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Parameters of the Apparent Relative Orbit of the Third Body in the SZ Cam System

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Abstract—A complete set of parameters of the apparent relative orbit of the third body in the SZ Cam system is determined for the first time based on new speckle-interferometric and photometric observations of the eclipsing binary SZ Cam made with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences and 0.5-m telescope of the Astronomical Observatory of Ural State University and published data. The mass of the third body and the distance to SZ Cam are estimated at $M_3 = 23.4 M_\odot$ and $d = 1125$ kpc, respectively. The binary nature of the third body is confirmed. It is suggested that SZ Cam is possibly not a member of the open star cluster NGC 1502 onto whose center it projects. A total of 16 new times of minima of SZ Cam are reported.

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1. INTRODUCTION

The eclipsing binary SZ Cam with O9–B0 early-type components is the northern component of the visual binary ADS 2984. The close binary SZ Cam and its visual companion, which has the same magnitude ($\sim 7^m$) and is located at an angular distance of 18″, are the brightest members of the open cluster NGC 1502. Guthnick and Prager [1] were the first to discover the variability of SZ Cam, and Wesselink [2] obtained the first photographic light curves of very high quality for this star in the 1940ies. In 1970–1971 Kitamura and Yamasaki [3] in Japan and Polushina [4] at Gissar Observatory obtained the first photoelectric light curves for SZ Cam. Several more photoelectric light curves of the system [5–8] were obtained in the ensuing years. Virtually all light curves exhibited small-amplitude depressions, especially, near the secondary minimum.

Chochol [9] was the first to perform photographic spectroscopy of SZ Cam in 1975. The above author could find only lines of the primary component in his spectra. He estimated the component mass ratio in SZ Cam to be $q = 0.25$ based on the primary-to-secondary luminosity ratio as inferred from the light curve.

Based on these data, the researchers classified the eclipsing variable SZ Cam as a semidetached binary where the primary fills its Roche lobe. The peculiarities of the light curves mentioned above were interpreted in terms of mass outflow from the secondary onto the more massive primary resulting in the formation of a disk-like envelope and mass loss by the system [6, 10].

Mayer et al. [11] and Lorenz et al. [12] analyzed high-dispersion spectra of SZ Cam taken with electronic detectors in 1993–1995 and their results altered substantially our perception of the evolutionary status of the system. The above authors easily identified the lines of the primary and secondary components in the HeI, HeII, and SiIII blends and constructed the corresponding radial-velocity curves to determine the new component mass ratio of $q = 0.69$. This result allowed SZ Cam to be classified as a detached binary.

In addition to the lines of the principal components, the spectra of SZ Cam revealed other lines whose positions also varied with time, but whose shifts were much smaller than those of the lines of the principal components. The above authors suggested that these lines should belong to the third body in the SZ Cam system, which also may be a close binary. They used their two-years long observing series to determine the light elements of this body and construct a low-amplitude and highly noisy radial-velocity curve of the purported primary of the third body and determine its total mass [12].

The above authors then analyzed the period-change curve of SZ Cam to conclude that SZ Cam participates in the orbital motion about its common mass center with the third body. The only speckle-interferometric study of SZ Cam available at that time was that of Mason [13], who found a visual companion at an angular distance of $0.071''$ from SZ Cam. They use the result of Mayer et al. [11] to compute four variants of the visual orbit of the third body for two periods, 50.7 and 60.1 years, and two tilt angles, $i = 60°$ and $i = 90°$ [12].

Thus an analysis of the results of spectroscopic observations of SZ Cam based on high-quality spectra made it possible to revise the evolutionary status of the system, discover the third body, and suspect its binary nature. However, the lack of sufficient photometric and spectroscopic data at the time prevented the accurate determination of the orbital parameters of the third body by the above authors.

The aim of this paper is to determine the orbital parameters of the close companion identified with the third body in the SZ Cam system based on new photometric and spectrophotometric data obtained during the period from 1996 through 2005.

2. BASIC RELATIONS

In the case of insufficient number of position measurements the parameters of the relative orbit of the close visual companion (third body) in an eclipsing binary system can be determined by invoking the data on the times of minimum light spanning a time interval comparable to the orbital period of the third body. Given that the ellipse of the relative orbits of the eclipsing system is similar to that of the third body [14], a complete set of orbital parameters can be determined in two stages. First, the period-change curve (O-C) of the eclipsing binary is used to find part of the parameters of the apparent relative orbit of the third body that determine the form of this curve. Another part of the parameters of the apparent relative orbit of the third body is then determined by invoking the results of position (in our case, speckle-interferometric) observations. The fact that the angles that determine the orientation of the orbits of the third body and of the eclipsing pair in space are the same or differ by 180° and the eccentricities of the two orbits coincide allows one to determine all the six parameters of the apparent relative orbit of the third body.

Below we give the corresponding equations [15] relating observational data as functions of orbital parameters.

$$\mathrm{tg}(\theta - \Omega) = \mathrm{tg}(\upsilon + \omega)\cos i\ , \qquad (1)$$

$$\rho = \frac{a(1-e^2)}{1+e\cos\upsilon} \cdot \frac{\cos(\upsilon+\omega)}{\cos(\theta-\Omega)}\ , \qquad (2)$$

$$z = a'(1 - e\cos E')\sin i \sin(\upsilon + \omega), \qquad (3)$$

$$\delta t = \frac{z}{c}, \qquad (4)$$

where Ω is the position angle of the line of nodes; ω, the longitude of the periastron; υ, the true anomaly; i, the tilt of the orbital plane with respect to the sky plane; a, the semimajor axis of the apparent relative orbit of the third body in arcsec; e, the eccentricity; a', the semimajor axis of the orbit of the eclipsing system (in AU) with respect to the barycenter of the binary — the third body system; E', the eccentric anomaly; ω, the longitude of the periastron, and c, the speed of light.

In our case equations (1,2) reflect the relation between the position measurements — angular separation ρ and position angle θ — on the one hand and the elements of the apparent relative orbit of the third body on the other hand. Equation (3) describes the variation of the line-of-sight projection z of the radius vector of the orbit of the binary and equation (4) describes the time lag or lead of the observed events in the eclipsing system as it moves in its orbit about the common mass center with the third body. Here δt corresponds, e.g., to the difference between the observed and true times of minimum light in the eclipsing system.

3. NEW OBSERVATIONAL DATA

3.1. Photometric observations of the times of minima in SZ Cam

Photoelectric photometric observations of the SZ Cam system were performed with the AZT-3 ($D = 0.5m$) telescope of the Astronomical Observatory of Ural State University during the period from 1996 through 2005 [7, 8]. The close visual companion of the same magnitude as the eclipsing binary prevented operation of the photoelectric photometer in accordance with classic scheme. We therefore used image scanning technique for all observations. Scanning was effected by swinging the plane-parallel glass plate introduced into the optical scheme of the photometer. We coadded the scans of the images of SZ Cam and of its visual companion until reaching a signal-to-noise ratio suitable for further reduction. We observed the comparison star in a similar way. We performed further reduction in accordance with the scheme described by Gorda [16]. The integration time for a single scan point was equal to 0.01s and up to

100 scans were coadded. We performed observations in UBVR filters.

Monitoring yielded repeatedly the photometric data for eclipsed portions of the light curve of SZ Cam. To solve our problem, we made equal use of the times of both the primary and secondary minima of SZ Cam, because they are almost of the same depth [7].

We determined the times of minima by fitting the eclipsed portions of the light curve to a fourth-degree polynomial and computing the abscissa corresponding to the minimum of the polynomial. This is a valid approach, because the light minima of SZ Cam are sufficiently symmetric. Figure 1 gives an example of a polynomial approximation of a portion of the eclipsing light curve. We averaged the measurements in each filter obtained on the same date and estimated the accuracy of the mean value by the scatter of the times of minima obtained in each of the four filters. Table 1 lists the times of minima of SZ Cam inferred from observations made at the Astronomical Observatory of Ural State University in 1985 (the first two lines) and during the period from 1996 through 2005.

3.2. Speckle interferometry of SZ Cam

Speckle-interferometric observations of SZ Cam were performed during the period from March 31 through April 4, 2002 with the digital speckle interferometer [17] attached to the primary focus of the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. Measurements were made in two narrow-band filters centered on 545 and 750 nm. We obtained a total of about 4500 20-ms exposure speckle interferograms of SZ Cam. We reduced the data using the method employed at the Special Astrophysical Observatory of the Russian Academy of Sciences to reduce speckle-interferometric observations [18] and obtained new estimates of the angular separation and position angle of the very close companion of SZ Cam for the second epoch of $T_2 = 2002.2485$. We list the now available results of speckle-interferometric observations of SZ Cam in Table 2. Column 1 gives the epoch of observation in fractions of the year; column 2, the angular separation ρ; column 3, the θ angle; column 4, the wavelength/bandwidth of the filter employed; column 5, the number of measurements in the given filter; column 6, the telescope aperture, and column 7, the reference. The last line in Table 2 gives the averaged values of our inferred position parameters and their errors. As is evident from the table, the position parameters of the close companion inferred from the results of observations made with the 6-m telescope differ significantly from those reported by Mason et al. [13], which are based on observations made in 1994. This discrepancy must be indicative of a physical link between the eclipsing system and its close visual companion.

Table 1. Times of minima of SZ Cam based on the results of photoelectric photometry performed with the AZT-3 telescope (D=0.5 m) of the Astronomical Observatory of Ural State University in 1984–2005.

N	Date	$JD_\odot$ 2400000.0+	Type of the minimum
1	02.03.1985	46127.3300 ± 0.0030	II
2	25.03.1985	46150.2684 ± 0.0025	I
3	17.02.1999	51227.3523 ± 0.0007	II
4	21.02.1999	51231.3966 ± 0.0010	I
5	09.10.1999	51463.4560 ± 0.0009	I
6	28.11.1999	51501.2366 ± 0.0010	I
7	07.12.2001	52251.3602 ± 0.0016	I
8	15.12.2001	52259.4873 ± 0.0018	I
9	05.12.2002	52614.3289 ± 0.0021	II
10	20.12.2002	52629.1658 ± 0.0059	I
11	12.02.2003	52683.1434 ± 0.0018	I
12	14.10.2003	52927.3461 ± 0.0055	II
13	24.03.2004	53089.2600 ± 0.0030	II
14	09.04.2004	53105.4676 ± 0.0072	II
15	12.02.2005	53406.3244 ± 0.0061	I
16	03.03.2005	53433.3094 ± 0.0022	I

Unfortunately the large size of the images (about $3'' - 4''$) prevented the determination of the magnitude difference between SZ Cam and its speckle-interferometric companion.

The speckle-interferometric observations of the visual companion of SZ Cam ($\rho = 18''$) failed to reveal any close neighbor in its vicinity, at least within $1''$.

4. DETERMINATION OF THE APPARENT RELATIVE ORBIT OF THE THIRD BODY

4.1. Fitting the O–C curve

We constructed the light time curve using, as far as possible, all the currently known times of minima of SZ Cam. In addition to Table 1, we used the results of photographic photometry of SZ Cam that Wesselink [2] reported in his pioneering work and also

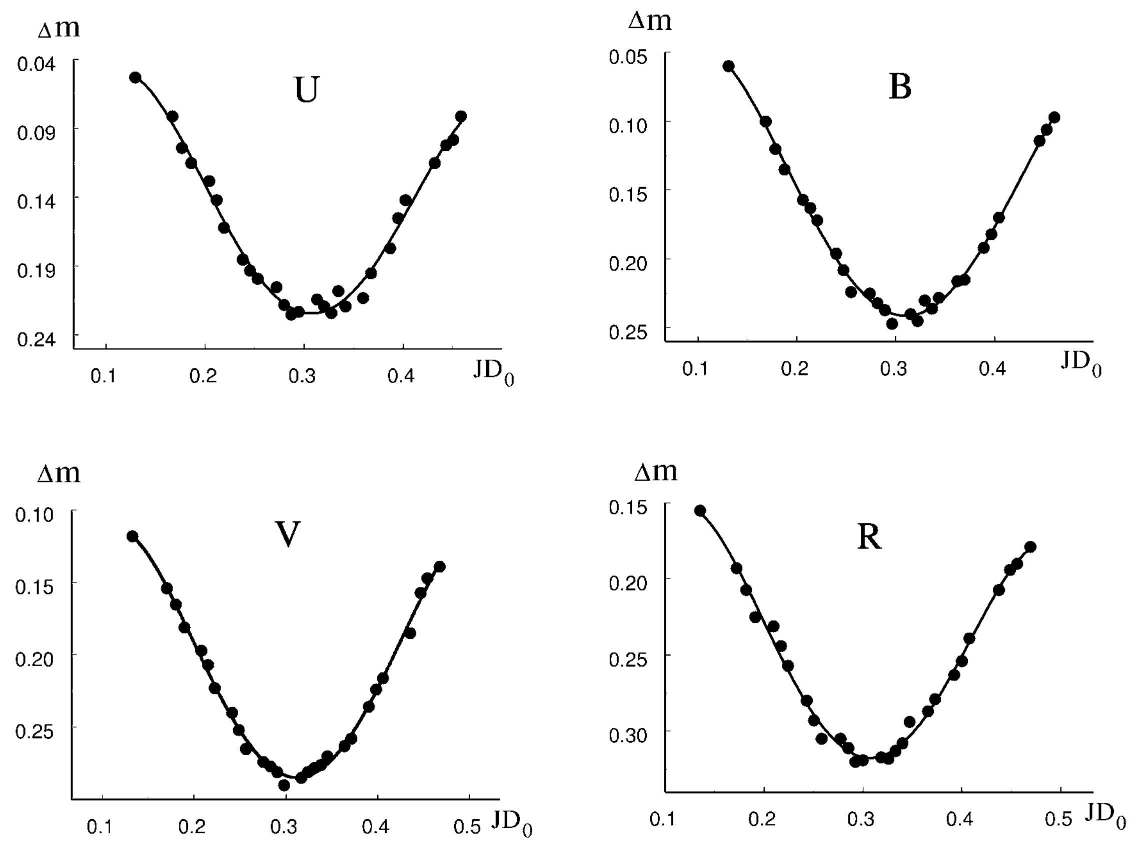

Fig. 1. Example of fitting the eclipse portions of the light curve of SZ Cam taken on March 3, 2005 ($JD = 2453433$) by a fourth-degree polynomial. The x-axis gives the time elapsed since JD-2453433 —$JD_0 = JD - 2453433$.

Table 2. Results of speckle-interferometric observations of the close companion of SZ Cam

Epoch	ρ, arcsec	θ, deg	Filter (nm)	Number of frames	Telescope	Reference
1994.7035	0.071	300	549/22		3.8-m	Mason et al. [13]
2002.2485	0.076	295.107	545/25	1500	6-m	our data
2002.2485	0.076	295.806	750/35	1500	6-m	our data
2002.2486	0.075	295.453	750/35	1500	6-m	our data
2002.2485	0.076 ± 0.001	295.6 ± 0.5		4500	6-m	our data

the measurements from Kitamura and Yamasaki [3], Polushina [4], Chochol [9], and Mayer et al. [11]. We used a total of 93 times of minima for SZ Cam.

We compute the $(O-C)$ values according to the following light equation:

$$O - C = JD^{obs}_{min} - (JD_{\odot} I_{min} + P \cdot E), \quad (5)$$

where JD^{obs}_{min} is the observed time of minimum light; $JD_{\odot}\, I_{min}$, the time of the primary minimum at a certain epoch; P, the true period of the eclipsing system, E, the number of cycles elapsed since $JD_{\odot} I_{min}$ until the given time of minimum. Our initial approximations for $JD_{\odot}\, I_{min}$ and P were the first time of minimum reported by Wesselink [2] and the true period of SZ Cam reported by Lorenz et al. [12], respectively.

To determine the orbital parameters of SZ Cam, we least-squares fitted the $(O-C)$ curve to theoretical δt curve (3)–(4). In our approximation procedure we used random search to fit $a' \sin(i)$, e, and ω values and also the time T_0 of the perihelion passage and the orbital period P_{orb} of SZ Cam in its motion about the third body. We also refined $JD_{\odot}\ I_{min}$ and P and recomputed the $O-C$ values in accordance with formula (5) at every step involving a change in $JD_{\odot}\ I_{min}$ and P.

4.2. Determination of the complete set of parameters of the relative orbit of the third body

We determined the remaining three parameters — the longitude Ω of the ascending node; semimajor axis a of the close companion (third body) of SZ Cam, and orbital inclination i — from the results of speckle-interferometric observations. We first transformed ρ and θ into Cartesian coordinates x and y, where the x axis points Eastward and the y-axis, Northward. We then varied the unknown parameters Ω, a, and i so as to minimize the sum of squared deviations of the coordinates of the two observed positions of the companion from the corresponding points of the computed orbit. We substituted the P_{orb}, ω, and e inferred from the light time curve into formulas (1) and (2), which we converted into Cartesian coordinates.

Note that the apparent relative orbit of the third body based on the computed parameters failed to approximate the results of speckle-interferometric observations accurately enough. That is why, although the sum of squared deviations was in our case based on only four terms (two coordinates per point), we had to vary one more parameter in addition to the three ones mentioned above. We minimized the sums of squared deviations by varying P_{orb}. It goes without saying that every time we found a new P_{orb} value, we refitted the $O-C$ curve at a newly fixed value of this parameter. Note that the sum of squared deviations of the resulting light curve from the observed $O-C$ values was somewhat higher than in the case of variation of all parameters that determine its form. Given that the magnitude of deviations of the observed coordinates from the corresponding points of the approximating curves was about the same in the cases of both the light curve and apparent orbit, we determined all parameters by minimizing the combined sum of squared deviations of the form S:

$$S = S_{O-C} + kS_{orb}, \tag{6}$$

where S_{O-C} and S_{orb} are the sums of squared deviations of the light curve and the relative orbit, respectively; $k = 20$ is the weight coefficient proportional to the ratio of the number of terms in S_{O-C} (the number of minima employed) to the number of terms in S_{orb}. We introduce this weight coefficient in order to balance the statistical significance of both terms and, correspondingly, that of the orbital parameters inferred from a particular curve.

Table 3. Orbital parameters of the SZ Cam system as inferred from the $O-C$ curve

P_{orb}	53.5 ± 1.5 yr
$(\delta t_{max} - \delta t_{min})/2$	$0^{\mathrm{d}}.093$
e	0.78 ± 0.05
ω	$26°.3 \pm 1°.6$
Epoch of the periastron, $T_0(JD)$	2444400 ± 30
$a' \sin i$	-22.8 ± 1.2 AU
a'	23.86 ± 1.8 AU
P_0 (SZ Cam)	$2^{\mathrm{d}}.6984688$
$JD_{\odot} I_{min}$	$2426286^{\mathrm{d}}.7644$

Table 3 lists the inferred values of the varied parameters of the light curve and Figure 2 shows the light curve graphically along with the $(O-C)$ values. Table 4, correspondingly, gives the parameters of the apparent relative orbit of the third body gravitationally bound to the SZ Cam system, and Figure 3 shows the position of the computed orbit with respect to two measurements of the third body based on the data of speckle-interferometric observations.

Below we list the light elements that can be used to compute the observed period of SZ Cam for the nearest epoch. We determined them by analyzing the times of minima for the past 20 years. They correspond to the descending branch of the light curve in Fig. 2. These data can be approximated rather accurately by the following parabolic dependence:

$$JD_{\odot} = 2451922.1883 + 2.69841927 \cdot E + 0.457 \cdot 10^{-8} \cdot E^2. \tag{7}$$

We derive from that the following light elements suitable for computing the times of minima of SZ Cam at present time:

$$JD_{\odot} I_{min} = 2453676.1628 + 2.6984222 \cdot E. \tag{8}$$

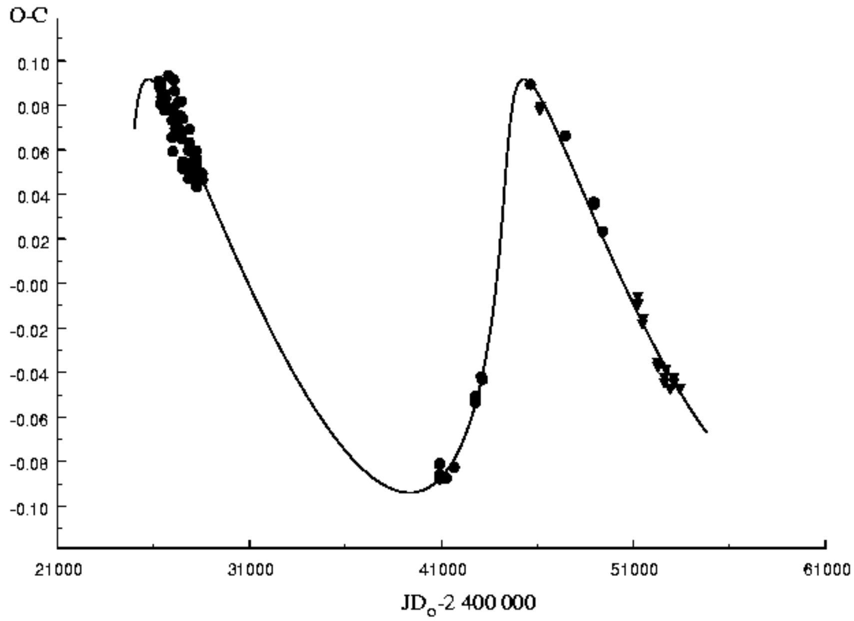

Fig. 2. Theoretical light time curve (the continuous curve); the triangles and circles show the $O-C$ values computed by the data obtained at the Astronomical Observatory of Ural State University and based on the results of other observers (see text for details), respectively.

Table 4. Parameters of the apparent relative orbit of the third body

$P_{orb}(year)$	T_0	e	a	i	Ω	ω
53.5 ± 1.5	1980.437 ± 0.082	0.78 ± 0.05	$0''.047 \pm 0''.002$	$72°.9 \pm 2°.1$	$302°.0 \pm 2°.1$	$26°.3 \pm 1°.6$

5. ESTIMATES OF THE MASS OF THE THIRD BODY AND THE DISTANCE TO SZ Cam

We estimate the mass M_3 of the third body using the mass function $f(M_3)$ of the SZ Cam — speckle-interferometric companion system, which in our case can be written as:

$$f(M_3) = \frac{(M_3 \sin i)^3}{(M_{12} + M_3)^2}, \quad (9)$$

where M_{12} is the total mass of the first and second components of the eclipsing system. As is well known, the mass function can also be written in terms of the orbital elements using the following relation:

$$f(M_3) = \frac{(a' \sin i)^3}{P_{orb}^2}. \quad (10)$$

We now equate the right-hand sides of formulas (9) and (10) to derive an equation for M_3. We then substitute the inferred a', i, and P_{orb} and $M_{12} = 28.5 \pm 0.5M_\odot$ from [19] into this equation to obtain the following estimate for the mass of the third body: $M_3 = 23.4 \pm 2.4M_\odot$. The large mass of the third body is, as Lorenz et al. [12] point out, most likely indicative of the binary nature of the object. The third body is, like SZ Cam, a close binary.

Given the mass of the third body, we estimated the distance to SZ Cam. To this end, we use the formula for the semimajor axis of the relative orbit of two gravitating centers, which in our case can be written as follows:

$$A = a' + a_3 = a'\frac{M_{12} + M_3}{M_3}, \quad (11)$$

where a_3 is the semimajor axis of the orbit of the third

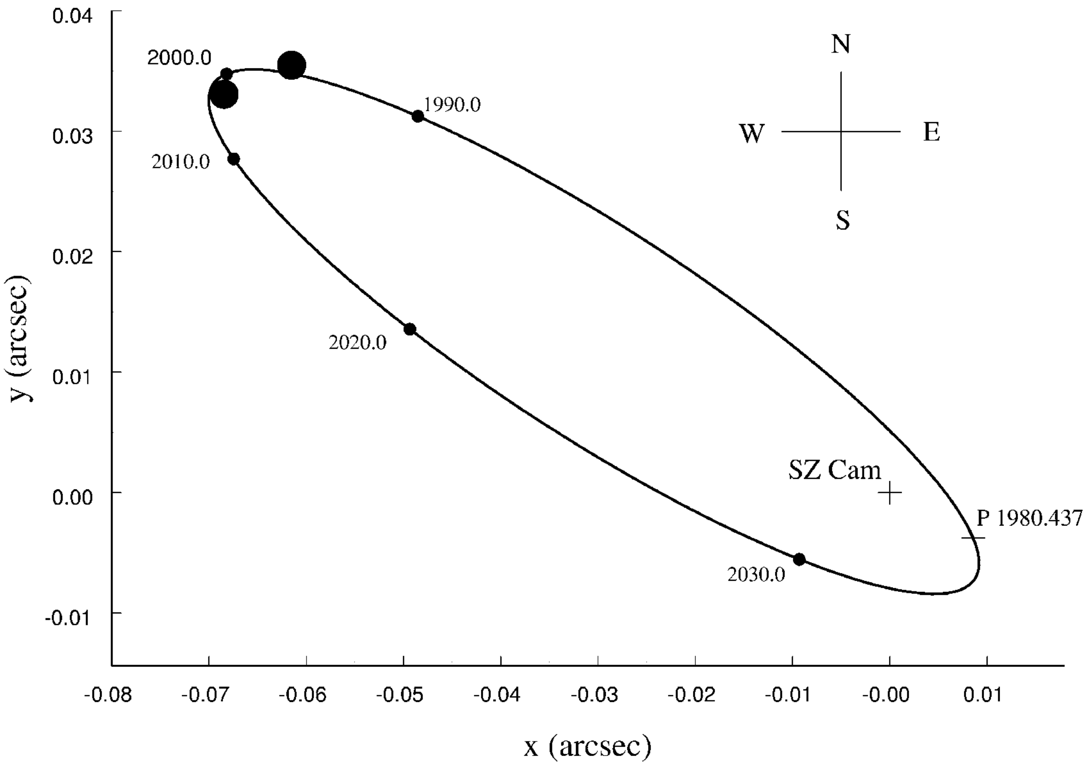

Fig. 3. Apparent relative orbit of the third body (the continuous line); large and small circles show the results of speckle-interferometric observations and the computed positions of third body, respectively, at the start-of-decade epochs.

body. We now substitute the M_{12}, M_3, and a' quantities mentioned above into formula (11) to infer the following value for the semimajor axis of the relative orbit of the third body — $A = 52.9 \pm 5.8$ AU. We then use the known value of a in angular units (see Table 4) to estimate the distance d to the SZ Cam system using the following evident relation:

$$d = \frac{A}{a} = \frac{52.9\ AU}{0''.047} = 1125 \pm 135\ pc. \qquad (12)$$

6. RESULTS AND DISCUSSION

New photometric and speckle-interferometric data that we use in this paper allowed us to detect the angular displacement of the close companion identified with the third body relative to SZ Cam and obtain unambiguous estimates for the parameters of its apparent relative orbit.

Substantial refinement of the orbital parameters of the close companion will be possible only after at least several more speckle-interferometric determinations of its position relative to SZ Cam are made. At present, according to our inferred orbital parameters, the third body is located in the vicinity of its apoastrum and its apparent displacement is minimal. Therefore it will be impossible to compute its accurate orbit based on position data exclusively within the next $5 - 10$ years.

Our inferred tilt angle of the orbit of SZ Cam ($i = 72^\circ.9$) is comparable to the tilt angle $i = 74^\circ - 78^\circ$ of the orbits of the components of the eclipsing system [12]. This fact leads us to suggest that the orbital planes of the components of this apparently quadruple hierarchical system are coplanar. This is at least true for SZ Cam.

The hypothesis about the coplanar arrangement of the orbit of the components of the third body should be advanced with much reservation, because if it is true, the system of the third body must exhibit eclipses, and given that the combined mass of the components of SZ Cam and the third body exceeds $20M_\odot$ and the masses are comparable in value it makes sense to suggest that the system of the third body is similar to SZ Cam and its brightness must vary substantially due to eclipses. This, in turn, must have a certain effect on the light curve of SZ Cam. However, no distortions are observed on the light curve of SZ Cam to exceed $0.^m03$ [8].

Our inferred distance to SZ Cam exceeds by more than 200 pc the distance to the NGC 1502 open cluster, which is estimated at, e.g., $d = 880$ pc according to the homogeneous catalog of open-cluster parameters by Loktin et al. [21]. Given that the maximum radii of open clusters do not exceed 10–15 pc [22], it is safe to suggest that the eclipsing system SZ Cam is not a member of the NGC 1502 open cluster onto whose center it projects.

7. CONCLUSIONS

As a result of this work, we determined for the first time a complete unambiguous set of parameters of the apparent relative orbit of the third body in the SZ Cam system and a consistent estimate for the mass of the third body.

The large, about 200-pc, distance difference of SZ Cam and the NGC 1502 cluster led us to conclude that visual binary ADS 2984, which hosts the eclipsing variable as one of its components, is possibly not a member of the NGC 1502 cluster.

Further speckle-interferometric observations of the SZ Cam system are required to refine the orbital parameters of the third body and determine its magnitude.

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