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OPTICAL FLARES AND A LONG-LIVED DARK SPOT ON A COOL SHALLOW CONTACT BINARY

S.-B. Qian[1,2,3], J.-J. Wang[1,2,3], L.-Y. Zhu[1,2,3], B. Snoonthornthum[4], L.-Z. Wang[5], E. G. Zhao[1,2], X. Zhou[1,2,3], W.-P. Liao[1,2], and N.-P. Liu[1,2,3]
[1] Yunnan Observatories, Chinese Academy of Sciences (CAS), P.O. Box 110, 650011 Kunming, China; qsb@ynao.ac.cn
[2] Key laboratory of the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, P.O. Box 110, 650011 Kunming, China
[3] University of the Chinese Academy of Sciences, Yuquan Road 19#, Sijingshang Block, 100049 Beijing, China
[4] National Astronomical Research Insititude of Thailand, 191 Siriphanich Bldg., Huay Kaew Rd., Chiang Mai 50200, Thailand
[5] National Astronomical Observatories, Chinese Academy of Sciences, 100012 Beijing, China
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ABSTRACT

W UMa-type stars are contact systems where both cool components fill the critical Roche lobes and share a common convective envelope. Long and unbroken time-series photometry is expected to play an important role in their origin and activity. The newly discovered short-period W UMa-type star, CSTAR 038663, was monitored continuously by Chinese Small Telescope ARray (CSTAR) in Antarctica during the winters of 2008 and 2010. There were 15 optical flares recorded in the i band during the winter of 2010. This was the first time such flares were detected from a W UMa-type star. By analyzing the nearly unbroken photometric data from 2008, it is discovered that CSTAR 038663 is a W-type shallow contact binary system ($f = 10.6(\pm2.9)\%$) with a high mass ratio of $q = 1.12(\pm0.01)$, where the less massive component is slightly hotter than the more massive one. The asymmetric light curves are explained by the presence of a dark spot on the more massive component. Its temperature is about 800 K lower than the stellar photosphere and it covers 2.1% of the total photospheric surface. The lifetime of the dark spot is longer than 116 days. Using 725 eclipse times, we found that the observed–calculated (O–C) curve may show a cyclic variation that is explained by the presence of a close-in third body. Both the shallow contact configuration and the extremely high mass ratio suggest that CSTAR 038663 is presently evolving into a contact system with little mass transfer. The formation and evolution is driven by the loss of angular momentum via magnetic braking, and the close-in companion star is expected to play an important role, removing angular momentum from the central eclipsing binary.

Key words: binaries: close – binaries: eclipsing – stars: activity – stars: evolution – stars: individual (CSTAR 038663)

Online-only material: color figure

1. INTRODUCTION

W UMa-type binary stars are composed of two cool, main-sequence stars with spectral types of F, G, and K. Both component stars are in contact with each other and share a common convective envelope (CCE) that lies between the inner and outer critical Roche-lobe surfaces. They are short-period, close binaries with orbital periods shorter than 1 day, and most of them have an orbital period shorter than 0.5 day. The light curves of these types of binary stars are typical EW-types, where light variation is continuous and has a very small difference between the depths of the two minima. The nearly equal depths of the two minima suggest that both components possess almost identical temperature in spite of different component masses. Because W UMa-type stars have the shortest periods and the lowest angular momentums among main-sequence binaries, they are expected to have a stellar companion that plays an important role in their origin by removing angular momentum from the central binary through early dynamical interaction and/or later evolution (e.g., Pribulla & Rucinski 2006; Qian et al. 2013a, 2013b; Zhu et al. 2013b). On the other hand, because of the rapid rotating and deep convective envelopes of the component stars, it is expected that they should have strong magnetic activity. However, we do not know what effect CCE has on the activity of the components. The properties of the magnetic activity are unclear.

The light curves of some contact binaries, such as AD Cnc (Qian et al. 2007c), BI CVn (Qian et al. 2008), VW Boo (Liu et al. 2011b), and QX And (Qian et al. 2007a), are variable on the timescale of a few days to a few months. These variations are evidence of star-spot activity on the stellar photospheres of both components. However, because of the lack of continuous and unbroken time-series photometry, the properties of the activity, such as the lifetime of the spot, are unknown. On the other hand, the lack of unbroken time series observations also prevents the detection of some close-in stellar companions.

The Antarctic plateau is an ideal location for carrying out long and unbroken time-series photometry with a single telescope because of its high altitude, low temperature, low absolute humidity, low wind, and extremely stable atmosphere (e.g., Wang et al. 2011). Therefore, an observatory at Dome A, called PLATO (PLATeau Observatory; e.g., Ashley et al. 2010; Luong-van et al. 2010; Yang et al. 2009), and the Chinese Small Telescope ARray (CSTAR) were constructed (e.g., Yuan et al. 2008; Zhou et al. 2010b) for use in this location. CSTAR is a small 2 × 2 Schmidt–Cassegrain telescope array in which each telescope has a field of view of $\sim4^{\circ}\!.5 \times 4^{\circ}\!.5$. Based on the observations obtained with CSTAR during the 2008 and 2010 Antarctic winters, Wang et al. (2011, 2013) discovered more than 150 variable stars. Most of them were included in the catalog of Zhou et al. (2010a). One of the reported variables, CSTAR 038663 ($\alpha_{2000} = 08^{\rm h}46^{\rm m}12^{\rm s}\!.6$; $\delta_{2000} = -88^{\circ}33'42''\!.9$) is a short-period W UMa-type binary star. This eclipsing binary was listed in the ASAS survey as ASAS 084613-8833.7 with a period of 0.267128 day (Pojmański 2003). In this paper, the photometric solutions, the properties of the light curve, and the variations of the orbital period of CSTAR 038663, are all analyzed based on those Antarctic astronomical data. Then, the magnetic activity, the triplicity, the formation, and the evolutionary state of the short-period cool W UMa-type star are investigated.

2. PHOTOMETRIC LIGHT CURVES AND OPTICAL FLARES OF CSTAR 038663

CSTAR 038663 was monitored using CSTAR in *i* band (e.g., Wang et al. 2011, 2013) during the Antarctic winters of 2008 and 2010. In total, the binary star was monitored for about 4167 hr and plenty of photometric observations for this eclipsing binary were obtained. Using the following linear ephemeris, the phases of those observations were calculated,

$$\text{Min. I} = 2454592.32202 + 0^{\text{d}}.267127 \times E, \tag{1}$$

where the initial epoch is one of our times of light minimum and the period is from Wang et al. (2011). The corresponding light curves are shown in Figures 1–6, where photometric data, observed on each observing day, were plotted. On the *y*-axis of those figures, "*M*" refers to the magnitude in *i* band. As displayed in the six figures, the light curve of CSTAR 038663 is a typical EW-type.

W UMa-type binary stars are usually monitored by ground-based telescopes either from night to night or over the time intervals of weeks or months. Night-to-night variations and long-term changes of the light curves have been reported for some systems such as AD Cnc (Qian et al. 2007c), CE Leo (Kang et al. 2004), BI CVn (Qian et al. 2008), VW Boo (Liu et al. 2011b), and QX And (Qian et al. 2007a). These variations may be observational evidence of dark-spot activity because of the fast rotation and deep envelope of the components. The magnitude differences between the two maxima in those light curves (i.e., the O'Connell effect) are plotted in Figures 7 and 8. As shown in Figure 7, the O'Connell effect of CSTAR 038663 in 2008 was stable from March 29 to June 23. This is more clearly seen in Figure 9, where normal light curves obtained from observations covering 2 week intervals are shown. The light curve in 2008 indications a negative O'Connell effect, where the light maxima following the primary minima are about 0.025 mag lower than the other ones. The O'Connell effect in 2010 is variable, indicating that there are two stages of dark-spot activity on the binary star, i.e., active stage (rapid change in the light curve) and inactive stage (stable light curve).

Fifteen optical flares were found during the Antarctic winter of 2010 when the light curve was variable with time, i.e., variable O'Connell effect. However, no flares were detected during the Antarctic winter of 2008, when the light curve was stable. These facts support the idea that the flares originated during a time interval when the binary was active. They are displayed in Figure 10, where the flares are superimposed on the light variation of the W UMa-type binary star. The parameters of those flares are shown in Table 1. The time durations of those flares range from 9.3 to 20.1 minutes and their amplitudes range from magnitudes of 0.151–0.271 (see Table 1 for details). Such flares, with a duration as short as 10 minutes, were also found by the *Kepler* satellite (e.g., Walkowicz et al. 2011; Ramsay et al. 2013). Since flares are most readily observed in short-wavelength bands, such as *U* and *B* bands (e.g., Moffett 1974; Lacy et al. 1976), the fact that the 15 flares were observed in *i* band suggests that they are highly energetic superflares. The average occurrence of the flares can be estimated from the number of detected flares and the total time of observation.

Table 1
Parameters of Optical Flares from the Contact Binary CSTAR 038663

Beginning Time (HJD)	Phase	Duration (hr)	Amplitude
2455347.80326	0.1379	0.1627	0.1626
2455348.79968	0.8680	0.1543	0.1877
2455349.79836	0.6066	0.2717	0.1785
2455350.79707	0.3453	0.1903	0.1913
2455362.75908	0.1255	0.2990	0.1839
2455364.75496	0.5972	0.3175	0.2425
2455365.75194	0.3294	0.1999	0.1509
2455378.71782	0.8677	0.3350	0.2254
2455380.70947	0.3235	0.3082	0.2266
2455381.70711	0.0582	0.2635	0.2490
2455382.70487	0.7934	0.2549	0.2264
2455383.70314	0.5304	0.2083	0.1946
2455384.70074	0.2650	0.2544	0.2145
2455419.60702	0.9379	0.2839	0.2714
2455420.60218	0.6634	0.2443	0.2357

This eclipsing binary was monitored for about 4167 hr in total, revealing a flare rate of 0.0036 flares per hour. However, since the flares were found in *i* band (energetic ones), we believe that the true flare rate might be higher than this value.

3. PHOTOMETRIC SOLUTIONS WITH THE W–D METHOD

To understand the geometrical structure and evolutionary state of CSTAR 038663, the photometric data were analyzed using the Wilson–Devinney (W–D) method (Wilson & Devinney 1971; Wilson 1994). Since the light curve of CSTAR 038663 was stable in 2008, all of the photometric observations were averaged to 200 normal data points; the corresponding data are listed in Table 2. The uncertainties of individual, normal points were used as weights. The original data were observed in an *i* band which was nearly the same as that used by the Sloan Digital Sky Survey (SDSS; Wang et al. 2011; Fukugita et al. 1996; Zhou et al. 2010b). Those *i*-band observations can be transformed into *I*-band data through the relation $I = i - 0.75$ (e.g., Windhorst et al. 1991). With the color index $(J - H) \simeq 0.57$, given by the ASAS survey (Pojmański 2003), the temperature for the primary component (star 1, the hotter component star eclipsed at primary light minimum) was estimated as $T_1 = 4616$ K (Cox 2000). This corresponds to a spectral type of K 4. The gravity-darkening coefficients $g_1 = g_2 = 0.32$ and the bolometric albedo $A_1 = A_2 = 0.5$ were used because of their convective envelopes.

For a detailed treatment of limb darkening, we used logarithmic functions for both the bolometric and bandpass limb-darkening laws. The corresponding bolometric limb-darkening coefficients $x_{1\text{bolo}}$, $x_{2\text{bolo}}$, $y_{1\text{bolo}}$, and $y_{2\text{bolo}}$, and the passband-specific limb-darkening coefficients, x_{1I}, x_{2I}, y_{1I}, and y_{2I} are taken from van Hamme's (1993) table and are listed in Table 3. First, we assumed $x_{1\text{bolo}} = x_{2\text{bolo}}$, $y_{1\text{bolo}} = y_{2\text{bolo}}$, $x_{1I} = x_{2I}$, and $y_{1I} = y_{2I}$. Then, after determining the temperature of the secondary star, the values of $x_{2\text{bolo}}$, $y_{2\text{bolo}}$, x_{2I}, and y_{2I} were redetermined according to its real temperature. We found that the solutions converged at mode 3 and the adjustable parameters were: the orbital inclination i; the mean temperature of star 2, T_2; the monochromatic luminosity of star 1, L_{1I}; and the dimensionless potential ($\Omega_1 = \Omega_2$ for mode 3).

Since no reliable mass ratios of CSTAR 038663 were obtained, a *q*-search method was used to determine its mass ratio.

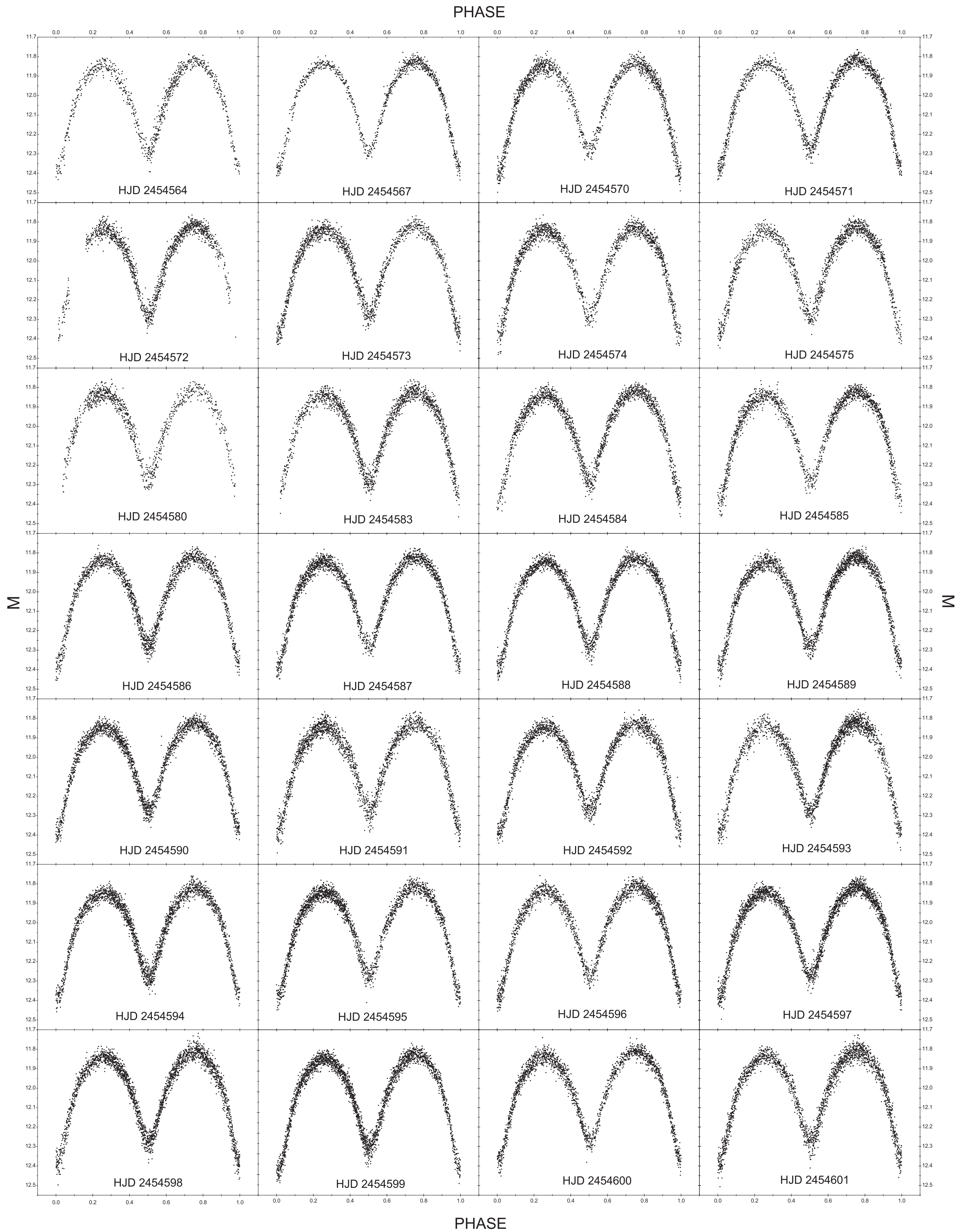

Figure 1. Daily light curves of CSTAR 038663 observed during the winter season in 2008.

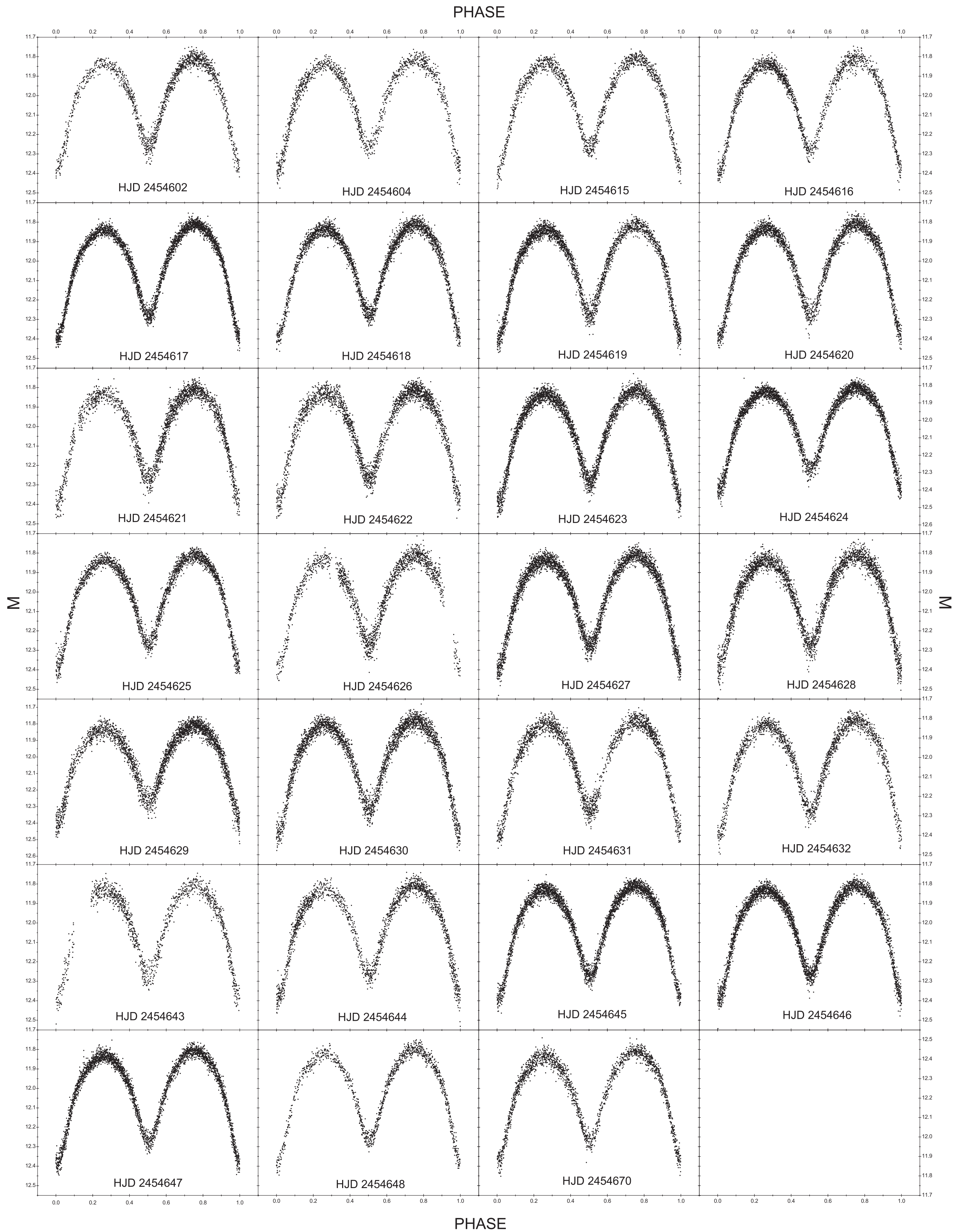

Figure 2. Same as those shown in Figure 1 but observed between HJD 2454602 and HJD 2454670.

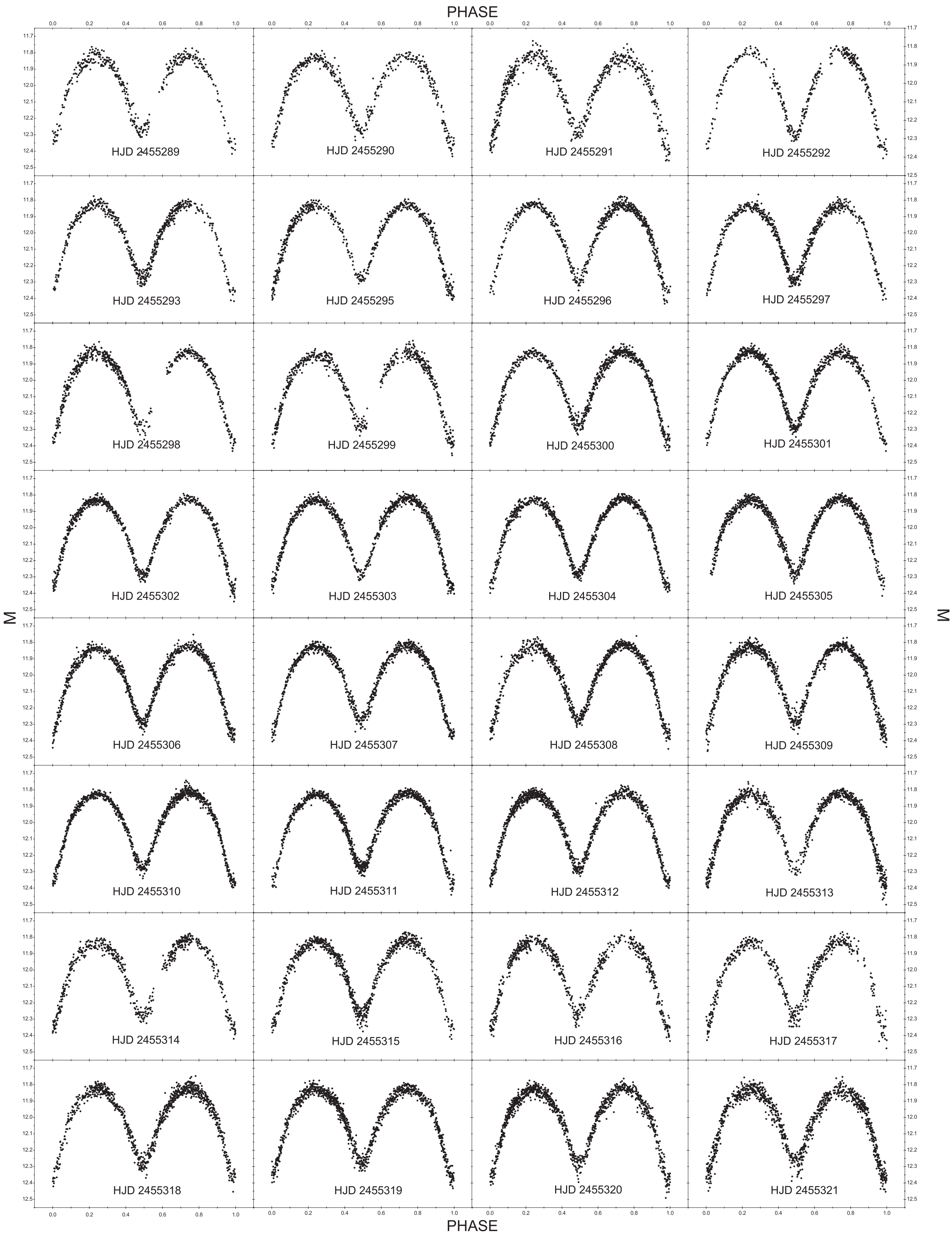

Figure 3. Daily light curves of CSTAR 038663 observed during the winter season in 2010.

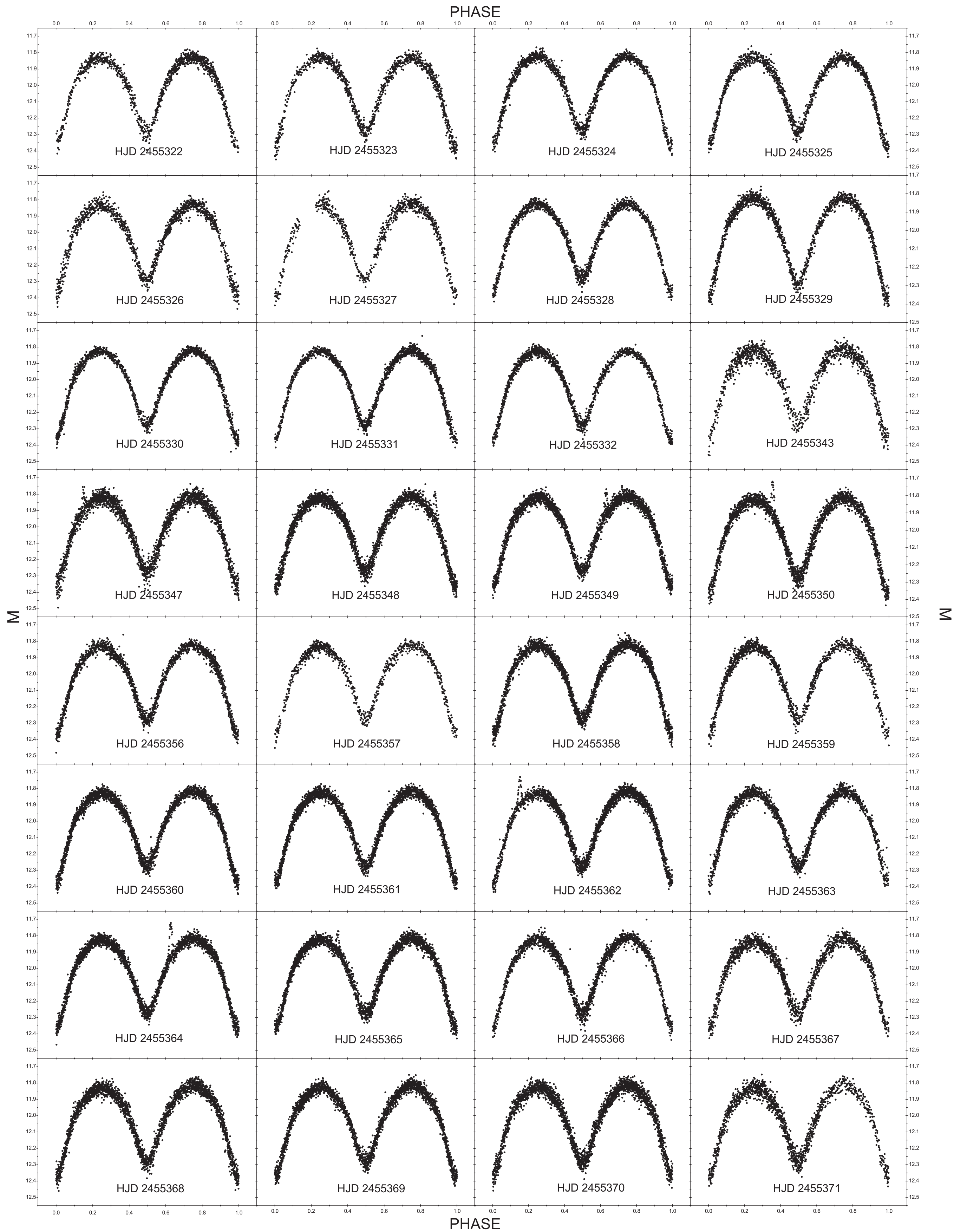

Figure 4. Same as those shown in Figure 3 but observed between HJD 2455322 and HJD 2455371.

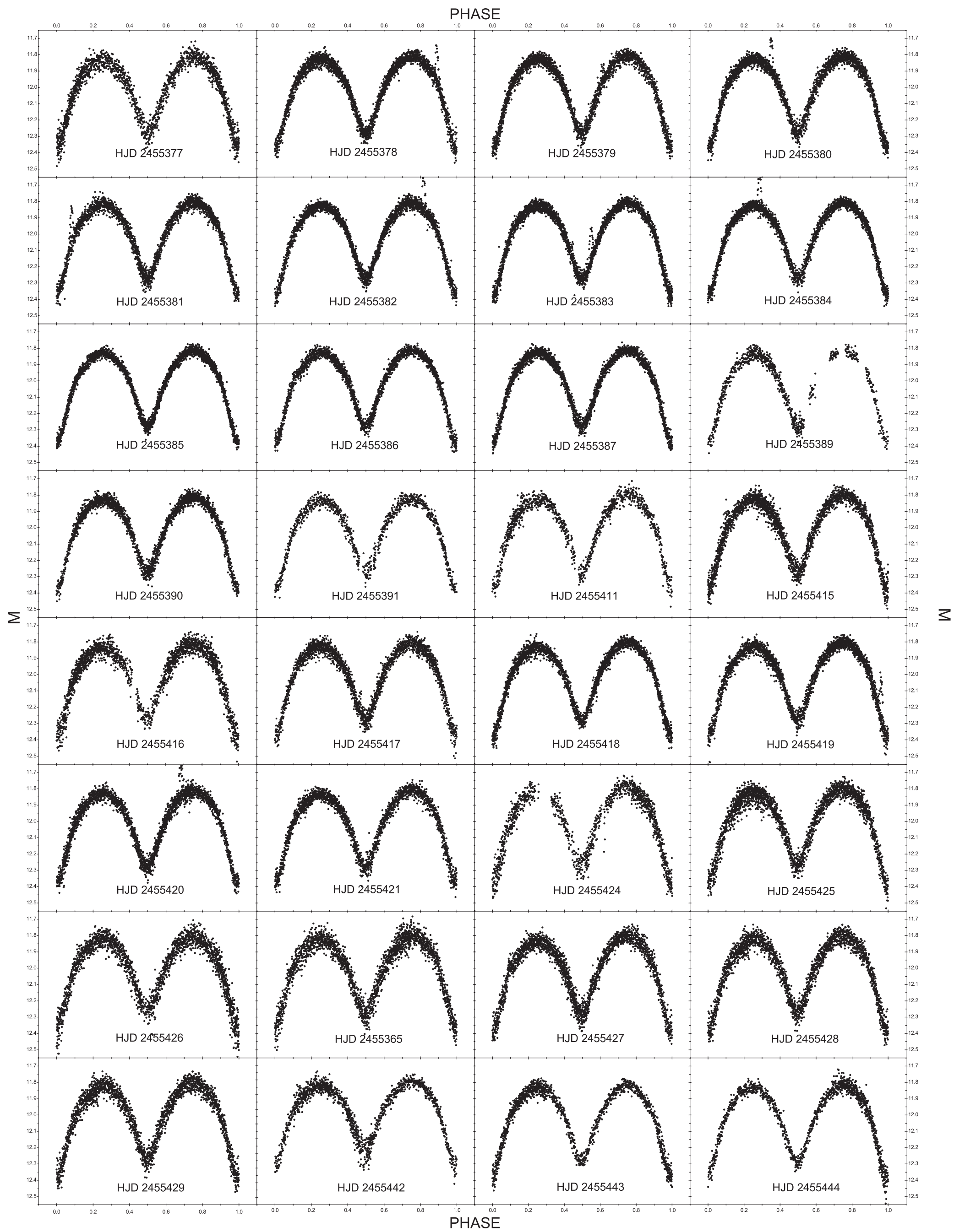

Figure 5. Same as those shown in Figures 3 and 4 but observed between HJD 2455377 and HJD 2455444.

We focus on searching for photometric solutions with a mass ratio between 0.24 and 4.0, and solutions were carried out for 53 values of the mass ratio. The relation between the resulting sum Σ of weighted square deviations and q is plotted in Figure 11. It is found that the solution converged at $q = 1.12$ with the lowest value of Σ, indicating that the theoretical light curve based on the solution is the best one to fit the observations. The corresponding photometric solutions are listed in Table 3.

As shown in Figures 1, 2, and 9, the light curves of CSTAR 038663 in 2008 displayed a negative O'Connell effect, i.e., the light maxima following the primary minima are lower than the other ones. The components of CSTAR 038663 are cool stars and they are rotating nearly 90 times faster than the Sun. As in the case of other K-type contact binary stars, such as AD Cnc and BI Vul (Qian et al. 2007c, 2013a), the deep convective envelope along with rapid rotation can produce a strong magnetic dynamo and solar-like magnetic activity. It is expected that dark spots should be observed on photospheres. In the W–D method, each spot has four parameters: spot center longitude (θ), spot center latitude (ϕ), spot angular radius (r), and spot temperature fact (T_f), all in units of radian. Our solution suggests that the asymmetry of the light curves can be plausibly explained as the presence of one dark spot on the secondary component (the more massive one due to the W-type system). The dark spot's parameters are listed in Table 4. The observed and theoretical light curves are plotted in Figure 12, which shows that the theoretical light curve fits the observations well. The corresponding geometric structure at phase 0.25 is displayed in Figure 13.

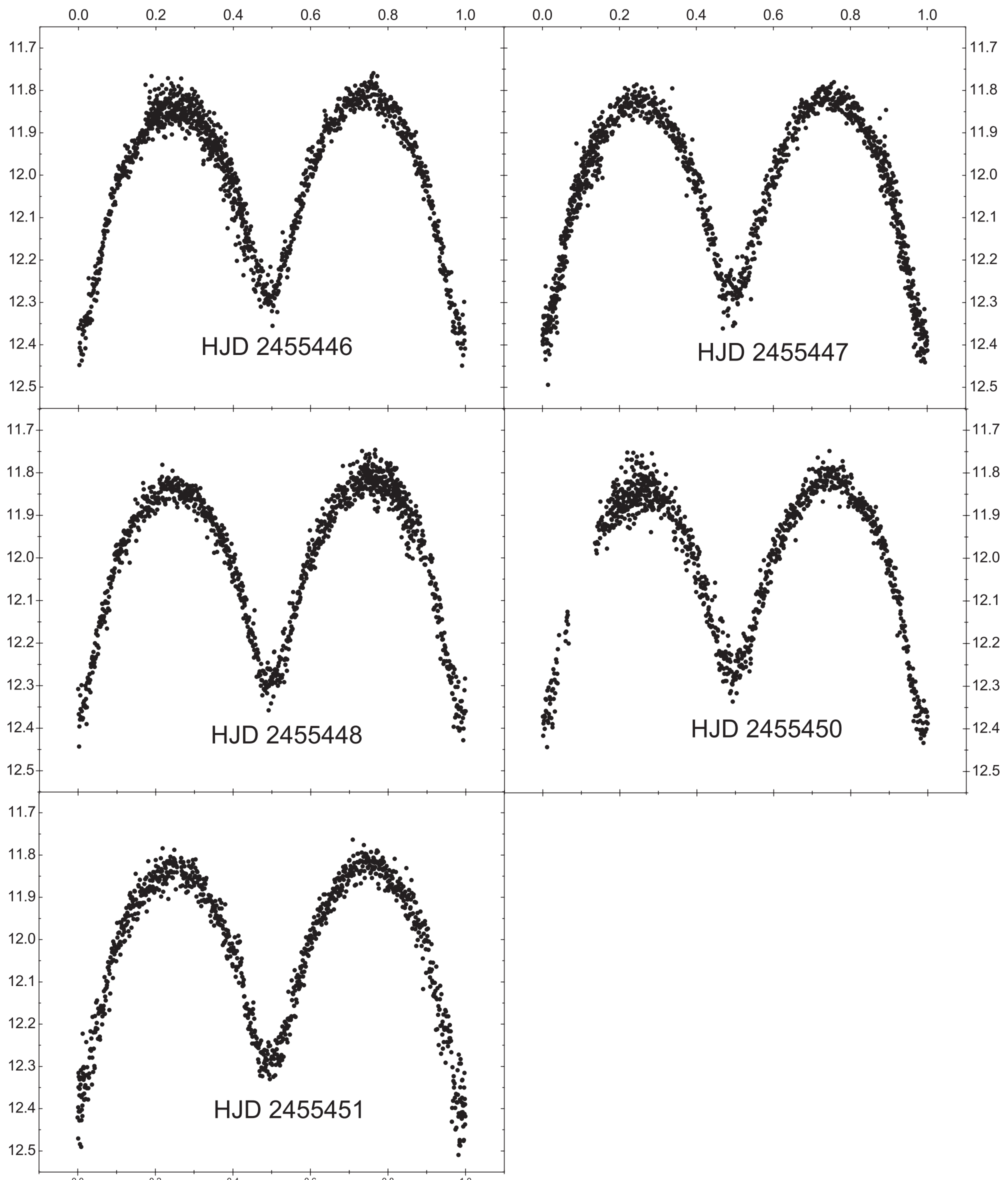

Figure 6. Same as those shown in Figures 3–5 but observed between HJD 2455446 and HJD 2455451.

The photometric solution indicates that the temperature of the dark spot is about 800 K lower than that of the stellar photosphere on the more massive component star, which is similar to that of a typical sunspot. However, the dark spot covers 2.1% of the total photospheric surface which is an area much larger than that of a spot on the Sun (the area of a sunspot is usually less than 1% of the Sun's photospheric surface). The long and unbroken time-series photometry of CSTAR 038663 implies that its light curve is stable for 116 days. This suggests that the lifetime of the spot is longer than 116 days and that it is a long-lived dark spot on a contact binary. However, the solution of the dark spot derived using the W–D method is definitely not unique. The spot may be composed of a group of small spots.

4. THE CHANGES OF THE ORBITAL PERIOD OF CSTAR 038663

Orbital periods of W UMa-type binary stars are usually variable with time. Some examples are BI Vul (Qian et al. 2013a), V396 Mon (Liu et al. 2011a), and AP Leo (Qian et al. 2007b). To understand the properties of the period change of CSTAR 038663, those Antarctic photometric data were used to determine times of light minimum. Since the eclipse minima are symmetric, times of light minimum were determined with a parabolic fitting method. In all, 725 eclipse times were determined and are listed in Table 1 together with their errors. The observed–calculated (O–C) values of all available times of light minimum, with respect to the linear ephemeris in Equation (1), were computed.

The O–C diagram is displayed in Figure 14. As shown in the figure, the linear ephemeris needs to be revised and there is a cyclic change in the O–C curve. A least-square solution yields,

$$\begin{aligned} \text{Min. I} = {} & 2454592.31951(\pm 0.00006) \\ & + 0^{\mathrm{d}}.267123849(\pm 0.000000013) \times E \\ & + 0.00223(\pm 0.00006)\sin[0^{\circ}.2567(\pm 0.0115) \\ & \times E + 67^{\circ}.3(\pm 0^{\circ}.7)]. \end{aligned} \qquad (2)$$

The first part in the equation is the revised linear ephemeris which can be used to predict the eclipse times in the future.

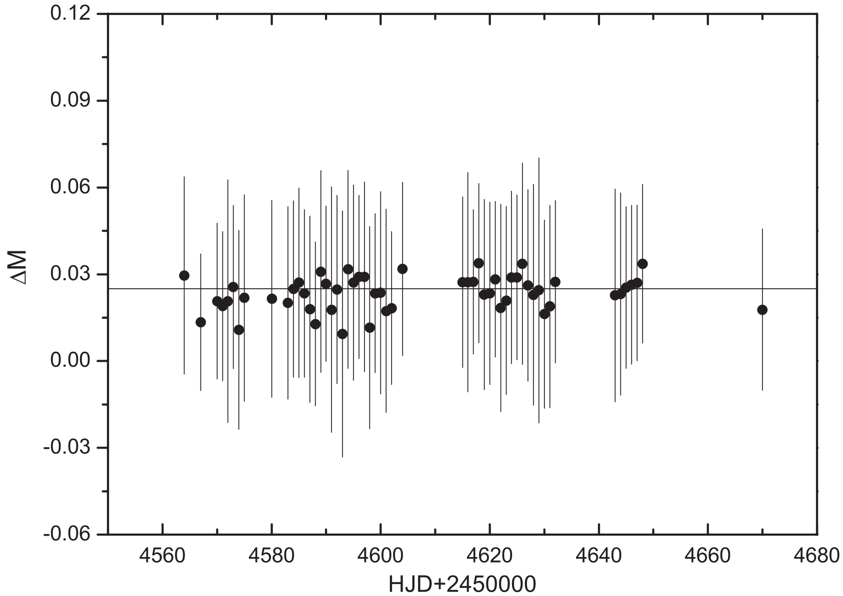

Figure 7. O'Connell effect of CSTAR 038663 in 2008. The light curve is stable and shows a negative O'Connell effect. The light maxima following the primary minima are about 0.025 mag lower than the other ones.

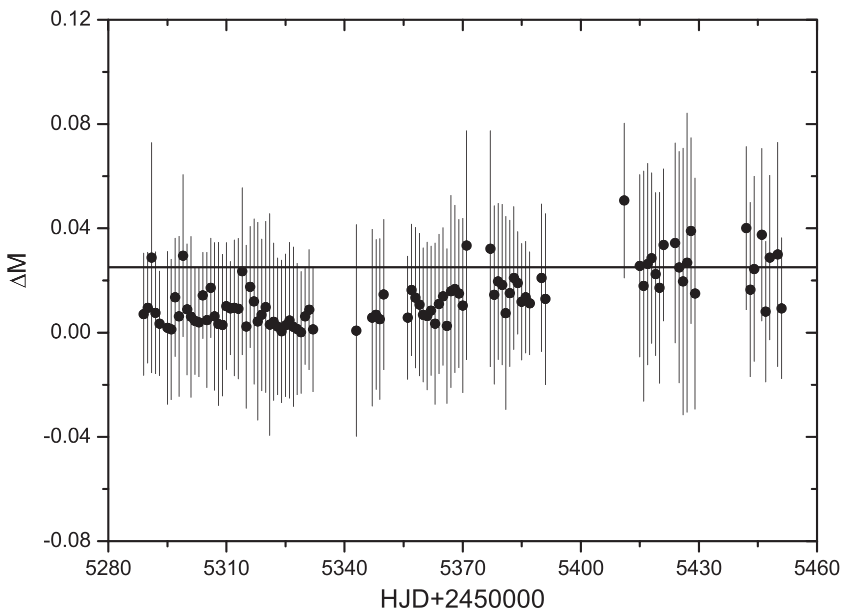

Figure 8. O'Connell effect in 2010. It is shown that the light curve is variable with time.

It indicates a small-amplitude, cyclic change with a period of 1.03 days and an amplitude of $0\overset{\mathrm{d}}{.}00223$ (Case A). This cyclic change has the shortest period and lowest amplitude among W UMa-type binary stars. However, more data are needed for it to be confirmed since there is a large gap between $E = 300$ and $E = 2600$. The other solution (Case B) is also obtained:

$$\begin{aligned} \text{Min. I} = {} & 2454592.31363(\pm 0.00021) \\ & + 0\overset{\mathrm{d}}{.}267123849(\pm 0.000000013) \times E \\ & + 0.00809(\pm 0.00021) \sin[0\overset{\circ}{.}1283(\pm 0.0230) \\ & \times E + 78\overset{\circ}{.}3(\pm 0\overset{\circ}{.}3)]. \end{aligned} \tag{3}$$

This equation describes a cyclic change with a period of 2.05 yr and an amplitude of 0.00809 day. As displayed in Figure 14, both cases (Case A and B) can give a good fit to the O–C curve.

5. DISCUSSIONS AND CONCLUSION

Photometric solutions of the short-period, cool binary, CSTAR 038663, were obtained with the W–D code by analyzing the Antarctic photometric data from 2008. The solutions suggest that CSTAR 038663 is a shallow contact binary with a degree of contact of 10.6(±2.9)%. It is found that the contact binary is a W-type system with a very high mass ratio of $q = 1.12$, where the hotter component is the slightly less massive one. According to the color index $(J - H) \backsimeq 0.57$ given by the ASAS survey (Pojmański 2003), the mass of the hotter component (the primary) is estimated as $M_1 = 0.72\, M_\odot$ (Cox 2000). The derived mass ratio of 1.12 reveals that the mass of the secondary is $M_2 = 0.81\, M_\odot$.

Fifteen i-band flares were detected during the Antarctic winter of 2010. The discovery of the first contact binary (W UMa) took place in 1903 (e.g., Muller & Kempf 1903), and contact binaries

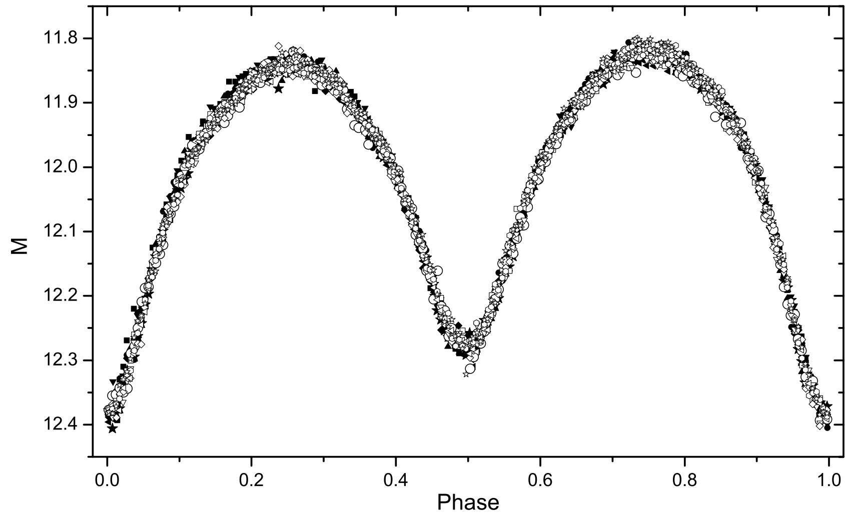

Figure 9. Comparison of normal light curves, averaged by observations and observed every two weeks. It is shown that the light curves overlap very well, suggesting that the light curve in 2008 is not variable.

Table 2
Normal Photometric Observations for CSTAR 038663

Phase	$M(i)$	Phase	$M(i)$	Phase	$M(i)$	Phase	$M(i)$	Phase	$M(i)$
0.0024	12.402	0.2025	11.857	0.4024	12.011	0.6026	11.981	0.8028	11.834
0.0075	12.375	0.2077	11.856	0.4074	12.009	0.6075	11.969	0.8077	11.836
0.0125	12.376	0.2127	11.849	0.4124	12.043	0.6124	11.962	0.8126	11.839
0.0176	12.361	0.2176	11.834	0.4173	12.053	0.6174	11.954	0.8174	11.849
0.0224	12.353	0.2226	11.84	0.4225	12.066	0.6224	11.934	0.8223	11.847
0.0276	12.323	0.2274	11.841	0.4276	12.085	0.6275	11.928	0.8272	11.872
0.0323	12.313	0.2323	11.837	0.4324	12.086	0.6325	11.918	0.8323	11.867
0.0373	12.288	0.2372	11.833	0.4375	12.122	0.6374	11.902	0.8375	11.877
0.0425	12.245	0.2421	11.835	0.4424	12.134	0.6424	11.897	0.8427	11.882
0.0474	12.232	0.2473	11.828	0.4475	12.161	0.6475	11.896	0.8476	11.885
0.0525	12.211	0.2527	11.829	0.4525	12.174	0.6525	11.888	0.8526	11.906
0.0575	12.191	0.2577	11.832	0.4575	12.188	0.6574	11.868	0.8575	11.916
0.0625	12.168	0.2627	11.813	0.4625	12.211	0.6624	11.869	0.8623	11.906
0.0676	12.129	0.2675	11.828	0.4675	12.220	0.6676	11.871	0.8673	11.927
0.0724	12.118	0.2724	11.831	0.4725	12.240	0.6726	11.864	0.8724	11.933
0.0773	12.103	0.2773	11.835	0.4774	12.245	0.6775	11.855	0.8774	11.944
0.0823	12.079	0.2822	11.829	0.4823	12.274	0.6824	11.842	0.8826	11.957
0.0873	12.067	0.2873	11.839	0.4875	12.260	0.6873	11.840	0.8875	11.969
0.0924	12.037	0.2924	11.842	0.4924	12.274	0.6923	11.835	0.8924	11.983
0.0977	12.006	0.2976	11.843	0.4975	12.274	0.6971	11.833	0.8975	11.996
0.1026	12.018	0.3027	11.851	0.5025	12.272	0.7024	11.835	0.9022	12.012
0.1076	11.996	0.3076	11.852	0.5076	12.268	0.7076	11.821	0.9075	12.022
0.1125	11.979	0.3125	11.855	0.5126	12.259	0.7125	11.816	0.9124	12.060
0.1175	11.976	0.3174	11.856	0.5175	12.262	0.7175	11.811	0.9175	12.051
0.1225	11.967	0.3222	11.873	0.5224	12.244	0.7226	11.822	0.9226	12.074
0.1277	11.954	0.3273	11.878	0.5273	12.218	0.7275	11.813	0.9276	12.088
0.1324	11.945	0.3324	11.880	0.5323	12.209	0.7324	11.799	0.9325	12.119
0.1378	11.935	0.3375	11.889	0.5373	12.188	0.7373	11.796	0.9374	12.143
0.1424	11.932	0.3426	11.891	0.5424	12.171	0.7422	11.808	0.9423	12.177
0.1473	11.919	0.3476	11.898	0.5476	12.157	0.7472	11.814	0.9473	12.207
0.1523	11.911	0.3525	11.907	0.5526	12.142	0.7524	11.801	0.9523	12.234
0.1575	11.913	0.3574	11.915	0.5576	12.120	0.7576	11.814	0.9574	12.262
0.1624	11.906	0.3623	11.922	0.5625	12.117	0.7627	11.821	0.9624	12.295
0.1677	11.895	0.3673	11.927	0.5674	12.089	0.7676	11.812	0.9676	12.315
0.1726	11.888	0.3724	11.936	0.5722	12.074	0.7725	11.813	0.9726	12.327
0.1775	11.881	0.3775	11.945	0.5773	12.065	0.7774	11.811	0.9775	12.350
0.1825	11.869	0.3825	11.959	0.5823	12.041	0.7822	11.827	0.9824	12.353
0.1873	11.870	0.3876	11.969	0.5874	12.024	0.7874	11.815	0.9872	12.382
0.1923	11.854	0.3926	11.973	0.5925	12.014	0.7924	11.833	0.9923	12.394
0.1973	11.860	0.3975	11.992	0.5975	12.001	0.7977	11.837	0.9976	12.378

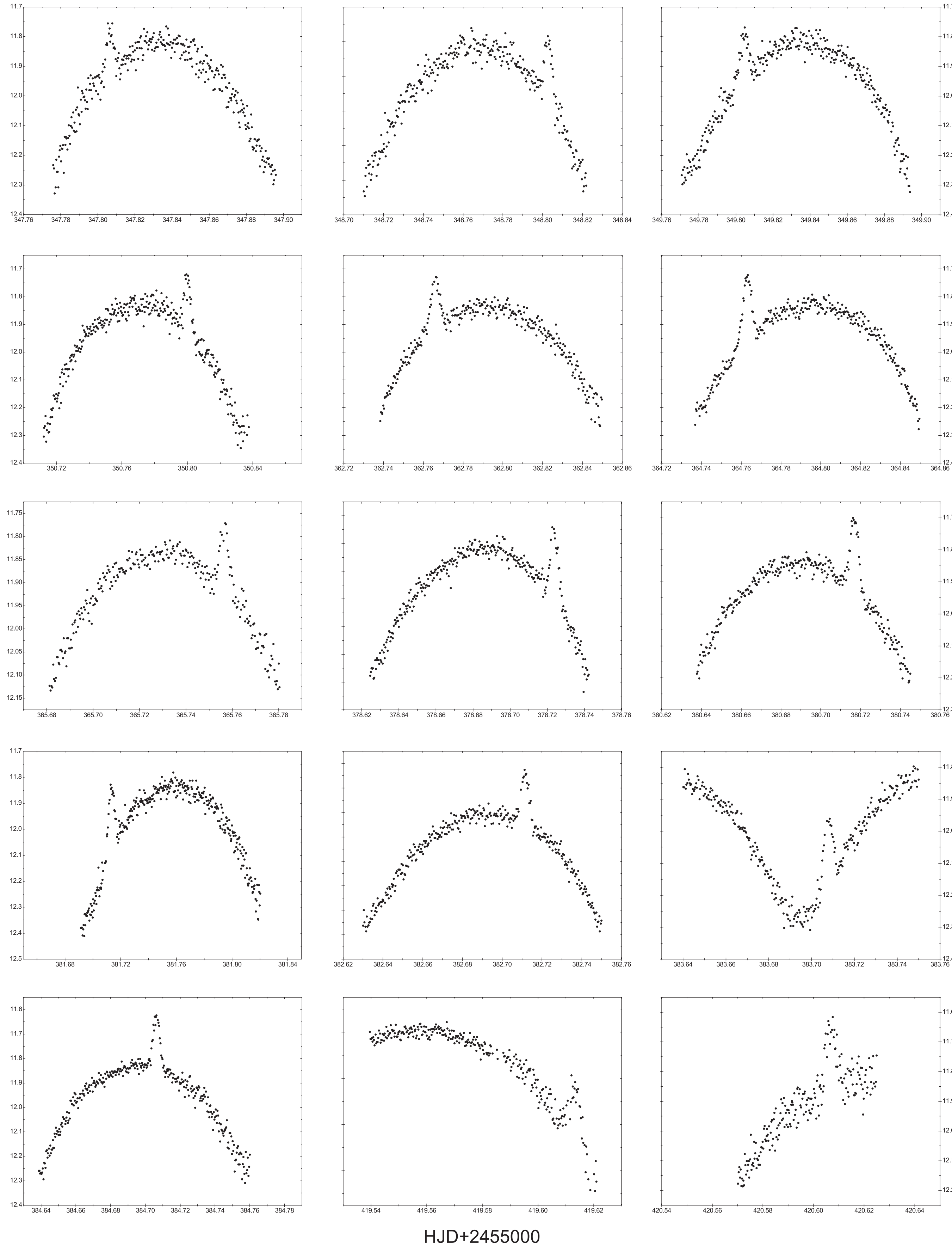

Figure 10. Optical flares observed during the winter of 2010.

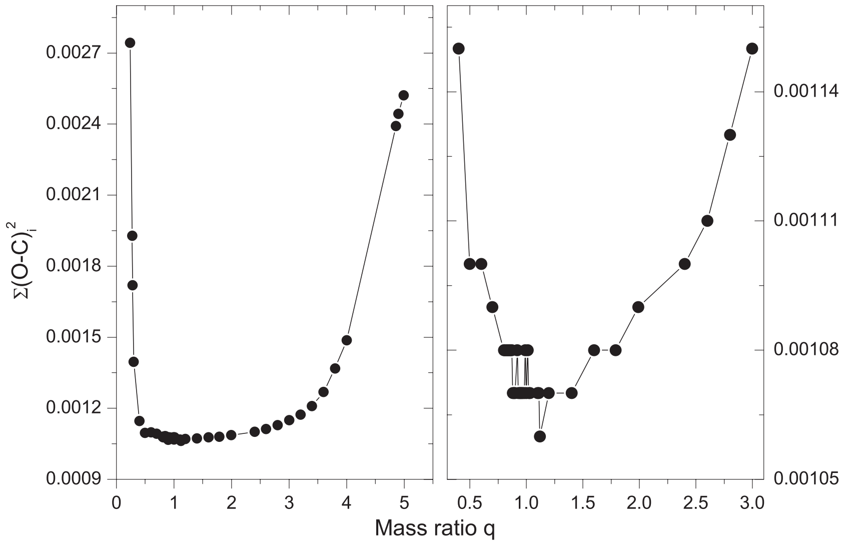

Figure 11. Relation between Σ and q for CSTAR 038663.

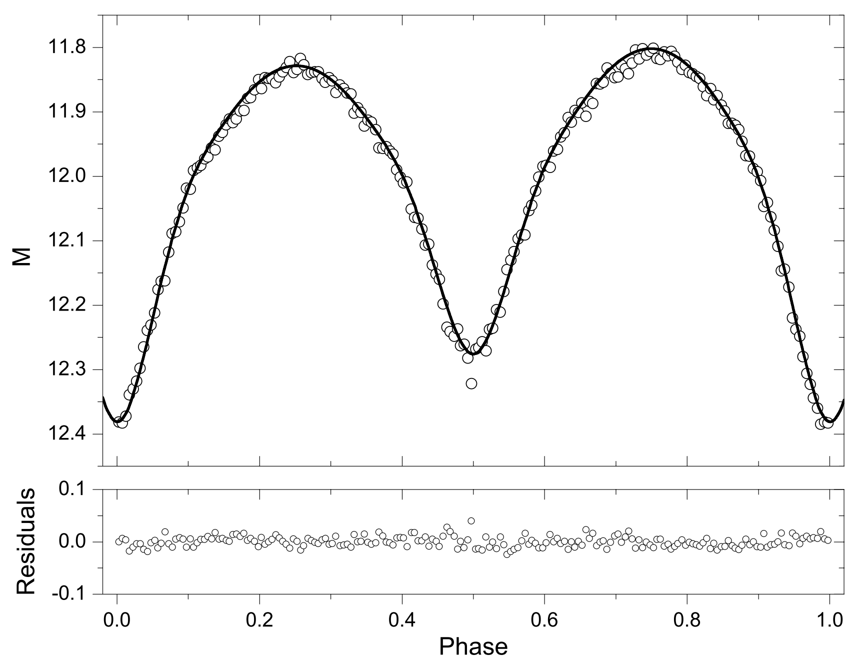

Figure 12. Theoretical and observational light curves of CSTAR 038663 are shown in the upper panel. Open circles in this panel refer to the normal data points of those photometric observations in i band. Residuals between the observations and theoretical light curves are shown in the lower panel. No changes can be traced there, indicating that the theoretical light curve fits those observations very well.

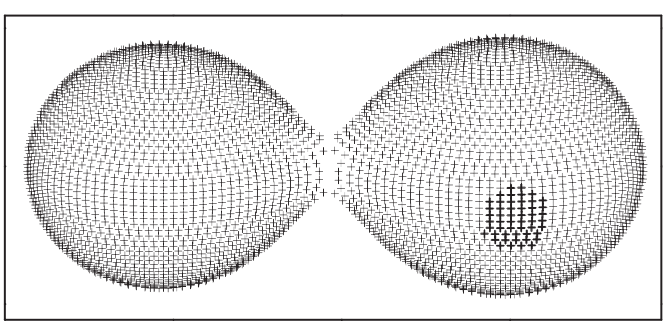

Figure 13. Geometrical structure of CSTAR 038663 at phase 0.25.

have now been monitored for more than 110 yr. However, no flares such as those observed in the winter of 2010 have been witnessed elsewhere. The distributions of the i-band flares, along with the phase, are displayed in Figure 15, where they are superimposed on the light curve of the binary star. It can be seen that the flares took place at many phases. The relation between the time duration (ΔT) and the flare amplitude (ΔA) is shown in Figure 16. It seems that ΔA is increasing along with ΔT. The longer ΔT is, the larger ΔA will be. The photometric solution, derived using the data obtained in 2008 (shown in Section 3), reveals a long-lived dark spot on the contact binary. Some evidence has shown that CSTAR 038663 was active during the observations of 2010. These observational facts indicate that

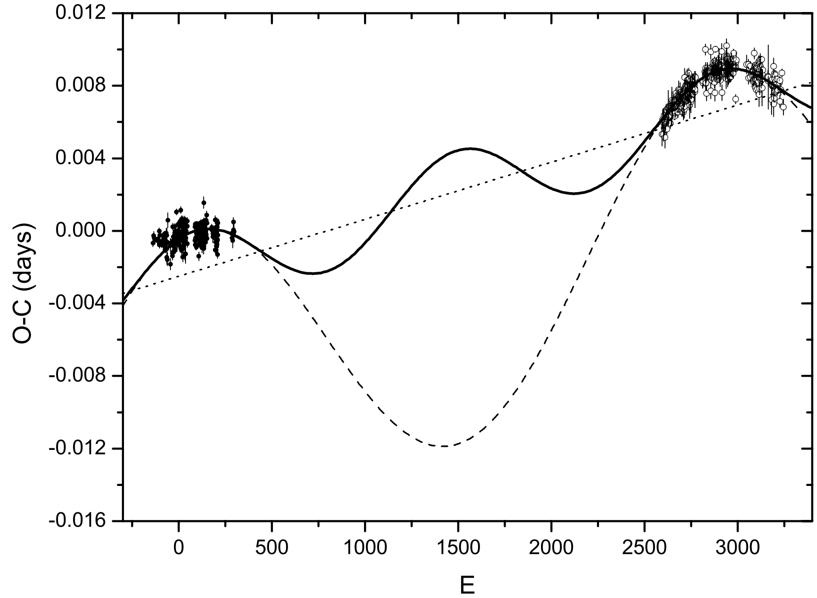

Figure 14. Cyclic change of the O–C curve. The O–C values are calculated with the linear ephemeris in Equation (1). To construct the O–C diagram, 725 eclipse times, determined with the Antarctic photometric data, are used. The dotted line in the panel represents the revised linear ephemeris in Equation (2). The solid line refers to the combination of the revised ephemeris, by which a cyclic variation with an amplitude of 0.00135 day and a period of 8.4 months is seen more clearly. The dashed line represents the cyclic change in Case B (Equation (3)).

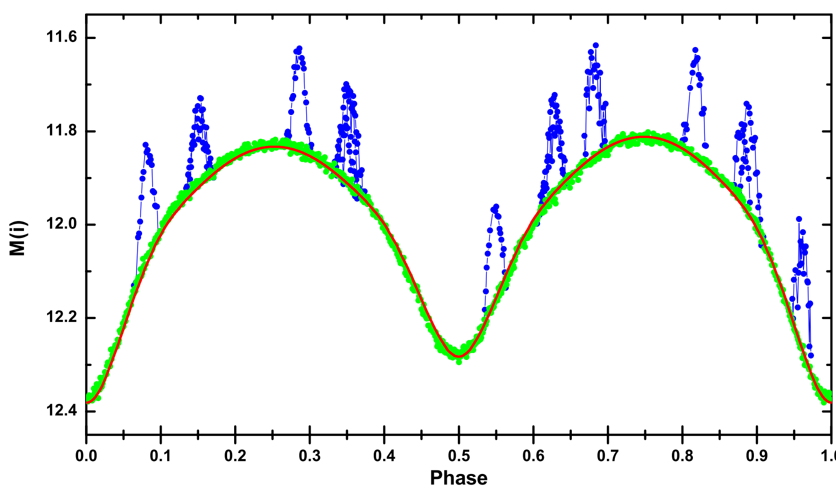

Figure 15. Distribution of the superflares on the light curve of the contact binary, CSTAR 038663. Blue dots represent the observed superflares. Phases of those data were calculated with the ephemeris in Equation (1). The red line refers to the theoretical light curve, computed with the W–D method, while green dots refer to the normal light curve.

(A color version of this figure is available in the online journal.)

those flares originated on the surface of the contact binary. On the other hand, some authors pointed out that the existence of the CCE tends to bury the very strong surface magnetic field (e.g., Qian 2001, 2003) and may prevent the production of flares. The effect of CCE on the activity of the components remains unknown.

The O–C diagram, shown in Figure 14, indicates a cyclic variation that can be explained by the light-travel time effect caused by the presence of a third body. Using the same method as Qian et al. (e.g., Qian et al. 2013a, 2013b), the parameters of the third body are determined, and they are shown in Table 5. The other possibility is that those optical flares took place on the third body orbiting the contact binary star. To check for the existence of the third body, we search for third light during the photometric solution. It is shown that the contribution of the third body accounts for less than 1% of the total light in the system. For Case A, the estimated mass of the third body is $M_3 \sin i' = 0.63(\pm 0.02)\, M_\odot$ and it is expected to contribute more third light to the total system. It is possible that the third body is also a close binary containing two red-dwarf stars ($\sim$0.3 $M_\odot$) in a close orbit that produce optical flares similar to those on other red-dwarf close binary stars (e.g., Qian et al. 2012). In this case, CSTAR 038663 is a quadruple system similar to PY Vir and VW LMi (Zhu et al. 2013a; Pribulla et al. 2008). For Case B, the mass of the third body is estimated as $M_3 \sin i' = 2.02(\pm 0.08)\, M_\odot$. In this case, the third body should be very luminous, which is impossible unless the third body is a compact object, i.e., a neutron star or black hole. In both cases, the orbital separation between the tertiary and central binaries is about $\sim$1 AU, revealing that it is a close-in companion to the contact binary. If the third body really exists, then the O–C diagram should strictly show periodic change. To check its presence, new data are required in the future.

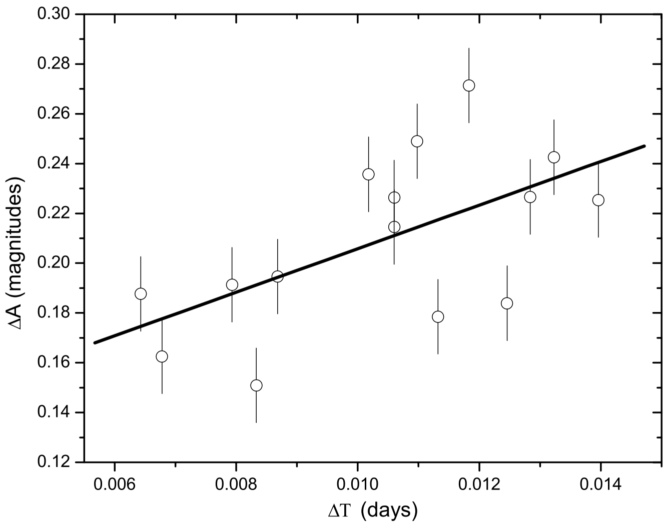

Figure 16. Possible relation between the time duration (ΔT) and the flare amplitude, ΔA. The solid line refers to the least-square solution: $\Delta A = 0.118(\pm 0.024) + 8.8(\pm 2.3) \times \Delta T$.

Table 3
Photometric Solutions for CSTAR 038663

Parameters	Photometric Elements	Errors
$g_1 = g_2$	0.32	Assumed
$A_1 = A_2$	0.5	Assumed
$x_{1\mathrm{bolo}}$	0.314	Assumed
$x_{2\mathrm{bolo}}$	0.278	Assumed
$y_{1\mathrm{bolo}}$	0.368	Assumed
$y_{2\mathrm{bolo}}$	0.398	Assumed
x_{1I}	+0.283	Assumed
x_{2I}	+0.286	Assumed
y_{1I}	+0.401	Assumed
y_{2I}	+0.409	Assumed
T_1	4616 K	Assumed
q (M_2/M_1)	1.123	±0.012
$\Omega_1 = \Omega_2$	3.8883	±0.0162
T_2	4352 K	±10 K
i	73.4	±0.2
$L_1/(L_1 + L_2)$ (I)	0.5360	±0.0016
r_1(pole)	0.3534	±0.0023
r_1(side)	0.3719	±0.0029
r_1(back)	0.4069	±0.0046
r_2(pole)	0.3727	±0.0022
r_2(side)	0.3933	±0.0029
r_2(back)	0.4273	±0.0043

Table 4
Parameters of the Dark Spot on the Secondary

Spot Parameters	Value
θ(radian)	1.690
ϕ(radian)	1.680
r(radian)	0.265
T_f(T_d/T_0)	0.820

The extremely high mass ratio of CSTAR 038663 suggests that it is presently evolving into contact with little mass transfer between the components, while the shallow contact configuration reveals that it is a newly formed contact binary and just at the beginning stages of contact evolution. It is possible that the formation is being driven by angular momentum loss (AML), via magnetic braking, because both components are rapidly rotating cool stars. On the other hand, the close-in stellar companions should play an important role in the origin and evolution by removing angular momentum from the central pair either during the early stellar dynamical interaction or the late evolution via Kozai oscillation (Kozai 1962). A combination of the Kozai cycle and tidal friction (e.g., Fabrycky & Tremaine 2007) may also cause the binary to have a very low angular momentum and a very short initial orbital period (e.g., $P <$ 1 day). In this case, the initially detached short-period binaries can evolve into contact configuration via magnetic torques from stellar winds (e.g., Bradstreet & Guinan 1994; Qian et al. 2007b, 2007d, 2008, 2013a). Observations of CSTAR 038663 suggest that it may have formed through the combination of AML, via magnetic braking, and angular momentum transfer, via the close-in stellar companion. It is a newly formed, shallow contact binary showing strong magnetic activity with a possible close-in stellar companion.

Table 5
Parameters of the Close-in Third Body

Parameters	Case A	Case B
Period (P_3 in years)	1.03(±0.05)	2.05(±0.10)
Eccentricity (e_3 assumed)	0.0	0.0
Amplitude (K_3 in days)	0.00223(±0.00006)	0.00809(±0.0021)
$a'_{12}\sin i'$ (AU)	0.39(±0.01)	1.40(±0.04)
$f(m)$ ($M_\odot$)	$5.44(\pm 0.44) \times 10^{-2}$	0.66(±0.05)
$M_3 \sin i'$ ($M_\odot$)	0.63(±0.02)	2.02(±0.08)
a_3 ($i' = 90°$) (AU)	0.93(±0.04)	1.06(±0.09)

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