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Physical and geometrical parameters of CVBS XI: Cou 1511 (HIP 12552)

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Abstract Model atmospheres of the close visual binary star Cou 1511 (HIP 12552) are constructed using grids of Kuruz's blanketed models to build the individual synthetic spectral energy distributions (SEDs) for both components. These synthetic SEDs are combined together for the entire system and compared with the observational one following Al-Wardat's complex method for analyzing close visual binary stars. The entire observational SED of the system is used as a reference for comparison between the synthetic SED and the observed one. The parameters of both components are derived as: $T^a_{\rm eff} = 6180 \pm 50\,{\rm K}$, $T^b_{\rm eff} = 5865 \pm 70\,{\rm K}$, $\log g_a = 4.35 \pm 0.12$, $\log g_b = 4.45 \pm 0.14$, $R_a = 1.262 \pm 0.08\,R_\odot$, $R_b = 1.006 \pm 0.07\,R_\odot$, $L_a = 2.09 \pm 0.10\,L_\odot$ and $L_b = 1.08 \pm 0.12\,L_\odot$, with spectral types F8V and G1.5V for components (a, b) respectively and age of 3.0 ± 0.9 Gyr. A modified orbit of the system is built and the masses of the two components are calculated as $M_a = 1.17 \pm 0.11\,M_\odot$ and $M_b = 1.06 \pm 0.10\,M_\odot$.

Key words: binaries — visual stars — fundamental parameters stars — Cou 1511 (Hip 12552)

1 INTRODUCTION

Recent surveys of the sky have shown that more than 50% of Galactic stellar systems are binaries, which demonstrates their importance in understanding the formation and evolution of the Galaxy. This role in precisely determining different stellar parameters gives the study of binary stars a special importance. The case is a bit more complicated in close visual binary stars (CVBSs), which are not resolved as binaries by inspecting images through traditional means but can be resolved in space based observations or by using modern techniques of ground-based observations, such as speckle interferometry or adaptive optics.

In addition, Docobo et al. (2001) pointed out that the study of orbital motion of visual and interferometric pairs remains an important astronomical discipline. Visual binaries are the main key source of information about stellar masses and distances, and they practically define our understanding of stellar physical properties, especially for stars on the lower part of the main sequence.

Currently, hundreds of CVBSs with periods on the order of 10 years or less are routinely observed by different groups around the world using high resolution techniques. This has helped in determining the orbital parameters and magnitude differences for some of these CVBSs. However, this is not sufficient to determine the individual physical parameters of the components of a system.

Al-Wardat's method for analyzing CVBSs (Al-Wardat 2012) offers a complementary solution for this problem by implementing differential photometry, spectrophotometry, atmospheric modeling and the orbital solution which leads to accurate determination of different physical and geometrical parameters of this category of stars. The method has been successfully applied to several solar type and subgiant binary systems such as HIP 70973, HIP 72479 (Al-Wardat 2012), HIP 689 (Al-Wardat et al. 2014) and HIP 11253 (Al-Wardat & Widyan 2009).

As a consequence of the previous work, this paper (number XI in this series) presents an analysis of the nearby solar type CVBS Cou 1511 (HIP 12552), with a modification to its parallax.

Table 1 shows the basic data of the system taken from the SIMBAD and NASA/IPAC catalogs, and Table 2 shows data from the Hipparcos and Tycho catalogs (ESA 1997), while Table 3 shows the magnitude difference of the system along with the filters that were used to observe them.

Table 1 Basic Data on the System

	HIP 12552	Reference
α_{2000}	$02^{\rm h}41^{\rm m}28.88^{\rm s}$	SIMBAD†
δ_{2000}	$+40°52'\,50.84''$	-
Tyc.	2849-1282-1	-
HD	16656	-
Sp. Typ.	G0	-
$E(B-V)$	0.076 ± 0.002	NASA/IPAC*
A_v	$0.24^{\rm m}$	NASA/IPAC

Notes: † *http://simbad.u-strasbg.fr/simbad/*; * *http://irsa.ipac.caltech.edu*.

Table 2 Data from the Hipparcos and Tycho Catalogs

	HIP 12552	Source of data
V_J(Hip)	$8.51^{\rm m}$	Hipparcos
$(B-V)_J$(Hip)	$0.60^{\rm m} \pm 0.018$	-
$\pi_{\rm Hip}$ (mas)	9.69 ± 1.29	-
B_T	$9.24^{\rm m} \pm 0.016$	Tycho
V_T	$8.59^{\rm m} \pm 0.014$	-
$\pi_{\rm Tyc}$ (mas)	14.7 ± 9.20	-
$\pi_{\rm Hip}{}^*$ (mas)	11.07 ± 1.07	New Hipparcos

Notes: *(van Leeuwen 2007)

Table 3 Magnitude difference between the components of the system HIP 12552, along with the filters used to obtain the observations.

Δm	Filter ($\lambda/\Delta\lambda$)	Reference
$0.65^{\rm m} \pm 0.06$	545 nm/30	[1]
$0.75^{\rm m} \pm 0.04$	545 nm/30	[2]
$0.88^{\rm m} \pm -$	562 nm/40	[3]
$0.86^{\rm m} \pm -$	692 nm/40	[3]

Notes: Ref. [1] Balega et al. (2007); [2] Docobo et al. (2006); [3] Horch et al. (2011).

2 ATMOSPHERIC MODELING

The observational spectral energy distribution (SED) of the system HIP 12552 obtained by Al-Wardat (2002) is used as a reference for comparison with the synthetic SED.

Using $m_V = 8.51^{\rm m}$ (see Table 2), $\Delta m = 0.76^{\rm m} \pm 0.03$ (as the average of all Δm using the different filters for V-band only (545–562 nm), see Table 3), and Hipparcos trigonometric parallax ($\pi = 11.83 \pm 1.07$ mas) the individual and absolute magnitudes of both components (a, b) of the system are calculated using the following relations:

$$\frac{F_a}{F_b} = 2.512^{-\Delta m}, \tag{1}$$

$$M_v = m_v + 5 - 5\log(d) - A_v \tag{2}$$

to get $m_v^a = 8.95^{\rm m} \pm 0.02$, $m_v^b = 9.71^{\rm m} \pm 0.05$ and $M_v^a = 4.07^{\rm m} \pm 0.18$, $M_v^b = 4.83^{\rm m} \pm 0.19$, where the extinction value A_v was taken from Table 1.

To calculate the preliminary input parameters used to build the atmospheric modeling, we use the bolometric magnitudes, the luminosities from Lang (1992) and Gray (2005), with the following relations:

$$\log(R/R_\odot) = 0.5\log(L/L_\odot) - 2\log(T_{\rm eff}/T_\odot), \tag{3}$$

Table 4 Positional Measurements of the System from the Fourth Interferometric Catalog

Epoch	θ (deg)	ρ (arcsec)	Reference
1979.7732	91.6	0.156	[1]
1982.7605	65.9	0.153	[2]
1982.7659	66.3	0.142	[2]
1983.7131	57.9	0.136	[2]
1984.7046	49.4	0.119	[2]
1985.8540	30.4	0.106	[2]
1991.8973	184.9*	0.105	[3]
1993.7652	161.0*	0.122	[4]
1994.7087	151.3*	0.136	[5]
1994.8989	143.0*	0.146	[6]
1995.7710	139.2*	0.135	[7]
1996.6912	132.7*	0.150	[5]
2000.8730	98.8	0.152	[8]
2003.9468	73.8	0.143	[9]
2003.9598	77.1	0.146	[10]
2004.8374	65.0	0.135	[11]
2004.9905	64.1	0.135	[12]
2007.6075	30.0	0.109	[13]
2008.861	334.9*	0.077	[14]
2010.0074	328.1	0.0659	[15]

Notes: * These points were modified by 180° to achieve consistency with nearby points. References: [1] McAlister & Hendry (1982), [2] McAlister et al. (1987); [3] Hartkopf et al. (1994); [4] Balega et al. (1994); [5] ten Brummelaar et al. (2000); [6] Balega et al. (1999); [7] Hartkopf et al. (1997); [8] Balega et al. (2006); [9] Balega et al. (2013); [10] Hartkopf et al. (2008); [11] Balega et al. (2007); [12] Docobo et al. (2006); [13] Mason et al. (2011); [14] Gili & Prieur (2012); [15] Horch et al. (2011).

$$\log g = \log(M/M_\odot) - 2\log(R/R_\odot) + 4.43, \tag{4}$$

to estimate the effective temperatures and gravitational acceleration. These values for the effective temperature and gravitational acceleration allow us to construct a model atmosphere for each component using grids of Kuruz's line blanketed models (ATLAS9) (Kurucz 1994). Here we use $T_\odot = 5777$ K and $M_{\rm bol}^\odot = 4.75^{\rm m}$ in all of the calculations.

The total energy flux from a binary star is due to the net luminosity of the components a and b located at a distance d from the Earth. The total energy flux may be written as

$$F_\lambda \cdot d^2 = H_\lambda^a \cdot R_a^2 + H_\lambda^b \cdot R_b^2. \tag{5}$$

Rearranging Equation (5) gives

$$F_\lambda = (R_a/d)^2[H_\lambda^a + H_\lambda^b \cdot (R_b/R_a)^2], \tag{6}$$

where R_a and R_b are the radii of the primary and secondary components of the system in solar units respectively, H_λ^a and H_λ^b are the fluxes at the surface of the respective stars and F_λ is the flux for the entire SED of the system.

Many attempts were made to achieve the best fit (Fig. 1) between the observed flux of Al-Wardat (2002) and the total computed one using an iteration method with different sets of parameters. The best fit is found using the following set of parameters:

$$T_{\rm eff}^a = 6180 \pm 50{\rm K}, \qquad T_{\rm eff}^b = 5865 \pm 70{\rm K},$$

Table 5 Orbital Elements of the System

Parameters	This work	Hartkopf & Mason (2001)	Couteau (1996)
P (yr)	21.90188 ± 0.07339	22.18	19.7
T_0 (yr)	2010.7566 ± 0.0714	1988.64	1988.49
e	0.4599 ± 0.0087	0.474	0.43
a (arcsec)	0.1209 ± 0.0017	0.124	0.121
i (deg)	152.10 ± 2.71	147.0	139.7
ω (deg)	274.90 ± 6.06	287.0	114.2
Ω (deg)	202.50 ± 6.32	217.2	44.50
$M_a + M_b (M_\odot)$	$2.72 \pm 0.75^{*}$		
	$2.23 \pm 0.57^{**}$		
	$3.26 \pm 1.18^{***}$		

Notes: * Based on new Hipparcos trigonometric parallax ($\pi = 11.07 \pm 1.07$ mas); ** Based on the parallax estimated in this work ($\pi = 11.83$ mas); *** Based on Hipparcos trigonometric parallax ($\pi = 10.42 \pm 0.2$ mas).

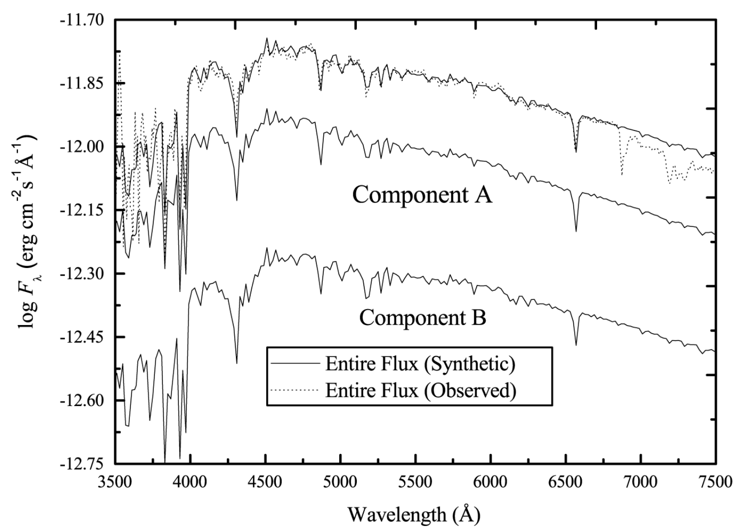

Fig. 1 Best fit between the entire observed spectrum (*dotted line*) (Al-Wardat 2002) and the entire synthetic SED (*solid line*) for the system HIP 12552 using the parameters $T_{\rm eff}^{A} = 6180 \pm 50\,{\rm K}$, $\log g_A = 4.35 \pm 0.10$, $R_A = 1.262 \pm 0.09\,R_\odot$, $T_{\rm eff}^{B} = 5865 \pm 70\,{\rm K}$, $\log g_B = 4.45 \pm 0.15$ and $R_B = 1.006 \pm 0.10\,R_\odot$ with $d = 84.53 \pm 0.009$ pc ($\pi = 11.83$ mas).

$$\log g_a = 4.35 \pm 0.12, \qquad \log g_b = 4.45 \pm 0.14,$$
$$R_a = 1.262 \pm 0.08\,R_\odot, \qquad R_b = 1.006 \pm 0.07\,R_\odot.$$

Using Equation (3), the luminosities are calculated yielding the following values: $L_a = 2.09 \pm 0.10\,L_\odot$ and $L_b = 1.08 \pm 0.12\,L_\odot$. Using tables in Gray (2005) or the $Sp{-}T_{\rm eff}$ empirical relation from Lang (1992), the spectral types of components (a, b) of the system are F8V and G1.5V respectively.

3 ORBITAL ANALYSIS

The orbit of the system is constructed using the positional measurements listed in Table 4, following Tokovinin's method (Tokovinin 1992). The modified orbital elements of the system along with those taken from the Sixth Interferometric Catalog are listed in Table 5. The table shows a good agreement between our estimated orbital period, P; eccentricity, e; semi-major axis, a; inclination, i; argument of periastron, ω; position angle of nodes, Ω; and time of primary minimum, T_0 and those previously reported.

4 MASSES

Using the estimated orbital elements, the masses of the system and the corresponding errors are calculated using the following relations:

$$M_A + M_B = \left(\frac{a^3}{\pi^3 P^2}\right) M_\odot, \tag{7}$$

$$\frac{\sigma_M}{M} = \sqrt{\left(3\frac{\sigma_\pi}{\pi}\right)^2 + \left(3\frac{\sigma_a}{a}\right)^2 + \left(2\frac{\sigma_{\rm p}}{p}\right)^2}. \tag{8}$$

The preliminary result obtained using the new Hipparcos trigonometric parallax ($\pi = 11.07 \pm 1.07$ mas) (van Leeuwen 2007) is $M_a + M_b$= $2.72 \pm 0.75\,M_\odot$, while it is $3.26 \pm 1.18\,M_\odot$ when using the Hipparcos trigonometric parallax ($\pi = 10.42 \pm 0.2$ mas, see Table 5). But depending on our analysis (Sect. 2), we achieved the best fit

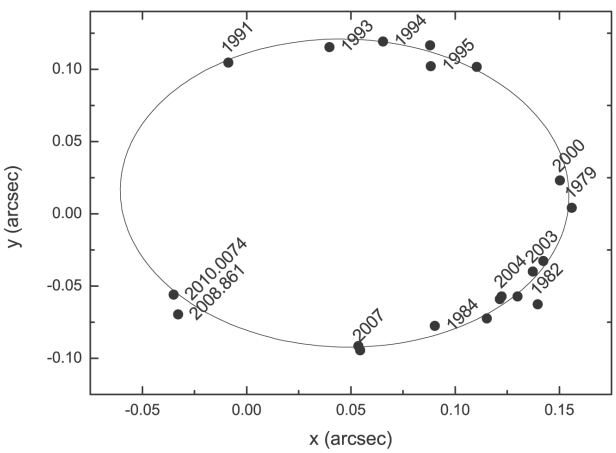

Fig. 2 Relative visual orbit of the system HIP 12552 showing the epoch of the positional measurements.

Table 6 Synthetic Magnitudes and Color Indices of the System

Sys.	Filter	Entire $\sigma = \pm 0.03$	Comp. a	Comp. b
Joh-Cou.	U	9.22	9.59	10.56
	B	9.11	9.51	10.38
	V	8.51	8.95	9.71
	R	8.18	8.64	9.36
	$U-B$	0.11	0.08	0.18
	$B-V$	0.60	0.57	0.66
	$V-R$	0.33	0.31	0.36
Ström.	u	10.38	10.76	11.70
	v	9.44	9.83	10.73
	b	8.85	9.27	10.08
	y	8.48	8.92	9.68
	$u-v$	0.94	0.93	0.97
	$v-b$	0.59	0.56	0.65
	$b-y$	0.37	0.35	0.40
Tycho	B_T	9.25	9.65	10.55
	V_T	8.58	9.01	9.79
	$B_T - V_T$	0.68	0.64	0.76

between the synthetic and observational entire SED using $\pi = 11.83$ mas. This new parallax value gives a mass sum of $M_a + M_b$= $2.23 \pm 0.57\, M_\odot$, which better fits the positions of the two components on the evolutionary tracks as shown in Figure 3.

5 SYNTHETIC PHOTOMETRY

As a double-check for the best fit and to present new synthetic photometric data of the unseen individual components of the system, we apply the following relation (Maíz Apellániz 2006, 2007)

$$m_\mathrm{p}[F_{\lambda,s}(\lambda)] = -2.5 \log \frac{\int P_p(\lambda) F_{\lambda,s}(\lambda) \lambda \mathrm{d}\lambda}{\int P_p(\lambda) F_{\lambda,r}(\lambda) \lambda \mathrm{d}\lambda} + \mathrm{ZP}_\mathrm{p}\,, \quad (9)$$

Table 7 Comparison between the Observational and Synthetic Magnitudes, Colors and Magnitude Differences of the System HIP 12552

	Observed ^{a}	Synthetic ^{b} (This work)
V_J	8.51^m	$8.51^\mathrm{m} \pm 0.03$
B_T	$9.24^\mathrm{m} \pm 0.02$	$9.25^\mathrm{m} \pm 0.03$
V_T	$8.59^\mathrm{m} \pm 0.01$	$8.58^\mathrm{m} \pm 0.03$
$(B-V)_J$	$0.60^\mathrm{m} \pm 0.02$	$0.60^\mathrm{m} \pm 0.03$
Δm	$0.76^{\mathrm{m}c} \pm 0.03$	$0.76^\mathrm{m} \pm 0.04$

Notes: ^{a} See Table 2; ^{b} See Table 6; ^{c} The average of all Δm using the different filters under the V-band (see Table 3).

Table 8 Parameters of the Components of the System HIP 12552

Parameters	Comp. a	Comp. b
T_eff (K)	6180 ± 50	5865 ± 70
Radius ($R_\odot$)	1.262 ± 0.08	1.006 ± 0.07
$\log g$	4.35 ± 0.12	4.45 ± 0.14
$L(L_\odot)$	2.09 ± 0.10	1.08 ± 0.12
M_bol	$3.95^\mathrm{m} \pm 0.18$	$4.67^\mathrm{m} \pm 0.19$
M_V	$4.07^\mathrm{m} \pm 0.18$	$4.83^\mathrm{m} \pm 0.19$
Mass ($M_\odot$)*	1.17 ± 0.11	1.06 ± 0.10
Spectral Type**	F8V	G1.5V
Parallax (mas)	11.83 ± 1.07	
$(\frac{M_a + M_b}{M_\odot})$***	2.23 ± 0.57	

Notes: * depending on the evolutionary tracks (Fig. 3); ** depending on the tables of Lang (1992); *** depending on the orbital solution.

to calculate total and individual synthetic magnitudes of the systems, where m_p is the synthetic magnitude of the passband p, $P_p(\lambda)$ is the dimensionless sensitivity function of the passband p, $F_{\lambda,s}(\lambda)$ is the synthetic SED of the object and $F_{\lambda,r}(\lambda)$ is the SED of the reference star (Vega). Here the zero points ($\mathrm{ZP_p}$) of Maíz Apellániz (2007) are adopted.

The calculated synthetic magnitudes and color indices of the entire system and individual components of different photometric systems are shown in Table 6.

6 RESULTS AND DISCUSSION

The synthetic SEDs of the individual components and the system HIP 12552 are constructed using atmospheric modeling and the visual magnitude difference between the two components along with the total observed SED. Least squares fitting with weights inversely proportional to the squares of the positional measurement errors is used to modify the orbit of the system. So, the physical and geometrical parameters of HIP 12552 are estimated.

Figure 1 shows the best fit of the total synthetic SED to the observed one.

Table 7 shows a comparison between the observational and synthetic magnitudes, colors and magnitude differences for the system HIP 12552. This gives a good indication of the reliability of the estimated parameters of the individual components of the system which are listed in Table 8.

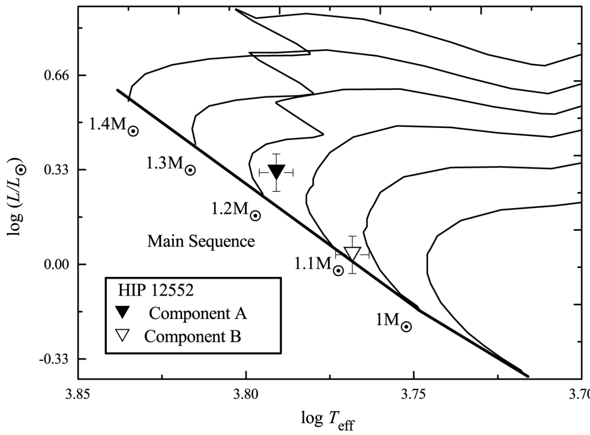

Fig. 3 The system components on the evolutionary tracks of Girardi et al. (2000b).

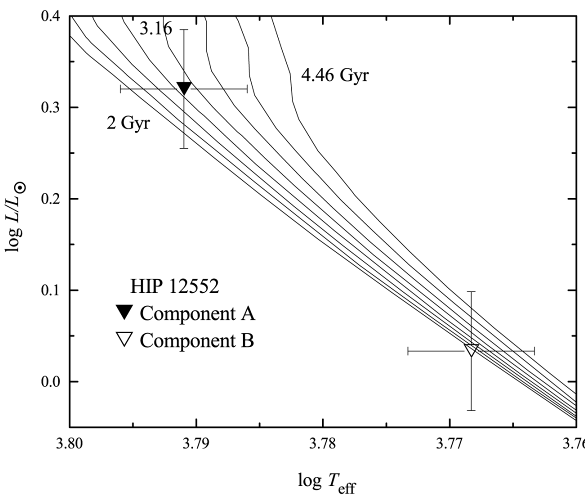

Fig. 4 Components of the system on isochrones representing low- and intermediate-mass stars with solar composition [$Z = 0.019, Y = 0.273$] from Girardi et al. (2000a).

The positions of the system's components on the evolutionary tracks of Girardi et al. (2000a) (Fig. 3) show that both components, with masses of $M_A = 1.20\, M_\odot$ and $M_B = 1.09\, M_\odot$, can be classified as main-sequence stars. Their positions on Girardi et al. (2000a) isochrones for low- and intermediate-mass stars, with a solar composition [$Z = 0.019, Y = 0.273$] and different metallicities, are shown in Figures 4 and 5 respectively, which give an age of the system around 3.0 ± 0.9 Gyr.

7 CONCLUSIONS

The CVBS Cou 1511 (HIP 12552) is analyzed using Al-Wardat's complex method for analyzing CVBSs, which is based on combining magnitude difference measurements from speckle interferometry, an entire SED from spectrophotometry, atmospheric modeling and orbital analysis to estimate the individual physical and geometrical parameters of the system.

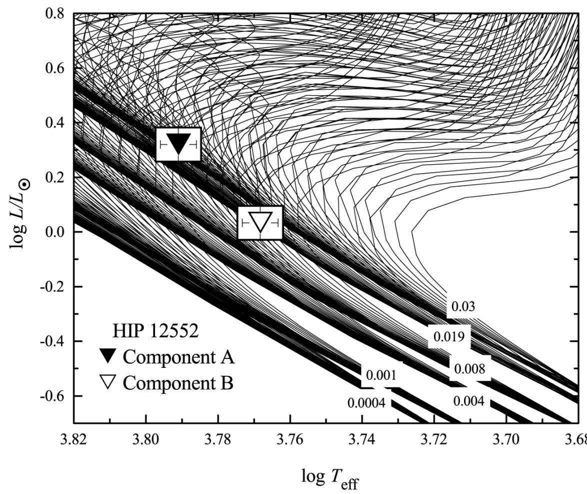

Fig. 5 Components of the system on isochrones representing low- and intermediate-mass stars with different metallicities from Girardi et al. (2000a).

The entire and individual Johnson-Cousin $UBVR$, Strömgren $uvby$ and Tycho BV synthetic magnitudes and color indices of the system are calculated. A modified orbit and geometrical elements of the system are introduced and compared with earlier results.

The positions of the two components on their evolutionary tracks and isochrones are shown. Their spectral types are estimated as F8V and G1.5V respectively with an age of 3.0 ± 0.9 Gyr.

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