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Research in Astronomy and Astrophysics

On the correctness of orbital solutions obtained from a small set of points. Orbit of HIP 53731

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Abstract HIP 53731 is a binary consisting of stars of the spectral types K0 and K9. The orbit of this object was constructed previously by Cvetković et al. and improved by Tokovinin. It should be noted that there is a 180° ambiguity in the position angles of some published measurements. Speckle interferometric observations were obtained in 2007–2020 (21 measurements) at the 6-m telescope of the SAO RAS (BTA) by the authors of this article. The analysis of new data together with previously published ones made it possible to construct an accurate orbit of HIP 53731 and to halve the already known values of the orbital period of the system. As a result of the study, the mass sum, the masses of each component and their spectral types were determined by two independent methods. According to the qualitative classification of orbits, the orbital solution has grade 2 – "good" (observations cover more than half of the orbital period and correspond to different phases).

Key words: techniques: high angular resolution, speckle interferometry — stars: low-mass, fundamental parameters — stars: binaries: spectroscopic — stars: individual: HIP 53731

1 INTRODUCTION

Currently, a significant part of the orbital solutions found from speckle interferometric data for binaries is obtained using a small number of measurements. This may be due to the lack of observations for a particular system, as well as to large orbital periods of such objects. An additional factor is the absence or inaccurate determination of the positions of the secondaries, which is difficult to identify due to a lack of observational data. Therefore, orbital parameters of objects and mass sums could be determined incorrectly. One of the solutions to this problem is the long-term monitoring of binaries, which allows for covering a big part of the orbit with measurements (it depends on the orbital period). In this paper, we studied the binary HIP 53731 (HD 95175, $V_{\rm mag} = 8.85^{\rm m}$, Bidelman 1985). The system under study, according to Cvetković et al. (2016), consists of two main sequence stars of spectral types K0 and K9 with masses $\mathfrak{M}_A = 0.9\,\mathfrak{M}_\odot$ and $\mathfrak{M}_B = 0.48\,\mathfrak{M}_\odot$ respectively, and the total mass of the system and dynamical parallax are $\mathfrak{M}_{\rm tot} = 1.72 \pm 0.4\mathfrak{M}_\odot$ and $\pi_{\rm dyn} = 29.33 \pm 3.03$ mas respectively. Positional parameters published earlier and obtained in this study are presented in Table 1. Speckle interferometric observations and the image reduction procedure are addressed in Section 2, Section 3 is dedicated to the process of orbit construction and determination of the fundamental parameters of HIP 53731, and results are discussed in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

Speckle interferometric observations of HIP 53731 were carried out at the Big Telescope Alt-azimuth (BTA) of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) from 2007 to 2020 utilizing a speckle interferometer (Maksimov et al. 2009) based on EMCCD detectors PhotonMAX-512B (until 2010), Andor iXon+ X-3974 (2010–2014) and Andor iXon Ultra 897 (since 2015). Speckle images were obtained under good weather conditions with seeing about $1''$–$2''$. Speckle interferograms were recorded with exposure time of 20 ms, and the standard series consisted of 1940 (until 2010) and 2000 images. The following interference

Table 1 Positional Parameters and Magnitude Differences

Epoch	Telescope	$\lambda/\Delta\lambda$ (nm)	θ (°)	ρ (mas)	Δm (mag)	Reference
1991.25	*Hipparcos*		291.0	287.0		ESA (1997)
2000.1460	3.5-m WIYN	648/41	275.8 ± 1	184 ± 3		Horch et al. (2002)
2001.2733	BTA	600/30	268.9 ± 0.6	177 ± 4		Balega et al. (2006)
2001.2733	BTA	750/35	268.9 ± 0.7	178 ± 4		Balega et al. (2006)
2002.2542	BTA	750/35	260.0 ± 0.6	144 ± 2		Balega et al. (2013)
2005.2323	BTA	800/110	118.8 ± 1.1	139 ± 3		Balega et al. (2013)
2006.3745	BTA	545/30	107.8 ± 1.2	180 ± 4		Balega et al. (2013)
2007.9019	BTA	600/30	277.8 ± 0.1	191 ± 1	2.05 ± 0.01	this work
2008.9559	BTA	550/20	270.4 ± 1	175 ± 1	2.55 ± 0.02	this work
2009.0954	BTA	600/40	268.7 ± 0.1	175 ± 1	2.29 ± 0.01	this work
2009.2645	BTA	600/40	267.7 ± 0.1	169 ± 1	1.64 ± 0.01	this work
2010.1601	BTA	800/100	259.3 ± 0.1	141 ± 1	1.45 ± 0.01	this work
2010.3416	2.1-m OAN	630/120	55.5 ± 12.9	160 ± 30		Orlov & Voitsekhovich (2015)
2011.1351	BTA	800/100	240.1 ± 0.3	83 ± 1	1.53 ± 0.02	this work
2011.9486	BTA	800/100	343.9 ± 0.2	34 ± 1	1.51 ± 0.01	this work
2013.3221	BTA	550/20	296.4 ± 0.1	150 ± 1	2.24 ± 0.01	this work
2014.1193	BTA	800/100	289.5 ± 0.1	179 ± 1	1.46 ± 0.01	this work
2014.9301	BTA	550/20	283.4 ± 0.2	188 ± 1	2.11 ± 0.01	this work
2015.9703	BTA	800/100	274.8 ± 0.1	189 ± 1	1.55 ± 0.01	this work
2016.1331	4.1-m SOAR	788/132	274.0 ± 0.3	193.5 ± 0.8	1.5	Tokovinin et al. (2018)
2016.8847	BTA	800/100	268.8 ± 0.1	174 ± 1	1.56 ± 0.01	this work
2017.9227	BTA	800/100	258.9 ± 0.1	141 ± 1	1.46 ± 0.01	this work
2017.9227	BTA	800/100	259.0 ± 0.1	141 ± 1	1.46 ± 0.01	this work
2017.9227	BTA	800/100	258.9 ± 0.1	141 ± 1	1.47 ± 0.01	this work
2017.9227	BTA	800/100	258.9 ± 0.1	142 ± 1	1.5 ± 0.01	this work
2018.1811	4.1-m SOAR	824/170	255.2 ± 0.8	134.5 ± 0.8	1.5	Tokovinin et al. (2019)
2018.3214	BTA	800/100	253.7 ± 0.1	124 ± 1	1.49 ± 0.01	this work
2019.0476	BTA	800/100	235.4 ± 0.1	76 ± 1	1.47 ± 0.02	this work
2019.2744	BTA	550/20	222.4 ± 0.1	61 ± 1	1.9 ± 0.04	this work
2019.2744	BTA	800/100	221 ± 0.2	64 ± 1	1.27 ± 0.04	this work
2020.3611	BTA	550/20	306 ± 0.1	103 ± 1	2.13 ± 0.01	this work

Table 2 Orbital Parameters of HIP 53731

$P_{\rm orb}$ (year)	T_0 (year)	e	a (mas)	Ω (°)	ω (°)	i (°)	Reference
16.244 ±0.682	2003.412 ±0.682	0.150 ±0.041	202.6 ±10.9	95.3 ±2.8	256.6 ±15.8	115.8 ±1.6	Cvetković et al. (2016)
15.83	2000.92	0.095	214	95.1	192.2	105.8	Tokovinin (2019)
7.83 ±0.01	2004.00 ±0.01	0.886 ±0.004	123.6 ±1.8	151 ±3	61 ±3	140.1 ±1.4	this work

Table 3 Comparison of Fundamental Parameters

	Parallax	$M_{V,A}$ (m)	Sp_A	$\mathfrak{M}_A$ ($\mathfrak{M}_\odot$)	$M_{V,B}$ (m)	Sp_B	$\mathfrak{M}_A$ ($\mathfrak{M}_\odot$)	$\sum\mathfrak{M}$ ($\mathfrak{M}_\odot$)
Cvetković et al. (2016)	*Hipparcos*	5.99 ± 0.12	K0	0.90	8.57 ± 0.77	K9	0.48	1.72 ± 0.40
This work	*Hipparcos*	6.11 ± 0.10	K2	0.78	8.30 ± 0.14	K7	0.63	1.68 ± 0.26
	Gaia	6.47 ± 0.10	K3	0.75	8.66 ± 0.14	K9	0.56	1.03 ± 0.07

filters were applied (central wavelength λ / bandpass $\Delta\lambda$): 550/20, 600/40 and 800/100 nm.

Positional parameters and magnitude differences were determined on the basis of the analysis of the power spectrum and the autocorrelation function of the speckle interferometric series described in Balega et al. (2002) and Pluzhnik (2005). The reconstruction of the position of the secondary was carried out by the bispectrum method (Lohmann et al. 1983). The log of observations, positional parameters and magnitude differences are presented in Table 1: epoch of observations in fractions of the Besselian year; telescope; $\lambda/\Delta\lambda$; θ is the position angle; ρ is the separation between the two stars; Δm is the magnitude difference and references. The formal errors of Δm corresponding to the method of model selection are presented in Table 1. Wherein, an analysis of the

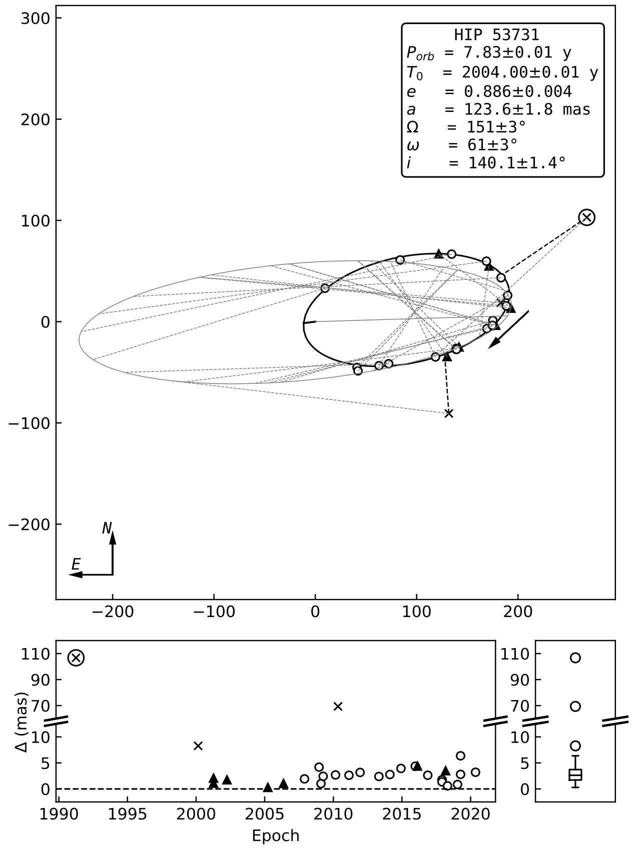

Fig. 1 Orbital solutions for HIP 53731. The orbit by Tokovinin (2019) is marked with *gray* and the orbit constructed in this work is *black*. *Triangles* correspond to the published data; *open circles* - data obtained in this study; *crosses* - data with large residuals; the *cross placed in a large circle* is the first measurement for the system. The *arrow* shows the direction of motion for the secondary. Δ signifies residuals corresponding to the angular distance between the observed and modeled value. The *dashed line on the residuals plot* indicates the orbital solution.

magnitude differences from the data obtained in different epochs shows that the actual measurement accuracy is about 0.1 mag.

3 ORBIT CONSTRUCTION

Preliminary estimates of the orbital parameters were calculated using the Monet method (Monet 1977). The final orbit was constructed employing the ORBIT software package (Tokovinin 1992). Depending on the values of residuals and deviations from the orbital solution, the corresponding weights were selected for each measurement. Measurements by ESA (1997), Horch et al. (2002) and Orlov & Voitsekhovich (2015) have the largest residuals (as displayed in Fig. 1), consequently less weight was set to them.

When constructing the orbit of HIP 53731, ambiguities in the positions of published measurements were found, which is probably due to the incorrect reconstruction of the position of the secondary or its absence. As a result, the position angles of the following measurements were changed by $\pm 180°$: 2005.2323 and 2006.3745 (Balega et al. 2013) and 2010.3416 (Orlov & Voitsekhovich 2015). Two orbits of HIP 53731 were constructed by Tokovinin (2019) and in this study are presented in Figure 1. The measurement residuals with respect to the new orbital solution are $4°$ by θ and 18 mas by ρ. However, they were overestimated due to the significant contribution of points that obviously does not match the model solution (in Fig. 1, these are marked with crosses). Estimates of residuals for ρ and θ are 2 mas and $0.8°$, respectively.

Table 2 presents our measurements for the orbital parameters of the system and previously published ones. The columns are: the orbital period, the epoch of passing the periastron, the eccentricity of the orbit, the semimajor axis, the longitude of the ascending node, the argument of the periastron, the inclination of the orbit and the references to the publications.

A comparison of orbital solutions affirms that the orbit of HIP 53731 constructed in this work fits the observational data much better than the orbits by Cvetković et al. (2016) and by Tokovinin (2019), obtained from a small amount of observational data. Also, mass sum, absolute magnitudes of components, their spectral types and masses were determined utilizing two independent methods and are presented in Table 3. Both *Hipparcos* (van Leeuwen 2007) and *Gaia* (Gaia Collaboration 2018) parallaxes and orbital parameters were used in the first method. This method allows for calculation of mass sum via *Kepler*'s third law

$$\sum \mathfrak{M} = \frac{(a/\pi)^3}{P_{\rm orb}^2}, \tag{1}$$

and the uncertainty is calculated considering

$$\sigma(\mathfrak{M}) = \sqrt{\frac{9(\sigma_\pi)^2}{\pi^2} + \frac{9(\sigma_a)^2}{a^2} + \frac{4(\sigma_{P_{\rm orb}})^2}{P_{\rm orb}^2}} * \mathfrak{M}\,. \tag{2}$$

The second method enables obtaining the masses of components via Pogson's relation. The magnitude of the object in the V band (Bidelman 1985) and the average magnitude difference ($\Delta m_{550} = 2.19^m \pm 0.10^m$ from Table 1) together with parallaxes ($\pi_{Hip} = 26.35 \pm 1.29$ mas and $\pi_{Gaia} = 31.0803 \pm 0.6137$ mas) were used. The work by Pecaut & Mamajek (2013) was applied to match the calculated absolute magnitudes of the components with spectral types and masses.

4 DISCUSSION

An analysis of speckle interferometric data obtained at the 6-m telescope of the SAO RAS from 2007 to 2020 made it possible to halve the previously known value of the orbital period of HIP 53731. It should be noted that the residuals of positional parameters are small, which indicates the high-precision of the orbit. This fact indicates a high accuracy of new orbital parameters and the justification for long-term monitoring of such objects carried out in the group of high-resolution methods in astronomy of the SAO RAS. As a result, the orbital solutions by Cvetković et al. (2016) and by Tokovinin (2019) are very different from the orbit, constructed in this work, because they were obtained using a small number of measurements, some of which have $\pm 180^{\circ}$ ambiguities.

The mass sum of the HIP 53731 components was determined with an accuracy of 15% (using the *Hipparcos* parallax) and 8% (using the *Gaia* parallax). The masses of the components obtained by the second method in this study are consistent with the mass sums calculated by the first method. The values obtained considering the *Hipparcos* parallax agree better with each other. The masses obtained utilizing *Gaia* parallax in this work are less consistent with each other. The reason is probably due to the *Gaia* parallax, so we are looking forward to the new data release from this mission. The proximity of the new parameters to the previous values is explained by the fact that Cvetković et al. (2016) utilized the magnitude difference from the *Hipparcos* catalog together with the table of star parameters from the book by Gray (2005), as well as erroneous values of both the orbital period and the semimajor axis.

The classification of the obtained orbital solutions was carried out using the qualitative grade of Worley & Heintz (1983). The orbit of HIP 53731 is “good” (Grade 2) – the observations correspond to different phases and cover more than half of the orbital period, which allows for fitting of orbit accurately enough.

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