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PHOTOMETRY, LIGHT CURVE SOLUTION AND PERIOD STUDY OF CONTACT BINARY BX AND

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SUMMARY: The photometry of the binary star BX And (HIP 10027) is performed during several nights in October and November 2019, and October 2020 using B, V, and R Johnson-Cousins filters in Dr. Mojtahedi Observatory of the University of Birjand. Astronomical image processing and data reduction are performed by the IRIS software and light curves are obtained. These curves, along with the radial velocity data of the binary star, are analyzed by the Phoebe program to determine the physical and geometric parameters of the system. The evolutionary state of this system is investigated using the Hertzsprung-Russell (H-R) and density vs color index diagrams. The O-C curve is plotted using the eclipse times obtained in this study and those reported in the literature. By fitting a quadratic function to this curve, a new linear ephemeris is obtained for the system, and the mass transfer rate between the components of the system is determined. A periodic behavior is observed in the residuals, after subtracting the quadratic function from the O-C curve. These periodic changes are attributed to the presence of a third component in the system. The parameters of the third component are determined by fitting the light-time function to the residuals curve.

Key words. Binaries: close – Binaries: eclipsing – Stars: individual: BX And – Techniques: photometric

1. INTRODUCTION

The binary system BX And (BD+40 442) was discovered by Soloviev (1945) as an Algol-type eclipsing binary system with an orbital period of 0.61 days. Moreover, this system is a brighter component of the visual binary ADS 1671. Ashbrook (1951) used 200 photographic images to show that the light changes of the system were similar to those of the β Lyrae systems. Gulmen et al. (1988) analyzed the O-C curve of eclipse times of this system and confirmed a change of 0.25 s per century in the orbital period of BX And as previously suggested by Ahnert (1975). The first radial velocity data and absolute parameters of this system were published by Bell et al. (1990). These authors showed that the primary component with a mass of 1.25 $M_\odot$ and radius of 1.78 $R_\odot$ has a luminosity of near the terminal age main sequence (TAMS). Additionally, they showed that the secondary component with a mass of 0.75 $M_\odot$ and radius of 1.3 $R_\odot$ is about 2 to 3 times larger than expected in the main sequence. Photometry and the light curve analysis of BX And were presented by Samec et al. (1989). These authors reported that BX And is a contact system with a fill-out factor of only 6%, which implies an early contact stage, so its components have a large temperature difference. Another photometric analysis of this system was performed by Kermani et al. (2005) who showed that the system is a detached binary. The light and radial velocity curves of this system and several other systems were analyzed by Siwak et al. (2010). These authors showed that BX And is a shallow contact binary. Furthermore, they added a hot spot on the equator of the secondary component to explain the asymmetry of the light curve at phases 0.3 and 0.7, but their spectroscopic examinations did not confirm the presence of a hot spot in this system. The orbital period changes of BX And were studied by Tvardovskyi and Marsakova (2015) and the presence of a third body in this system with a minimum mass of 0.5 $M_\odot$ was suggested.

2. PHOTOMETRY AND DATA REDUCTION

Photometry of the eclipsing binary star BX And was performed in B, V, and R Johnson-Cousins filters using SBIG-ST7 CCD connected to a 14-inch Schmidt-Cassegrain telescope, during several nights in October and November 2018, and October 2019 in Dr. Mojtahedi Observatory of the University of Birjand. The Maxim DL[1] software was used as interface between the CCD and the computer in the photometry. The star TYC 2833-53-1 was selected as the comparison star; the position and magnitude of this star and BX And are presented in Table 1.

The following linear ephemeris was used to calculate the orbital phase (Tvardovskyi and Marsakova 2015):

$$\text{Min } I(\text{HJD}) = 2452500.3462 + 0.61011357 \times E. \quad (1)$$

Image processing and data reduction were performed with the IRIS software (Build 2005), and the obtained light curves in the B, V, and R Johnson-Cousins filters are shown in Fig. 1.

3. LIGHT CURVE SOLUTION

The physical and geometrical parameters of the eclipsing binary BX And were determined using the Phoebe Legacy software (Prša and Zwitter 2005). We used the “overcontact binary not in the thermal contact” mode. The primary star temperature was selected to be $T_1 = 6650$ K, based on spectroscopic observations (Bell et al. 1990) as a fixed parameter. The initial value of the mass ratio, $q = 0.497$, was also chosen based on the radial velocity curve (Bell et al. 1990). The bolometric albedo and gravity darkening coefficients were selected as $A_1 = A_2 = 0.5$ (Rucinski 1969) and $g_1 = g_2 = 0.32$ (Lucy 1967), respectively, based on the primary component temperature ($T_1 < 7200$ K). The limb darkening coefficients were automatically calculated by the software based on the van Hamme tables (van Hamme 1993) and using logarithmic law.

Cold or hot spots were expected in this system due to the asymmetry in light curves at phases 0.25 and 0.75 (O’Connell 1951). We placed a cold spot on the surface of the secondary component and changed the position, temperature ratio, and size for better matching between observational data and theoretical light curves. Finally, the radial velocity and light curves were analyzed simultaneously. The results of this analysis are given in Table 2, where i, $V_{\rm com}$, Ω , L, and r, are the orbital inclination, center of mass velocity, Roche potential, luminosity, and relative radii of the stars, respectively; $f_{\rm over} = (\Omega_{\rm in} - \Omega)/(\Omega_{\rm in} - \Omega_{\rm out})$ is the fillout factor. Moreover, the results reported by other researchers are given in this table for comparison. Figs. 1 and 2 show the simulated light curves in the B, V, and R filters and theoretical radial velocity curves (without proximity effect), respectively. The three-dimensional configuration of the BX And system with a cold spot on the secondary star at phase 0.75 is shown in Fig. 3.

We used K_1 and K_2 obtained from the theoretical radial velocity curves (Fig. 2) to calculate the absolute geometrical and physical parameters of the BX And components. These results are presented in Table 3 along with the results reported by other researchers for comparison.

4. EVOLUTIONARY STATE INVESTIGATION

One of the most useful and powerful tools for studying the evolutionary status of stars is the Hertzsprung-Russell (H-R) diagram. Fig. 4 shows the position of the primary and secondary components of BX And in this diagram. Furthermore, some contact binary stars with a large temperature difference between their components (CLdTs) and near-contact binaries are shown for comparison (Kreiner et al. 2006). In this figure, the zero-age main sequence (ZAMS) and TAMS[2] lines are plotted for solar metallicity. The positions of the primary and secondary components in the H-R diagram indicate that the primary component has not yet evolved but the secondary component left the main sequence towards the giants.

The evolutionary status of stars can be examined further by finding their positions in the density vs color index diagram (Mochnacki 1981). To use this diagram for components of contact binary systems, the actual temperature of the components must be used. In contact binaries, a common envelope covers both components and prevents observing the actual temperature, so we modified the temperature of the primary and secondary components based on the following relationships (Hilditch et al. 1988):

[1] http://diffractionlimited.com

[2] ZAMS and TAMS lines were obtained using MESA-Web http://Mesa-Web.asu.edu

Table 1: Position and magnitude of variable and comparison stars*.

Star	RA	Dec	Magnitude (V)
BX And (Variable)	2h 9m 2.20s	+40° 47′ 39.16″	8.98
TYC 2833-53-1 (Comparison)	2h 9m 4.91s	+40° 47′ 49.18″	10.5

* Coordinates taken from: http://simbad.u-strasbg.ft/simbad/

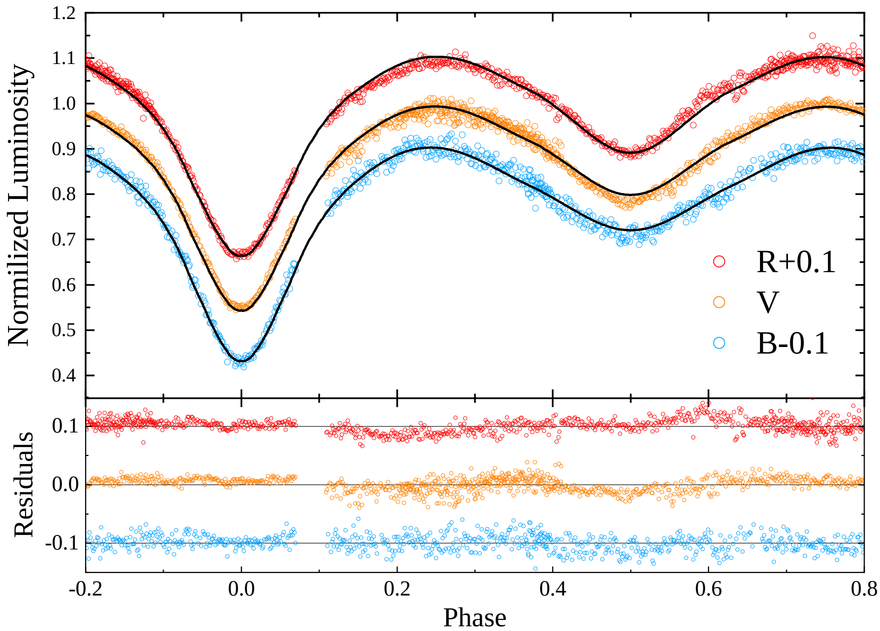

Fig. 1: Light curves of the BX And in three B, V, and R filters. The points represent the observational data and the solid lines are the simulated curves.

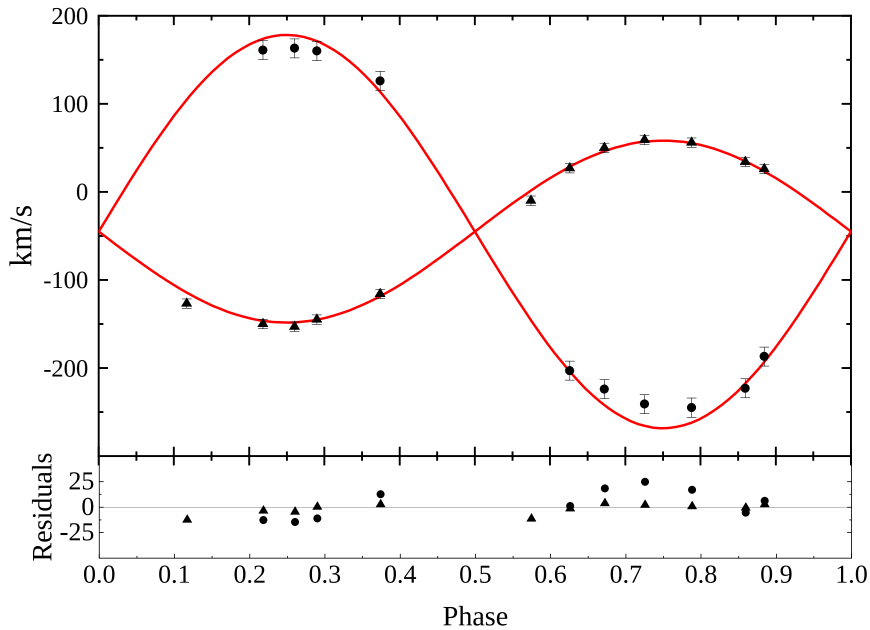

Fig. 2: Radial velocity curves of BX And. Points represent data obtained by Bell et al. (1990) and solid lines are theoretical curves.

Table 2: Parameters obtained from the light curve solution in this work and reported by others for BX And.

Parameter	B+V+R+radial velocity data	(Samec et al. 1989)	(Siwak et al. 2010)
$i(^\circ)$	75.82(4)	75.6(3)	75.862(33)
$V_{\rm com}$ (km/s)	45.18(30)	-	-
$q(M_2/M_1)$	0.4742(9)	0.623(4)	0.455(8)
Ω_1=Ω_2	2.8150(25)	3.085(56)	2.7760(5)
T_1(K)	6650	6500	6650
T_2(K)	4843(11)	4637(14)	4758(5)
$(L_1/L_1+L_2)_B$	0.94(2)	-	-
$(L_1/L_1+L_2)_V$	0.91(3)	-	-
$(L_1/L_1+L_2)_R$	0.88(3)	-	-
r_1(pole)	0.42(17)	0.3990(15)	-
r_1(side)	0.45(22)	0.427(2)	-
r_1(back)	0.47(29)	0.454(3)	-
r_2(pole)	0.30(18)	0.3205(11)	-
r_2(side)	0.31(21)	0.336(1)	-
r_2(back)	0.34(33)	0.370(2)	-
$f_{\rm over}$(%)	1.85	6	4.5
$\sqrt{\frac{\sum(O-C)^2}{N}}$	0.01255	0.007964	-
Spot Parameters			
$\frac{T}{T_2}$	0.90 (1)	-	1.177 (15)
Radius (rad)	0.87 (17)	-	0.34 (2)
Longitude (rad)	1.571 (17)	-	0.052 (8)
Latitude (rad)	4.712 (17)	-	1.57

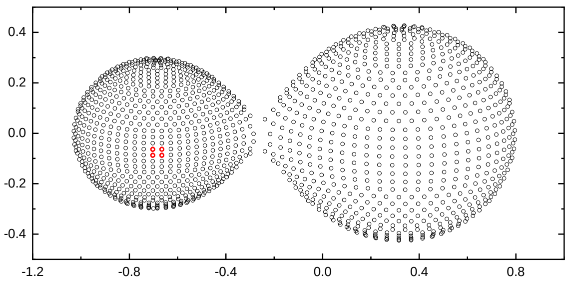

Fig. 3: Three-dimensional configuration of BX And at phase 0.75. The position of the cold spot on the surface of the secondary star is also illustrated.

$$T'_1 = 10^{(0.05+\log T_1)}, \quad (2)$$

$$T'_2 = 10^{(-0.09+\log T_2)}, \quad (3)$$

where T'_1 and T'_2 are the temperatures of the primary and secondary components, respectively, after correction, and from now on, are denoted by T_1 and T_2. After applying the corrections, the temperatures of the primary and secondary components were obtained as T_1=7464.5 K and T_2=3935.5 K, respectively. The $B-V$ color indices of these stars, $(B-V)_1$=0.413 and $(B-V)_2$=1.015, were obtained using tables reported in (Worthey and Lee 2011). Fig. 5 shows positions of the primary and secondary components of BX And in the density vs color index diagram. Additionally, the ZAMS and TAMS lines are plotted to better identify the evolutionary status of the stars. As can be seen in this figure, the primary component is in the main sequence near the TAMS, while the secondary component has evolved and left the main sequence towards the subgiant stage. Thus, the results of Figs. 4 and 5 are in good agreement.

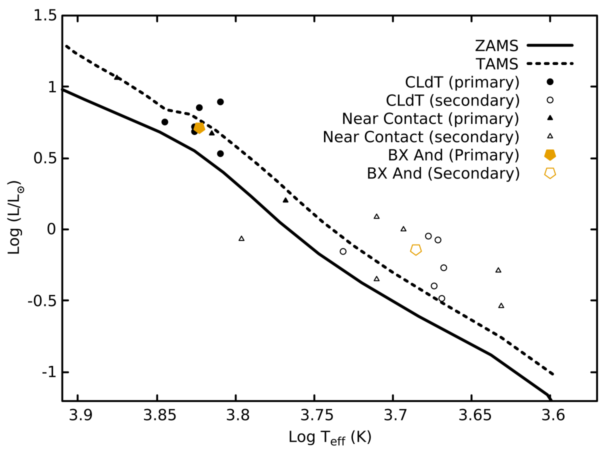

Fig. 4: Positions of primary and secondary components of the BX And in H-R diagram. Some other near-contact binaries and CLdT systems are shown for comparison.

Table 3: Absolute parameters of BX And.

Parameter	This study	(Bell et al. 1990)	(Siwak et al. 2010)
K_1(km/s)	97.97(5.39)	105.5(1.9)	106.35(0.61)
K_2(km/s)	210.43 (12.96)	212.3(4.0)	233.58(1.77)
M_1($M_\odot$)	1.39 (29)	1.52(5)	2.148 (52)
R_1($R_\odot$)	1.54 (11)	1.78(3)	2.01 (5)
L_1($L_\odot$)	4.19 (59)	6.17(75)	7.08
M_2($M_\odot$)	0.65 (13)	0.75(3)	0.977 (41)
R_2($R_\odot$)	1.15 (8)	1.30(3)	1.40
L_2($L_\odot$)	0.663 (98)	0.63(11)	0.90
a($R_\odot$)	3.84 (26)	3.97(11)	4.424 (36)

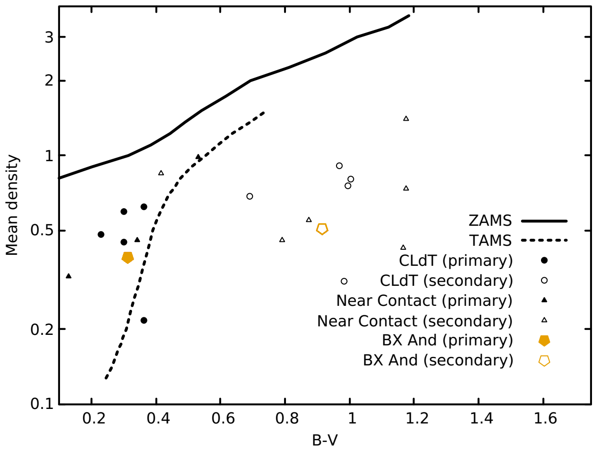

Fig. 5: Positions of the BX And binary system components in the density vs color index diagram based on the modified temperature of each component. The ZAMS and TAMS lines adapted from Worthey and Lee (2011).

Eker et al. (2006) statistically analyzed 119 chromospherically active binaries (CAB_s) and 102 W UMa binaries. These authors determined the relation between the critical orbital angular momentum, J, and the total mass of the binary system, $M(M_\odot) = M_1 + M_2$, as follow:

$$\log J_{\rm cr} = 0.522(\log M)^2 + 1.664(\log M) + 51.315. \quad (4)$$

Most detached (contact) binary systems have angular momenta larger (smaller) than this critical angular momentum. The orbital angular momentum of BX And was calculated using the following equation (Hu et al. 2018):

$$J = \frac{q}{(1+q)^2}\left[\frac{G^2(M_1+M_2)^5 P}{2\pi}\right]^{\frac{1}{3}}, \quad (5)$$

where P, G, q, M_1 and M_2 are the period, gravitational constant, mass ratio, primary mass and secondary mass, respectively. Using the values obtained in this study, $\log J = 51.97$ was obtained for this system. Fig. 6 shows BX And below the critical orbital angular momentum line, $J_{\rm cr}$, so it is confirmed that the components of BX And are in contact.

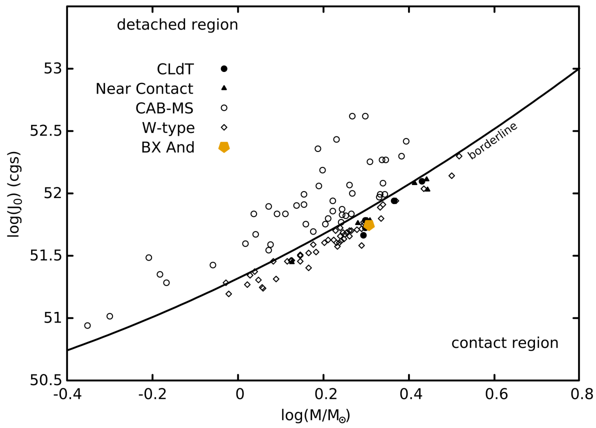

Fig. 6: Position of BX And in the $\log(J_{\rm cr})$ vs $\log(M)$ diagram.

5. ORBITAL PERIOD

We obtained some primary and secondary eclipse times for BX And during our observations. These minima times are presented in Table 4.

We collected all BX And CCD and photoelectric eclipse times from the O-C gateway[3] and AAVSO[4] databases. After removing the overlap between these data, we used only photoelectric and CCD data due to higher accuracy of CCD and photoelectric data compared to visual/photographic data, and the availability of these data over a long period of time (about 50 years). The O-C curves of this system (Fig. 7) were plotted using these data and minima times reported in Table 4. The epoch and O-C were calculated using the following linear ephemeris [5]:

[3]http://var2.astro.cz/ocgate/

[4]www.aavso.org

[5]https://www.as.up.krakow.pl/o-c/

Table 4: Primary and secondary eclipse times obtained in this work.

Filter	(HJD)	Type
B	2458779.27249(64)	II
	2458760.35929(61)	II
	2458426.32550(15)	I
	2458408.32725(834)	II
	2458404.36162(297)	I
V	2458779.27229(23)	II
	2458760.35775(7)	II
	2458426.32591(8)	I
	2458408.32893(42)	II
	2458404.36272(1)	I
	2458372.33028(73)	II
R	2458779.27193(24)	II
	2458760.35831(26)	II
	2458426.30319(16)	I
	2458408.33595(28)	II
	2458404.36141(596)	I
	2458372.33175(793)	II

$$\text{Min } I(\text{HJD}) = 2447434.5779 + 0.61011419 \times E. \quad (6)$$

The O-C changes of the primary and secondary eclipse times are the same, so this binary system does not have apsidal motion, as expected. A quadratic function was fitted to the O-C curve and its coefficients were obtained using the least-squares method. The results are presented in Table 5 and the final quadratic function is shown in Fig. 7.

Table 5: Coefficients of the quadratic function ($\mathrm{O} - \mathrm{C} = C_0 + C_1 \times E + C_2 \times E^2$) fitted to the O-C curve.

Coefficient	Value
C_0	0.00806(88)
C_1	-3.04096(1.4)$\times 10^{-7}$
C_2	-2.080(74)$\times 10^{-10}$

Orbital period change rate, $\dot{P} = -2.49(9) \times 10^{-7}$ (day/year), can be determined using these coefficients based on the following equation (Hilditch 2001):

$$\dot{P} = \frac{dP}{dt} = 2\frac{C_2}{P_{\rm le}}. \quad (7)$$

Where $P_{\rm le}$ is the base period accepted.

Additionally, a new linear ephemeris for BX And can be obtained based on the method proposed by Kalimeris et al. (1994) as follows:

$$\text{Min } I(\text{HJD}) = 2458426.3255(2) + 0.61010639(4) \times E. \quad (8)$$

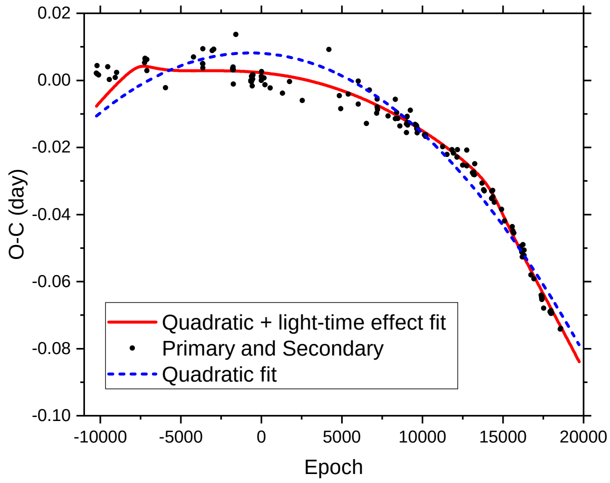

Fig. 7: O-C curve of eclipse times for BX And. The dashed line demonstrates a quadratic function fitted to the O-C data and the solid line shows both the quadratic function and light-time effect.

The mass transfer rate between the two components was determined as $\dot{m}_1 = -\dot{m}_2 = -1.67(27) \times 10^{-7}$ ($M_\odot$/year) by assuming mass conservation and using the following equation (Hilditch 2001):

$$\frac{\dot{P}}{P} = 3\frac{\dot{m}_1(m_1 - m_2)}{m_1 m_2}. \quad (9)$$

After subtracting the quadratic function from the O-C data, a periodic behavior was observed in the residuals (Fig. 8). The period of these changes was determined to be 34.8 years by using Period04 software (Lenz and Breger 2005). We assume that these changes are caused by the presence of a third body and the light-time effect due to the long periodicity of the O-C residuals. According to the method proposed by Irwin (1959), Eq. (10) was used to calculate the light-time effect of the third body in BX And:

$$\tau = k\frac{1}{\sqrt{1 - e^2\cos^2\omega}}\left[\frac{1 - e^2}{1 - e\cos\nu}\sin(\nu + \omega) + e\sin\omega\right]. \quad (10)$$

where k, ν, e, and ω are the amplitude of changes in the residuals, true anomaly, eccentricity, and longitude of the periastron of the third body orbit, respectively. We fitted Eq. (10) to the residuals using the least-squares method and the final results are shown in the top panel of Fig. 8. The final residuals are illustrated in the bottom panel of this figure. Moreover, the sum of the quadratic function and light-time effect is shown in Fig. 7. The orbital and physical parameters of the third body are reported in Table 6 where a_{12} is the semimajor axis of the orbit of binary stars around the center of mass of the ternary system and T_0.

Table 6: Orbital and physical parameters of the third body.

Parameter	Value
e	0.688(6)
$\omega(^\circ)$	125(7)
K(day)	0.0058(1)
T_0(HJD)	2442934
$a_{12}\sin i$(AU)	1.10(6)
$f(M_3)$	0.0010(2)
$(M_3)_{\min}(M_\odot)$	0.17(1)
P_3(year)	36.34

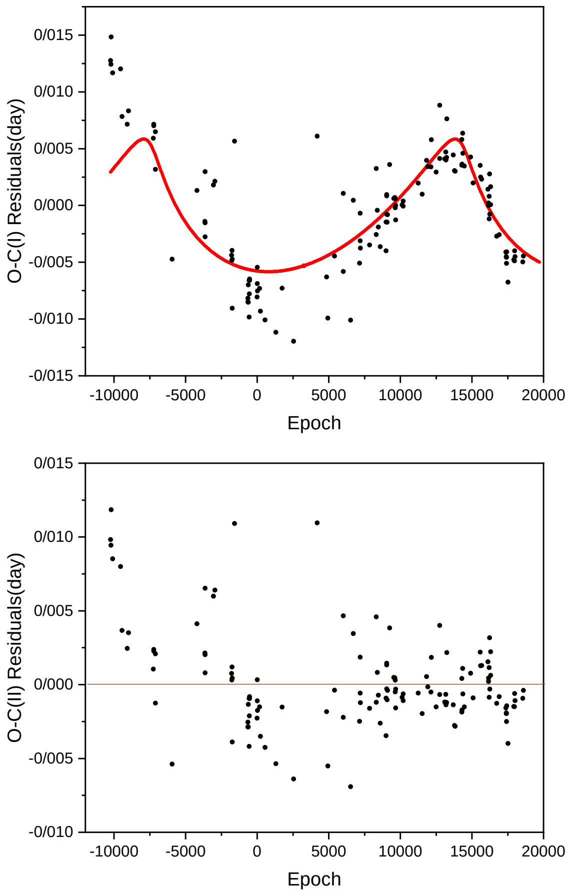

Fig. 8: Top: the light-time function (solid line) fitted to the O-C residuals data. Bottom: final residuals after eliminating the quadratic function and the light-time effect from the O-C data.

6. DISCUSSION AND CONCLUSIONS

We performed the photometry analysis of the BX And binary system and obtained its light curves in the B, V, and R Johnson-Cousin filters. The geometrical and physical parameters of this system were obtained by the simultaneous analysis of light and radial velocity curves. The asymmetry of the light curves at phases 0.25 and 0.75 was explained by adding a cold spot on the surface of the secondary component. These results are given in Tables 2 and 3. These tables also report the parameters obtained by other researchers. In Table 2, a relatively good agreement can be seen between the results of our study and theirs. While in Table 3, there exist gaps between the values obtained from this study and Siwak et al. (2010). The main reason for the dissimilarity of the values can be the difference between the values of K_1 and K_2 used in the two studies. As noted in Siwak et al. (2010), the broadening function (BF) profiles method was used to measure the radial velocity from their spectroscopy, while Bell et al. (1990) used the cross-correlation function (CCF) method to do this (we used this data). We know that the BF method produces larger values for K_1 and K_2 than the CCF method (Siwak et al. 2010).

We showed that BX And is a shallow contact binary, according to the filling factor, $f_{\rm over} = 1.85\%$, obtained from the analysis of the light curves. The evolutionary state of BX And was investigated to address the doubts about its geometry. The positions of the BX And components in H-R and density vs color index diagrams (Figs. 4 and 5) indicate that the primary star is near the TAMS and the secondary star has left the main sequence towards giants. The position of this system in the diagram of orbital angular momentum vs total mass (Fig. 6) confirms that the components of BX And are in contact.

The orbital period changes of BX And were studied by fitting a quadratic function to the O-C data, we obtained that the orbital period of this system decreases at the rate of 2.2 seconds per century, and 1.64×10^{-7}M$_\odot$ for the mass transfer rate in this system, as the cause of these period changes. Moreover, a new linear ephemeris were obtained for this system. We observed a periodic behavior in the residuals and attributed this to the presence of a third body whose orbital and physical parameters were obtained. The obtained minimum mass of the third body, $0.17M_\odot$, indicates that it may be an M7V dwarf star. According to the official tables (Carroll and Ostlie 2014), the luminosity of an M7V dwarf star is approximately 0.0025 $L_\odot$, so the effect of luminosity of the third body is absent in light curves of the BX And system. After eliminating the quadratic function and light-time effect from the O-C data (bottom panel of Fig. 8), we cannot see any systematic behavior and the data points are randomly scattered around zero lines. Therefore, it seems that probably no other factor changes the orbital period of the eclipsing binary system BX And, so we need more accurate data to reveal the effects with shorter periods or smaller amplitudes.

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ФОТОМЕТРИЈА, РЕШЕЊЕ КРИВЕ СЈАЈА И СТУДИЈА ПЕРИОДИЧНОСТИ ТЕСНОГ ДВОЈНОГ СИСТЕМА BX AND

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Оригинални научни рад

Фотометрија двојне звезде BX And (HIP 10027) извршена је током неколико ноћи у октобру и новембру 2019. и октобру 2020. године, користећи B, V и R Џонсон-Казинс филтере на опсерваторији Др Мојтахеди Универзитета у Бирџанду. Астрономска обрада и редукција урађена је користећи софтвер IRIS и добијене су криве сјаја. Ове криве заједно са подацима о радијалним брзинама двојне звезде анализирани су софтверским пакетом Фиби (Phoebe) да одреде физичке и геометријске параметре система. Еволуционо стање система истражено је користећи Херцпрунг-Раселов $(H-R)$ и густина-колор индекс дијаграм. $O-C$ крива је представљена користећи времена помрачења добијена у овој студији и она из литературе. Фитујући ову криву квадратном функцијом добијена је нова линеарна ефемерида за систем, и одређена је стопа трансфера масе међу компонентама. Примећена је периодичност у резидуалима након одузимања квадратне функције од $O-C$ криве. Ове периодичне промене приписују се присуству треће компоненте у систему. Параметри за трећу компоненту су одређени фитовањем резидуала криве сјаја функцијом светлосног кашњења.