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First photometric analysis of magnetic activity and orbital period variations for the semi-detached binary BU Vulpeculae

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Abstract

Four sets of multi-color CCD photometric observations of the close binary BU Vul were carried out for four successive months in 2010. From our observations, there are obvious variations and asymmetry of light curves on the timescale of a month, indicating high-level stellar spot activity on the surface of at least one component. The Wilson–Devinney (2010) program was used to determine the photometric solutions, which suggest that BU Vul is a semi-detached binary with the cool, less massive component filling with the critical Roche lobe. The solutions also reveal that the spots on the primary and the secondary have changed and drifted in 2010 July, August, and September. Based on analysis of the $O - C$ curves of BU Vul, its orbital period shows a cyclic oscillation ($T_3 = 22.4\,\mathrm{yr}$, $A_3 = 0.0029\,\mathrm{d}$) superimposed on a secular increase. The continuous increase is possibly a result of mass transfer from the less massive component to the more massive one at a rate of $dM/dt = -2.95 \times 10^{-9}\,M_\odot\,\mathrm{yr}^{-1}$. The cyclic variation maybe be caused by the presence of a tertiary companion with extremely low luminosity. Combined with the distortions of the light curve on 2009 November 4, we infer that BU Vul has two additional companions in a quadruple system.

Key words: stars: activity — stars: binaries: eclipsing — stars: evolution — stars: solar-type

1 Introduction

Algol-type eclipsing binaries are important astrophysical laboratories for understanding intrinsic variations (Cook 1993), mass transfer (Qian & Zhu 2002), third bodies (Zavala et al. 2002; Hoffman et al. 2006; Liao & Qian 2010), and angular momentum loss (Qian 2000a, 2000b, 2001). Because of synchronization between the rotational period and the orbital period in Algol systems (Richards & Albright 1993), the rapidly rotating Solar-type components have enhanced magnetic activities (Olson 1987; Olson & Etzel 1993; Richards & Albright 1993), which have been investigated from the distortions of light curves (Samec et al. 2015; Zhang et al. 2014a, 2014b). It is diffcult to study most Algol binaries with longer orbital periods. The Algol-like binary BU Vul has a period of 0.568993 d (Brancewicz & Dworak 1980), and the short period and fast rotation is helpful for understanding magnetic activity and stellar evolution in Algol-type binaries.

BU Vulpeculae ($\alpha_{J2000.0} = 20^{h}46^{m}18\overset{s}{.}87$, $\delta_{J2000.0} = +28^{\circ}15'44\overset{''}{.}35$) was the subject of photographic observations by Guthnick and Schneller (1939), who determined its period to be 5.59 d. Whitney (1959) revised the period to 0.5689926 d. Later, Koch (1974) argued that BU Vul is possibly an Algol-like binary. Brancewicz and Dworak (1980) suggested that BU Vul is a detached binary with $M_1 = 1.11\,M_{\odot}$, $M_2 = 0.86\,M_{\odot}$, $T_1 = 5980$ K, $T_2 = 5830$ K, period = 0.568993 d. According to visual observations of primary eclipses, weak light curve shape changes in a month were confirmed by Cook (1993). But, he asserted that there were variations in the light curves of BU Vul from 1984 to 1993, which variations are explained by star-spot activity as per the members of RS CVn binaries.

Due to the lack of high-quality observations, the crucial parameters and activity of BU Vul are still uncertain. We monitored this system for four continuous months in 2010. It is a good chance to make a detailed analysis of BU Vul.

2 Observations

The CCD photometric observations of BU Vul were carried out in 2010 June, July, August, and September with the 85 cm reflecting telescope at Xinglong Station of the National Astronomical Observatories of the Chinese Academy of Sciences (NAOC). This telescope is equipped with a 1024 × 1024 BFT CCD camera, and the effective field of view (FOV) was $16\overset{'}{.}5 \times 16\overset{'}{.}5$. The filter system was a standard Johnson–Cousins–Bessell multi-color photometric system built on the primary focus (Zhou et al. 2009). To get more times of light minimum, we also monitored it with the 60 cm and 1.0 m telescopes at Yunnan Observatories (YNO). These two telescopes were equipped with the same Cassegrain-focus multi-color CCD photometer, where an Andor DW436 2K CCD camera was used. Two stars near BU Vul in the CCD field of view, TYC 2182-2120 and TYC 2182-639, were chosen as the comparison star and the check star. The mean photometric errors of individual observations are 0.005 mag in the B band, 0.004 mag in the V band, and 0.003 mag in the $R_c I_c$ bands. All the light curves are displayed in figure 1; some CCD times of minimum light were determined, and are listed in table 1.

Because of the bad sky conditions and a telescope filter breakdown, we did not obtain the complete light curves in 2010 June, July, and August. But, fortunately, noticeable variations were found. From figure 1, not only did the magnitudes of Min II (at a phase of 0.50) change obviously, but Max I (at a phase of 0.25) and Max II (at a phase of 0.75) also did. These variations of light curves and the asymmetries at maximum light are remarkable, indicating high-level stellar spot activities on the surface of at least one component. The intrinsic variations of BU Vul are obtained for the first time by high-quality CCD observations, which confirmed the curve shape change in a month (Cook 1993). It is possible that a component of this system may be an active dynamo star.

3 Photometric solutions with the W–D program

Owning to the lack of high-quality observations and complete light curves, the configuration and evolution of BU Vul are uncertain. Our light curves obtained in 2010 are important for understanding this system. The photometric solutions have been derived with the Wilson–Devinney program, version 2010 (Wilson & Devinney 1971; Wilson 1979, 1990, 2008; Van Hamme & Wilson 2007), which is a very useful tool for analyzing eclipsing binary parameters (contains spot parameters). This version of the W–D code does not need to input limb-darkening coefficients by band; the program itself can automatically input them with the subroutine LIMDARK, which is based on the limb-darkening tables calculated with the method of Van Hamme (1993).

We have assumed synchronous rotation and zero eccentricity for BU Vul. The temperature for the primary (star eclipsed at primary light minimum) was fixed to be $T_1 = 5940$ K (Cox 2000), corresponding to the G0 spectral type presented by Kharchenko (2001) and Avvakumova, Malkov, and Kniazev (2013). Considering the convective atmospheres of the components, the same values of the gravity-darkening coefficients and the bolometric albedo, i.e., $g_1 = g_2 = 0.32$ (Lucy 1967) and $A_1 = A_2 = 0.5$ (Ruciński 1969), were taken into the model.

The complete BVR_cI_c-band light curves observed in 2010 September are used to look for a suitable mass ratio $q = M_2/M_1$ (the secondary divided by the primary). In this process, we tried to use mode 2 (detached), mode 3 (contact), mode 4 (semi-detached, primary filling with Roche lobe), mode 5 (semi-detached, secondary filling with Roche lobe) to analyze the configuration. However, only mode 5 gave us converged results, which suggests that BU Vul is a semi-detached binary in which the secondary is filling with the critical Roche lobe. The relations between the sum of the squared residuals $\sum[\omega_i(O - C)_i]^2$ and q are displayed in figure 2, which also shows that the grid search used a 0.01 step. The minimum residuals were located at $q = 0.37$ and $q = 1.88$ with differential correction (DC) code. If the secondary has much more mass with $q = 1.88$, this system would be at the stage of instantaneous mass transfer, and the orbital period will vary instantaneously (Zhang & Qian

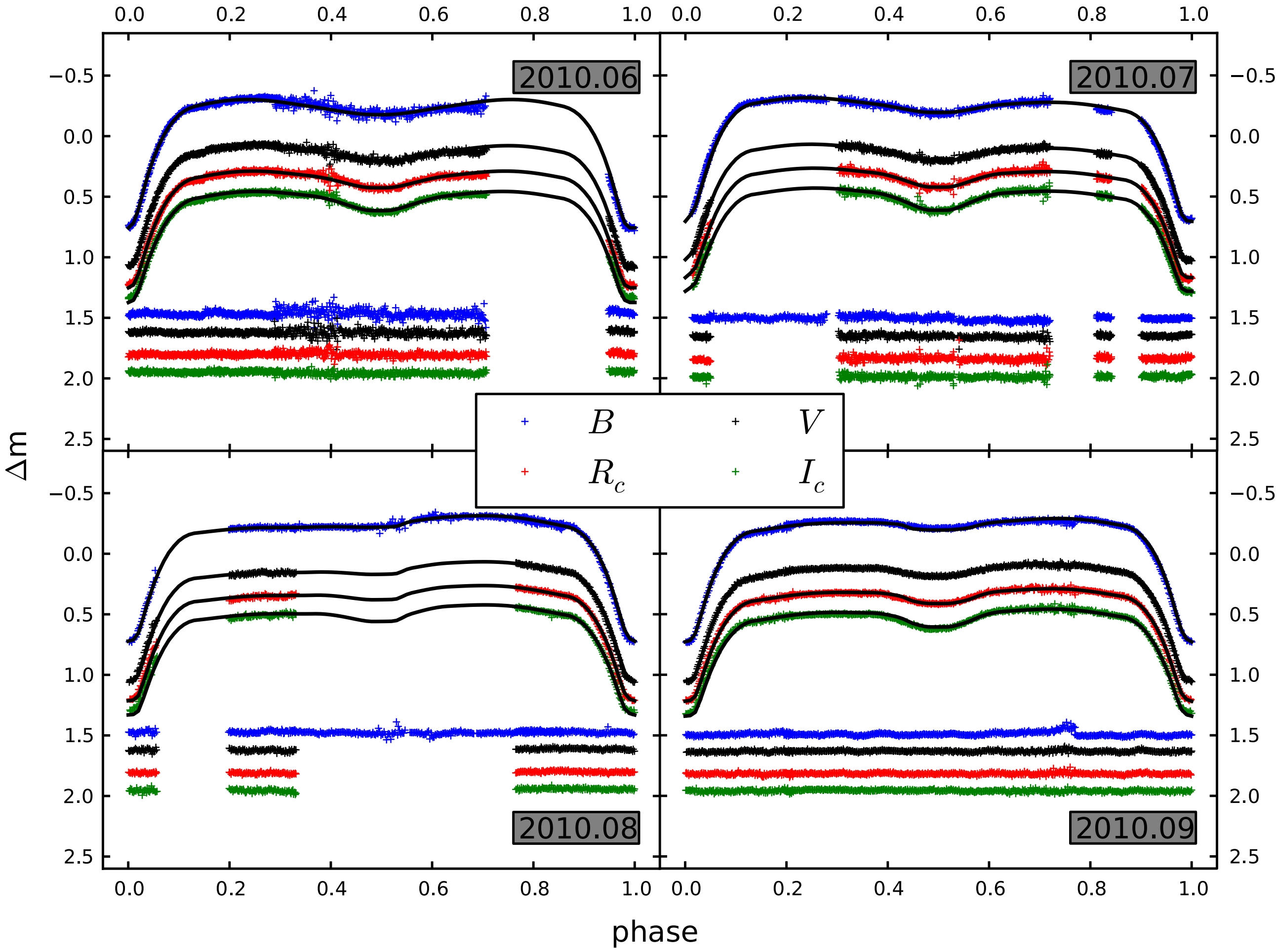

Fig. 1. *BVR*c*I*c-band observations of BU Vul in 2010 June, July, August, and September with the 85 cm telescope at Xinglong Station. For each subgraph: (Top) The blue plus signs denote the *B*-band light curve, the black the *V*-band, the red the R_c-band, and the green the I_c-band; the solid lines represent the theoretical fits calculated with the W–D (2010) program. (Bottom) BVR_cI_c-band magnitudes of the comparison star minus the check star. (Color online)

Table 1. Our CCD times of minimum light.

HJD (d)	Error (d)	Min.	Telescope	HJD (d)	Error (d)	Min.	Telescope
2455136.08902	0.00039	I	YNO 1.0 m	2455380.18545	0.00007	I	NAOC 85 cm
2455140.07083	0.00005	I	YNO 60 cm	2455386.16146	0.00051	II	NAOC 85 cm
2455159.98680	0.00012	I	YNO 60 cm	2455438.22476	0.00010	I	NAOC 85 cm
2455163.96880	0.00012	I	YNO 60 cm	2455450.17404	0.00009	I	NAOC 85 cm
2455336.37563	0.00012	I	NAOC 85 cm	2455451.02672	0.00075	II	NAOC 85 cm
2455171.93419	0.00039	I	NAOC 85 cm	2455452.16308	0.00036	II	NAOC 85 cm
2455372.21934	0.00007	I	NAOC 85 cm	2455726.13552	0.00020	I	NAOC 85 cm
2455374.21534	0.00069	II	NAOC 85 cm				

2013). But, we did not find this phenomenon in the $O-C$ diagram (next section). Therefore, $q = 0.37$ is the optimum mass ratio from our search. The final mass ratio q of photometric solutions will change a bit around $q = 0.37$ when we set the mass ratio as a free parameter.

According to the variations and asymmetries in different observing months, it is inferred that there are stellar spot regions on the surface of at least one component, e.g. AD Cnc (Qian et al. 2007), BI CVn (Qian et al. 2008), RZ Com (Qian & He 2007), DD Com (Zhu et al. 2010). Therefore, our light curves were also analyzed with a spot model. When testing solutions, we added the cool spots and hot spots into the individual observations every month. In adjusting the parameters, we tried many times to make the minimum

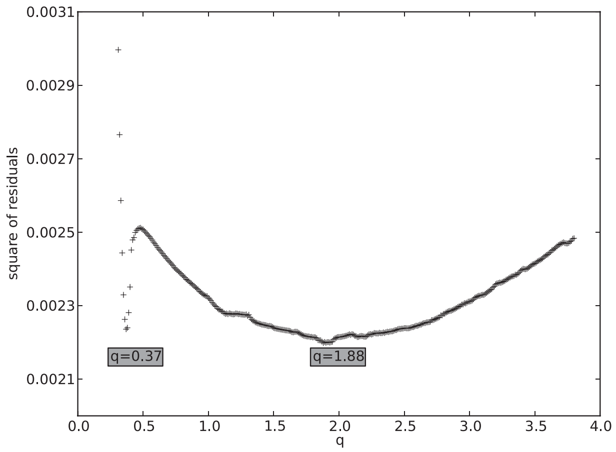

Fig. 2. q vs. squared residuals Σ for BU Vul with light curve from 2010 September.

numbers of stellar spots fit these light curves, but no converged solutions were determined. Thus, the final solutions with some spots are the best-fit results for light curves over several months. The different configurations of spots determined were: one cool spot on the primary for the light curves in July; two cool spots and one hot spot on the primary, one hot spot on the secondary for August; two cool spots on the primary, two hot spots on the secondary for September. The photometric solutions are listed in table 2, and the corresponding configurations of BU Vul at the 0.25, 0.75 phases are displayed in figure 3. The theoretical and observational light curves are shown in figure 1.

4 The $O - C$ changes of BU Vul

Many eclipsing binary systems show long-term variations in their orbital periods. These changes are typically displayed in an $O - C$ (observed minus calculated times) diagram, which maybe provide further information about the stellar evolution of binary systems, i.e., mass transfer, magnetic activity, and tertiary stars. Of course, Algol-type binaries are included, like FG Gem (Zhang & Qian 2013), XX Cep (Hoffman et al. 2006), Y Cam (Hoffman et al. 2006), and V404 And (Zhang et al. 2014b).

Times of minimum light for BU Vul have been obtained since 1931, covering over 56000 orbital cycles. Besides th eCCD times obtained from the literature (list in table 3), other visual and photographic ones can be found in the database of the $O - C$ gateway (Paschke & Brát 2006). We combined our new CCD times (listed in table 1) with those collected ones to analyze $O - C$ changes.

The $(O - C)_1$ were calculated with respect to the ephemeris equation,

$$\mathrm{Min.\,I(HJD)} = 2455450.17404 + 0^{\mathrm{d}}.5689935 \times E, \quad (1)$$

and are plotted in the top panel of figure 4. The open circles refer to visual and photographic data, and the solid ones to photoelectric and CCD data.

To find the best way to fit $(O - C)_1$, we assigned weight 1 to photographic or visual observations and weight 10 to photoelectric or CCD ones, and then performed some tests such as linear ephemeris term, quadratic term, and cyclic term to fit all of these data. The residuals of the different fitting methods are listed in table 4, suggesting the cyclic plus quadratic ephemerises to be reliable. Finally, a periodic term superposed on the quadratic increase is required; the least-square result yields

$$\begin{aligned}\mathrm{Min.\,I(HJD)} = {} & 2455450.17295(\pm 0.00032) \\ & + 0^{\mathrm{d}}.56899389(\pm 0.00000007) \times E \\ & + 6.01(\pm 1.93) \times 10^{-12} \times E^2 \\ & - 0.0029(\pm 0.0014) \sin[0^{\circ}.025 \times E \\ & + 21^{\circ}.5(\pm 7^{\circ}.4)]. \quad (2)\end{aligned}$$

The quadratic term in equation (2) indicates a long-term period increase at a rate of $dP/dt = +7.7(\pm 2.5) \times 10^{-9}\,\mathrm{d}^{-1}$. The cyclic variation is shown in the middle panel of figure 4, which reveals a periodic variation with an amplitude of $A_3 = 0.0029$ d and a period of $T_3 = 22.4$ yr. The residuals from equation (2) are shown in the bottom panel of figure 4, which illustrates that this equation can give a good fit to the $O - C$ curve.

5 Discussions and conclusions

Based on the light curve, Koch (1974) argued only that BU Vul is possibly an Algol-like binary, but without a detailed analysis. Brancewicz and Dworak (1980) suggested that this system is a detached binary by the iterative method for computation of geometric and physical parameters of some eclipsing binary stars. We first obtained the complete multi-color CCD photometric observations, and also analyzed its configuration. Photometric solutions of the close binary BU Vul were obtained with the W–D (2010) program. The solutions suggest that BU Vul is a semi-detached binary in which the cooler, less massive component is filling the critical Roche lobe. According to *Allen's Astrophysical Quantities* (Cox 2000), the calibrated primary mass in main sequence stars of G0 spectral type is determined as $M_1 = 1.05\,M_{\odot}$. Based on the mean mass ratio $q_{\mathrm{mean}} = 0.384$ of four sets of solutions in different months, the secondary mass is estimated as $M_2 = 0.40\,M_{\odot}$.

Comparing the light curves (LCs) for different times, Zhang, Pi, and Yang (2014a) found the LCs to be variable over several years for NSVS 02502726, NSVS 07453183,

Table 2. *BVR*$_c$*I*$_c$-band photometric solutions of BU Vul.*

Parameters	June	July	August	September
i	88.39 ± 0.24	89.57 ± 0.14	88.70 ± 0.26	89.66 ± 0.14
q (M_2/M_1)	0.417 ± 0.001	0.365 ± 0.001	0.366 ± 0.002	0.386 ± 0.001
T_1 (K)	5940	5940	5940	5940
T_2 (K)	3588 ± 18	3942 ± 11	3454 ± 21	3676 ± 11
$g_1 = g_2$	0.32	0.32	0.32	0.32
$A_1 = A_2$	0.50	0.50	0.50	0.50
Ω_1	2.8968 ± 0.0027	2.8637 ± 0.0033	2.8592 ± 0.0031	2.8643 ± 0.0020
Ω_2	2.7126	2.6058	2.6079	2.6494
$L_1/(L_1+L_2)(B)$	0.9906 ± 0.0008	0.9791 ± 0.0008	0.9938 ± 0.0010	0.9886 ± 0.0007
$L_1/(L_1+L_2)(V)$	0.9803 ± 0.0012	0.9605 ± 0.0012	0.9865 ± 0.0016	0.9766 ± 0.0009
$L_1/(L_1+L_2)(R_c)$	0.9679 ± 0.0016	0.9398 ± 0.0014	0.9773 ± 0.0020	0.9626 ± 0.0011
$L_1/(L_1+L_2)(I_c)$	0.9479 ± 0.0019	0.9159 ± 0.0015	0.9607 ± 0.0024	0.9417 ± 0.0013
r_1 (pole)	0.3986 ± 0.0005	0.3964 ± 0.0005	0.3970 ± 0.0005	0.3991 ± 0.0003
r_1 (point)	0.4625 ± 0.0012	0.4494 ± 0.0011	0.4507 ± 0.0011	0.4581 ± 0.0008
r_1 (side)	0.4189 ± 0.0006	0.4154 ± 0.0007	0.4162 ± 0.0007	0.4191 ± 0.0004
r_1 (back)	0.4369 ± 0.0007	0.4304 ± 0.0008	0.4314 ± 0.0008	0.4357 ± 0.0005
r_2 (pole)	0.2856 ± 0.0003	0.2757 ± 0.0003	0.2759 ± 0.0003	0.2799 ± 0.0002
r_2 (point)	0.4110 ± 0.0003	0.3982 ± 0.0003	0.3984 ± 0.0003	0.4036 ± 0.0002
r_2 (side)	0.2978 ± 0.0003	0.2873 ± 0.0003	0.2875 ± 0.0003	0.2917 ± 0.0002
r_2 (back)	0.3305 ± 0.0003	0.3200 ± 0.0003	0.3202 ± 0.0003	0.3244 ± 0.0002
spot1	no	$\phi_1 = 51\overset{\circ}{.}6$ $\lambda_1 = 90\overset{\circ}{.}0$ $R_1 = 26\overset{\circ}{.}0$ $\tau_1 = 0.70$	$\phi_1 = 286\overset{\circ}{.}6$ $\lambda_1 = 90\overset{\circ}{.}0$ $R_1 = 28\overset{\circ}{.}9$ $\tau_1 = 0.70$	$\phi_1 = 286\overset{\circ}{.}6$ $\lambda_1 = 90\overset{\circ}{.}0$ $R_1 = 28\overset{\circ}{.}9$ $\tau_1 = 0.70$
spot2	no	no	$\phi_1 = 73\overset{\circ}{.}4$ $\lambda_1 = 90\overset{\circ}{.}0$ $R_1 = 22\overset{\circ}{.}6$ $\tau_1 = 0.70$	$\phi_1 = 73\overset{\circ}{.}4$ $\lambda_1 = 90\overset{\circ}{.}0$ $R_1 = 22\overset{\circ}{.}6$ $\tau_1 = 0.70$
spot3	no	no	$\phi_1 = 154\overset{\circ}{.}8$ $\lambda_1 = 90\overset{\circ}{.}0$ $R_1 = 26\overset{\circ}{.}5$ $\tau_1 = 1.05$	$\phi_2 = 29\overset{\circ}{.}2$ $\lambda_2 = 90\overset{\circ}{.}0$ $R_2 = 23\overset{\circ}{.}3$ $\tau_2 = 1.50$
spot4	no	no	$\phi_2 = 309\overset{\circ}{.}6$ $\lambda_2 = 90\overset{\circ}{.}0$ $R_2 = 31\overset{\circ}{.}4$ $\tau_2 = 1.50$	$\phi_2 = 338\overset{\circ}{.}8$ $\lambda_2 = 90\overset{\circ}{.}0$ $R_2 = 25\overset{\circ}{.}6$ $\tau_2 = 1.30$
Σres^2	0.00035570	0.00067559	0.00022391	0.00045015

*ϕ refers to the longitude of the stellar spot, λ to the co-latitude, R to the angular radius, τ to $T_{spot}/T*$. The subscripts 1 and 2 represent the star spot on the primary and secondary star, respectively.

NSVS 11868841, NSVS 06550671, and NSVS 10653195. Variation over several months was also found in other eclipsing binaries, e.g. NSVS 065007557 (Coughlin & Shaw 2007) and K10200948 (Harrison et al. 2012). Continuous observations of semi-detached binaries such as BU Vul are rarely presented. Our four successive sets of light curves show remarkable distortions, which reveals the presence of high-level surface activity on the components.

Using the W–D code with a spot model, the parameters were obtained and are listed in table 2. These elements reveal that there is no stellar spot in June; the spots on the primary and the secondary have changed and drifted in July, August, and September. Comparing the parameters of spots, the cool Spot1 and Spot2 on the primary are stable in August and September, while the hot Spot3 and Spot4 are variable. For Spot1 in July, the longitudes and radius are different from that in the other months. The star spots' preferred longitudes can be explained by tidal effects on the dynamics of magnetic flux tubes with the emergence of star spots on the stellar surface; the variation in the spot radius may be caused by star-spot evolution. The positions of the cool spots (Spot1 and Spot2) are stable over a short timescale of two months, similar to NSVS 07453183 and NSVS 06550671 (Zhang et al. 2014a). The hot spots are

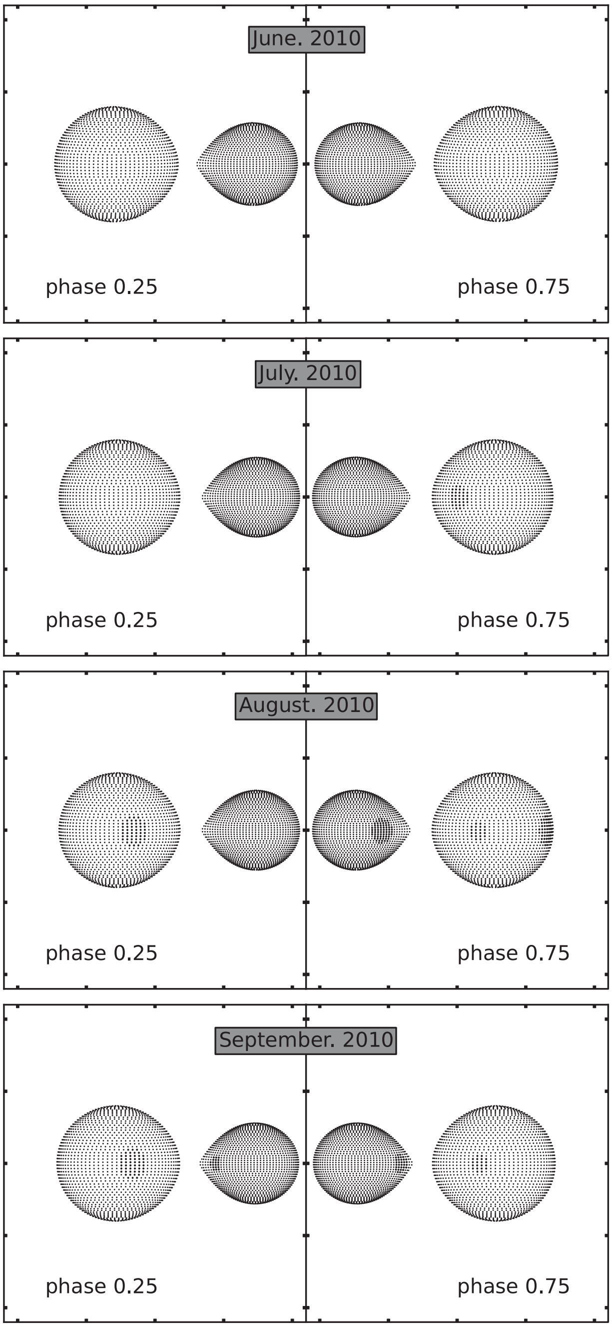

Fig. 3. Configurations and distributions of star spots for BU Vul at 0.25, 0.75 phases in 2010 June, July, August, and September.

different from each other, perhaps resulting from a mass-transferring gas stream between the components (Wilsey & Beaky 2009).

Meanwhile, we collected all times of minimum light to analyze the orbital period changes. The quadratic trend of $(O - C)_1$ reveals that the period of BU Vul is increasing continuously. The long-term increase maybe results from mass transfer, which is in agreement with the semi-detached configuration of a lobe-filling less massive component. According to the following well-known equation (Singh & Chaubey 1986),

$$\dot{P}/P = 3\dot{M}_2(1/M_1 - 1/M_2), \tag{3}$$

the mass transfer rate from the less massive component to the more massive one is determined as $dM_2/dt = -2.95 \times 10^{-9}\, M_\odot\, \mathrm{yr}^{-1}$. These properties are similar to some semi-detached systems, such as GQ Dra (Qian et al. 2015), TW Dra (Liao et al. 2016), BF Vir (Zhu et al. 2012), DD Mon (Qian et al. 1997, 2009), EG Cep (Zhu et al. 2009), and V836 Cyg (Yakut et al. 2005). Both the semi-detached configuration and the increasing orbital period indicate that they are undergoing a low mass-transferring evolutionary stage.

Also, a cyclic change ($A_3 = 0.0029$ d, $T_3 = 22.4$ yr) was found in the $O - C$ curve. The light travel time effect via the presence of a third body is one plausible explanation for the cyclic oscillation (Liao & Qian 2010). This method has been used to search for substellar objects orbiting other types of close binary stars, e.g. HU Aqr (Qian et al. 2011), RR Cae (Qian et al. 2012a), and NY Vir (Qian et al. 2012b). As for BU Vul, by using the equations

$$a'_{12} \times \sin i' = A_3 \times c, \tag{4}$$

$$f(m) = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2} = \frac{4\pi^2}{GT_3^{\,2}} \times \left(a'_{12} \sin i'\right)^3, \tag{5}$$

where i' is the inclination of the orbit of the tertiary component and c is the speed of light, the mass function was determined as $f(m) = 0.00025\, M_\odot$. The relations between the orbital semimajor axis (a_3), the mass (m_3), and the orbital inclination (i') for an assumed third body are shown in figure 5.

If the orbital inclination i' equals 90°, we can estimate its mass as being $m_3 = 0.084\, M_\odot$, and the corresponding orbital semimajor axis a_3 as 8.7 au. To certify the presence of a third body, we added a third light with the Wilson–Devinney program: a negative convergence value was always obtained. Thus, it is possible that the third body is a cool dwarf star with extremely low luminosity.

When we observed the minimum light in the R_c band with the DW436 2048 × 2048 CCD photometric system attached to the 60 cm reflecting telescope at Yunnan Observatories, the dimming displayed in figure 6 was found after the primary minimum on 2009 November 4. Because these dimming observations are less than the complete light curve, we did not use them for light curve fitting with the W–D code. But, the R_c-band theoretical light curve in 2010 was applied to analyze this distortion in 2009. After subtracting the theoretical fit from the observed ones, the results are

Table 3. CCD times of minimum light from literature.

HJD (d)	Error (d)	Reference	HJD (d)	Error (d)	Reference
2451483.71885	0.00005	Nelson (2000)	2454630.8214	0.0001	Samolyk (2009)
2452124.4077	0.0003	Baldinelli and Maitan (2002)	2454389.2973	0.0006	Brát et al. (2008)
2452136.3578	0.0009	Baldinelli and Maitan (2002)	2454748.3179	0.0004	Brát et al. (2008)
2452934.6546	0.0006	Cook et al. (2005)	2454410.3456	0.0050	Hubscher, Paschke, and Walter (2009a)
2453293.6883	0.0004	Cook et al. (2005)	2454709.3415	0.0003	Hubscher, Paschke, and Walter (2009b)
2453297.6723	0.0009	Cook et al. (2005)	2455058.7044	0.0001	Samolyk (2010)
2453301.6547	0.0004	Cook et al. (2005)	2455101.3771	0.0004	Brát et al. (2011)
2453525.8389	0.0005	Cook et al. (2005)	2455101.3774	0.0002	Brát et al. (2011)
2453529.8209	0.0004	Cook et al. (2005)	2455101.3779	0.0004	Brát et al. (2011)
2453538.9245	0.0006	Cook et al. (2005)	2455378.4783	0.0003	Brát et al. (2011)
2453323.2759	0.0025	Hubscher, Paschke, and Walter (2005)	2455378.4784	0.0003	Brát et al. (2011)
2453549.4537	0.0020	Hubscher, Paschke, and Walter (2006)	2455378.4785	0.0003	Brát et al. (2011)
2453601.5142	0.0033	Hubscher, Paschke, and Walter (2006)	2455429.3983	0.0012	Brát et al. (2011)
2453612.3247	0.0002	Zejda, Mikulasek, and Wolf (2006)	2455429.4008	0.0007	Brát et al. (2011)
2453676.6210	0.0001	Baldwin and Samolyk (2006)	2455437.6562	0.0001	Samolyk (2011)
2453932.6693	0.0001	Baldwin and Samolyk (2006)	2455439.3613	0.0001	Samolyk (2011)
2454267.8037	0.0001	Baldwin and Samolyk (2006)	2455378.4776	0.0001	Hubscher, Lehmann, and Walter (2012)
2454382.7400	0.0001	Samolyk (2008)			

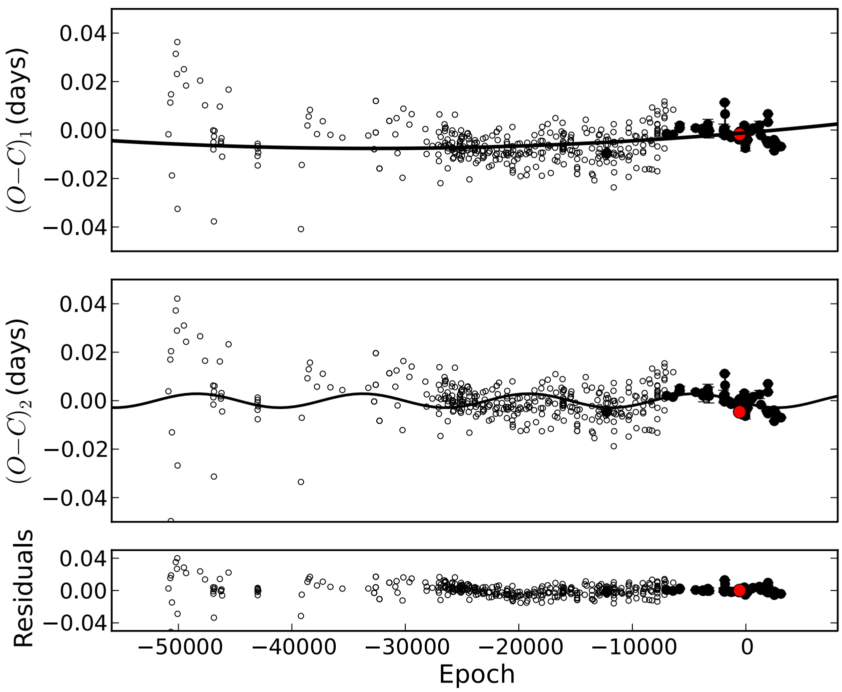

Fig. 4. $O-C$ diagram for BU Vul; open circles refer to visual and photographic data, the solid ones to photoelectric and CCD. Top: Solid linear to the quadratic trend. Middle: Solid line corresponds to the cyclic change. The red solid circle represents the time of the secondary minimum light observed using the 60 cm telescope on 2009 November 4. (Color online)

shown with O − C in figure 6. Maybe this dimming results from the third body eclipsing this binary system. Then, we marked this primary minimum with a red solid circle in the O − C diagram of figure 4. The red solid circle is close to the minimum of the $(O-C)_2$ cyclic change. Considering the light travel time effect through a third body, when the binary is periodically close to us, the observed time will be less than that calculated time in the O − C diagram, and the

Table 4. Fitting residuals of different ephemeris terms for $(O-C)_1$.

Linear	Cyclic	Quadratic	Linear+cyclic	Quadratic+cyclic
2.3585×10^{-6}	2.1157×10^{-6}	2.3539×10^{-6}	1.9489×10^{-6}	1.9055×10^{-6}

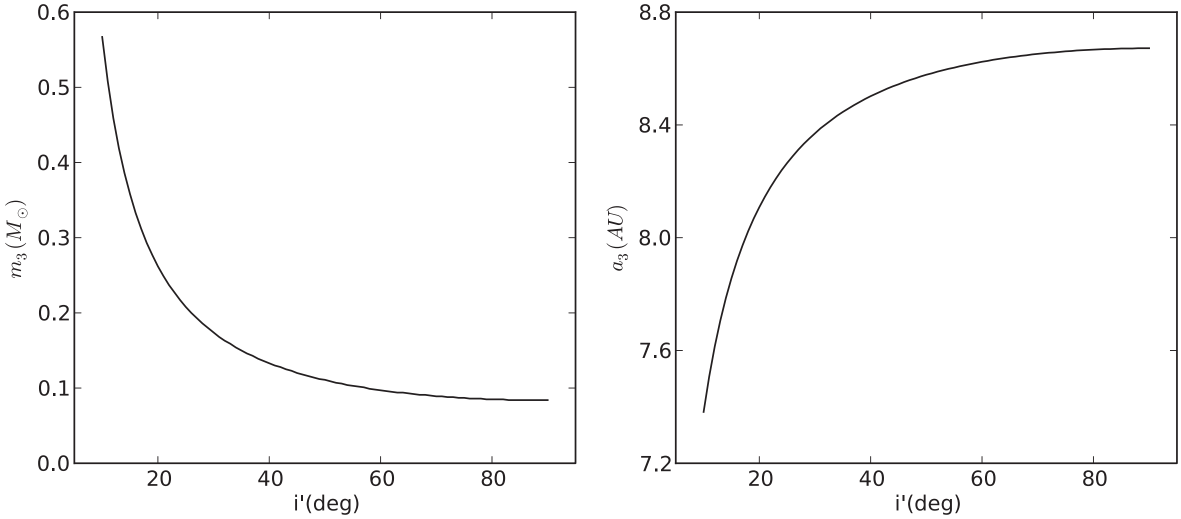

Fig. 5. Relation between the mass (m_3), orbital semimajor axis (a_3), and the orbital inclination (i') for an assumed third body for BU Vul.

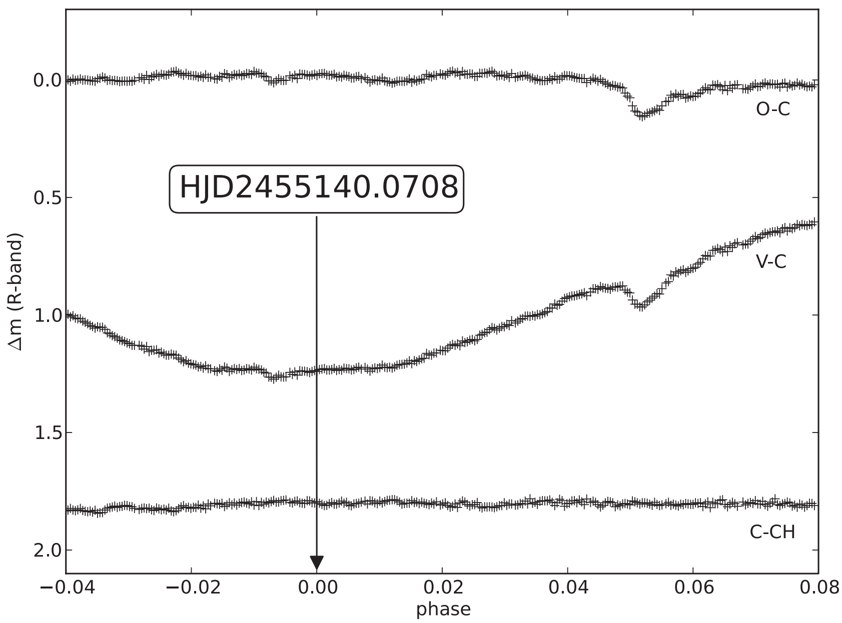

Fig. 6. Distortions in the light curve observed on 2009 November 4. C–CH refers to the differential magnitudes between the comparison and check star, V–C to the magnitudes between the target BU Vul and the comparison, and $O-C$ to the magnitudes of observations minus calculations with the W–D code.

third body is eclipsed by the binary and difficult to observe. And, comparing the light curves obtained in 2010, the magnitude amplitude of the dimming is near or a little bigger than that of the secondary eclipse. Therefore, this dimming maybe comes from an additional body rather than the third body. It is possible that BU Vul is a semi-detached binary in a quadruple system, as in the cases of KOI-126 (Carter et al. 2011), HD 181068 (Derekas et al. 2011), KIC4150611 (Hełminiak et al. 2017), and EPIC220204960 (Rappaport et al. 2017).

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