage $\tau_{\text{preMS}}(m_2)$) is already an MS star, and massive primary (with mass $m_1$ and duration of preMS + MS stages $\tau_{\text{MS}}(m_1)$) is still an MS star. We have found three candidates with $\tau_{\text{preMS}}(m_2) > \tau_{\text{MS}}(m_1)$, the results can be found in Malkov (2000).

The aim of the present study is to use another approach to find non-coeval pairs among visual binaries. For indication of non-coevality we compared spectral classes and masses of the components, estimated from the spectral classification.

The structure of this paper is as follows: in Section 2 we describe our sample selection, in Section 3 we describe our observations for the first three objects and spectral data reductions. Data analysis is described in Section 4 and the results are discussed in Section 5. Section 6 summarizes this paper.
Table 1. Systems under study. Pairs

| Name     | $V$, mag | $\varpi$, mas | $\sigma_{\varpi}$ |
|----------|----------|---------------|-------------------|
| HD 101379 | 5.095    | 8.397         | 0.507             |
| HD 156331 | 6.267    | 16.703        | 0.048             |
| HD 160928 | 5.871    | 13.053        | 0.599             |

Parallax $\varpi$ and visual brightness $V$ are taken from Gaia EDR3 and SIMBAD, respectively.

Table 2. Observational log

| Name     | Date           | Exposure (s) | Seeing (arcsec) | SNR   |
|----------|----------------|--------------|-----------------|-------|
| HD 101379| 2021 July 14   | 3 × 25       | 1.5             | 150–400|
| HD 156331| 2021 May 10    | 1 × 40       | 1.1             | 150–280|
| HD 160928| 2021 May 10    | 1 × 40       | 1.2             | 200–300|

2 Sample selection

The general method of this work is an applying the simple idea to find non-coeval pairs among visual binaries. For indication of non-coevality we compared spectral classes and masses of the components, estimated from the spectral classification. Applying this idea to the Sixth Catalog of Orbits of Visual Binary Stars, ORB6 (Hartkopf et al. [2001]), we found thirteen systems where less massive component looks more evolved, and, consequently, the components are probably non-coeval (Malkov [2020]).

We have made a search for additional data on these thirteen systems in ORB6 [Hartkopf et al., 2001], Catalogue of Stellar Spectral Classifications [Ski[ff], 2014], Multiple star catalogue, MSC [Tokovinin, 2018], as well as in the SIMBAD database. The parameters of three systems presented in this paper are shown in Table 1.

3 Observations and Data Reduction

Three of these thirteen systems have been observed with the Southern African Large Telescope (SALT; Buckley et al. [2006]; O’Donoghue et al. [2006]) using the High Resolution Spectrograph (HRS; Barnes et al. [2008]; Bramall et al. [2010]; 2012; Crause et al. [2014]). The HRS is a thermostabilized double-beam echelle spectrograph, the entire optical part which is housed in a vacuum to reduce the influence of temperature variations and mechanical interference. The blue arm of the spectrograph covers the spectral range 3735–5580 Å, and the red arm covers the spectral range of 5415–8870 Å, respectively. The spectrograph is equipped with two fibers (object and sky fibers) and can be used in the low (LR, $R=14,000$–15,000) medium (MR, $R=40,000$–43,000) and high (HR, $R=67,000$–74,000) resolution modes. For our observation HRS was used in MR, where for both the object and sky fibers have 2.23 arcsec in diameter. The both blue and red arms CCD were read out by a single amplifier with a 1×1 binning. All additional details of observations are summarized in the Table 2. Generally, each star was observed once, but in case HD 101379 three spectra were obtained, where for both HD 156331 and HD 160928 only one spectrum was obtained. Exposures were selected in the way to accumulate Signal-to-Noise Ratio (SNR) more than 150 in the spectral region 4300–8800 Å. Unfortunately, sensitivity of HRS drops down fast bluer of 4300 Å and the final SNR in this spectral region is very hard to predict.

Three spectral flats and one spectrum of ThAr lamp were obtained in this mode during a weekly set of HRS calibrations that enough to get average external accuracy of 300 m s$^{-1}$. Method of analysis, described in Section 4, needs to use spectra corrected for sensitivity curve. For this reason spectra of spectrophotometric standard from the list [Kniazev, 2017] were observed and used during HRS data reduction.

Primary reduction of the HRS data, including overscan correction, bias subtractions and gain correction, was done with the SALT science pipeline [Crawford et al., 2010]. Spectroscopic reduction of the HRS data was carried out using standard HRS pipeline and our own additions to it described in details in [Kniazev et al., 2019].

4 Spectral Data Analysis

Analysis of totally reduced HRS spectra was done with a dedicated software package fbs (Fitting Binary Stars; Kniazev et al. [2020]) developed by our team for the stellar spectra analysis and used by us in the different studies (Berdnikov et al. [2019]; Gvaramadze et al. [2019]; Kniazev [2020]; Gvaramadze et al. [2021]). This software is fitted observed spectra with use of the library of high-resolution theoretical stellar spectra and is designed to derive radial velocities and stellar parameters[1]

[1] https://astronomers.salt.ac.za/software/hrs-pipeline/
errors, we use errors for each parameter in this work as they shown in the last row of Table 3.

### 5 Parameters of the studied systems

The parameters of three systems observed with SALT are shown in Fig. 2 and presented in Tables 1 and 3. Absolute magnitudes of the components $M_V$ are calculated from parallax and visual brightness (see Table 1) and from weight in $V$ band and interstellar reddening $E(B-V)$ values (see Table 3).

We can see from Fig. 2 that more massive (and more luminous) components of HD 101379 and HD 160928 look more evolved than the less massive ones. It should be added that according to MSC (Tokovinin, 2018), HD 101379 (= WDS 11395-6524 = HIP 56862) is in fact a quadruple system, where HD 101379 A is a spectroscopic binary SB1, and HD 101379 B is an eclipsing binary.

Contrary, the secondary (less massive) component of HD 156331 is more evolved than the primary (see Fig. 2), and, consequently, it is a good candidate to the wide binary with non-coeval components. It is an indication of the non-coevality of the components and, consequently, we can assume that this system could be formed by a capture.

In addition, another assessment can be made. HD 156331 was included in our list of pairs with probably non-coeval components (Malkov, 2020) because the spectral classification of the components, F8III+B9V, given in WDS (Mason et al., 2001), corresponds to masses of 1.76 and 2.58 (hereafter in solar mass), respectively, and hence the less massive component looks more evolved. The val-

| System | $T_{eff}$ (K) | log g | $V_{sin i}$ (km s$^{-1}$) | $V_{rad}$ (km s$^{-1}$) | Weight in V band | $M_V$ (mag) | $[\text{Fe/H}]$ | E(B−V) (mag) |
|--------|---------------|-------|--------------------------|--------------------------|------------------|-------------|--------------|--------------|
| HD 101379 A | 5160±100 | 4.1±0.19 | 3.0±0.2 | −6.1±0.3 | 0.73±0.01 | −0.69±0.13 | 0.42±0.18 | 0.24±0.01 |
| HD 101379 B | 5000±25 | 3.8±0.01 | 10.4±0.2 | −5.9±0.2 | 0.72±0.01 | −0.70±0.13 | 0.19±0.01 | 0.25±0.01 |
| HD 101379 | 10460±55 | 4.6±0.08 | 104.5±2.3 | 30.5±0.4 | 0.27±0.01 | 0.39±0.13 | 0.42±0.18 | 0.24±0.01 |
| HD 101379 B | 10230±180 | 3.9±0.03 | 90.3±0.9 | 30.3±0.3 | 0.28±0.01 | 0.32±0.13 | 0.19±0.01 | 0.25±0.01 |
| HD 156331 A | 6000±10 | 4.0±0.01 | 35.1±0.2 | 9.8±0.2 | 0.72±0.01 | 2.74±0.01 | −0.28±0.01 | 0.00±0.01 |
| HD 156331 B | 5990±10 | 3.8±0.06 | 36.8±0.2 | 9.9±0.1 | 0.68±0.01 | 2.80±0.01 | −0.20±0.02 | 0.00±0.01 |
| HD 156331 | 8190±20 | 3.8±0.03 | 60.8±0.3 | 33.7±0.2 | 0.28±0.01 | 3.76±0.01 | −0.28±0.01 | 0.00±0.01 |
| HD 156331 B | 8090±30 | 4.0±0.04 | 60.0±0.3 | 31.1±0.3 | 0.32±0.01 | 3.62±0.01 | −0.20±0.02 | 0.00±0.01 |
| HD 160928 A | 8270±10 | 3.7±0.02 | 238.4±0.7 | −7.3±0.3 | 0.79±0.01 | 1.71±0.10 | −0.34±0.01 | 0.00±0.01 |
| HD 160928 A | 8450±20 | 3.9±0.01 | 225.0±0.8 | −8.5±1.3 | 0.73±0.01 | 1.79±0.10 | −0.15±0.03 | 0.00±0.02 |
| HD 160928 B | 6400±20 | 4.5±0.06 | 173.5±0.5 | −15.4±0.6 | 0.21±0.01 | 3.14±0.10 | −0.34±0.01 | 0.00±0.01 |
| HD 160928 B | 6880±60 | 4.8±0.01 | 190.3±1.5 | −16.5±1.6 | 0.27±0.01 | 2.87±0.10 | −0.15±0.03 | 0.00±0.02 |

Errors: 300. 0.35 10. 1.3 0.02 0.06 0.01

**Table 3.** Stellar parameters found with fbs software
Fig. 1. The results of the fbs fit all stars from this work: HD 101379 (top), HD 156331 (middle) and HD 160928 (bottom). Each panel consists of two sub-panels: the top one shows the result of the fit in the spectral region 3900-8870 Å. The observed spectrum is shown in black. Both found components are shown in blue and orange respectively, where their sum is shown in red. The bottom one shows the difference between the observed spectrum and its model in black, altogether with errors that were propagated from the HRS data reduction (continuous dark blue line). Grey vertical areas mark the spectral ranges that were excluded from the fit for different reasons, mainly due to bands of lines from the Earth atmosphere. Only blue spectra are shown for HD 156331 and HD 160928 just for more details.

Fig. 2. HD 101379, HD 156331 and HD 160928 systems on the HRD. Solid curves represent main sequence, subgiant and giant sequences (blue, grey and red, respectively), and dashed blue curve represents ZAMS [Straižys 1992]. Green circles and black squares represent primary (more luminous) and secondary components of the binaries, respectively, with uncertainty bars. Top and bottom panels: Coelho and Phoenix stellar models, respectively.
ues of $T_{\text{eff}}$, $\log g$ obtained in this work for this system (see Table 3, Phoenix library) rather indicate the spectral types F5III$+$A7IV, which corresponds to masses of 1.51 and 1.82. The difference in masses has decreased, but the situation has not changed qualitatively. Here we use the scales SpT $-$ $T_{\text{eff}}$ $-$ $\log g$ $-$ mass from (Straižys 1992), the typical mass error value when estimating it from the spectral type is 0.1.

However, the assumption that HD 156331 B has LC$=$IV or V contradicts with its position on the HRD (see Fig. 2). The star is located well below ZAMS. According to WDS (Mason et al. 2001), the components of HD 156331 have the same brightness in the V-band (which is contrary to our Weight values in Table 3), but even under this assumption absolute magnitude of HD 156331 B “rises” only to a value of $M_V = 3.13$ mag and the star remains under ZAMS.

In his detailed study of several fast visual binaries, based on speckle interferometry (Tokovinin 2017), in particular, found orbital elements and calculated dynamical parallax for HD 156331 ($\varpi_{\text{dyn}} = 14.2$ mas), which turned out to be different from the Hipparcos value ($\varpi_{\text{HIP}} = 16.9$ mas). The recent Gaia observations rather confirm the latter value ($\varpi_{\text{Gaia}} = 16.7$ mas, see Table 1 and note that the parallax is given with a fairly high accuracy, 3%). But even relying on dynamical parallax will only make the components brighter by about 0.3 mag, and HD 156331 B will still remain under ZAMS in Fig. 2.

Our values of HD 156331 components’ radial velocities (see Table 3) are quite consistent with RV difference of $\sim 30$ km s$^{-1}$ near the periastron, predicted by Tokovinin (2017). Contrary, components’ magnitude difference found by Tokovinin (2017) corresponds to WDS values and not to values, found in this paper and given in Table 3.

Finally, it should be pointed out that the formal errors derived from the separation of the spectra of the parameters of the components significantly underestimate the real ones. Moreover, the output parameters can be correlated (for example, $\log g$ and $V \sin i$), so the analysis of the position of the components on the HRD must take into account the errors of the total brightness, and of the magnitude difference, as well as errors and a possible correlation of the obtained temperatures.

So the HD 156331 system requires further observation and analysis.

6 Conclusion

We have studied several stars from our preliminary list of candidates to wide pairs with non-coeval components, and we have found that the less massive component of HD 156331 is probably more evolved than the more massive. We can assume that this system could be formed by a capture. To prove the non-coevality one needs a detailed investigation of this and other candidates.

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