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Searching For Wide Binary Stars with Non-coeval Components in the Southern Sky

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Abstract

We have completed our observational program to search for wide binary systems with non-coeval components in the southern sky and report our results here. The final set of four systems was spectroscopically investigated in this paper. No binary systems with components of different ages were found among them. Taking into account our previous studies, we estimate the fraction of such binaries (i.e., binaries formed, presumably, by capture) to be not higher than 0.06%. The study will be continued on the northern sky.

Key words: (stars:) binaries: general – (stars:) binaries: visual – stars: formation

1. Introduction

According to current understanding, the formation of binary stars follows one of two scenarios: the fission of rotating clouds of molecular gas during the gravitational collapse and inelastic collisions of stars during the formation of young star clusters (Tutukov & Cherepashchuk 2020). A possible (but obviously rare) phenomenon could be the formation of a binary star by capture. Capture occurs when two stars pass close to each other. There must necessarily be a scattering medium (e.g., a circumstellar disk or a third star) to which the excess kinetic energy can be transferred.

Obviously, a sufficient (but not necessary) observational condition to demonstrate a binary system was formed by capture is the difference in age of the components. The age of a star is a rather difficult parameter to define. However, the presence in a wide binary system (where the transfer of matter between the components is excluded) of a more evolved and yet less massive component is irrefutable evidence for an age difference in the components. In our previous attempt to find such pairs, we compared the lifetime of a star on the main sequence (MS) and on the pre-MS stage and found three candidates (Malkov 2000).

In this study, we compare two-dimensional spectral classes and component masses estimated from the spectral classification. The situation where the less massive component evolved further from the MS can be considered as a binary system formed by capture.

The structure of this article is as follows: Section 2 describes our sample selection. Data from the literature on the systems under study are presented in Section 3. Section 4 describes our observations and reduction of the spectral data. Data analysis is described in Section 5 and the results are discussed in Section 6. Section 7 summarizes this article.

2. Sample Selection

Comparing the spectral classes and component masses (estimated from the spectral classification) of binary systems from the Sixth Catalog of Orbits of Visual Binary Stars, ORB6 (Hartkopf et al. 2001), we found thirteen systems in which the less massive component appears more evolved and, therefore, the pair was probably formed by capture (Malkov 2020).

For these systems, data available in the literature and other catalogs and databases were further studied: Washington Double Star Catalog, WDS (Mason et al. 2001), Catalogue of Stellar Spectral Classifications (Skiff 2014), Multiple Star Catalog, MSC (Tokovinin 2018), Binary star DataBase, BDB (Kovaleva et al. 2015) as well as in the SIMBAD database. Our spectral observations of three of these systems and their analysis revealed that at least one of the systems, HD 156331, could have formed by capture (Malkov & Kniazev 2022). Four other systems out of those listed in Malkov (2020) are the subject of the present study. Their parameters are listed in Table 1.

3. Known Information About Studied Systems

3.1. HD 20121 = WDS 03124-4425

HD 20121 AB ($6^{\mathrm{m}}.50+6^{\mathrm{m}}.90$, F7III+A0V) has the orbital solution with semimajor axis and orbital period of $a=0''.410$ and $P=45.2$ yr respectively. It has a remote $8^{\mathrm{m}}.91$ companion at separation $\rho=3''.8$ (Gaia DR3 parallax $\varpi=22.74\pm0.02$

Table 1
Parameters of the Systems Under Study and Observational Log

Name	V (mag)	ϖ (mas)	Date	Exposure (s)	Seeing (arcsec)	SNR
HD 20121	5.93	23.53 ± 0.62	2021.07.24	3×40	2.0	160
HD 26722	5.05	9.83 ± 0.64	2021.09.04	3×25	1.5	200
HD 114330	4.40	11.18 ± 0.41	2021.07.11	3×15	1.8	240
HD 187949	6.48	8.67 ± 0.14	2021.07.10	3×45	1.4	190

Note. Visual brightness V is taken from The Bright Star Catalogue (Hoffleit & Jaschek 1991) for HD 26722, and from SIMBAD for HD 20121, HD 114330 and HD 187949. Parallax ϖ is referenced from Hipparcos (van Leeuwen 2007) for HD 20121 and HD 26722, and from Gaia Data Release 3 (DR3, Gaia Collaboration et al. 2016, 2022) for HD 114330 and HD 187949.

mas) with common proper motion. Apparently, its presence does not affect our spectral observations (the diameter of the fiber entrance was $2\farcs23$ during our spectral observations, as described in Section 4).

3.2. HD 26722 = WDS 04139+0916 = 47 Tau

HD 26722 ($5\overset{m}{.}05 + 7\overset{m}{.}32$, G5IV+A8V) has the orbital solution with the semimajor axis and orbital period of $a = 1\farcs053$ and $P = 479$ yr respectively. No evidence of additional components in this binary system was found in the literature. Note that the Gaia DR3 parallax of $\varpi = 7.62 \pm 0.11$ mas differs from the Hipparcos one of $\varpi = 9.83 \pm 0.64$, which is included in SIMBAD and listed in Table 1.

3.3. HD 114330 = WDS 13099–0532 = θ Vir

HD 114330 is a spectroscopic (S1) binary ($4\overset{m}{.}50 + 6\overset{m}{.}84$, A1IVs+Am). Various orbital solutions for this pair were published in the literature. According to comments received from the author of the MSC (Tokovinin 2018), Dr. A. Tokovinin, the solution with the semimajor axis and orbital period of $a = 0\farcs219$ and $P = 33$ yr is certainly wrong, and the solution $a = 0\farcs116$ and $P = 17.8$ yr (Beardsley & Zizka 1977) is inconsistent with speckle observations (A. A. Tokovinin 2022, private communication).

HD 114330 has a remote companion at $\rho = 7''$ ($V = 8$ mag) with common proper motion and orbital solution with $a = 1\farcs243$ and $P = 695$ yr (Zirm 2015), though A. A. Tokovinin (2022, private communication) considers this solution to be unreliable. There is also another remote companion at $\rho = 71''$ ($V = 10.38$ mag, K2III), which appears to be an optical companion with HD 114330. Apparently, the presence of these two remote companions does not affect our spectral observations.

3.4. HD 187949 = WDS 19531–1436 (HD 187949 A = V505 Sgr)

HD 187949 AB is a wide pair ($6\overset{m}{.}58 + 9\overset{m}{.}13$, A2V+F7V) with orbital period $P = 349.2$ yr and semimajor axis $a = 0\farcs68$. A brighter component, HD 187949 A, is a close (spectroscopic S2 +eclipsing) binary ($6\overset{m}{.}72 + 8\overset{m}{.}88$, A2V+G8IV, $P = 1.183$ d) with an eclipse timing variation, with $P = 38.4$ yr, caused probably by another, unseen companion at $a = 0\farcs157$.

4. Observations and Data Reduction

All four systems from this paper were observed with the High Resolution Spectrograph (HRS; Barnes et al. 2008; Bramall et al. 2010, 2012; Crause et al. 2014), which is a thermostabilized double-beam échelle spectrograph installed at the Southern African Large Telescope (SALT; Buckley et al. 2006; O'Donoghue et al. 2006). The acquired spectrum covered the total spectral range 3735–8870 Å that consists of the blue arm spectrum (3735–5580 Å) and the red arm spectrum (5415–8870 Å). The spectrograph can be used in the low (LR, $R \approx 14{,}000$–$15{,}000$), medium (MR, $R \approx 40{,}000$–$43{,}000$) and high (HR, $R \approx 67{,}000$–$74{,}000$) resolution modes. It is equipped with two fibers (object and sky fibers) for each mode. For our observation, we used HRS in MR mode, where both the object and sky fibers are $2\farcs23$ in diameter. All additional details of observations are summarized in Table 1. Generally, each star was observed during one night with three exposures. Exposures were selected in a way to accumulate Signal-to-Noise Ratio (SNR) of more than 150 in the spectral region 4300–8800 Å. Unfortunately, the sensitivity of HRS drops down fast bluer of 4300 Å and the final SNR in this spectral region is very hard to predict.

The HRS calibration plan consists of three spectral flats and one spectrum of the ThAr lamp that were obtained in each mode weekly, which is enough to get average external accuracy of about 300 m s^{-1}. The method of analysis, described in Section 5, needs to use spectra corrected for the sensitivity curve. For this reason, spectra of spectrophotometric standards from the list of Kniazev (2017)[6] 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 the

[6] https://astronomers.salt.ac.za/software/hrs-pipeline/

Table 2
Stellar Parameters Found with `fbs` Software

System	$T_{\rm eff}$ (K)	$\log g$ (cm s^{-2})	$V \sin i$ (km s^{-1})	$V_{\rm hel}$ (km s^{-1})	Weight in V band	M_V (mag)	[Fe/H] (dex)	$E(B-V)$ (mag)	St. lib.
HD 20121 A	6692 ± 20	4.36 ± 0.05	77.2 ± 0.9	-7.8 ± 0.5	0.60 ± 0.09	3.34 ± 0.11	-0.22 ± 0.05	0.00 ± 0.01	Coelho
HD 20121 A	6540 ± 10	4.14 ± 0.03	79.6 ± 2.4	-10.4 ± 0.5	0.51 ± 0.01	3.52 ± 0.11	-0.22 ± 0.02	0.00 ± 0.01	Phoenix
HD 20121 B	6500 ± 15	4.35 ± 0.16	89.5 ± 0.8	56.3 ± 3.8	0.40 ± 0.09	3.78 ± 0.11	-0.22 ± 0.05	0.00 ± 0.01	Coelho
HD 20121 B	6473 ± 10	4.15 ± 0.04	76.2 ± 1.5	38.6 ± 2.6	0.49 ± 0.01	3.56 ± 0.11	-0.22 ± 0.02	0.00 ± 0.01	Phoenix
HD 26722 A	7980 ± 10	3.50 ± 0.01	29.5 ± 0.5	27.8 ± 1.0	0.10 ± 0.01	2.30 ± 0.28	-0.36 ± 0.01	0.00 ± 0.01	Coelho
HD 26722 A	7600 ± 25	3.10 ± 0.08	26.1 ± 0.7	2.4 ± 0.4	0.16 ± 0.01	1.79 ± 0.22	-0.33 ± 0.01	0.00 ± 0.01	Phoenix
HD 26722 B	5000 ± 10	2.04 ± 0.01	1.3 ± 0.2	-8.0 ± 0.1	0.90 ± 0.01	$\cdots 0.83 \pm 0.28$	-0.36 ± 0.01	0.00 ± 0.01	Coelho
HD 26722 B	5100 ± 10	2.06 ± 0.01	5.6 ± 0.2	-8.0 ± 0.2	0.84 ± 0.01	$\cdots 0.01 \pm 0.22$	-0.33 ± 0.01	0.00 ± 0.01	Phoenix
HD 114330 A	9550 ± 10	3.62 ± 0.01	0.0 ± 0.1	-1.5 ± 0.3	1.00 ± 0.01	$\cdots 0.36 \pm 0.09$	0.04 ± 0.01	0.00 ± 0.01	Coelho
HD 114330 A	9350 ± 10	3.54 ± 0.01	2.8 ± 0.1	-1.6 ± 0.3	1.00 ± 0.01	$\cdots 0.36 \pm 0.09$	0.18 ± 0.05	0.00 ± 0.01	Phoenix
HD 187949 A	8920 ± 30	4.36 ± 0.03	91.8 ± 0.5	-41.0 ± 0.6	0.90 ± 0.01	1.28 ± 0.25	-0.29 ± 0.01	0.00 ± 0.01	Coelho
HD 187949 A	8380 ± 10	4.32 ± 0.01	89.7 ± 0.8	-38.8 ± 0.7	0.91 ± 0.01	1.27 ± 0.27	-0.31 ± 0.02	0.00 ± 0.01	Phoenix
HD 187949 B	6130 ± 25	3.72 ± 0.04	0.6 ± 0.3	1.7 ± 0.3	0.10 ± 0.01	3.67 ± 0.25	-0.29 ± 0.01	0.00 ± 0.01	Coelho
HD 187949 B	6280 ± 10	3.52 ± 0.13	6.3 ± 0.6	1.9 ± 0.1	0.09 ± 0.01	3.78 ± 0.27	-0.31 ± 0.02	0.00 ± 0.01	Phoenix
Errors	300.	0.15	5.	1.3	0.02	$\cdots$	0.05	0.01	

standard HRS pipeline and our own additions to it, as described in detail in Kniazev et al. (2019).

5. Spectral Data Analysis

For the analysis of reduced data we relied on the software package Fitting Binary Stars (`fbs`; Kniazev et al. 2020). This software was developed for the analysis of stellar spectra of binary systems and was used previously by us in different studies (Berdnikov et al. 2019; Gvaramadze et al. 2019; Kniazev 2020; Gvaramadze et al. 2021; Malkov & Kniazev 2022).

This package was designed to fit observed stellar spectra with a library of theoretical stellar spectra to determine velocities and values of stellar parameters like ($T_{\rm eff}$, $\log g$, $v \sin i$, [Fe/H], $W)_{1,2}$ for both components in the binary system, where parameter $W_{1,2}$ is the weight of each spectrum ($W_1 + W_2 = 1$) in V band (at the wavelength $\lambda = 5550$ Å). Additionally, the *E(B-V)* value could be found in case spectra were corrected for the sensitivity of the observational system. Different theoretical stellar libraries could be used with the `fbs` software, but we utilized usual stellar models from Hubeny & Lanz (1995); Husser et al. (2013); Coelho (2014).

As was noted previously by Kniazev (2020), `fbs` software can underestimate the real errors. Since échelle spectra consist of hundreds of thousands of points, the minimization of the function described in Kniazev et al. (2020) is a very time-consuming process and for that reason Monte-Carlo simulations or application of Markov chain Monte Carlo methods could not be used. Kniazev et al. (2020) suggested executing `fbs` for each échelle spectrum separately (Kniazev 2020; Malkov & Kniazev 2022). For that reason we use `fbs` in the same way here and our results are presented in Table 2 and displayed in Figure 1. We analyzed all spectra with `fbs` independently, and present parameters and their errors, which are average values for each star. We produced this analysis with both Coelho (2014) and Husser et al. (2013) stellar models. Both libraries were convolved to match the HRS MR instrumental resolution. These results are also shown in Table 2. Finally, after comparing these results, we use errors for each parameter in this work; they are expressed in the last row of Table 2.

6. Parameters of the Studied Systems and Discussion

The parameters of four systems observed with SALT are displayed in Figures 2 and 3 and are presented in Tables 1 and 2. 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 2).

We were unable to detect a secondary component in the spectrum of HD 114330, which is why this system is not shown in the figures. One can see from Figure 2 that both components of HD 20121 and HD 187949 belong to the MS, within observational errors, or are not far away from it. Note that the cataloged spectral types of the HD 187949 components (A2V+F7V) fit the Coelho solution slightly better than the Phoenix solution.

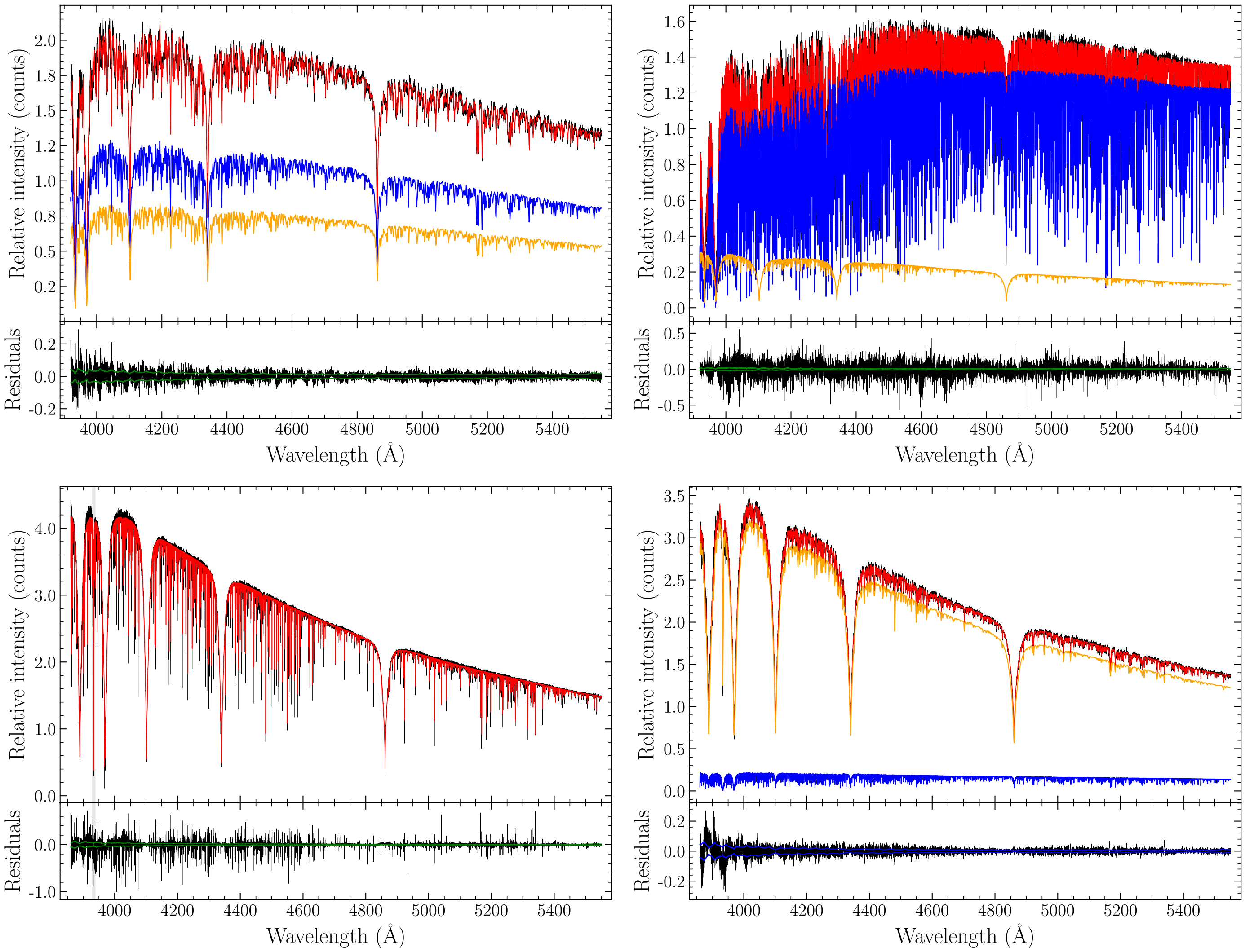

Figure 1. The results of the fit for all stars from this work by `fbs` software: HD 20121 (top left), HD 26722 (top right), HD 114330 (bottom left) and HD 187949 (bottom right). Each panel consists of two sub-panels: the top one features the result of the fit in the spectral region 3900–5550 Å. The observed spectrum is drawn in black. Both identified components are shown in blue and orange respectively, whereas their sum is depicted in red; the bottom one represents the difference between the observed spectrum and its model in black, together with errors that were propagated from the HRS data reduction (continuous green line).

On the contrary, the more luminous component of HD 26722 looks more evolved than the hotter one. However, as can be seen from Figure 3, both components fit the isochrones well (Ekström et al. 2012). We estimate the age of the system to be $\log\tau = 8.4 - 8.6$ yr, and masses of the components are $m_g = 3.18 \pm 0.16\, m_\odot$ (the cooler component is a more luminous giant) and $m_{\rm ms} = 1.70 \pm 0.02\, m_\odot$ (the hotter component is a less luminous MS star).

This preliminary list was compiled from the ORB6 catalog. We have finished the inspection of the southern sky and, given our previous research, where we found one candidate for systems with non-coeval components, we can roughly estimate the proportion of systems suspected of being formed by capture to be no more than 0.06 per cent. We now plan to continue our research on the northern sky.

Note that another indicator that a binary system has formed as a result of capture could be the observed difference in the chemical abundance of the components. Such an effect was found for the RR Lyn system (Khaliullin et al. 2001) and probably for V966 Per (I. M. Volkov 2022, private communication). In the latter case, the components, being placed on the Hertzsprung-Russell diagram (HRD) and evolutionary tracks, in addition exhibit very different ages. However, both systems are relatively close (period $P = 9.945$ days and $P = 4.309$ days, respectively) eclipsing binaries, so it is possible that the system exchanged masses in the past.

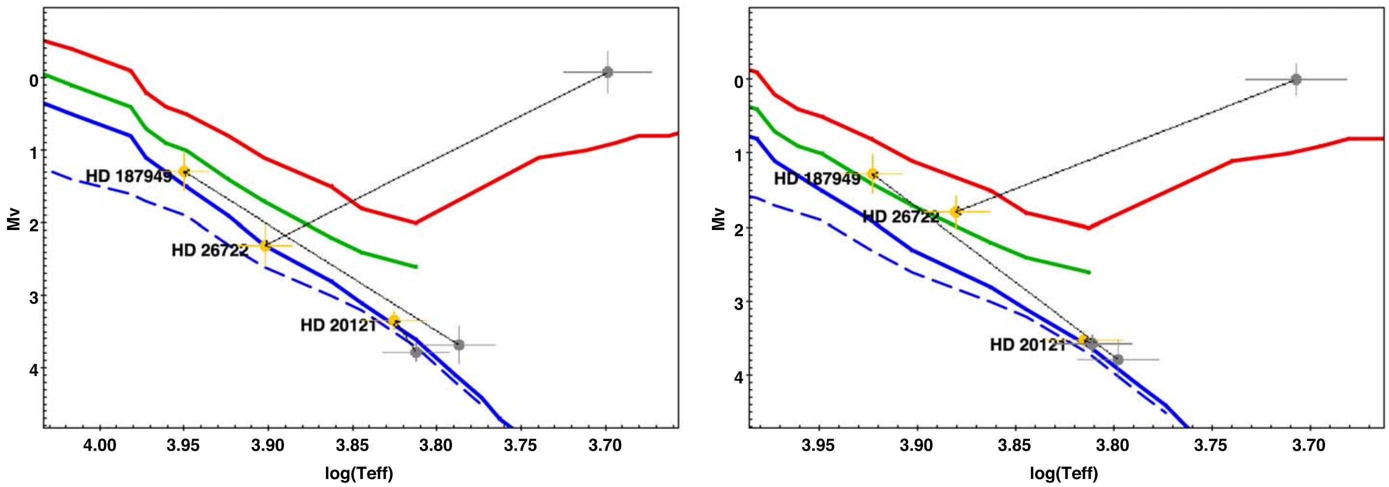

Figure 2. HD 20121, HD 26722 and HD 187949 systems on the HRD. Solid curves represent MS, subgiant and giant sequences (blue, green and red, respectively), and dashed blue curve represents Zero Age Main Sequence (ZAMS) (Straižys 1992). Yellow and gray circles signify primary (hotter) and secondary components of the binaries, respectively, with uncertainty bars. Left and right panels: Coelho and Phoenix stellar models, respectively.

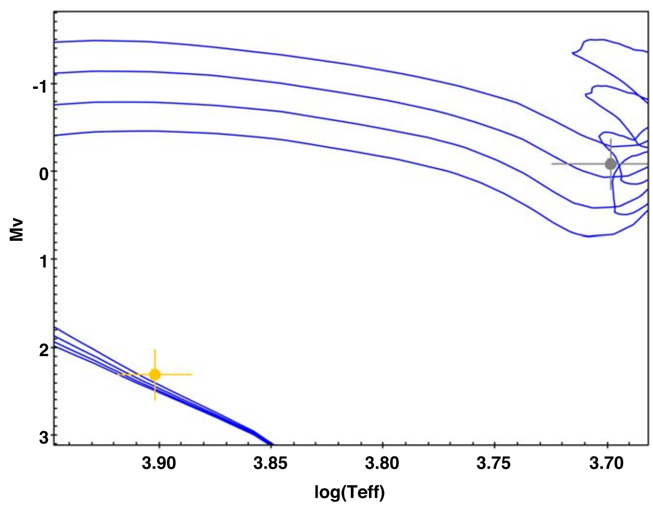

Figure 3. HD 26722 system (solution for Coelho stellar model) on the HRD. Thin blue curves are isochrones from Ekström et al. (2012) for ages (from top to bottom) $\log\tau = 8.3, 8.4, 8.5, 8.6$ yr, "no rotation" case and initial metallicity $Z = 0.014$. Other designations are the same as in Figure 2.

7. Conclusion

We have spectroscopically studied the last four stars in the southern sky from our preliminary list of candidates for wide pairs with non-coeval components, and we have found no evidence of non-coevality. The study will be continued on the northern sky.

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