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The BV light and *O-C* curves analyses of the triple system V505 Sagittarii

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Abstract. The new UBV light curves and times of minimum light for V505 Sgr are presented. The B and V band light curves were analyzed by the Wilson-Devinney code and the contribution of the third star to the total light of the triple system was found to be 2.62% for the B and 3.56% for V band. The colour and absolute visual magnitude of the third star were estimated to be $0^m.46$ and $4^m.00$, respectively. The apparent visual magnitude of the third star seems fainter by about $3^m.6$ than the eclipsing pair. Only photoelectric times of minimum light were used to determine the parameters for the light-time orbit. The semi-major axis of the third star's orbit around the eclipsing pair was found to be 18.8 AU. The third body completes a revolution on this orbit in 38.13 yr. The semi-amplitude of the radial velocity of the eclipsing pair's mass center was estimated to be 2.37 km s^{-1} while 6.4 km s^{-1} was found for the third star which agrees with the spectroscopic measurements.

Key words: stars: binaries: eclipsing – stars: binaries: visual – stars: individual: V 505 Sgr – stars: late-type

1. Introduction

The eclipsing nature of V505 Sgr (HR 7571, HD 187949, BD -14° 5578, HIP 978449) was revealed by Hoffmeister (1934). The system is a short-period Algol type eclipsing binary. It consists of an A2V primary and a cooler, evolved, much fainter G-type secondary. The secondary component has been classified by various investigators between F8 and G8 subgiants. This star fills its corresponding Roche lobe and mass transfer from the cooler star to the hotter primary is expected.

Photoelectric light curves of the system were obtained by Oosterhoff (1950, published by Kwee 1953), Chambliss (1972) and Walter (1981a,b). These light curves were analyzed by various investigators using different methods developed for the light curve analysis. In 1985 McAlister et al. (1987) found a visual companion which had an angular separation of about $0''.3$ from the eclipsing pair. The high signal-to-noise ratio Reticon observations of V505 Sgr were obtained by Tomkin (1992). He detected not only the secondary's NaD lines but also the atomic lines of the third companion for the first time. Tomkin was able to measure the contribution of the third companion to the total light at 5600 Å as 8 percent. Therefore, the brightness difference of 2.7 mag between the third star and the eclipsing pair was suggested. The sharp-lined spectrum of the third star led to the suggestion that it should be a late-type F dwarf.

Chambliss et al. (1993) collected all photographic, visual and photoelectric observations of minimum light and plotted the residuals of the times of minimum light calculated from the linear ephemeris against epoch number. There were two minima and two maxima in the *O-C* curve separated by about 34 yr. Therefore, the orbital period change was attributed to the light-time effect of the third star orbiting about the eclipsing pair in 34 yr. Very recently an attempt to obtain the orbital parameters of the third body was made by Mayer (1997). Due to the inadequate photoelectric data, Mayer was obliged to use the photographic times of minima obtained in the 1930s. His analysis found that the center of mass of the eclipsing pair revolves around the center of mass between the eclipsing pair and a third-body with a period of about 38 yr. The orbit is highly eccentric, i.e. 0.77, and an inclination of 27°was suggested. He noted that the orbital parameters found by him must be considered as preliminary and new times of minima were badly needed.

The aim of this paper is to analyze all the photoelectric times of minima including new ones obtained by the present authors and also to analyze our BV light curves to reveal the physical properties of the components.

2. Observations and light curves

V505 Sagittarii was observed on 15 nights during July, August, and September, 1998 with the 48 cm Cassegrain Reflector of the Ege University Observatory. SSP5A type photometer was attached to the telescope. The Johnson's wide-band U, B and V filters were used. Each measurement is the mean of two 10 s integrations. The main comparison star was HD 187664 (BD -15° 5484), as was used by previous investigators. The extinction coefficients were obtained for each night using the observations of the comparison star. Then, all differential magnitudes in the sense *variable minus comparison* were corrected for differen-

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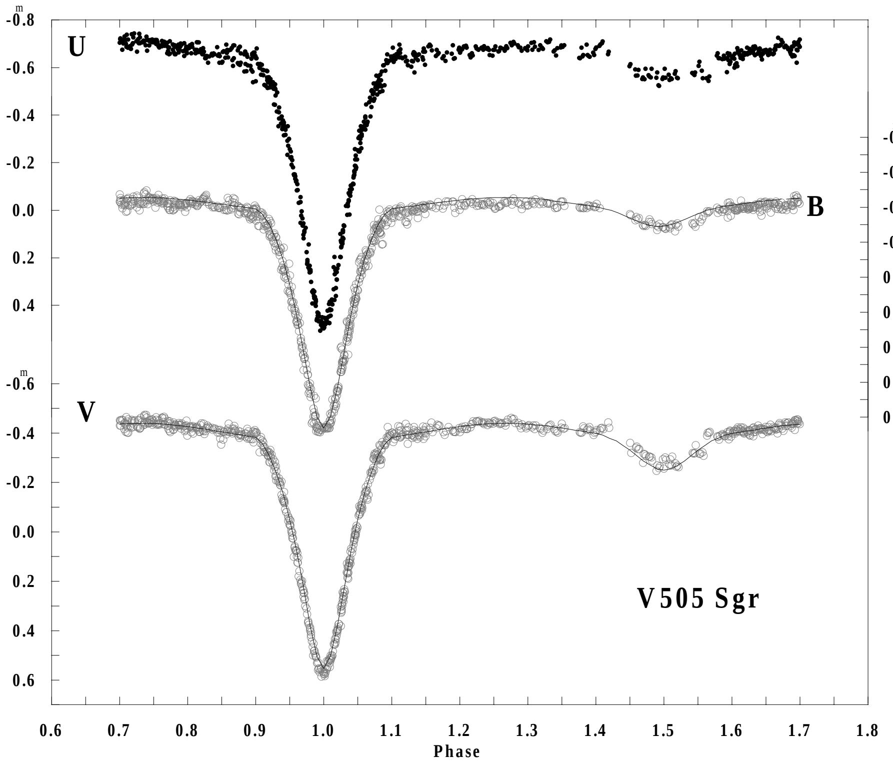

Fig. 1. U, B, and V light curves of V505 Sagittarii and the computed curves for B and V bands.

tial atmospheric extinction. The orbital phases were calculated using the following light elements:

$$\mathrm{Min\ I} = \mathrm{JD\ (Hel)}\,24\,50999.3118 + 1\overset{d}{.}182868927E. \qquad (1)$$

The differential magnitudes corrected for atmospheric extinction for each band were plotted against the orbital phase and are shown in Fig. 1.

3. Light curve solution

It is known that if there is a third star, near in the field of binary, the depths of the eclipses will change and the slopes will differ. Therefore the light curve analysis will lead to incorrect orbital elements without making a correction for the third light. However, the detection of the third light from the light curve analysis seems to be so difficult; for this detection very accurate observations are needed.

Walter's dataset was analyzed by Walker (1993) taking the light contribution of the the third star to the system into account. The solutions with the SIMPLEX algorithm (SA) revealed that the third star is contributing 7%, 5% and 5% in the V, B and U bands, respectively. However, the results derived in the Differential Correction (DC) code were 7%, 5% and 4% (U, B, V). The same methods were used by Chambliss et al. (1993) to analyze the Chambliss and Karle (λ 4600) datasets. They used SA method and found that the third star contributes 6%, 4% and 4% in the V, B and U bands to the light of the system. However, DC solution of the same light curves gave 4%, 2% and 2%. The discrepancy between the SA and DC solutions for Chambliss' observations was shown as evidence of a measure of the difficulty in extracting third light from the light curve. On the other hand, the contribution of 5% was obtained from both methods for the Karle dataset. The last light curve analysis was made by Rovithis-Livaniou & Rovithis (1994) who assumed that the contribution of the third star was 7.3% in the V and 4.3% in the B bandpass.

The light curves obtained by us in a relatively short time interval are shown in Fig. 1. The photomultiplier used is more sensitive to the B and V bands. In addition, the system V505 Sgr follows a way not too far from the horizon due to its small declination. Therefore, the U band observations are more severely affected from atmospheric extinction even if they were corrected for differential extinction. So, we used only BV light curves for the analysis to obtain the orbital parameters of the system.

In the methods used for light curve analysis, some parameters of the components should be fixed. These parameters may be estimated from the known characteristics of the stars. Since the spectral types of the primary and secondary components were derived as A2 and G, we may take some parameters as fixed value. The parameters chosen are nearly identical with those used by Chambliss et al. and are given in Table 1.

During the observations 2500 individual measurements were obtained in each band of the UBV system. The observed points were grouped to the normal points and 86 and 87 normal points were obtained for the B and V bands, respectively. The Mode 5 in the DC code (Wilson & Devinney 1971) was used for the V505 Sgr's light curves analysis. This mode, as discussed by Leung & Wilson (1977), solves the light curves of semi-detached eclipsing binaries, where the secondary component fills its corresponding Roche lobe.

As was stated in the introduction, V505 Sgr has a visual companion. Such a body will affect the depth and slopes of the

Table 1. The result of the light curve analysis with WD code (relative intensities at phase 0.250).

Parameters	**B**	**V**
i	$79^\circ.97\pm0^\circ.17$	
x_1	0.63	0.50
x_2	0.98	0.63
g_1	1.00	
g_2	0.40	
T_1	9070 K	
T_2	5466±28 K	
A_1	1.0	
A_2	0.5	
Ω_1	4.0395±0.0210	
Ω_2	2.9141	
q	0.52	
L_1	0.841±0.027	0.782±0.028
L_2	0.133	0.182
l_3	0.026±0.002	0.036±0.002
σ	0.0104	

Table 2. Physical parameters for V505 Sgr.

Parameter	Primary	Secondary
$M/M_\odot$	2.20±0.09	1.14±0.05
$R/R_\odot$	2.02±0.04	2.26±0.05
T_e (K)	9070	5466±28
$L/L_\odot$	25.0±1.3	5.8±0.3
M_v	$1^m.29\pm0.06$	$2^m.87\pm0.07$

Table 3. Times of minimum light, their standard deviations and the differences between observed and computed times obtained by the linear light elements of Chambliss et al. (1993)

JD Hel.	σ	Band	E	*O-C*
24 51 000.4951	± 0.0003	V	14803	$0^d.0140$
.4946	0.0003	B		0.0135
.4948	0.0003	U		0.0137
51.3579	0.0003	V	14846	0.0135
.3584	0.0004	B		0.0140
.3561	0.0009	U		0.0117
57.2747	0.0006	V	14851	0.0159
.2704	0.0004	B		0.0116
.2717	0.0003	U		0.0129
64.3693	0.0002	V	14857	0.0133
.3690	0.0003	B		0.0130
.3691	0.0002	U		0.0131

minima. Therefore, the light curves were analyzed by assuming that there was a third light in the system. The parameters i, Ω_1, T_2, L_1 and l_3 were taken as adjustable parameters. Initial values of l_3 were selected as 4%, 4% for both bandpasses. The results obtained after several dozen iterations with the DC code are given in Table 1. The computed curves are compared with the observations in Fig. 1.

Wilson (1992) clarified the meaning of the third light. As he stated, many papers have listed values of the third light, with no indication of what the number means. His suggestion about the unit of l_3 was to express it in the light of the triple star system at a definite phase. By taking his suggestion the total light of the triple system at phase 0.250 was calculated by LC using the parameters obtained by DC and found to be 1.030 and 1.039 in the B and V bandpasses, respectively. Then the direct l_3 program outputs of 0.0268 and 0.0366 were divided by the total light at phase 0.250. Thus, the values of l_3 were found to be 0.0262 and 0.0356 in the B and V bandpasses, at this reference phase. A similar procedure was applied for the prediction of their errors. Knowing the light contributions of the stars to the total light, the ratios of l_3/l_1, l_3/l_2 and $l_3/(l_1+l_2)$ were simply calculated to be 0.031, 0.197 and 0.027 for the B band, and 0.045, 0.195 and 0.037 for the V band. Using the ratios given above we found the absolute magnitudes of the third star as $M_3\ (B) = 5^m.10$ and $M_3\ (V) = 4^m.64$. The B-V colour of $0^m.46$ is smaller than those of the G type secondary, which corresponds to the F6V stars. However the absolute magnitudes of the F6V stars, as given by Walker (1993), are: $M(B) = 4^m.47$ and $M(V) = 4^m.00$. The absolute visual magnitude derived by us is fainter by about $0.^m64$ than that estimated by Walker. The difference between the apparent visual magnitudes of the third star and the eclipsing pair is roughly $3^m.6$.

Combining the results obtained from light curve analysis and semi-amplitudes of the radial velocities obtained by Tomkin (1992), we obtained the physical parameters of the components and presented them in Table 2. The mean fractional radii are taken to be 0.2875 ± 0.0011 and 0.3220 ± 0.0011 for the primary and secondary, respectively.

4. Analysis of the *O-C* curve

During the observations we obtained four times of minimum light in three bands which are presented in Table 3. The *O-C* residuals are the differences between the observed and computed times with the Chambliss et al.'s (1993) ephemeris:

$$\text{Min I=JD (Hel)24 33490.4870}+1\overset{d}{.}18286794E. \qquad (2)$$

The photoelectric times of minimum light obtained up to mid-1990 were collected by Chambliss et al. (1993). We added the times of minima obtained later than this date by Rovithis-Livaniou & Rovithis (1992), Paschke & Diethelm (1992), Müyesseroğlu et al. (1996) and ours. The residuals were computed using the linear ephemeris given by Mayer (1997) and plotted against the epoch number. They indicate a sine-like variation with definite two maxima and a minimum. Such a sinusoidal change of the *O-C* deviations may be interpreted as either a light-time effect or apsidal motion. Since the *O* -C residuals for secondary eclipse are changing in the same direction with those of primary minimum and the orbit of secondary component about the primary is circular, the advance of the apsis may easily be excluded. Thus, the remaning reason may be the orbiting of the eclipsing pair about the center of mass with a third component. This foresight was supported by Tomkin (1992), who found that the radial velocity of the third component changed from -13 to -8 km s^{-1} over an eleven-year time interval.

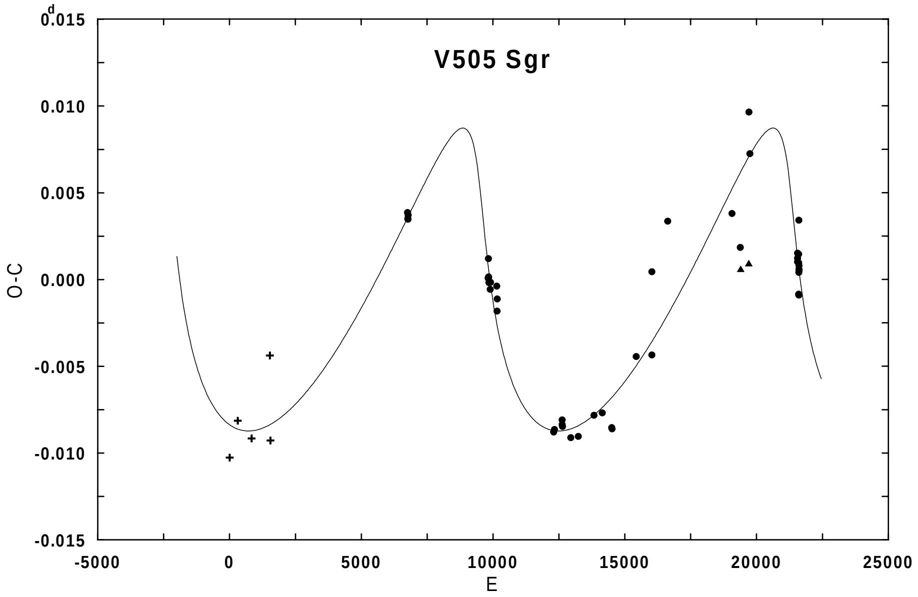

Fig. 2. Residuals for the photoelectric times of minimum light of V505 Sgr with respect to the linear light elements. The continuous curve represents the light time effect. Triangle denotes the secondary eclipses, and the plus old photographic data which were not used for the calculation.

Table 4. Parameters of the third body orbit.

Parameter	*Value*	*Standard deviation*
$a_{12}\sin i(\mathrm{km})$	3.01×10^8	0.32×10^8
e	0.73	0.07
$\omega\,(deg)$	154	3
T_2	JD 2436766	121
$P_2\,(day)$	13928	66
T_1	HJD 2425501.3929	0.0013
$P_1\,(day)$	1.18286887	2×10^{-8}
$A\,(day)$	0.0087	0.0004
$f(m)(M_\odot)$	0.0056	0.0002

The *O-C* curve for V505 Sgr was interpreted by Mayer (1997) in light of the above considerations. He found that the system V505 Sgr revolves around the common center of gravity with a tertiary body. Its period was estimated to be 38.4 yr.

The additional time delay of any observed eclipse due to orbiting around a third body can be represented by (Mayer 1990),

$$\Delta T = \frac{A}{\sqrt{1-e^2\cos^2\omega}}\left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega)+e\sin\omega\right] \quad (3)$$

where A is the semi-amplitude of the light-time effect. In this case the resulting eclipse ephemeris is given by,

$$T_{ec} = T_1 + EP_1 + \Delta T, \quad (4)$$

where T_1 is the starting epoch, E is the integer eclipse cycle number and P_1 is the orbital period of the eclipsing binary. To obtain the parameters of the third body, i.e. P_2, T_2, e, ω and $asini$ as well as the light elements of the eclipsing pair T_1 and P_1 we used weighted least squares solution. The iterations were continued up to the best fit achieved with the McAlister et al.'s interferometric measurements. The results are presented in Table 4.

The final parameters, given in Table 4, were used to obtain the calculated light-time values and the computed light times were plotted in Fig. 2 along with the observed values. The *O-C* values in Fig. 2 were computed with the light elements of the eclipsing pair, i.e. T_1 and P_1. The computed light times not only agree well with the photoelectric *O-C* values, but also represent the older photographic data which were not used in the computation.

We found the semi-amplitude of the *O-C* curve to be $0^d.0087$, while it was estimated by Mayer (1997) as $0^d.0086$. We derived the semi-amplitude of the radial velocity of the eclipsing pair's gravity center as 2.3 km s^{-1}. Using the projected semi-major axis of 2.01 AU and a period of 38.13 yr, the mass function for the third star was calculated as 0.0056 $M_\odot$. Since masses of the components of the eclipsing pair were derived by Tomkin as 2.20 and 1.14 solar masses and the eclipsing pair orbiting around common center of mass with a period of 38.13 yr the mass of the third star may be obtained from the mass function. The mass of the third body was estimated depending on the inclination of the long-period orbit. We can easily compute the mass of the third star as 1.4, 1.2 and 1.0 $M_\odot$ for the inclination of 21°, 24° and 28°, respectively. If we assume that the mass of the third component is 1.2 $M_\odot$, as suggested by Tomkin (1992), the inclination of the third body orbit should be about 24°. Then, the projected semi-major axis ($acosi$) of the third body around the eclipsing pair may be easily computed as 18.43 *AU*.

5. Discussion

The physical parameters of the eclipsing pair's components were given in Table 2. The location of the components on the mass-luminosity and mass-radius relation was discussed by Khalesseh & Hill (1991). They concluded that the primary was underluminous for its mass and, therefore, this mass-gainer should not be a normal star. However, our results indicate that the mass-gainer locates very close to the normal stars on both of these diagrams. On the other hand, the donor seems to locate near the mass losing components of semi-detached binaries. The radius of the mass-losing star is larger than the normal stars in the mass-radius relation, which is expected for the subgiant G stars.

The light curve analysis yielded third star's light contributions of 0.026 and 0.036 in the B and V bandpasses, at the reference phase of 0.250. Using the light ratios we found the absolute visual magnitude of $4^m.64$ and B-V colour index of $0^m.46$ for the third star. These values correspond to a F6 main sequence star. This star is about $3^m.6$ fainter than the eclipsing pair in visual band. On the other hand, the photoelectric times of minimum light were analyzed under the consideration of the light-time effect. We found semi-amplitude of the *O-C* curve to be $0^d.0087$. The center of mass of the eclipsing pair is orbiting around the third star with a period of 38.13 yr. The semi-major axis of the orbit is about 18.8 AU, and the eccentricity of 0.73. Using the known parameters of the orbit we derived semi-amplitude of the radial velocity of the third body as 6.4 km s^{-1}, and a mass function of 0.0056 $M_\odot$. Tomkin (1992) reported that the radial velocity of third component increased from about -13 to -8 km s^{-1}. This result agrees with our findings.

The inclination of the third body orbit may be constrained by the parameters of the orbit and masses of the components. Since the third star was classified as a main sequence F6 star, its mass should be about 1.2 $M_\odot$. One of the most accurate parameters found from the *O-C* analysis is the period of the third body orbit. This period was determined to be 38.13 yr. If we take the mass of the third star, which was derived from spectroscopic data as 1.2 $M_\odot$, Kepler's third law gives the semi-major axis of the orbit to be 18.8 AU. Since we derived the mass function from the *O-C* analysis as 0.0056 $M_\odot$ the inclination of the third body orbit should be about 24°. Then, the mean angular separation between the third star and eclipsing pair may easily be calculated as $0''.17$ for the distance of 102 pc, and $0''.14$ for 120 pc. McAlister et al. (1993) measured the separation between $0''.214$ and $0''.311$. These results are in agreement with our findings if we assume that the distance of the system is about 100 pc. The results obtained by us indicate that the maximum projected separation between the third star and eclipsing pair will be about 226 *mas* during the apastron passage of the third companion which took place in about 1978. If we reduce the distance of the system to about 100 pc the separation will reach 291 *mas* near the apastron passage which is in agreement with the measurements made by McAlister et al. However, the parallax of the system was given in the Hipparcos/Tycho Catalogue as 8.58 *mas* which is in good agreement with our estimation of 8.33 *mas*.

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