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ORIGINAL ARTICLE

Photospheric and chromospheric activity of the short period X-ray and Algol eclipsing binary UX CrB

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Abstract We present six V$R_c I_c$ light curves of UX CrB from observations carried out from 2011–2015. We also obtained three optical spectra using the 2.16-m optical telescope and LAMOST survey at the national astronomical observatories. We classified its spectral type as G2 ± 2V. We noticed that there are strong absorptions in the H_α, H_β, Ca II H&K and infrared triplet lines in the observed spectra. By subtracting away the photospheric contribution, we also noticed that there are small excess emissions in these chromospheric active lines, which indicate there are weak chromospheric activities. We tried and obtained four photometric solutions with different spot positions from our full and high time-resolution light curves in 2012, using the updated Wilson-Devinney code. The model with two spots on the primary produced the best result for explaining the observed light curves from 2012. Moreover, we explained all other light curves based on our photometric solution using our 2012 light curves. There are two active longitudes at about 68° and 255°. We noticed that the starspots have both long-time (years) and short-time (about two months) variation by analyzing the light curves and its starspot parameters. There is also an obvious oscillation of light curve maximum between 0.25 and 0.75 phases by analyzing the values of Max. I − Max. II. We conclude UX CrB are the evolved main-sequence stars with strong photometric and chromospheric activities.

Keywords Stars: late-type · Binaries: eclipsing · Stars: starspots · Stars: individual: UX CrB

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1 Introduction

Algol eclipsing binaries are excellent astrophysical laboratories for studying orbital physical parameters (e.g., Yang et al. 2010; İbanoğlu et al. 2007), magnetic activities (e.g., Olson and Etzel 1993; Richards and Albright 1993; Zhang et al. 2014), orbital period variations (e.g., Qian 2001; Erdem et al. 2007; Zhu et al. 2009; Soydugan et al. 2007; Yang and Wei 2009), and magnetic interactions (e.g., Richards et al. 2012). Rapid rotation with deep convection envelopes produces photometric and chromospheric activities, such as starspots, plages, and flares (see e.g., Frasca and Catalano 1994; Berdyugina 2005; Strassmeier 2009; Lanza 2009; Patel et al. 2013; Vida et al. 2009). Many eclipsing binary systems show period increase or decrease, period cyclic variation, and combination of them. There are several physical mechanisms that cause the orbital period variation in a binary system, such as mass transfer or loss, angular momentum transfer or loss, a third companion or magnetic cycle (e.g., Applegate 1992; İbanoğlu et al. 2006).

UX CrB (1E1615.0+3114) is an X-ray candidate of RS CVn class of binary with an X-ray flux intensity of 1.77 $\mathrm{erg\,cm^{-2}\,s^{-1}}$ (Fleming et al. 1989a,b). It is also a detached eclipsing binary with a orbital period about 0.568 days and an amplitude of 0.4 mag (Gioia et al. 1990; Robb et al. 1990; Shugarov 1992). Fleming et al. (1989b) identified it as a close binary system and found the spectral type of one object as G0. Robb et al. (1990) published the light curves in VR bands, and got the linear ephemeris (HJD = 2448117.7714(4)+0.56789(5)E). The precision of the observed light curves is about 0.02 mag. They obtained preliminary stellar parameter values (effective temperatures of 6030 K and 3900 K for primary and secondary components, respectively, and inclination about 70 degree). However, they did not consider some asymmetrical brightness of the

Table 1 Coordinates and magnitudes of UX CrB, comparison and check stars

Star name	$\alpha;\delta$(2000)	Mag_B	Mag_V	Mag_R	Mag_J	Mag_H	Mag_K	References
	h:m:s;°:′:″	mag	mag	mag	mag	mag	mag	
UX CrB	16:16:54.3;31:07:21	13.12	12.6	11.500	11.151	10.809	10.703	1, 2
TYC 2580-1156-1	16:17:18.5;31:07:58	12.44	12.13		10.726	10.417	10.345	3
TYC 2580-2390-1	16:16:44.7;31:00:24	12.97	12.01		10.404	9.945	9.838	3

Reference: 1. Samus et al. (2003); 2. Robb et al. (1990); 3. Hog et al. (2000)

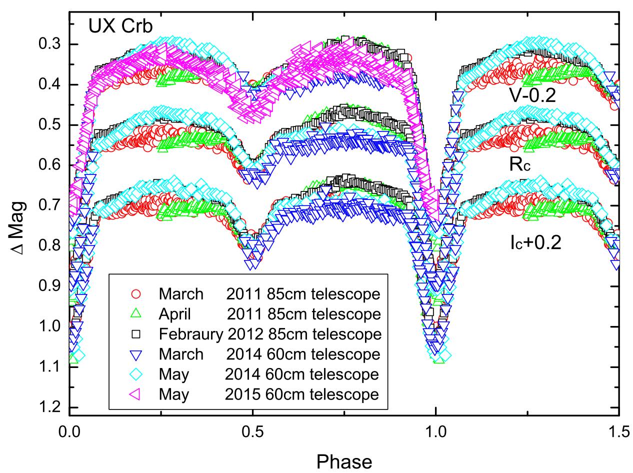

Fig. 1 VR_cI_c CCD light curves of UX CrB from 2011–2015 observations. Squares (□) indicate February 2012, circles (◯) March 2011, up triangles (△) April 2011, down triangles (▽), March 2014, diamond (◇) May 2014, and Left triangles (◁) May 2015

maxima. Shugarov (1992) also studied UX CrB using photographic plates and the UBV photoelectric photometry, and obtained an improved value for the orbital period. New minima of UX CrB were published at the O–C gate site (Paschke and Brát 2006; Brát et al. 2009, 2011). No analyses on the asymmetrical brightness of the maxima and the period variation have been carried out previously. We decided to carry out a long term program to monitor UX CrB with the aim to better constrain the orbital parameters and characterize the system in terms of magnetic activity.

To better understand photometric and chromospheric activity of UX CrB, we monitor it by CCD photometry and spectroscopy. In this paper, we will present six new multi-color V, R_c, and I_c light curves and three low-resolution spectra of UX CrB. We will also present new physical and starspot parameters using the Wilson-Devinney code, and discuss its chromospheric activity.

2 Observation

We carried out our photometric observations on 9 nights (March 22, 24, 2011; April 15, 17, 18, 2011; February 16, 17, 18, 19, 2012) with the 85-cm telescope, and 10 nights (March 13, 14, 15, 23, 2014; May 20 and 22, 2014; March 3, 4, 5, 6, 2015) with the 60-cm telescope at Xinglong Station of the National Astronomical Observatories of China (NAOC). The camera is a 1024 × 1024 pixel CCD and filter is the Johnson-Cousin-Bessell BVR_cI_c system (Zhou et al. 2009). Because the filter wheel was defective at that time, we observed UX CrB in only V filter in March, 2015. We reduced CCD images using IRAF,[1] which includes trimming, bias subtraction, flat-field division, and aperture photometry. We listed the parameters of the comparison and check stars in Table 1. The magnitude differences of UX CrB and comparison star (UX CrB-comparison star) are shown in Fig. 1. We calculated phases using our updated ephemeris. We listed the heliocentric Julian dates and the magnitude differences in Table 2 for VRI bands. The errors in our data are about 0.01 mag.

We made new spectroscopic observations of UX CrB with the OMR spectrograph on the 2.16 m telescope of NAOC on Feb. 16, 2012. The OMR spectrograph has a spectral wavelength range of 3700–4960 Å and a spectral resolution of 4000 (Fan et al. 2016). The exposure time was 40 min and its corresponding signal to noise (S/N) was about 40. We also reduced our data using IRAF packages. We plotted UX CrB spectra of 2.16-m telescope in Fig. 2. LAMOST (Cui et al. 2012) provided an opportunity for studying spectroscopic properties and chromospheric activity of eclipsing binary (Qian et al. 2017; Zhang et al. 2017, 2018). We took advantage of LAMOST survey and found two low-dispersion spectroscopic spectra from LAMOST database (Luo et al. 2015). These UX CrB spectra were obtained by LAMOST survey on March 6, 2014 and April 23, 2016. We plotted them in Fig. 3. The H_α, H_β, Ca II H&K and IRT lines are useful chromospheric activity indicators (Montes et al. 1995; Gunn and Doyle 1997). As can be seen from Figs. 2 and 3, we found that there are obvious absorptions in these lines.

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 2 New V$R_c I_c$ light curve data of UX CrB observed in 2011–2015

V band		R_c band		I_c band		Telescope
HJD(+2400000)	Δ mag	HJD(+2400000)	Δ mag	HJD(+2400000)	Δ mag	
55643.1821	0.537	55643.1830	0.504	55643.1836	0.476	85 cm telescope
55643.1843	0.538	55643.1852	0.498	55643.1858	0.466	
⋮	⋮	⋮	⋮	⋮	⋮	
55643.3892	1.005	55643.3867	0.917	55643.3903	0.880	
55643.3908	0.988	55643.3882	0.923	55643.3918	0.883	
55645.2312	0.586	55645.2333	0.552	55645.2322	0.523	
55645.2327	0.598	55645.2348	0.560	55645.2337	0.524	
⋮	⋮	⋮	⋮	⋮	⋮	
55645.3919	0.611	55645.3925	0.575	55645.3899	0.580	
55645.3935	0.614	55645.3940	0.573	55645.3914	0.589	
55667.1813	0.561	55667.1820	0.508	55667.1826	0.484	
55667.1833	0.578	55667.1840	0.527	55667.1846	0.497	
⋮	⋮	⋮	⋮	⋮	⋮	
55667.3650	0.569	55667.3637	0.533	55667.3643	0.500	
55667.3670	0.564	55667.3657	0.522	55667.3663	0.513	
55669.1796	0.576	55669.1803	0.531	55669.1809	0.510	
55669.1816	0.542	55669.1823	0.555	55669.1827	0.502	
⋮	⋮	⋮	⋮	⋮	⋮	
55669.3516	0.545	55669.3522	0.506	55669.3527	0.474	
55669.3533	0.538	55669.3539	0.516	55669.3543	0.466	
55670.1767	0.568	55670.1774	0.510	55670.1780	0.488	
55670.1787	0.558	55670.1794	0.544	55670.1800	0.490	
⋮	⋮	⋮	⋮	⋮	⋮	
55670.3663	0.636	55670.3669	0.604	55670.3673	0.590	
55670.3678	0.623	55670.3684	0.639	55670.3689	0.629	
55974.2751	0.506	55974.2761	0.474	55974.2769	0.438	
55974.2778	0.497	55974.2788	0.476	55974.2796	0.457	
⋮	⋮	⋮	⋮	⋮	⋮	
55974.4258	0.863	55974.4268	0.797	55974.4276	0.762	
55974.4285	0.870	55974.4295	0.831	55974.4303	0.763	
55975.2596	0.560	55975.2607	0.539	55975.2641	0.533	
55975.2623	0.575	55975.2634	0.552	55975.2677	0.544	
⋮	⋮	⋮	⋮	⋮	⋮	
55975.4171	0.514	55975.4185	0.481	55975.4232	0.443	
55975.4208	0.513	55975.4221	0.478	55975.4268	0.435	
55976.2795	0.510	55976.2805	0.476	55976.2812	0.455	
55976.2822	0.504	55976.2832	0.481	55976.2839	0.452	
⋮	⋮	⋮	⋮	⋮	⋮	
55976.4248	0.623	55976.4231	0.594	55976.4266	0.591	
55976.4275	0.621	55976.4258	0.611	55976.4293	0.599	

Table 2 (*Continued*)

V band		R_c band		I_c band		Telescope
HJD(+2400000)	Δ mag	HJD(+2400000)	Δ mag	HJD(+2400000)	Δ mag	
55977.2392	0.579	55977.2402	0.541	55977.2409	0.520	
55977.2418	0.588	55977.2429	0.566	55977.2436	0.543	
⋮	⋮	⋮	⋮	⋮	⋮	
55977.4222	0.520	55977.4232	0.474	55977.4239	0.453	
55977.4249	0.504	55977.4259	0.486	55977.4266	0.453	
57085.19387	0.56800	–	–	–	–	60 cm telescope
57085.19526	0.58100	–	–	–	–	
57085.19610	0.56900	–	–	–	–	
⋮	⋮	–	–	–	–	

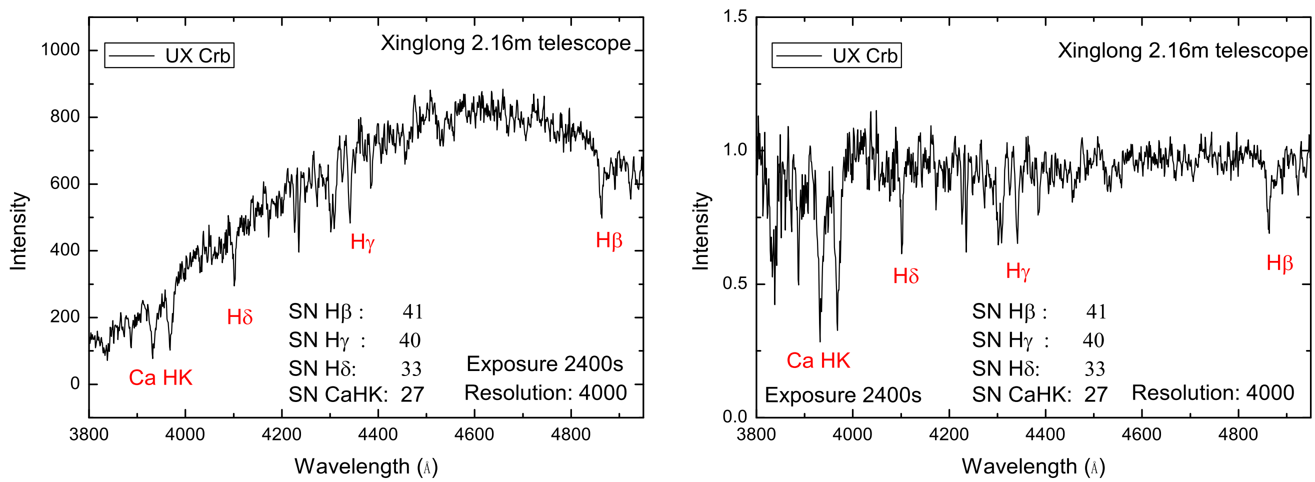

Fig. 2 Observed spectra of UX CrB using the 2.16-m telescope, NAOC. The left panel represents the observed spectrum and the right one represents the same spectrum normalized to its continuum

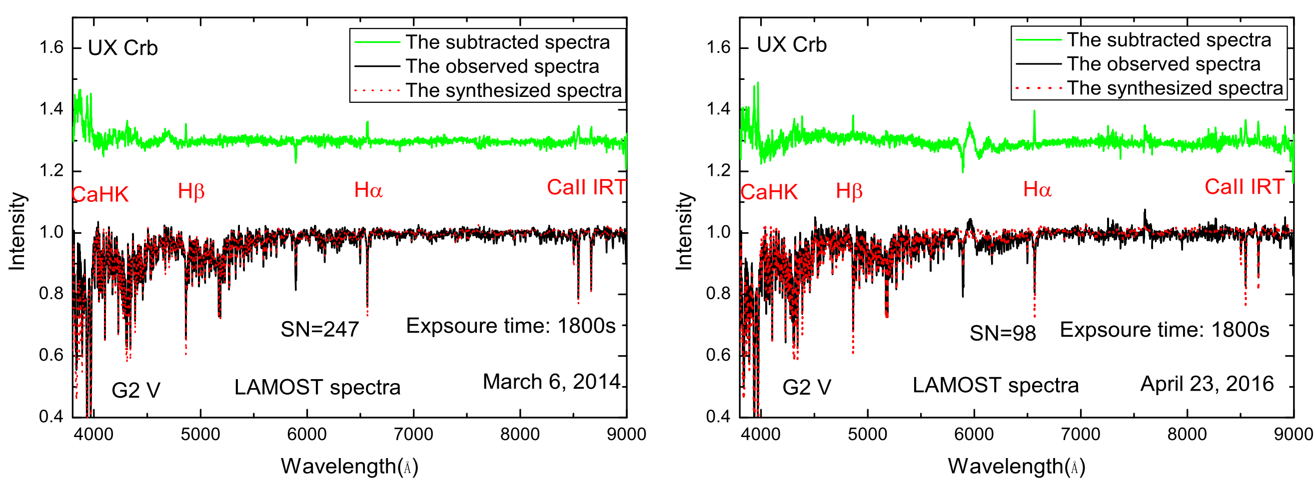

Fig. 3 LAMOST spectra for UX CrB in the H_α, H_β and Ca II H&K and IRT lines. The green (upper) spectra are the subtracted spectra

Table 3 Minimum times of UX CrB

HJD(24, +)	Error	Method	Cycle	Type	$(O-C)_1$	Source
48117.7714		CCD	−8826.0	P	−0.0004	Robb et al. (1990)
53129.5500		CCD	0.0	P	0.0011	Butters,* Paschke and Brát (2006)
54941.5339	0.0001	CCD	3191.0	P	0.0000	Brát et al. (2009)
55265.4863	0.0002	CCD	3761.5	S	−0.0017	Brát et al. (2011)
55690.5188		CCD	4510.0	P	0.0007	Lehky M.,* Paschke and Brát (2006)
55692.5051		CCD	4513.5	S	−0.0004	Lehky M.,* Paschke and Brát (2006)
56058.4798		CCD	5158.0	P	−0.0001	Paschke and Brát (2006)
56073.5288		CCD	5184.5	S	0.0010	Trnka J.,* Paschke and Brát (2006)
56354.6057		CCD	5679.5	S	−0.0041	Lehky M.,* Paschke and Brát (2006)
56406.5679		CCD	5771.0	P	0.0006	Lehky M.,* Paschke and Brát (2006)
55645.3741	0.0004	CCD	4430.5	S	−0.0005	Our paper
55667.2372	0.0002	CCD	4469.0	P	0.0007	...
55669.2234	0.0002	CCD	4472.5	S	−0.0006	...
55975.2935	0.0001	CCD	5011.5	S	0.0025	...
55977.2794	0.0001	CCD	5015.0	P	0.0009	...
56731.3723	0.0001	CCD	6343.0	P	−0.0009	...
56798.0986	0.0001	CCD	6460.5	S	0.0039	...
56800.0822	0.0001	CCD	6464.0	P	0.0001	...
57086.2720	0.0002	CCD	6968.0	P	−0.0027	...

Our collected data marked by (*) were collected from http://var2.astro.cz/EN/ (Paschke and Brát 2006) and we also gave the name of observer

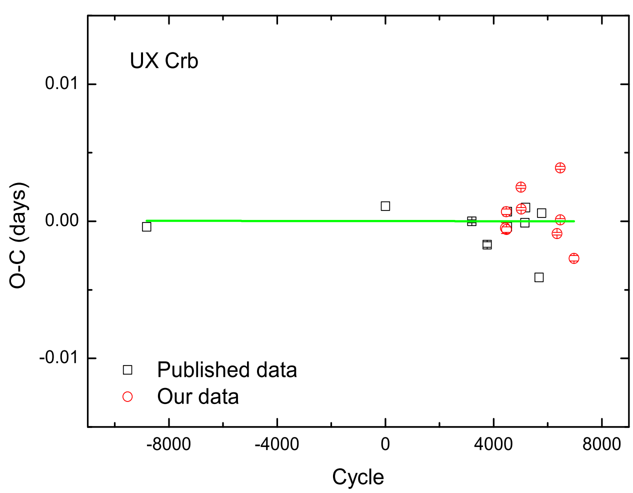

Fig. 4 (O–C) diagram with a linear fit for the minimum times for UX CrB, where the square symbols refer to the published minima and circles symbols represent our data

3 Updated ephemeris

Using our newly acquired data, we calculated the light curve minimum times of UX CrB using the program by Nelson (2010) with the method of Kwee and van Woerden (1956), and listed them in Table 3. To update the ephemeris, we collected its published minimum times (Paschke and Brát 2006). We calculated the epochs using a previous ephemeris by Paschke and Brát (2006). We listed all the minima, observational methods, and types of minima in Table 3. We obtained the modified linear ephemeris of UX CrB as follows:

$$\text{Min. I} = \text{JD(Hel.)}2453129.5489(\pm 0.0006) + 0^{d}.5678424(\pm 0.0000001)E. \quad (1)$$

We listed the $(O-C)_1$ values in 7th Column of Table 3 and plotted them in Fig. 4. We do not detect any obvious period variation from Fig. 4. Since there is only one data point at about 25 years ago and a large gap afterwards in the epoch (see Fig. 4), more data are needed to discuss its period variation in the future.

4 Photospheric and chromospheric activities

4.1 Spectral analysis

For weak chromospheric activity of late-type stars, it will produce fill-in absorptions in these chromospheric activity lines (Montes et al. 2004, etc.). We used a spectral subtraction technique by STARMOD program (Barden 1985; Montes et al. 2004) to discuss the chromospheric activity of

Table 4 EWs for UX CrB

'+' means emission and '−' means absorption

Time (year)	Observed spectra		Subtracted spectra	
	H_α (Å)	H_β (Å)	H_α (Å)	H_β (Å)
2014	-2.496 ± 0.497	-3.447 ± 0.410	$+0.836 \pm 0.070$	$+0.419 \pm 0.006$
2016	-2.686 ± 0.520	-3.011 ± 0.048	$+0.914 \pm 0.085$	$+0.447 \pm 0.003$
2012		-3.170 ± 0.513		

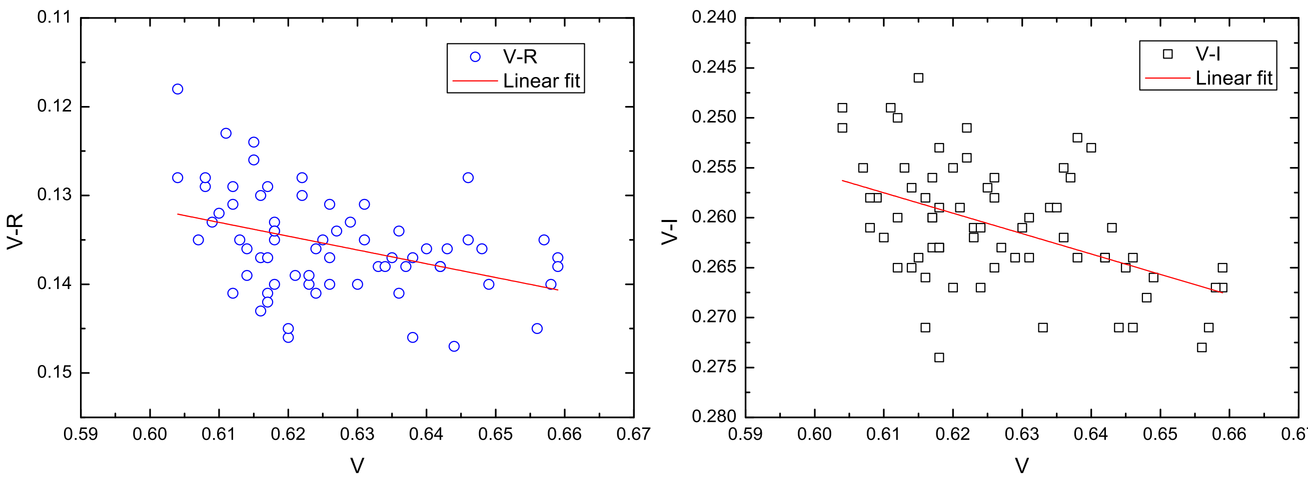

Fig. 5 Observed different magnitude V–R vs. V (Left) and V–I vs. V (right) variation. The solid and red lines represent their linear fits

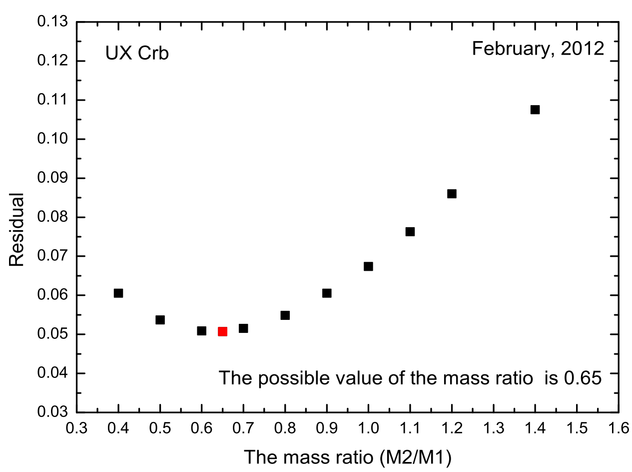

Fig. 6 Weighted square deviation of the $\Sigma(O-C)^2$ versus mass ratio. The minimum of the parabola is at the mass ratio of about 0.65

UX CrB. We normalized our spectra to their continuum using the IRAF software. We also downloaded the LAMOST spectra of Hipparcos Standard Stars with the spectral type from F9V to G4V (Vacca et al. 2003). By comparison, we found that the inactive star BD+28 2174 with the spectral type G2V is the best template for UX CrB. The subtracted (the observed spectra minus the synthesized one) and synthesized spectra are shown in Fig. 3, where the green (upper) spectra represent the subtracted spectra, the dotted lines represent synthesized spectra and black lines represent the observe spectra. From Fig. 3, we can see weak emissions of H_α, H_β, Ca II H&K and IRT lines in the subtracted spectra. We calculated its equivalent widths (EWs) for UX CrB in observed and subtracted spectra of H_α and H_β lines with high SNs, which are listed them in Table 4. In conclusion, there is a weak chromospheric activity in UX CrB.

4.2 Light curve analysis

First, we obtained photometric solutions of UX CrB by analyzing the data with full phase coverage acquired in February 2012. as they had a completed phase. We used the updated version of the Wilson-Devinney program in a Mode 2, which is appropriate for detached binaries (e.g., Wilson and Devinney 1971; Wilson 1979, 1990, 1994). Then, we analyzed the other six light curves based on our new orbital parameters with a starspot model.

4.2.1 Analysis of the light curves in February 2012

There are obvious distortions around phases 0.1–0.4 and 0.6–0.7 from the asymmetries of the light curves in 2012 (Fig. 1). We can analyze whether a spot is a hot spot or cool spot because our light curves are in multiple photometric bands (Alekseev 2001; Berdyugina 2005). We plot the relationship between color index V–R vs. V magnitude

Table 5 Orbital results of UX CrB in 2012

Element	Case 1	Case 2	Case 3	Case 4
T_1 (K)	5700[a]	5700[a]	5700[a]	5700[a]
q	0.662 ± 0.002	0.662 ± 0.002	0.660 ± 0.003	0.662 ± 0.002
i	$80.81° \pm 0.08$	$80.72° \pm 0.04$	$80.88° \pm 0.04$	$81.17° \pm 0.09$
T_2 (K)	4157 ± 8	4214 ± 3	4265 ± 8	4317 ± 8
Ω_1	3.667 ± 0.006	3.673 ± 0.006	3.717 ± 0.007	3.692 ± 0.006
Ω_2	4.945 ± 0.014	4.950 ± 0.013	4.962 ± 0.017	4.987 ± 0.016
$L_{1V}/(L_1+L_2)_V$	0.96320 ± 0.00009	0.95948 ± 0.00003	0.95504 ± 0.00004	0.95073 ± 0.00003
$L_{1R}/(L_1+L_2)_R$	0.94480 ± 0.00005	0.94078 ± 0.00005	0.93521 ± 0.00006	0.93053 ± 0.00005
$L_{1I}/(L_1+L_2)_I$	0.92582 ± 0.00007	0.92218 ± 0.00007	0.91650 ± 0.00007	0.91213 ± 0.00006
$Radius_1$ (pole)	0.3290 ± 0.0007	0.3285 ± 0.0007	0.3237 ± 0.0007	0.3265 ± 0.0007
$Radius_1$ (point)	0.3623 ± 0.0011	0.3613 ± 0.0010	0.3539 ± 0.0012	0.3583 ± 0.0011
$Radius_1$ (side)	0.3396 ± 0.0008	0.3389 ± 0.0007	0.3334 ± 0.0008	0.3367 ± 0.0008
$Radius_1$ (back)	0.3519 ± 0.0009	0.3511 ± 0.0009	0.3448 ± 0.0010	0.3485 ± 0.0009
$Radius_2$ (pole)	0.1745 ± 0.0007	0.1743 ± 0.0006	0.1733 ± 0.0008	0.1731 ± 0.0008
$Radius_2$ (point)	0.1783 ± 0.0007	0.1780 ± 0.0007	0.1770 ± 0.0009	0.1767 ± 0.0008
$Radius_2$ (side)	0.1757 ± 0.0007	0.1755 ± 0.0006	0.1744 ± 0.0008	0.1743 ± 0.0008
$Radius_2$ (back)	0.1777 ± 0.0007	0.1775 ± 0.0007	0.1764 ± 0.0009	0.1762 ± 0.0008
$Latitude_{spot1}$	90°[a]	90°[a]	90°[a]	90°[a]
$Longitude_{spot1}$	$83.0° \pm 0.7°$	$83.1° \pm 4°$	$82.3° \pm 0.2°$	$82.0° \pm 2.5°$
$Radius_{spot1}$	$3.1° \pm 0.2°$	$50.0° \pm 4.0°$	$11.7° \pm 0.2°$	$48.1° \pm 3.0°$
$Temperature_{spot1}$ (K)	3664 ± 267 K	3543 ± 57 K	5015 ± 171 K	3643 ± 37 K
$Latitude_{spot2}$	90°[a]	90°[a]	90°[a]	90°[a]
$Longitude_{spot2}$	$233.1° \pm 0.2°$	$238.5° \pm 3.0°$	$218.2° \pm 0.5°$	$232.5° \pm 0.2°$
$Radius_{spot2}$	$9.4° \pm 0.4°$	$10.4° \pm 3.0°$	$31.3° \pm 0.3°$	$38.8° \pm 4.5°$
$Temperature_{spot2}$ (K)	4030 ± 214	4099 ± 137	3342 ± 58	3384 ± 143
$\Sigma i(O-C)_i^2$	0.019	0.023	0.022	0.020

[a]Parameters not adjusted in the solution

different, and color index V–I and different magnitude of V between the phases 0.1 and 0.4 in Fig. 5. As can be seen from Fig. 5, we found that the V–R and V–I become redder when the star becomes fainter. This phenomenon might be caused by cool spots. Therefore we add cool photospheric spots to explain our new light curves. We reproduced the light-curve variation in 2012 with two spots (spot1 around phase 0.25 and spot2 around phase 0.65) in 2012. Because we had no high-resolution spectroscopic observations, we could not pre-determine whether spots were on the primary or secondary components. Therefore, we tried four cases (case 1: both spot1 and spot2 on the primary; case 2: spot1 on the secondary and spot2 on the primary; case 3: spot1 on the primary and spot2 on other component; case 4: both spot1 and spot2 on the secondary component).

We assume a synchronous rotation for the short period UX CrB. We used a bolometric albedo of 0.5 (Rucinski 1973) and a gravity-darkening coefficient of 0.32 (Lucy 1967) for both components. We set limb-darkening coefficients $X1_V = 0.608$, $X2_V = 0.705$, $X1_{R_c} = 0.503$, $X2_{R_c} = 0.612$, $X1_{I_c} = 0.413$, $X2_{I_c} = 0.476$ (Van Hamme 1993). We estimated the effective temperature of the primary was estimated from $J - H$ to be about 0.34 ± 0.03 using the following relationship of Collier Cameron et al. (2007) for stars with 4000 K $< T_{\text{eff}} <$ 7000 K:

$$T_{\text{eff}}\ (\text{K}) = -4369.5(J - H) + 7188.2 \tag{2}$$

The resulting effective temperature was 5700 ± 131 K, which is consistent with the spectral type that we derived. Since previous authors have not published the spectroscopic mass ratio for UX CrB (Robb et al. 1990; Shugarov 1992), we analyzed the relationship between the fitting residuals and the mass ratio $q = M_2/M_1$. The relationship is plotted in Fig. 6. The minimal fitting residual $\Sigma(O-C)_i^2$ was found to be at the mass ratio $q = 0.65$. Other adjustable orbital parameters are an orbital inclination, a temperature of the secondary component, dimensionless potentials of the primary component Ω_1 and the secondary component Ω_2, and

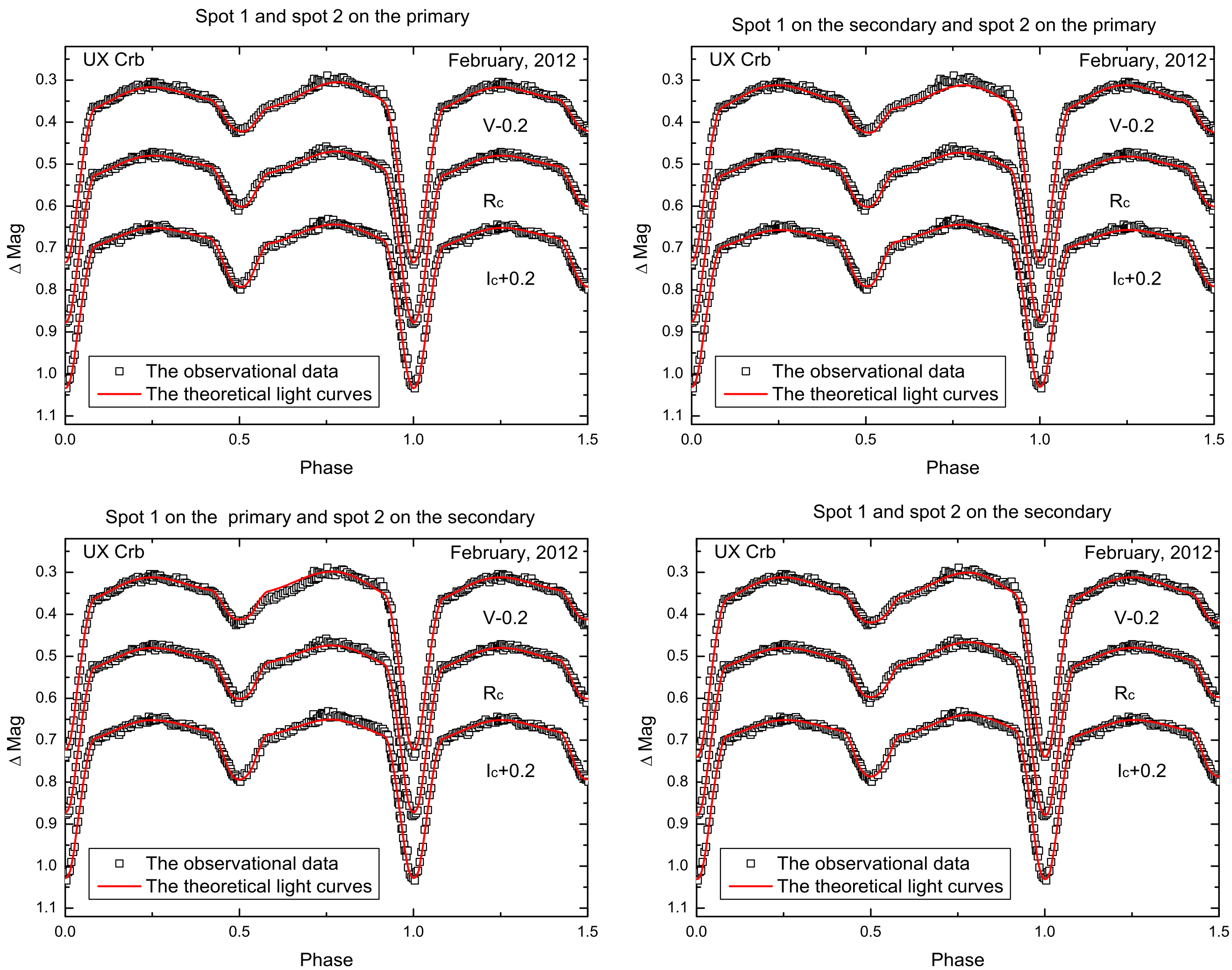

Fig. 7 Light curves and their theoretical fits of UX CrB for the four different cases in 2012. The points are the observational data, and the solid lines correspond to their theoretical light curves

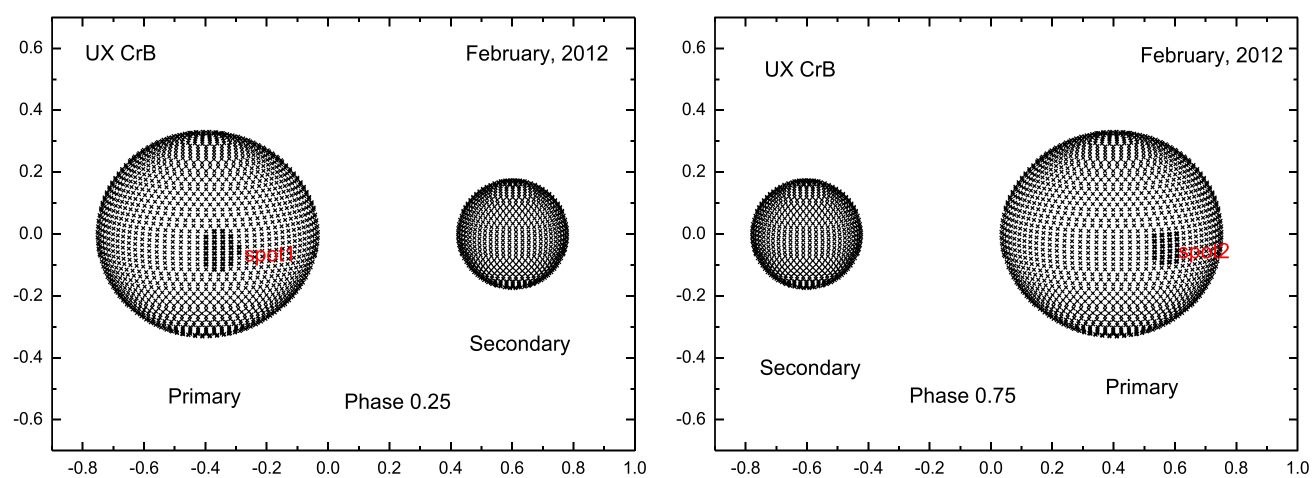

Fig. 8 Configuration with the spot distributions for the best results (Case 1) of UX CrB in 2012

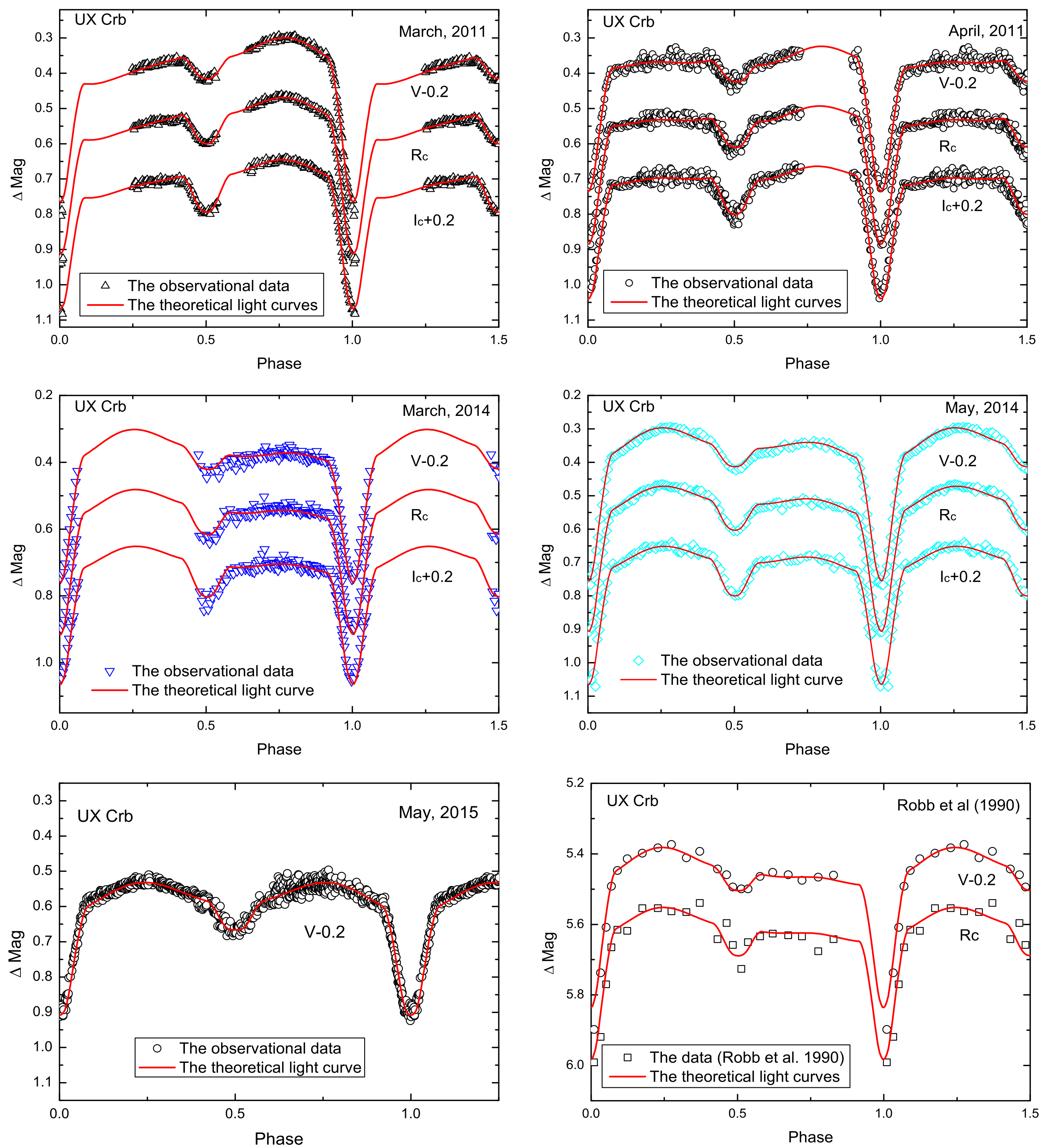

Fig. 9 Observed (points) and theoretical (solid lines) light curves of UX CrB for our data in the March and April 2011 runs, March and April 2014 runs, and May 2015 runs, and the data published by Robb et al. (1990)

a monochromatic luminosity of the primary derived from the approximate Kurucz atmosphere model option (Kurucz 1993). We derived four photometric solutions for UX CrB for all of the four cases mentioned previously, and listed the results in Table 5. The procedure of the orbital photometric solution is described in our previous paper focused on RT And (Zhang and Gu 2007), while similar methods for studying starspot evolution were used by Pribulla et al. (2000) for RT And and Pi et al. (2014) for DV Psc. We plotted the theoretical and observed light curves in Fig. 7. The weighted sums of squares of residuals for the case 1 (both spot1 and spot2 on the primary) are smaller than those of the other three results; therefore we conclude that case 1 is the best result for explaining the observed light curve. Corresponding configurations of UX CrB in 2012 are shown in Fig. 8.

4.2.2 Analysis of the other light curves

We tried to reproduce our five light curves based on our new photometric orbital solutions from our 2012 data with a two-spot (spot1 with a phase about 0.25 and spot2 with a phase about 0.75) model. We fixed the orbital parameters as the values given in Sect. 4.2.1, and adjusted only the starspot parameters to reproduce our light curves from 2011, 2014, and 2015 observations. If there is a gap in the light curve during the observation runs, we will fix the starspot parameters about the gap using the results near this run. For example, there is a gap in 0.1–0.5 during March runs 2014. We fixed the result of spot1 parameters obtained in April 2014, and only adjust the spot2 parameters to explain the light curves in March 2014. In the end, we obtained the starspot2 parameters in March, 2014. This method was also used in the previous paper (Zhang and Gu 2007; Zhang et al. 2014). We listed the resulting starspot parameters in Table 6. We plotted the LCs in Fig. 9 and their configurations in Fig. 10. The spot parameters obtained for the light curve from April, 2011 should be reliable because there is a very small gap. The spot2 parameters for the light curves from March 2011 and 2014 might be also realistic, while the spot1 parameters are less reliable because of the presence of a large data gap in phases 0.0–0.25. Comparison of the light curves of March and April, 2011, and March and May, 2014 indicates UX CrB having short time variations with a time scale of about two months. We also tried to reproduce the light curve published by Robb et al. (1990). In particular, we used a one-spot model (spot2 at phase 0.75) on the primary component. We listed the resulting starspot parameters in Table 6 and plotted its configuration in Fig. 10.

5 Discussion and conclusion

We updated the ephemeris for UX CrB. Our period is similar to those of Robb et al. (1990) and Paschke and Brát (2006). It seems that there are no period variation. We first derived firstly four orbital solutions for the eclipsing binary UX CrB by analyzing VR_cI_c LCs that we acquired in 2012. We reproduced the observed data with a two-spot model. The results obtained with two spots on the primary component is the best one for explaining the LCs. The ratio of the luminosity of the primary component to the total luminosity of the binary is 0.9632 in V, 0.9448 in R_c, and 0.9258 in the I_c bands. The mass ratio of 0.662 is smaller than the value of

Table 6 All the starspot parameters for UX CrB

Time	Spot1 (phase about 0.25)					Spot2 (phase about 0.75)					Residual	Reference
	Location	Latitude	Longitude	Radius	Temperature	Location	Latitude	Longitude	Radius	Temperature		
1990	P	90°[a]				P	90°[a]	$274.9^\circ \pm 4.2^\circ$	$15.4^\circ \pm 1.0^\circ$	4030 ± 214 K[a]	0.024	1, 2
Mar. 2011	P	90°[a]	$73.2^\circ \pm 3.0^\circ$	$17.3^\circ \pm 6.0^\circ$	3664 ± 267 K[a]	P	90°[a]	$236.0^\circ \pm 2.0^\circ$	$7.5^\circ \pm 0.6^\circ$	4030 ± 214 K[a]	0.029	2
Apr. 2011	P	90°[a]	$88.4^\circ \pm 1.7^\circ$	$15.3^\circ \pm 0.8^\circ$	3664 ± 267 K[a]	P	90°[a]	$244.0^\circ \pm 0.1^\circ$	$12.3^\circ \pm 0.4^\circ$	4030 ± 214 K[a]	0.135	2
Feb. 2012	P	90°[a]	$83.0^\circ \pm 0.7^\circ$	$3.1^\circ \pm 0.2^\circ$	3664 ± 267 K[a]	P	90°[a]	$233.1^\circ \pm 0.2^\circ$	$9.4^\circ \pm 0.4^\circ$	4030 ± 214 K[a]	0.190	2
Mar. 2014	P	90°[a]	$25.7^\circ \pm 0.3^\circ$[a]	$6.2^\circ \pm 30.2^\circ$[a]	3654 ± 344 K[a]	P	90°[a]	$267.1^\circ \pm 0.1^\circ$	$15.0^\circ \pm 0.2^\circ$	3957 ± 31 K	0.064	2
May 2014	P	90°[a]	$25.7^\circ \pm 0.3^\circ$	$6.2^\circ \pm 30.2^\circ$	3654 ± 344 K[a]	P	90°[a]	$273.4^\circ \pm 0.1^\circ$	$11.6^\circ \pm 0.3^\circ$	3957 ± 287 K	0.033	2
May 2015	–	–	–	–	–	–	–	–	–	–	–	2

[a]Parameters not adjusted in the solution

(1) Robb et al. (1990). (2) Our study

'P' means the primary. '–' means there are no starspots

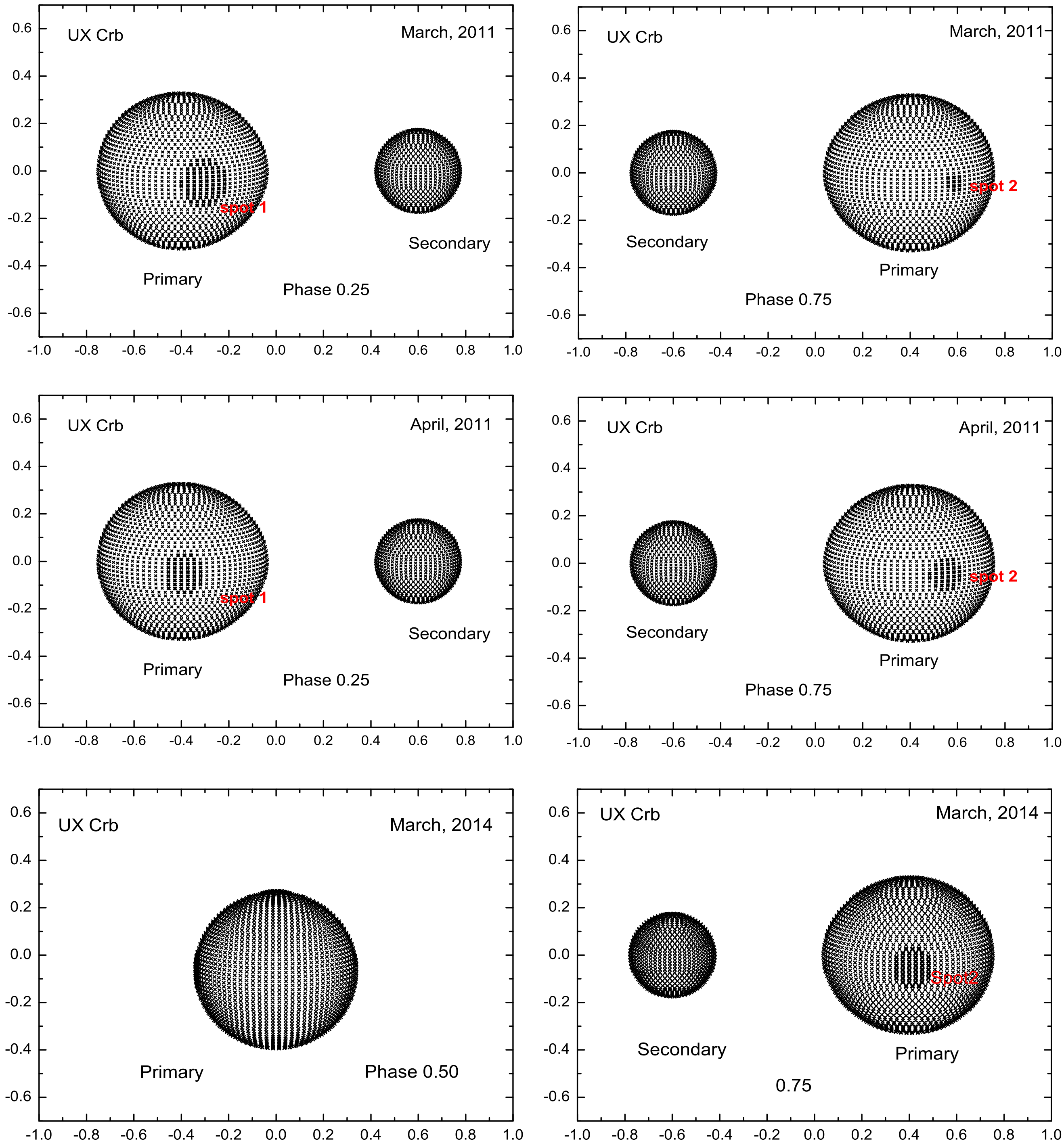

Fig. 10 Configurations and spot distributions for UX CrB in our data of 2011–2015 and that published by Robb et al. (1990)

0.7 (Robb et al. 1990) and, our derived inclination (80.810°) is larger than the result (70°) of Robb et al. (1990). The reason for this may be that our data is more precise and complete than that of Robb et al. (1990). Moreover. Robb et al. (1990) gave very preliminary results and they did not consider the starspot effect. We believe our solutions are more reliable than the previous results (Robb et al. 1990).

A comparison of the LCs of 1990, March and April 2011, and February 2012 indicates a long-term variation in UX CrB. As for the light curves of Robb et al. (1990), Max. I (phase 0.25) is brighter than Max. II (Phase 0.75). However, the Max. I is fainter than the Max. II for our light curves in March 2011. In order to discuss its variations outside the eclipse, we calculated the difference Max. I − Max. II from

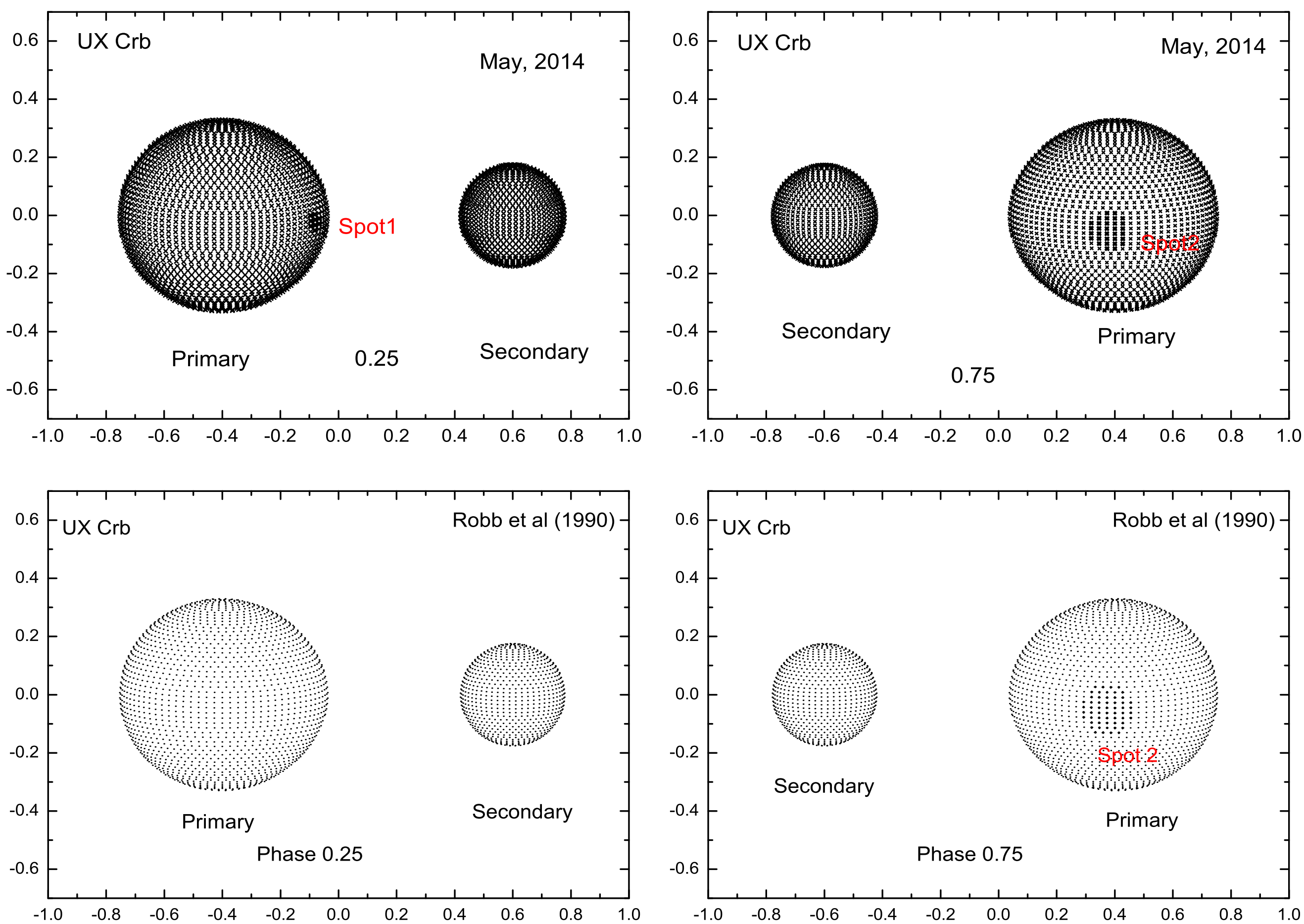

Fig. 10 (*Continued*)

Table 7 Vales of Max. I – Max. II for UX CrB

HJD	V-band (mag)	R-band (mag)	I-band (mag)	Reference
2448118	−0.093	−0.097		1
2455976	0.016	0.011	0.012	2
2455644	0.092	0.091	0.073	2
2455669	0.025	0.009	0.027	2
2456799	−0.045	−0.046	−0.030	2
2457086	−0.009	–	–	2

(1) Robb et al. (1990).
(2) Our paper

all available light curves. The values are listed in Table 7. We plotted them in Fig. 11. From Fig. 11, we found there is an obvious long-term variation (oscillation of light curve maximum between 0.25 and 0.75 phases). Because there is obvious lack of data, we do not add up it period of variation although there is oscillation. We were able to explain these variations by a two-spot model. The most reliable starspot parameters are their longitudes (Berdyugina 2005). The longitudes of two starspots were 88° and 244° in April 2011. However, the longitudes of spot1 and spot2 became 83° and 233° in February 2012. We plotted their spot longitudes in Fig. 12. From the diagram of spot longitudes, these indicates a starspot variability on a short (about two months) and long (years) time scales. We calculated the mean value of the spot longitudes about 68° and 255°. There are two active longitudes at about longitudes of 68° and 255°. These phenomena were also found in other active eclipsing binaries, such as RT And (Zhang and Gu 2008; Pribulla et al. 2000), WY Cnc (Kjurkchieva et al. 2004), and DV Psc (Zhang et al. 2010; Pi et al. 2014). The starspots changed over a long-time scales variation which can be detected analyzing their light curves and starspot parameters. This phenomenon were also found in AR Lac (Lanza et al. 1998); V1048 Aql (Mason et al. 2012); and U Sge (Olson 1987).

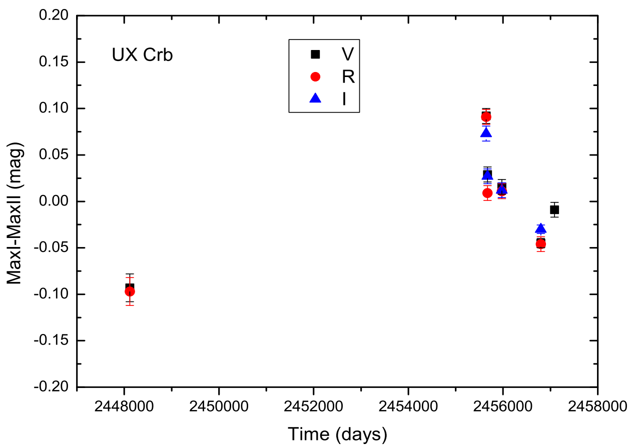

Fig. 11 Magnitude difference of Max. I (0.25) − Max. II (0.75) versus observing time (HJD)

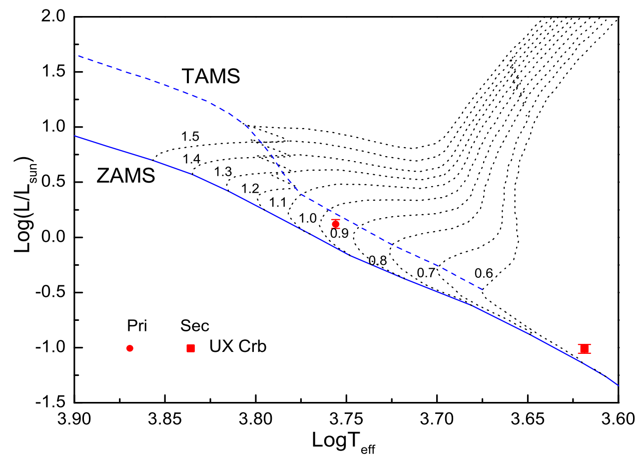

Fig. 13 Positions of both primary and secondary components for UX CrB in the $\log T_{\mathrm{eff}} - \log(L/L_{\mathrm{sun}})$ diagram. Circles represent the primary component and squares represent the secondary component

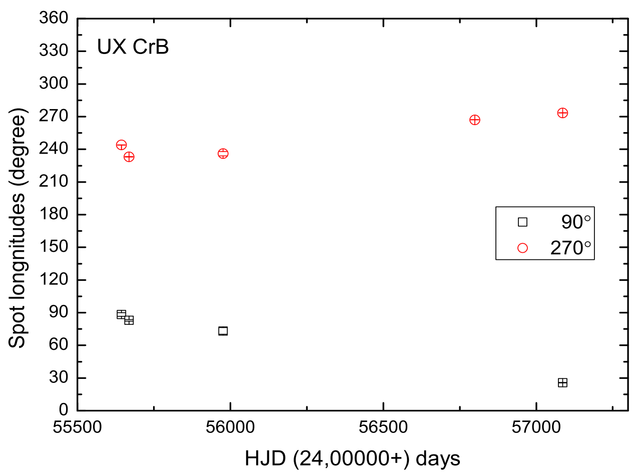

Fig. 12 Spot longitudes versus observing time. Squares (□) represent spot1 on longitude of about 68° and Circle (○) represent spot2 on the longitude 255°

We estimated the mass to be about 0.998(±0.05) $M_{\odot}$ and radius to be about 1.18(±0.03) $R_{\odot}$ for the primary component of UX CrB using the relation between these parameters and spectra type derived by Cox (2000). We derived the mass of 0.66(±0.05) $M_{\odot}$ and radius of about 0.60(±0.03) $R_{\odot}$ for the second component based on our photometric results (the mass ratio and relative radius). We calculated the semi-major axis (a) to be about 3.418(0.06) $R_{\odot}$ using Kepler's third law. We also obtained the luminosities 1.32(0.09) $L_{\odot}$ and 0.10(0.04) $L_{\odot}$ of primary and secondary components using $L_{1,2} = (R_{1,2}/R_{\odot})^2(T_{1,2}/T_{\odot})^4$. To discuss the evolution of both the primary and secondary components of UX CrB, we plotted a $\log T_{\mathrm{eff}} - \log(L/L_{\mathrm{sun}})$ diagram of zero-age main sequence (ZAMS), terminal-age main sequence (TAMS) and evolutionary tracks for different mass stars with solar chemical compositions (Girardi et al. 2000) and marked their positions of both components of UX CrB in Fig. 13. Because these two components are in the middle of the ZAMS and TAMS lines, we conclude that both components might be the evolved main-sequence stars.

There are weak chromospheric activities of UX CrB in the H_{α}, H_{β}, Ca II H&K lines and IRT lines. For photospheric activity, there are starspot variations in a long-term time scale. The chromospheric excess emission is consistent with the result of photospheric starspots. We conclude that UX CrB are the evolved main-sequence stars with strong photometric and chromospheric activities.

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