Apsidal motion and physical parameters in the eclipsing system V490 Sct

Igor M. Volkov and Alexandra S. Kravtsova
Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskii pr.13, 119991 Moscow, Russia and
Institute of Astronomy of the Russian Academy of Sciences, Pyatnitskaya str.48, 119017 Moscow, Russia
(Dated: January 17, 2022)

We report long-termed \(UBVRI\)\(RC\)\(IC\) photometry of the highly eccentric 12.04 day detached eclipsing binary V490 Sct (\(V=13.1, B9.5+\)A0, \(e = 0.40\)), which we use to determine its relative and absolute parameters. The absolute masses, radii, and temperatures are \(M_A = 2.33\pm0.1\, M_\odot\), \(R_A = 1.91\pm0.04\, R_\odot\), and \(T_A = 9960\pm60\, K\) for the primary and \(M_B = 2.24\pm0.1\, M_\odot, R_B = 1.86\pm0.04\, R_\odot, T_B = 9700\pm80\, K\) for the secondary. The system displays a slow periastron advance that is dominated by general relativity (GR). Our measurement, \(\dot{\omega} = 0.86\) deg century\(^{-1}\), is 32% less then the expected rate, \(\dot{\omega} = 1.24\) deg century\(^{-1}\), which has an 83% contribution from GR. A comparison with current stellar evolution models shows a good match to the measured properties at an age of about 130 mlr. years and Solar abundance. The photometrical parallax of the system \(\pi = 0.77\pm0.02\) mas, matches quite well the \(GAIA\) DR2 value, \(\pi = 0.76\pm0.04\) mas.

INTRODUCTION

V490 Sct was found to be variable by Dr H. van Gent who has investigated the variability of the stars in a region of 100 square degrees in the constellation of Sagittarius around the central star BD\(=18^\circ5206\). Most of the plates (382 pieces) were obtained by him with the help of the Franklin-Adams camera (\(D=25\)cm) of the Union Observatory. 8 more plates were received by P. Th. Oosterhoff with the Mount Wilson 10-inch refractor. J. Uitterdijk has investigated all new variables on these plates. He found that the star with serial number 42 in his list was the eclipsing variable. He derived its true period and due to displacement of the secondary minimum estimated its eccentricity as 0.4, Uitterdijk [1]. He noted that the data obtained need confirmation so he published individual observations in minima for further use. These relatively inaccurate photographical estimates obtained by the Neiland-Blazko method have played a role in our study of the apsidal motion due to the fact that they are 80 years away from the epoch of our observations.

The star was firstly designated as V1049 Sgr but when GCVS research group realized that it is situated in Scutum constellation 8' west from the Sagittarius border it was renamed to V490 Sct Samus’ et al. [2]. Based on Uitterdijk’s data, the star was included in the lists of promising for internal structure and relativistic effect investigation objects such as Gimenez and Crawford [3] (named as V1049 Sgr), Kim et al. [4] (named as V490 Sct) and several other catalogues. No further researches followed the work of Uitterdijk although from the very beginning it was clear that due to the significant eccentricity and favorable orientation of the orbital ellipse, the star is a very promising object for the internal structure studying and general relativity (GR) testing.

OBSERVATIONS AND DATA REDUCTION

We included the star in our program of eclipsing eccentric systems study, Volkov and Volkova [5]. The observations started as far as in 1989 year at Tien-Shan high altitude observatory of SAI. That time we failed to detect minima. We continued occasional observations of the star according the Uitterdijk’s ephemeris, but things did not get off the ground until we began systematic observations of the star in 2004 in Crimean observatory of SAI and in Simeiz observatory of INASAN regardless the predictions of the ephemeris. In 2005 we finally found one of the minima and a meaningful accumulation of the observational data has begun. It turned out that the initial ephemeris gave an error of 10 hours for modern epoch. Also we found that the less deep minimum was assumed to be primary by Uitterdijk’s ephemeris. Further we give the true formulae for mimima timings prediction where the deeper minimum is designated as primary or Min I. Our further analysis showed that a less massive component with a lower temperature is eclipsed at this minimum. This situation is caused by the current orientation of the orbital ellipse, when at a deeper minimum the stars are closer to each other and the eclipsed area of the less brighter star is larger than eclipsed area of the more brighter star in shallower minimum. More massive and brighter component is designated "A" and it is eclipsed in secondary minimum or Min II. Less massive component with less temperature named "B" is eclipsed in primary minimum.

The star was observed at the following observatories (telescope, type of CCD array and photometric system):

- 60-cm reflector, VersArray 512UV CCD, \(UBVRI\)
- 1-m reflector, FLI PL09000 CCD, FLI PL18603, \(BVRcIc\)
- INASAN Simeiz observatory:
- 18-m reflector, FLI PL09000 CCD, FLI PL18603, \(BVRcIc\)
Crimean Observatory of SAI, Nauchny:
- 60-cm reflector, VersArray 1300x1340 CCD, \(UBVRI\)
- 60-cm reflector, Ap47p CCD, \(V\)
- 50-cm Maksutov, Pictor 416 CCD, \(V\)

Tien-Shan high altitude observatory of SAI:
- 48-cm reflector, EMI 9863, \(WBVR\)

Moscow observatory of SAI:
- 70-cm reflector, Ap-7 CCD, \(V\)

Stará Lesná Observatory of the Slovak Academy of Sciences:
- 60-cm reflector, Moravian Mono G4-9000 CCD, \(V\)
- 60-cm reflector, VersArray 512UV CCD, \(BVRI\)
- 15-cm Maksutov, ST-10XME CCD, \(V\) \(RcIc\)

During minima searching we used every opportunity to obtain observations of the star, and this explains the wide range of tools and observatories used. Most of the observations were made with the 60-cm telescope and VersArray 512UV CCD during 18 nights in the same instrumental system. Comparison stars (TYC 5718-588-1=st1 and 2MASS 18584008-1352174=st2, with \(V\) \(= 12.56\) and \(12.26\), respectively, their colour indices are close to variable) within 3 arcmin in the same field of view as the variable star were used to determine differential magnitudes. Normally the variable star differential magnitudes were referenced to the magnitude of the combined light of both comparison stars (variable minus comparison) in each image. Sometimes, when observing with a CCD of small linear dimensions and a long-focus telescope, such as 1-m reflector and VersArray 512UV, only TYC 5718-588-1 was used as a comparison star, as it is only 1.3 arcmin from the variable. All the observations were corrected for the instrumental systems differences. The magnitudes were corrected also for nightly variations in the photometric zero point as we have done previously in similar studies (see, e.g., Volkov et al. \([6]\)). These corrections found in the course of Light Curve (LC) solutions reached \(\pm 0.01\) mag of the mean.

A total of 4754 measurements in all photometrical bands were obtained over 54 nights between 2004 and 2021. All the original data can be found in a suitable computer form on-line.

We present 24 individual minima timings for V490 Sct, of which all, without exception, were observed or recalculated (two photographic timings) in this study and have never been published elsewhere.

**LIGHT CURVE ANALYSIS, COLOUR INDICES, ABSOLUTE DIMENSIONS**

We have derived the magnitudes of the variable and nearby stars relatively to equatorial standards 109 1082, 110 340, Moffett and Barnes \([7]\) with 60-cm cassegrain and VersArray1340x1300 CCD in Nauchny and to nearby standard star from SAI catalogue HD171130 Kornilov et al. \([5]\) with 48-cm reflector and \(WBVR\) photometer with photomultiplier EMI 9863 at Tien-Shan observatory. The averaged data of all estimates and their errors are presented in Table \([1]\). The temperatures of the components can be found as the colour indices of the light loss in minima. The corresponding calculations were performed for the most numerous and accurate \(BV\) observations, see \([2]\). The result is presented in Fig. \([1]\) which demonstrates that a star with a little bit less colour indices (what means with higher temperature) is eclipsed in secondary minimum. Other possibility to get colour indices is to calculate them from relative luminosities, see Table \([1]\) obtained in the course of the LCs solutions in different passbands. Both methods are not completely independent and gave the same result. To get temperatures of the stars from their measured colour indices, one should correct them for interstellar absorption. We can use \((U - B), (B - V)\) two-colour diagram, see Fig. \([2]\) \(E(U - B)/E(B - V) = 0.70\) was accepted for the B9-A0 spectral classes from Table 11 in Straižys \([9]\). The reddening line crosses the fifth class of luminosity normal sequence in two points - firstly close to A7 spectral class, the father one near B9.5 - A0. Both positions correspond to a different temperatures and masses of the stars. It is necessary to make a right choice between them. Fig. \([2]\) shows that the straight line connecting the position of the components in diagram is parallel to the line of normal colour indices precisely in the B9.5 – A0 area not in A7, where it just perpendicular to it. In other words, only B9.5 – A0 position provides the same interstellar extinction for both components of the eclipsing system. So for subsequent analysis, we used the hypothesis of significant interstellar absorption, which corresponds to the spectral types of B9.5 – A0 for the components. The colour indices calculated this way, \([1]\) were applied to determine the temperatures with the help of Flower \([10]\)

| \(V\) | \(U - B\) | \(B - V\) | \(V - R\) | \(R - I\) |
| --- | --- | --- | --- | --- |
| V490 Sct | 13.131 | 0.382 | 0.611 | 0.555 | 0.366 |
| 0.006 | 0.014 | 0.011 | 0.014 | 0.029 |
| V490 Sct,"A" | 13.828 | 0.344 | 0.599 | 0.540 | 0.362 |
| 0.006 | 0.014 | 0.011 | 0.014 | 0.029 |
| V490 Sct,"B" | 13.942 | 0.426 | 0.624 | 0.572 | 0.370 |
| 0.006 | 0.014 | 0.011 | 0.014 | 0.029 |
| st1 | 12.560 | 0.327 | 0.447 | 0.454 | 0.320 |
| 0.007 | 0.008 | 0.009 | 0.008 | 0.008 |
| st2 | 12.257 | 0.264 | 0.400 | 0.391 | 0.256 |
| 0.004 | 0.017 | 0.006 | 0.005 | 0.006 |

\[\text{Table I. Magnitudes of V490 Sct in quadratures with comparison stars.}\]
FIG. 1. The colour indices $B - V$ and $V - R$ of the star in both minima.

calibrations.

"A" component:

$$(U - B)_0 = -0.094 \pm 0.010, \ (B - V)_0 = -0.027 \pm 0.010, \ (V - R)_0 = 0.016 \pm 0.012 \tag{1}$$

"B" component:

$$(U - B)_0 = -0.012 \pm 0.010, \ (B - V)_0 = -0.002 \pm 0.010, \ (V - R)_0 = 0.048 \pm 0.012$$

Let us compare the obtained value of interstellar reddening with surveys. At the $GAIA$ DR2 distance of 1.3 kpc, the Pan-STARRS 1 3D reddening map Green et al. [11] indicates a reddening of $E(B - V) = 0.27 \pm 0.03/0.01$ mag which is much less than obtained value of $E(B - V) = 0.626$. Note that the effect has been already encountered in the study of young eclipsing stars with elliptical orbits such as GG Ori Volkov and Khaliullin [12], V944 Cep Volkov et al. [13], V2544 Cyg Volkov et al. [14], V839 Cep Volkov et al. [15] and V1103 Cas (unpublished). These colour indices correspond to $T_A = 9960$ K and $T_B = 9560$ K according to Flower [10] calibration. In the subsequent analysis the temperature of component "B" had to be increased by 140K. We used most accurate $B - V$ temperature calibration, other measured indices $(V - R), (V - I), (V - Rc), (V - Ic)$ do not contradict the obtained values of temperatures. The LCs of the binary show no proximity effects. Therefore, we used a model of two spherical stars with linear limb-darkening law moving on an elliptic orbit. We simulated the LCs using our program based on the algorithm described in Khaliullina and Khaliullin [17]. The limb-darkening coefficients were fixed according to Wade and Rucinski [18] for the temperatures and gravitational acceleration of the components. The final solution is given in Table II and Table III.

Assuming a normal distribution for the residuals we

FIG. 2. The $(U - B), (B - V)$ diagram. Arrow indicate the direction of the interstellar reddening. The bold line stands for the standard luminosity class V sequence, Stražys [9]. Cloud of points represents observations in the Johnson $UBV$ system from the Mermilliod [16] catalogue. Black crosses mark the observed colour indices of "A" and "B" components. Empty circles stand for dereddened position of the colour indices of the components.

FIG. 3. The differential $V$-band observations in Min I, where component "B" is eclipsed, upper panel. Out of eclipse brightness is accepted to be equal zero. Residuals of solutions in different photometric bands are shown in the lower panels.
FIG. 4. The same as Fig. 3 but for Min II, where component "A" is eclipsed.

TABLE II. LCs solution

| Parameter | Value               |
|-----------|---------------------|
| \(r_A\)   | 0.0520(2)           |
| \(r_B\)   | 0.0507(2)           |
| \(r_A+r_B\)| 0.1027(1)          |
| \(i^0\)   | 88.10(3)            |
| \(e\)     | 0.4008(4)           |
| \(\omega^0\)| 50.71(9)          |
| \(L_AU\)  | 0.5508(30)          |
| \(L_AB\)  | 0.5321(10)          |
| \(L_AV\)  | 0.5262(8)           |
| \(L_AR_c\)| 0.5238(10)          |
| \(L_AR\)  | 0.5197(10)          |
| \(L_AI_c\)| 0.5202(20)          |
| \(L_AI\)  | 0.5180(20)          |

calculated the mean errors for an individual point in every spectral band. The number of points used in calculations is indicated in brackets:

\[
U - 0.045 \ (98), \ B - 0.0165 \ (882), \ V - 0.0104 \ (1520), \ R_C - 0.0107(413), \ R - 0.0140 \ (644), \ I_C - 0.0105 \ (432), \ I - 0.021 \ (502).
\]

As it often happens the obtained solutions are insensitive to the ratio of the radii of the components \(k = r_B/r_A\) for values of \(k\) between 0.7 and 1.3, see Figure 5. Popper [19] recommend to make a true choice by examination of systematic effects of residuals from various solutions in minima. When we used this recommendation for our observations at the minima, we did not find any systematics, see Figure 6.

We point three factors which can explain the failure of the method in the case. 1. V490 Sct has inclination of the orbit near 88 deg, which implies partial eclipses in which the dependence of the LC on the ratio of the radii is not as pronounced as for DI Her, which Popper used for such analysis. 2. Popper, see Fig. 5 in Popper [19], does not consider the photometric zero point in his analysis of DI Her, the underestimation of which can also lead to systematic differences in the residuals. 3. Error
in darkening coefficient of the eclipsed component also can produce the same systematic deviations near conjunction.

So, in order to determine the correct value of $k$, we should use additional information. It’s natural to assume that the distances to both components of the system should be the same. From our multicolour observations we directly get the temperatures of the components. Then fixing $k$ in considered range we get a set of solutions from which we estimate the distances to each component. The plot in Figure 7 for most precise V-band observations and temperatures $T_A = 9960$ K and $T_B = 9700$ K demonstrates much more pronounced than in Figure 5 minimum at $k = 0.9744$. Assuming this value we obtain the final geometrical parameters shown in Table I.

The flux ratio in V light, $J_B/J_A = 0.9516$, corresponds (Popper [20], Table 1) to a difference in $B - V$ of 0.013 mag or 200K in temperature. Close enough to adopted value of 260K.

We estimated the absolute parameters such as semi-major axe, radii and masses by the non-direct method described in details in Khaliullin [21] and Volkov et al. [22].

Let us estimate the precision of the method. The obtained parameters are close to the parameters of other three eccentric systems derived by a similar method from our own $UBV$ observations which we have calibrated by temperature according to Flower [10]. They are V541 Cyg, Volkov and Volkova [23], GG Ori, Volkov and Khaliullin [12] and AS Cam, Khaliullin and Kozyreva [24]. But these systems have well established masses derived from spectral observations, correspondingly: Torres et al. [25], Torres et al. [26], Pavlovski et al. [27]. We solved our LCs of these three systems and obtained their absolute parameters the same way as we did for V490 Sct, see Table IV. We found that the indirect estimations for this limited sample are enclosed with probability 68.2% in $\pm 0.06 \text{M}_\odot$ interval assuming Student’s t-distribution of errors for this small sample. We conclude that the indirect method works quite good for the stars similar to V490 Sct. The absolute parameters of the system are presented in Table III. The derived photometric para-

![FIG. 7. The dependence of components distances from $k$.](image)

![FIG. 8. Measurements for V490 Sct in the $\log g$ vs $\log T_{eff}$ diagram compared with evolutionary tracks and isochrones from Girardi et al. [28] for a Solar metallicity that perfectly matches the observations. Component "A" - filled square, component "B" - filled circle. ZAMS is shown with solid line, isochrones for selected ages are shown with dashed lines. Evolutionary tracks are presented with solid grey lines.](image)

| Parameter | "A" comp. | "B" comp. |
|-----------|-----------|-----------|
| $T$ K     | $9960 \pm 60$ | $9700 \pm 80$ |
| B.C.      | -0.241    | -0.187    |
| $M$ (M$_\odot$) | 2.33 ± 0.07 | 2.24 ± 0.07 |
| $q(M_B/M_A)$ | 0.961 ± 0.001 |
| $R$ (R$_\odot$) | 1.91 ± 0.04 | 1.86 ± 0.04 |
| $\log L$ (L$_\odot$) | 1.466 ± 0.02 | 1.398 ± 0.02 |
| $\log g$ | 4.244 ± 0.008 | 4.250 ± 0.008 |
| $a$ (R$_\odot$) | 36.65 ± 0.10 |
| $d$ [pc] | 1300 ± 40 |

| Star      | M obs | M calc | M obs - M calc |
|-----------|-------|--------|----------------|
| V541 Cyg "A" | 2.369 | 2.420  | -0.051         |
| V541 Cyg "B" | 2.288 | 2.385  | -0.097         |
| GG Ori "A"  | 2.336 | 2.301  | +0.035         |
| GG Ori "B"  | 2.287 | 2.343  | -0.056         |
| AS Cam "A"  | 3.213 | 3.191  | +0.022         |
| AS Cam "B"  | 2.323 | 2.305  | +0.018         |
lax, $\pi = 0.77 \pm 0.02$ mas, matches quite well the GAIA DR2 value, $\pi = 0.76 \pm 0.04$ mas, of Luri et al. [29]. Figure 8 presents the position of the components of V490 Sct on the evolutionary diagram $\log g - \log T$ which corresponds to the age of 130 mln. years. The position of components in $\log L - \log T$ diagram, Figure 9, demonstrate lack of luminosity in comparison with theoretical expectations.

**APSIDAL MOTION**

We’ve got precise minima timings from our data by fitting the synthetic LCs to observations obtained during single overnight run by means of the same program as we used for LCs solution. All the geometrical parameters were fixed according to their values from Table II except of the specific epoch. In the case of simultaneous observations in several filters, the minima timings were weighted and mean values were calculated. The minima timings are listed in Table V. Note that no other data exist at the moment for the star. The same way we obtained mean timings for photographic observations assuming $B$ band for them. Their formal weight calculated as $1/\epsilon^2$ (given in the second column of Table V) appeared to be only $10^{-2}$ of CCD observations weight, but they have sense, as they are 70 years away from the epoch of our observations. Solving the data from Table V by the least squares method separately for the primary and secondary minima we get the following ephemeris:

HJD Min I = 2455073.39094(2) + 12.0439515(9) × $E$, 
HJD Min II = 2455069.39288(16) + 12.0439480(7) × $E$. 

(3)

The plots which illustrate the residuals given in the 5th column of Table V are presented at Figure 10. The difference between the periods (3) is evidence of the rotation of the line of apsides. The rate of apsidal motion from the periods difference may be found according to formula (6) from Khalilullin and Khalilullina [30]:

$$\dot{\omega}_{obs} = 0.0086(7) \text{ yr}^{-1}, \quad U = 41900(3400) \text{ years.}$$

Errors in eccentricity and periastron longitude, see Table II, are small and have a little effect on the resulting error of the measured value. The error in the received value is ten percent and is caused mainly by errors of the periods.

We estimate the predicted rate of periastron advance from classical terms (tidal and rotational distortions) to be $\dot{\omega}_{class} = 0.00219(5) \text{ yr}^{-1}$, where we have adopted internal structure constants for the two stars of $\log k_A = -2.352$ and $\log k_B = -2.355$ from the models by Claret [31] for 130 mln. years age and assuming that the components are synchronized in periastron. The GR contribution (e.g., Levi-Civita [32]; Gimenez [33]) is calculated to be $\dot{\omega}_{rel} = 0.0103(2) \text{ yr}^{-1}$ which is 4.8 times larger than the classical effect. The total expected apsidal motion is then $\dot{\omega}_{theor} = 0.0125(2) \text{ yr}^{-1}$. Our measurement is 32% less. We can say with confidence that the observed apsidal rotation is slower than it follows from synchronization conditions. Deceleration is not as pronounced as in the case of DI Her and AS Cam systems, but is quite noticeable. The reason for the apparent discrepancy could be the inclination of axial axes of the system components to the orbital plane, proposed in the work Shakura [34].

**CONCLUSIONS**

We obtained reliable parameters for the Algol-type binary V490 Sct: colour indices, interstellar reddening, masses, inclination, effective temperatures of the compo-
The apsidal motion measured with reliable precision demonstrates slowness. V490 Sct joined to a very small group of eclipsing systems with accurately measured apsidal motion in which the contribution from GR is significant.

The masses of the components computed by a non-direct method are in agreement with the theoretical diagrams.

We’d like to encourage high-resolution and high signal-to-noise spectroscopic observations of the system in order to determine the masses of the components from radial velocity curves.

This study was partly supported by the scholarship of the Slovak Academic Information Agency(IMV, ASK), RNF grant 14-12-00146 and RFBR grant 18-502-12025(IMV).

### Notes
Columns list the measurement error; the type of eclipse - 1 primary, 2 - secondary; method of observations; residuals from the linear fits.

### References
(1) Dr H. van Gent, P.Th.Oosterhoff and J.Uiterdijk photographic observations reprocessed in present work; (2) timings from V observations; (3) mean weighted timing from BVRI observations; (4) mean timing from BVReIc measurements.

### TABLE V. Times of Eclipse for V490 Sct.

| HJD (2,400,000+) | $\epsilon$ | $O - C$ | Reference |
|------------------|-----------|--------|-----------|
| 27657.371        | 0.009     | 2      | +0.0037   | 1         |
| 28757.328        | 0.009     | 1      | -0.0122   | 1         |
| 53471.5447       | 0.0011    | 1      | +0.0004   | 2         |
| 55699.3927       | 0.0007    | 2      | -0.0002   | 2         |
| 55073.3909       | 0.0008    | 1      | -0.0000   | 2         |
| 55358.4477       | 0.0007    | 2      | +0.0000   | 3         |
| 55362.4461       | 0.0002    | 1      | +0.0001   | 3         |
| 56165.3897       | 0.0007    | 2      | -0.0024   | 2         |
| 56169.3908       | 0.0009    | 1      | -0.0005   | 2         |
| 56442.4038       | 0.0001    | 2      | +0.0000   | 3         |
| 56936.2046       | 0.0002    | 2      | +0.0005   | 4         |
| 57554.4464       | 0.0001    | 1      | -0.0002   | 4         |
| 57562.4907       | 0.0003    | 2      | +0.0006   | 4         |
| 58345.3454       | 0.0004    | 2      | -0.0013   | 3         |
| 58349.3473       | 0.0001    | 1      | -0.0005   | 3         |
| 58646.4474       | 0.0007    | 2      | +0.0020   | 2         |
| 58650.4473       | 0.0001    | 1      | +0.0005   | 4         |
| 58658.4873       | 0.0005    | 2      | -0.0021   | 3         |
| 58662.4911       | 0.0003    | 1      | +0.0003   | 3         |
| 58670.5321       | 0.0005    | 2      | -0.0012   | 3         |
| 59128.2054       | 0.0004    | 2      | +0.0020   | 2         |
| 59144.2940       | 0.0003    | 1      | -0.0001   | 3         |
| 59393.1699       | 0.0010    | 2      | -0.0003   | 3         |

[1] J. Uitterdijk, Annalen van de Sterrewacht te Leiden 20, 41 (1949).
[2] N. N. Samus’, E. V. Kazarovets, O. V. Durlevich, N. N. Kireeva, and E. N. Pastukhova, Astronomy Reports 61, 80 (2017).
[3] D. L. Gimenez and A. Crawford, Experimental Astronomy 5, 91 (1994).
[4] C. H. Kim, J. M. Kreiner, B. Zakrzewski, W. Ogloza, H. W. Kim, and M. J. Jeong, ApJS 235, 41 (2018).
[5] I. M. Volkov and N. S. Volkova, Astronomy Reports 53, 136 (2009).
[6] I. M. Volkov, N. S. Volkova, and D. Chochol, Astronomy Reports 54, 418 (2010).
[7] T. J. Moffett and T. G. Barnes, III, AJ 84, 627 (1979).
[8] V. G. Kornilov, I. M. Volkov, A. I. Zakharov, L. N. Kozyreva, L. N. Kornilova, and et al., Trudy Gosudarstvennogo Astronomicheskogo Instituta 63, 4 (1991).
[9] V. Stražys, Multicolor stellar photometry, Tucson: Pachart Pub. House (1992).
[10] P. J. Flower, Astrophys. J. 469, 355 (1996).
[11] G. M. Green, E. F. Schlafly, D. F.inkbeiner, H.-W. Rix, N. Martin, W. Burgett, P. W. Draper, H. Flewelling, K. Hodapp, N. Kaiser, et al., Astrophys. J. 810, 25 (2015), 1507.01005.
[12] I. M. Volkov and K. F. Khaliullin, Astronomy Reports 46, 747 (2002).
[13] I. M. Volkov, L. A. Bagaev, and D. Chochol, in Living Together: Planets, Host Stars and Binaries, edited by S. M. Rucinski, G. Torres, and M. Zajda (2015), vol. 496 of Astronomical Society of the Pacific Conference Series, p. 266.
[14] I. M. Volkov, L. A. Bagaev, and D. Chochol, in the ESO Workshop on the Impact of Binaries on Stellar Evolution, ESO Garching, July 3-7, 2017, edited by G. Becari and H. M. J. Boffin (2017), Cambridge Univ.Press, Cambridge, 2019.
[15] I. M. Volkov, L. A. Bagaev, A. S. Kravtsova, and D. Chochol, Contributions of the Astronomical Observatory Skalnate Pleso 49, 434 (2019).
[16] J. C. Mermilliod, VizieR Online Data Catalog 2168 (1997).
[17] A. I. Khaliullina and K. F. Khaliullin, Soviet Ast. 28, 228 (1984).
[18] R. A. Wade and S. M. Rucinski, A&AS 60, 471 (1985).
[19] D. M. Popper, Astrophys. J. 254, 203 (1982).
[20] D. M. Popper, ARA&A 18, 115 (1980).
[21] K. F. Khaliullin, Astrophys. J. 299, 668 (1985).
[22] I. M. Volkov, D. Chochol, J. Grygar, M. Mašek, and J. Juryšek, Contributions of the Astronomical Observatory Skalnate Pleso 47, 29 (2017).
[23] I. M. Volkov and N. S. Volkova, Astronomical and Astrophysical Transactions 26, 129 (2007).
[24] K. F. Khaliullin and V. S. Kozyreva, Ap&SS 94, 115 (1983).
[25] G. Torres, C. H. S. Lacy, A. Claret, and J. A. Sabby, AJ 120, 3226 (2000), astro-ph/0008299.
[26] G. Torres, C. D. McGruder, R. J. Siverd, J. E. Rodriguez, J. Pepper, D. J. Stevens, K. G. Stassun, M. B. Lund, and D. James, Astrophys. J. 836, 177 (2017), 1612.02141.
[27] K. Pavlovski, J. Southworth, and V. Kolbas, ApJL 734, L29 (2011), 1104.2179.
[28] L. Girardi, A. Bressan, G. Bertelli, and C. Chiosi, A&AS 141, 371 (2000), astro-ph/9910164.
[29] X. Luri, A. G. A. Brown, L. M. Sarro, F. Arenou, C. A. L. Bailer-Jones, A. Castro-Ginard, J. de Bruijne, T. Prusti, C. Babusiaux, and H. E. Delgado, A&A 616, A9 (2018), 1804.09376.
[30] K. F. Khaliullin and A. I. Khaliullina, Soviet Ast. 33, 41 (1989).
[31] A. Claret, A&A 424, 919 (2004).
[32] T. Levi-Civita, American Journal of Mathematics 59, 225 (1937).
[33] A. Gimenez, Astrophys. J. 297, 405 (1985).
[34] N. I. Shakura, Soviet Astronomy Letters 11, 224 (1985).