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Modified Masses and Parallaxes of the Close Visual Triple System HD 2893

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Abstract

We present the essential stellar parameters of the close visual triple system HD 2893 using Al-Wardat's method for analyzing binary and multiple star systems in conjunction with Kurucz's model atmospheres. This method accurately computes the spectrophotometric stellar masses through a combined synthetic spectral energy distribution approach that compares the results with observed data. The vigorous approach uses spectroscopic, photometric, and dynamical analysis to yield precise results. The method implements Gaia DR3 measurements and other measurements like those of Hipparcos and 2MASS All-Sky Catalog as a guide for the best fit between the synthetic spectra and observed photometry. The analysis gives precise spectrophotometric stellar masses for the system being $\mathcal{M}^{A}_{\rm Sph} = 1.20 \pm 0.07\,\mathcal{M}_{\odot}$, $\mathcal{M}^{B}_{\rm Sph} = 1.09 \pm 0.06\,\mathcal{M}_{\odot}$, and $\mathcal{M}^{C}_{\rm Sph} = 0.46 \pm 0.01\,\mathcal{M}_{\odot}$. It shows that the three components are main sequence stars with an estimated age of around 1.0 Gyr. When integrated with the dynamical analysis, a new dynamical parallax for the system is obtained, $\pi_{\rm dyn} = 13.8528 \pm 0.20$ mas. Additionally, the discussion covers the formation and evolution of the triple system.

Key words: (stars:) binaries (including multiple): close – stars: fundamental parameters – stars: individual (HD 2893)

1. Introduction

Stellar systems represent a milestone in the history of astrophysics and in understanding our Galaxy. The stars in our Galaxy are classified as singles, binaries, triples, and higher-order hierarchies. Triple systems with F- & G-spectral type stars, which are the hierarchical stellar systems, make up 10% (Toonen et al. 2020) of the stellar systems in our Galaxy, while binary systems make up 50% of them. That is why the formation and evolution of single and binary systems have been widely studied (Lund & Bonnell 2018; Echeveste et al. 2020; Luna et al. 2020; Kummer et al. 2023) and it is understood that their dynamics are not like those of triple systems (Toonen et al. 2020). Understanding the dynamics of the hierarchical stellar systems with three or more components is critical for understanding the formation processes and their evolution (Batten 1973).

The Multiple Star Catalog (also referred to as MSC), which includes roughly 10,000 hierarchical stellar systems within 100 parsecs (Tokovinin 2023), can be used as a reference and an indicator of the results of the synthetic analysis for the multiple systems. The MSC is the primary source of crucial information about the hierarchical stellar systems with three or more components (Tokovinin 2018b). It offers vital information, including the stellar masses of each system component. However, Tokovinin (2018b) pointed out that the stellar masses derived from the absolute magnitudes of the main sequence components with the aid of evolutionary tracks are more reliable than those derived from the spectral types. Because of this, studying the hierarchical star systems is a very challenging task that calls for a variety of analysis and observational methods as well as a combination of binaries (Tokovinin 2021).

It is well known that the study and analysis of binary and multiple systems are essential for determining fundamental stellar parameters, especially stellar masses. They also play a crucial role in refining and testing evolutionary models, which help investigate theories regarding the formation and evolution of stars (Duquennoy & Mayor 1992; Tokovinin et al. 2016).

Estimating the spectroscopic and dynamical masses of binary and multiple systems is primarily dependent on stellar evolutionary models as well as trigonometric parallaxes. The fundamental stellar characteristics and inclination, which are extracted from synthetic analysis and visual orbits, are among the many aspects that must be taken into account while estimating their masses (Novaković 2007).

Despite the accuracy of the trigonometric parallaxes relating to Gaia, several authors have provided new trigonometric parallaxes for some stellar systems, unlike those observed by Hipparcos and Gaia (Cvetković et al. 2014; Taani et al. 2020; Hussein et al. 2022; Mardini et al. 2022, 2024; Masda &

Al-Wardat 2023; Masda et al. 2023; Placco et al. 2023; Masda 2024). Most of them have relied on the spectro-photometric analysis or the spectral types to determine the stellar masses and the orbital solution to estimate precise orbital parameters.

The stellar parameters of systems (e.g., binary, triple, and hierarchical stellar systems) are derived using Al-Wardat's complex method for analyzing binary and multiple star systems (Al-Wardat 2002, 2003, 2007) following the stages of observation and data reduction processes. In this method, the main key to constructing the synthetic spectral energy distributions (SEDs) is the observed parameters. These include the combined visual magnitudes and the results of astrometry and speckle interferometry. To build the individual SEDs and combine the results to obtain the combined synthetic SED and synthetic photometry of a binary or triple system, the method makes use of Kurucz's models (Kurucz 1994). The stellar parameters of the close binary and multiple systems, including giant, subgiant and supergiant stars as well as the triple and quadruple systems, are determined by utilizing Al-Wardat's complex method when achieving the best agreement between the synthetic and observed data (whether they are observed SEDs or photometry) (Al-Wardat 2012, 2014; Al-Wardat et al. 2014, 2014a, 2014b, 2016, 2017; Masda et al. 2016, 2018a,2018b, 2019a, 2019b, 2021; Yousef et al. 2021; Hussein et al. 2024; Masda 2024).

A lot of the orbital solutions of visual binaries, including our system HIP 2532 (HD 2893), have been published in the Sixth Catalog of Orbits of Visual Binary Stars (also known as ORB6). This catalog includes about 3655 orbits of visual binaries, some of which have two or more orbital solutions because of some discovered measurements. For these solutions, the orbits have been graded on a 1–5 scale for each published solution (1 is definitive, 2 is good, 3 is reliable, 4 is preliminary, and 5 is indeterminate) (Hartkopf et al. 2001; Malkov et al. 2012; Cvetković et al. 2014). When further speckle observations of the system become available, orbits need to be revised. Here, we use Tokovinin's method, which combines the positional parameters to estimate the orbital parameters of the system (Tokovinin 1992).

In our previous papers (e.g., Masda et al. 2023; Masda 2024), we used speckle interferometry observations such as separation angle ρ, position angle θ, and magnitude differences $\triangle m$ between system components to analyze the close binary systems and provide their fundamental properties. In this scenario, we analyze a hierarchical stellar system, the triple system HD 2893, and if needed we will provide improved parallax and stellar masses for the triple system. In this system, the designations of the triple systems are very important as shown in Figure 1. In this figure, there are subsystems and individual stars. The subsystems of the triple system are AB, C, and AB, while the individual stars of the system are A, B, and C.

The goal of this work is to determine the fundamental stellar parameters and refine the stellar masses and trigonometrical parallaxes of system HD 2893. It is the first in a series about modified masses and parallaxes of triple systems. Primary information about the triple system is contained in Table 1 which includes the magnitudes and color indices of the system from the Hipparcos and Tycho Catalogues (ESA 1997), Strömgren (Hauck & Mermilliod 1998), Two Micron All Sky Survey (2MASS; Cutri et al. 2003), the Tycho-2 Catalogue (Høg et al. 2000), and Gaia (Gaia Collaboration 2022). Table 2 provides the positional parameters, including the magnitude differences between the system's components (which were taken from the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2001) and the MSC) (Tokovinin 2018b).

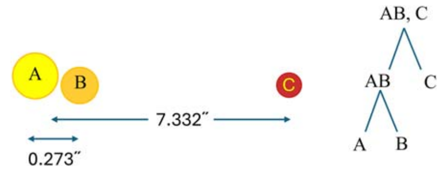

Figure 1. Composition of the triple system HD 2893 (HIP 2532) showing the separations and individual stars.

Table 1
Positions, Primary Information, and Observed Photometric Data of System HD 2893

HD 2893, HIP 2532		
Parameter	Value	Reference
R.A. (J2000)	$00^h32^m07^s\!.071$	Gaia Collaboration (2022)
Decl. (J2000)	$-21°17'42''\!.290$	Gaia Collaboration (2022)
π_{H97} (mas)	13.78 ± 1.06	ESA (1997)
π_{H07} (mas)	14.47 ± 0.84	van Leeuwen (1997)
π_{DR3} (mas)	13.28	Gaia Collaboration et al. (2021), Brown et al. (2021)
Spectral type	G1V	Houk & Smith-Moore (1988), ESA (1997)
Gaia DR3	2423653107445310720	Gaia Collaboration (2022)
Photometry		
V_J (mag)	8.27	ESA (1997)
$(B-V)_J$ (mag)	0.58 ± 0.015	ESA (1997)
$(V-I)_J$ (mag)	0.65 ± 0.010	ESA (1997)
Tycho-2 B mag, B_T	9.01 ± 0.015	Høg et al. (2000)
Tycho-2 V mag, V_T	8.35 ± 0.013	Høg et al. (2000)
2MASS J mag, J	7.22 ± 0.027	Cutri et al. (2003)
2MASS H mag, H	6.88 ± 0.029	Cutri et al. (2003)
Gaia B_P mag, B_P	8.45	Gaia Collaboration (2022)
Gaia R_P mag, R_P	7.71	Gaia Collaboration (2022)
Gaia G mag, G	8.73	Gaia Collaboration (2022)

Table 2
Positional Parameters and the Observed Magnitude Differences of HD 2893

HD HIP	Data epoch	$\theta \pm \sigma_\theta$ (deg)	$\rho \pm \sigma_\rho$ (")	$\triangle m \pm \sigma_{\triangle m}$ (mag)	Filter $\lambda/\Delta\lambda$ (nm)	Reference
2893	1991.25	23.	0.148	0.49 ± 0.027	511/22	Turon (1997)
2532	1999.8855	…	…	0.39 ± 0.15	648/41	Horch et al. (2004)
	1999.8855	352.3	0.252	0.0	648/41	Horch et al. (2002)
	2000.7591	…	…	0.49 ± 0.15	648/41	Horch et al. (2004)
	2000.7591	348.1	0.261	0.0	648/41	Horch et al. (2002)
	2003.5386	340.4	0.279	0.67	550/40	Horch et al. (2008)
	2003.5386	337.8	0.284	0.36	754/44	Horch et al. (2008)
	2004.8342	153.7 ± 0.4	0.292 ± 0.002	0.41 ± 0.10	545/30	Balega et al. (2007)
	2006.5257	148.1	0.314	0.62	550/40	Horch et al. (2008)
	2007.8256	324.7	0.314	0.52	550/40	Horch et al. (2010)
	2008.6938	320.8	0.308	0.77	692 40	Horch et al. (2009)
	2010.7171	315.81	0.3179	0.22	692/40	Horch et al. (2017)
	2010.7171	315.9	0.3185	0.34	880 /50	Horch et al. (2017)
	2011.6892	312.9	0.3187	0.45	692 /40	Horch et al. (2017)
	2011.6892	312.9	0.3182	0.6	0.36	Horch et al. (2017)
	2011.9432	311.7	0.3174	0.33	692/40	Horch et al. (2017)
	2011.9432	311.8	0.3161	0.53	562/40	Horch et al. (2017)
	2014.7632	305.2 ± 0.1	0.3140 ± 0.0002	0.3	788/132	Tokovinin et al. (2015)
	2018.5620	293.2 ± 0.1	0.2886 ± 0.0001	0.2	788/132	Tokovinin et al. (2019b)
	2019.9523	288.1 ± 0.1	0.2753 ± 0.0001	0.2	788/132	Tokovinin et al. (2020)
	2021.5657	281.9 ± 0.2	0.2540 ± 0.0002	0.0	788/132	Tokovinin et al. (2022)

2. Method and Analysis

Most previous publications focused on the synthetic analysis of binary systems, using Al-Wardat's method, and the dynamical analysis, using Tokovinin's method. Here, we employ the same methods to approach the spectrophotometric and dynamical analysis of the close triple system. These analyses are spectroscopic, photometric, and orbital.

2.1. Spectrophotometric Analysis

The spectrophotometric analysis of binary and multiple systems is subject to two analyses: spectroscopic and photometric analyses. The former represents the individual and combined synthetic SED of the binary and multiple systems based on precise stellar parameters, and the latter represents the individual and combined magnitudes and color indices of the binary and multiple systems based on the results of the spectroscopic analysis.

To implement the first analysis on our system, we must first estimate the input parameter of the triple system (AB, C components) to get the synthetic SED. This includes two observed parameters which are combined visual magnitude (total visual magnitude) and magnitude differences between the components. This means that the magnitude difference occurs between the binary system (A and B) and then between the binary and single system (AB and C). The combined visual magnitude of the triple system is $V_J^{\mathrm{A+B+C}} = 8\overset{\mathrm{m}}{.}27$. Since there are measurements from the fourth catalog of the binary system A and B, which is the primary component of the triple system, the magnitude difference is $\Delta m_{\mathrm{A,B}} = 0\overset{\mathrm{m}}{.}54 \pm 0.02$. This value is the average value given in Table 2 under the speckle V-band filters 543–551 nm of the system. The magnitude difference between AB and C of the triple system is $\Delta m_{\mathrm{AB,C}} = 6\overset{\mathrm{m}}{.}73$ based on the apparent magnitude of the component C, which is given as $m_v^{\mathrm{C}} = 15\overset{\mathrm{m}}{.}00$ from Tokovinin (2018b). To calculate the apparent magnitudes of the binary system as the primary component of the triple system, we use the following equations (Heintz 1978):

$$m_v^i = m_v^{i,j} + 2.51 + 10^{-0.4\triangle m_{i,j}}), \tag{1}$$

$$m_v^j = m_v^i + \triangle m_{i,j}, \tag{2}$$

where i and j indicate the components of the system. The absolute magnitudes of the triple system can be calculated using the following equation

$$M_V^i = m_v^i + 5 - 5\log(d) - A_V. \tag{3}$$

Here, d represents the distance of the system from the Earth in pc, and A_V represents the visual extinction, which is set to zero because of the triple system being very nearby (Chontos et al. 2021). Thus, these magnitudes, as well as the tables from Lang (1992) and Gray (2005), allow us to estimate the input parameters of the close triple system based on the following two equations

$$\log\frac{R}{R_\odot} = \frac{M_{bol}^{\odot} - M_{bol}}{5} - 2\log\frac{T_{\mathrm{eff}}}{T_\odot}, \tag{4}$$

$$\log g = \log \frac{\mathcal{M}}{\mathcal{M}_\odot} - 2\log \frac{R}{R_\odot} + \log g_\odot. \quad (5)$$

In these equations, we use $T_\odot = 5777$ K, $M_{\rm bol}^\odot = 4^{\rm m}.75$ and log $g_\odot = 4.44$, and M_{bol} indicates the bolometric magnitude. For nearby stars, the uncertainty in the final effective temperatures ($T_{\rm eff.}$), which are based on the best combined synthetic SED, is approximately 100 K, while the uncertainties in the gravitational accelerations (log g) and radii (R) are estimated based on the following equations

$$\sigma_R \approx \pm R\sqrt{\left(\frac{\sigma_L}{2L}\right)^2 + 4\left(\frac{\sigma_{T_{\rm eff}}}{T_{\rm eff}}\right)^2}, \quad (6)$$

$$\sigma_{\log g} \approx \pm\sqrt{\left(\frac{\sigma_{\mathcal{M}}}{\mathcal{M}}\right)^2 + 4\left(\frac{\sigma_R}{R}\right)^2}. \quad (7)$$

Next, we implement Al-Wardat's complex method for analyzing binary and multiple systems to create the combined synthetic SED of the triple system. Kurucz's models (Kurucz 1994) are used to construct the individual synthetic SED for three components of the system. In general, the combined synthetic SED of the multiple system at a distance in parsecs from Earth, which is related to the components of the system, is estimated based on the following equation

$$F_{\lambda,s} = \frac{1}{d^2}\left(\sum_i H_\lambda^i \cdot R_i^2\right). \quad (8)$$

The combined synthetic SED of the triple system is estimated as follows

$$F_{\lambda,s} = \left(\frac{R_{\rm A}}{d}\right)^2\left(H_\lambda^{\rm A} + H_\lambda^{\rm B}\left(\frac{R_{\rm B}}{R_{\rm A}}\right)^2 + H_\lambda^{\rm C}\left(\frac{R_{\rm C}}{R_{\rm A}}\right)^2\right), \quad (9)$$

where $H_\lambda^{\rm A}$, $H_\lambda^{\rm B}$, and $H_\lambda^{\rm C}$ are the fluxes of the three components of the triple system, respectively, and $R_{\rm A}$, $R_{\rm B}$, and $R_{\rm C}$ are the radii of the three components in solar units. The result of Equation (9), which is the synthetic SED, is the main reference to obtain the synthetic photometry.

The second analysis is synthetic photometry, i.e., V_J, $B-V$, Δm, etc., which is the individual and combined synthetic magnitudes and color indices of the system. This is used to ensure precise atmospheric parameters including $T_{\rm eff.}$, log g, and R when obtaining the best agreement between the synthetic and observed photometry.

The synthetic magnitudes and color indices of the individual components and combined system are calculated by integrating the model fluxes over each bandpass of the system calibrated to the reference star (Vega) as follows (Al-Wardat 2002)

$$m_p[F_{\lambda,s}(\lambda)] = -2.5\log\frac{\int P_p(\lambda)F_{\lambda,s}(\lambda)\lambda d\lambda}{\int P_p(\lambda)F_{\lambda,r}(\lambda)\lambda d\lambda} + {\rm ZP}_p, \quad (10)$$

where the synthetic magnitude of the passband p is denoted by m_p. The dimensionless sensitivity function of the passband p is $P_p(\lambda)$. The synthetic SED of the object is $F_{\lambda,s}(\lambda)$ and Vega's SED is $F_{\lambda,r}(\lambda)$. The zero-points (ZP$_p$) were obtained from Maìz Apellániz (2007).

The results of the synthetic photometric analysis should be well consistent with the observed ones in three photometrical filters: Johnson-Cousins: U, B, V, R, I, $U-B$, $B-V$, $V-R$, $V-I$; Strömgren: u, v, b, y, $u-v$, $v-b$, $b-y$ and Tycho: B_T, V_T, B_T-V_T as well as other filters such as Gaia's filters (Gaia Collaboration 2022) and 2MASS's filters (Cutri et al. 2003). In addition, the synthetic magnitude difference between the components of the system should be in good agreement with the observed one to obtain the best radii of the individual components.

2.2. Dynamical Analysis

In the dynamical analysis, we should estimate the new orbital solution of the system because of the new speckle interferometric measurements, thereby estimating the dynamical stellar masses of the systems. To estimate the orbital solution of the system, Tokovinin's method should be applied (Tokovinin 1992). The method is used for deriving the ultimate orbital solutions of the visual binary and multiple systems (Tokovinin 2016, 2017, 2018a; Tokovinin et al. 2019a; Vrijmoet et al. 2022). Consequently, the orbital parameters and their associated uncertainties are computed using a least-squares fitting method within the IDL platform.

The new modifications of the orbits are based on the grades of the orbits and the new relative positional measurements provided in the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2001) and the MSC (Tokovinin 2018b).

It is noteworthy that the orbit of the triple system HD 2893 has been previously published by Cvetković (2013) and Cvetković et al. (2014), but it requires a revision in light of the new positional parameters presented in the MSC (Tokovinin 2018b). Enhancing these orbits will improve the dynamical stellar mass of the system as well as root mean square (rms) of the visual binary systems, resulting in more precise orbital parameters, whereby determining accurate dynamical stellar masses.

The dynamical stellar masses of a binary system require solving its orbit, thereby determining the orbital parameters. The dynamical stellar masses of the binary systems are estimated based on Kepler's Third Law represented by the following equation

$$\mathcal{M}_d = \mathcal{M}_{\rm A} + \mathcal{M}_{\rm B} = \left(\frac{a^3}{\pi^3 P^2}\right) \mathcal{M}_\odot, \quad (11)$$

while the dynamical stellar masses of the triple systems are estimated based on Kepler's Third Law represented by the following equation

$$\mathcal{M}_d = \mathcal{M}_\mathrm{A} + \mathcal{M}_\mathrm{B} + \mathcal{M}_\mathrm{C} = \left(\frac{a^3}{\pi^3 P^2}\right) \mathcal{M}_\odot, \quad (12)$$

where $\mathcal{M}_\mathrm{A}$, $\mathcal{M}_\mathrm{B}$ and $\mathcal{M}_\mathrm{C}$ indicate the stellar masses of the three components of the system, respectively, while a and P indicate the semimajor axis in arcsec and the orbital period in years, respectively.

In general, the error for the total dynamical stellar mass is calculated by using the following equation

$$\frac{\sigma_{\mathcal{M}_d}}{\mathcal{M}_d} = \sqrt{9\left(\frac{\sigma_\pi}{\pi}\right)^2 + 9\left(\frac{\sigma_a}{a}\right)^2 + 4\left(\frac{\sigma_P}{p}\right)^2}. \quad (13)$$

Based on the orbital solution, along with the parallax measurements, we can calculate the total dynamical mass of the systems. The best agreement between the total dynamical stellar mass and the spectrophotometric stellar masses indicates the reliability of the orbital parameters, the trigonometric parallaxes, and spectral types of the system. In cases of poor agreement, the dynamical parallaxes of the systems based on the spectrophotometric stellar masses derived by Al-Wardat's method will be calculated as follows

$$\pi_\mathrm{dyn} = \frac{a}{P^{2/3}\left(\sum\mathcal{M}_\mathrm{Sph}\right)^{1/3}}, \quad (14)$$

where $\sum\mathcal{M}_\mathrm{Sph}$ indicates the spectrophotometric masses in solar mass and π_dyn indicates the dynamical parallaxes in arcsec. The error of the dynamical parallaxes is determined as follows

$$\frac{\sigma_{\pi_\mathrm{dyn}}}{\pi_\mathrm{dyn}} = \sqrt{\frac{4}{9}\left(\frac{\sigma_P}{P}\right)^2 + \left(\frac{\sigma_a}{a}\right)^2 + \frac{1}{9}\left(\frac{\sigma_{\sum\mathcal{M}_\mathrm{Sph}}}{\sum\mathcal{M}_\mathrm{Sph}}\right)^2}. \quad (15)$$

3. Results

We have calculated the fundamental stellar and orbital parameters of the close triple system HD 2893 based on the spectrophotometric and dynamical analyses. The fundamental stellar parameters of the close triple system are derived using Al-Wardat's method for binary and multiple systems while the orbital parameters are derived using Tokovinin's method for visual binaries. The combination of the analyses led to the best agreement between the synthetic and observed data, the modified stellar masses, and the new dynamical parallax of the close triple system HD 2893.

The results of the synthetic SED of the close triple system HD 2893 have been presented as the synthetic magnitudes and color indices of three individual components as well as the combined system. The final synthetic magnitudes and color indices of the triple system HD 2893 for the combined and three components are listed in Table 3 based on three photometrical systems: Johnson-Cousins: U, B, V, R, I, $U-B$, $B-V$, $V-R$, $V-I$; Strömgren: u, v, b, y, $u-v$, $v-b$, $b-y$ and Tycho: B_T, V_T, B_T-V_T.

To ensure the accuracy of the stellar parameters, the best agreement between the combined synthetic and observed photometry of the triple system should be achieved, as listed in Table 4. As shown in this table, the best agreement between the synthetic and observed magnitudes and color indices indicates the reliability of the fundamental stellar parameters and the spectrophotometric stellar masses as well as the accuracy of the method used in the analysis.

Table 3
The Determined Synthetic Magnitudes and Color Indices of the HD 2893 Triple System

Sys.	Filter	Combined Synthetic $\sigma = \pm0.03$	A	B	C
Johnson-Cousins	U	8.96	9.36	10.26	17.60
	B	8.87	9.30	10.10	16.49
	V	8.29	8.75	9.44	15.00
	R	7.96	8.44	9.09	14.06
	I	7.65	8.15	8.76	13.14
	$U-B$	0.09	0.06	0.16	1.11
	$B-V$	0.59	0.55	0.65	1.49
	$V-R$	0.32	0.30	0.35	0.94
	$V-I$	0.63	0.60	0.69	1.86
Strömgren	u	10.12	10.52	11.41	19.10
	v	9.19	9.60	10.45	17.22
	b	8.62	9.06	9.81	16.05
	y	8.26	8.72	9.41	14.99
	$u-v$	0.94	0.91	0.96	1.87
	$v-b$	0.57	0.54	0.64	1.17
	$b-y$	0.36	0.34	0.39	1.06
Tycho	B_T	9.01	9.43	10.26	16.81
	V_T	8.35	8.81	9.52	15.21
	B_T-V_T	0.66	0.61	9.52	1.60

Table 4
The Best Agreement between the Observed and Synthetic Photometry of the HD 2893 Triple System

Filter	HD 2893	
	Combined Observed[a] Table 1	Combined Synthetic (This Work) Table 3
V_J	8.27	8.29 ± 0.03
B_J	8.85 ± 0.01	8.87 ± 0.03
$(B-V)_J$	0.58 ± 0.02	0.59 ± 0.03
$(V-I)_J$	0.65 ± 0.01	0.63 ± 0.03
B_T	9.01 ± 0.02	9.01 ± 0.03
V_T	8.35 ± 0.01	8.35 ± 0.03
$\triangle m$	0.54 ± 0.02	0.54 ± 0.06

Table 5
The Fundamental Stellar Parameters of the HD 2893 Triple System as well as the New Dynamical Parallax of the System

Parameter	Units	HD 2893		
		A	B	C
$T_{\rm eff.}$	[K]	6250 ± 100	5900 ± 100	3900 ± 100
R	[$R_\odot$]	1.20 ± 0.05	1.00 ± 0.05	0.42 ± 0.02
log g	[cgs]	4.30 ± 0.10	4.40 ± 0.11	4.70 ± 0.10
$M_{\rm V}$	[mag]	4.41 ± 0.09	4.95 ± 0.10	10.62 ± 0.11
L	[$L_\odot$]	1.97 ± 0.10	1.09 ± 0.09	0.04 ± 0.001
$\mathcal{M}$	[$\mathcal{M}_\odot$]	1.20 ± 0.07	1.09 ± 0.06	0.46 ± 0.01
Sp. Type		F7.5V	G1.5V	M5V
$\pi_{\rm dyn}$	[mas]		13.8528 ± 0.20	

Based on the results of Table 3 and the best agreement between the data in Table 4, Table 5 lists the best fundamental stellar parameters of the three components of the system.

According to those parameters in Table 5, the combined and individual synthetic SED for the three components of the system are displayed in Figure 2. On the other hand, the combined observational magnitudes of the triple system are positioned on the combined synthetic flux, which indicates the best agreement between the observed and synthetic SED of the system in the case of the available observed SED of the system HD 2893. In addition, the observed magnitudes of Gaia are consistent with the synthetic SED of the system, as affirmed in Figure 2.

Figure 3 depicts the evolutionary tracks of Girardi et al. (2000b) and isochrone tracks of Girardi et al. (2000a). The evolutionary tracks are used to estimate the spectrophotometric stellar masses of three individual components of the triple system, while the isochrone tracks are used to estimate the age and metallicity of the triple system. Both tracks are based on the best two stellar parameters, such as the effective temperature ($T_{\rm eff.}$) and luminosity (L). Based on the positions of the components of three components on the Hertzsprung–Russell (H–R) diagram, all components belong to the main sequence star group, as shown in Figure 3. Additionally, we have determined the spectrophotometric stellar masses to be: $\mathcal{M}^{\rm A}_{\rm Sph} = 1.20 \pm 0.07\ \mathcal{M}_\odot$, $\mathcal{M}^{\rm B}_{\rm Sph} = 1.09 \pm 0.06\ \mathcal{M}_\odot$, and $\mathcal{M}^{\rm C}_{\rm Sph} = 0.46 \pm 0.01\ \mathcal{M}_\odot$ for the three components.

Figure 3 also shows the age of the system. The positions of the three components indicate that the system is aged at 1.0 Gyr based on the isochrone tracks of Girardi et al. (2000a) for low- and intermediate-mass stars of different metallicities and solar compositions. The helium and metal mass fractions of the system are estimated as: $Z = 0.019$ and $Y = 0.27$, respectively. From the positions of the three components on the H–R diagram in Figure 3, it is evident that the system is metal-rich.

In the dynamical analysis, Table 6 shows the orbital solution of the primary component (the binary system) of the triple system HD 2893 compared with the previous solutions of the system. We found three new measurements of the speckle interferometry, which led us to the best orbits and grades of the primary component of the system. The dynamical stellar mass of the triple system is determined as $3.12 \pm 0.11\ \mathcal{M}_\odot$ based on Gaia DR3's parallax and $2.41 \pm 0.50\ \mathcal{M}_\odot$ based on H07's parallax. Under the best orbital parameters of the system, Figure 4 shows the best orbit of the binary system (A and B) with a good rms of the system.

4. Discussion of Individual System

4.1. HD 2893 = HIP 2532 = HDS 71

Cvetković (2013) and Cvetković et al. (2014) classified the system as binary. However, according to the MSC (Tokovinin 2018b, 2023), the studied system is the triple system with three components (A, B and C) as shown in Figure 1. It is a close triple system with Gaia's distance of 13.28 mas, which is estimated as 75.30 pc.

Relying on the apparent magnitudes and Gaia DR3's trigonometric parallax of the system, the absolute magnitudes of three components of the system are: $M^{\rm A}_{\rm V} = 4\overset{\rm m}{.}41 \pm 0.09$, $M^{\rm B}_{\rm V} = 4\overset{\rm m}{.}95 \pm 0.10$ and $M^{\rm C}_{\rm V} = 10\overset{\rm m}{.}62 \pm 0.11$ for the primary component (the binary system A and B) and secondary component, respectively. In the synthetic analysis of the system as a triple system, we obtained the best stellar parameters of the triple system as listed in Table 5.

According to the stellar parameters listed in Table 5, the spectral types of the three components are F7.5V, G1.5V, and M5V, respectively, while the luminosities of the individual components are $L_{\rm A} = 1.97 \pm 0.10\,L_\odot$, $L_{\rm B} = 1.09 \pm 0.09\,L_\odot$ and $L_{\rm C} = 0.04 \pm 0.001\,L_\odot$. We can see that our spectral types are in line with those of SIMBAD and WDS. Cvetković et al. (2014) classified the system as a binary system. Consequently, the spectral types of the components were estimated as G2 and G5, which were almost in line with our spectral types of the primary component (the binary system) of the triple system.

Since the system is a binary system as mentioned by Cvetković et al. (2014), the stellar masses of the binary system (the primary component of the triple system) were estimated to be $\mathcal{M}^{\rm A} = 1.1\mathcal{M}_\odot$ and $\mathcal{M}^{\rm B} = 1.05\mathcal{M}_\odot$ for the primary and secondary components, respectively. But, Tokovinin (2023) revealed that the system was classified as a triple system and the stellar masses of the primary component (two components) were estimated as $\mathcal{M}^{\rm AB} = 2.03\mathcal{M}_\odot$, while the secondary component was estimated as $\mathcal{M}^{\rm C} = 0.45\mathcal{M}_\odot$, based on the spectral types of the triple system. In our analysis, we characterize the system as a triple system. As a result, Tokovinin (2023)'s stellar masses were not in line with our results from the evolutionary tracks.

The first orbit of the primary component of the triple system was derived by Cvetković (2013). In the calculation of this

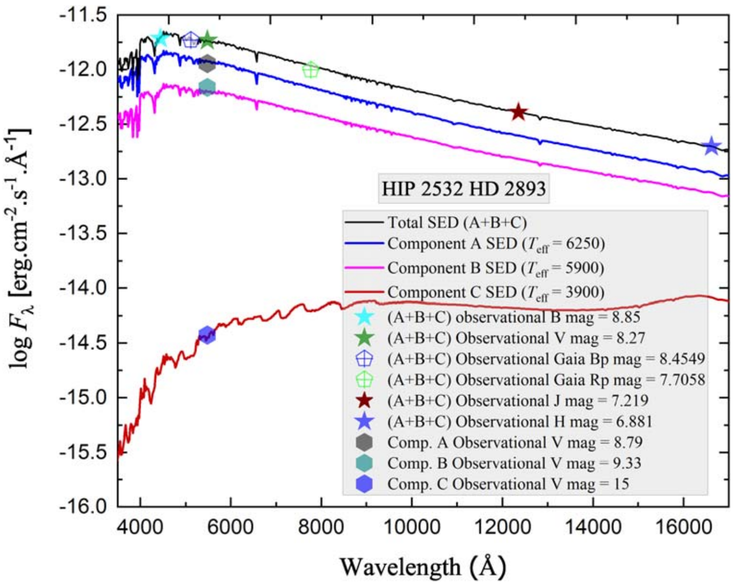

Figure 2. The combined synthetic SED and its individual components of HD 2893 as well as the observed magnitudes of the system.

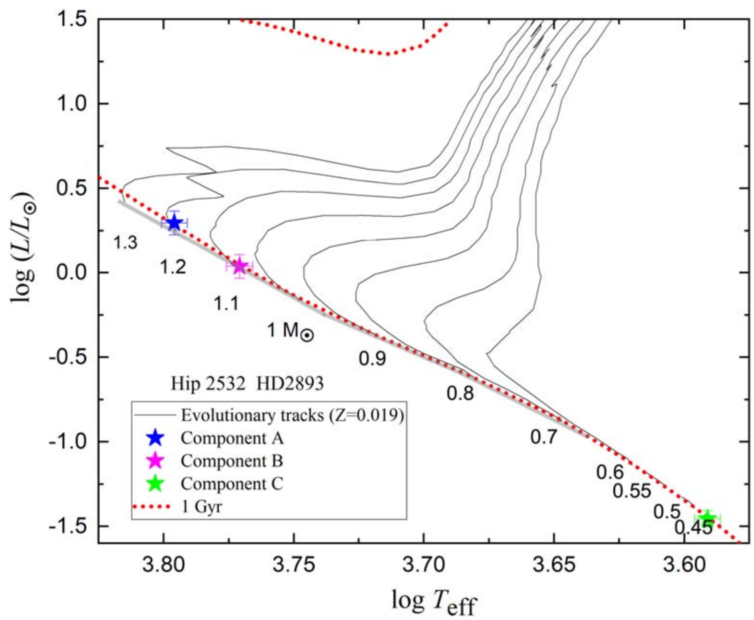

Figure 3. The synthetic evolutionary tracks of Girardi et al. (2000b) and isochrone tracks of Girardi et al. (2000a) for the three components of the HD 2893 system on the H–R diagram.

orbit, the dynamical stellar masses were estimated to be $\mathcal{M} = 4.97 \pm 1.08\mathcal{M}_\odot$ based on the HIP97's measurements and $\mathcal{M} = 4.30 \pm 0.09\mathcal{M}_\odot$ based on the H07's measurements. These are both approximately double the value expected from our evolutionary tracks of the primary component of the triple system. So, we see that the problem is in the parallax of the system.

The second orbit of the primary component of the triple system was derived by Cvetković et al. (2014). In the calculation of this orbit, the dynamical stellar masses of the primary component are estimated as $\mathcal{M} = 2.16 \pm 0.50\mathcal{M}_\odot$ based on the HIP97's measurements and $\mathcal{M} = 1.86 \pm 0.15\mathcal{M}_\odot$ based on the H07's measurements. Cvetković et al. (2014) claimed that the expected stellar mass should be $\mathcal{M} = 2.16\mathcal{M}_\odot$ from the spectroscopy for the primary component of the triple system. In that case, our results for the primary component of the triple system are $\mathcal{M}_{\mathrm{Sph}} = 2.29\mathcal{M}_\odot$, which are almost consistent with those of the spectroscopy of the binary system. Our result of the

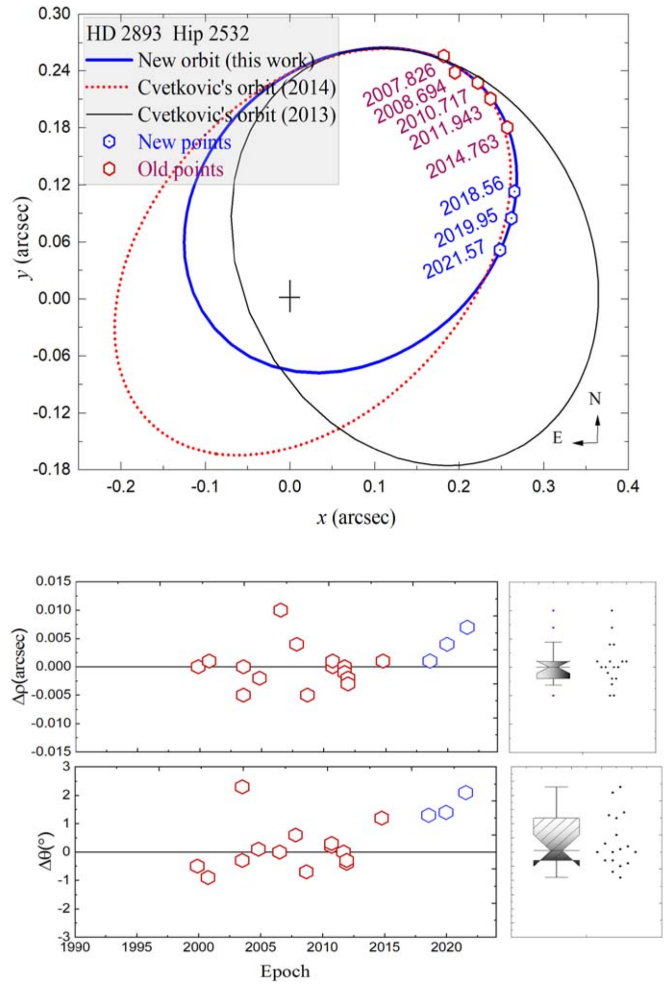

Figure 4. New and old orbits of the HD 2893 system. The positional parameters of the system are represented by filled circles and the new points are represented by blue circles.

Table 6
Orbital Parameters of the HD 2893 Triple System and the Last Published Orbital Solutions

	HD 2893	
Param.	Cvetković et al. (2014)	This Work
P [yr]	57.943 ± 1.966	40.796 ± 0.49
T_0 [yr]	2034.432 ± 0.950	2028.755 ± 0.247
e	0.233 ± 0.096	0.604 ± 0.006
a [arcs]	0.2666 ± 0.0038	0.230 ± 0.001
i [deg]	132.3 ± 7.9	141.21 ± 0.19
Ω [deg]	126.6 ± 9.7	90.91 ± 0.51
ω [deg]	325.3 ± 21.0	301.70 ± 0.42
rms (θ) [°]	…	0.71
rms (ρ) [″]	…	0.003

primary and secondary components of the triple system is estimated as $\mathcal{M}_{\rm Sph} = 2.75\mathcal{M}_\odot$ based on Al-Wardat's method, while the stellar masses of the triple system from the MSC were estimated as $\mathcal{M} = 2.48\mathcal{M}_\odot$ (Tokovinin 2018b). The results of Tokovinin (2018b) relied on the spectral types, while our results relied on the evolutionary tracks, which are more precise than those obtained by the spectral types.

Based on previous studies of the system, we can see that the parallax should be improved based on precise spectrophotometric masses. As a result, Cvetković et al. (2014) estimated the new dynamical parallax of the binary system to be $\pi_{\rm dyn} = 14.06$ mas based on the stellar masses from the spectroscopy. In light of this, we should give the new dynamical parallax of the triple system based on our spectrophotometric masses and new orbital parameters.

We use the results of the spectrophotometric analysis, which are the stellar masses ($\Sigma\mathcal{M} = 2.75 \pm 0.09\mathcal{M}_\odot$) using Al-Wardat's method and the results of the dynamical analysis, which are the orbital parameters ($P = 40.796 \pm 0.49$ yr and $a = 0\farcs230 \pm 0\farcs001$) using Tokovinin's method, to estimate the new dynamical parallax of the triple system to be $\pi_{\rm dyn} = 13.8528 \pm 0.20$ mas.

5. Conclusions

We have used Al-Wardat's and Tokovinin's methods to derive the fundamental stellar parameters and orbital parameters for the close triple system HD 2893. Both methods are used to analyze binary and multiple systems based on spectrophotometric and dynamical analyses. The spectrophotometric analysis was used to construct the synthetic SEDs, while the dynamical analysis was used to estimate the orbital solution and grade of the orbit in the close triple system.

The combination of spectrophotometric analyses has been explicitly introduced to derive magnitudes and color indices for binary and multiple systems. The determined magnitudes and color indices of the triple system are obtained based on three different photometrical systems: Johnson-Cousins: U, B, V, R, I, $U-B$, $B-V$, $V-R$, $V-I$; Strömgren: u, v, b, y, $u-v$, $v-b$, $b-y$ and Tycho: B_T, V_T, B_T-V_T. We inferred the evolutionary and isochrone tracks of the hierarchical system and found the spectrophotometric stellar masses to be $\Sigma\mathcal{M} = 2.75 \pm 0.09\mathcal{M}_\odot$ and an age of 1.00 ± 0.09 Gyr.

We computed the orbital parameters of the triple system (the primary components A and B) based on new speckle interferometric measurements from the MSC. These have contributed not only to estimating the orbital parameters and grades of the system more precisely, but also to improving the total mass of the system. Relying on our results of the spectrophotometric and dynamical analysis, we have determined the new dynamical parallax of the triple system to be $\pi_{\rm dyn} = 13.8528 \pm 0.20$ mas, which is close to H97's parallax value.

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