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First four-color photometric investigation of extreme mass-ratio contact binary AS coronae borealis

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HIGHLIGHTS

- The first photometric analysis of AS CrB with quality four-color light curves.
- The physical parameters are well estimated due to the totally eclipsing.
- Finding the period of AS CrB is long-term increasing.
- AS CrB is close to the merge condition.

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ABSTRACT

The first high-precision *BVRI* light curves of the eclipsing binary AS CrB were presented and were analyzed by the 2015 version of the W-D code. It is found that AS CrB is an extreme mass-ratio, deep contact binary with a fill-out factor of $f = 59.6 \pm 2.5\%$ and a mass ratio of $q = 0.172 \pm 0.008$. Based on the photometric solution and the Dartmouth isochrones model, the masses, radii, and luminosities of the components are estimated as follows: $M_1 = 1.25 \pm 0.15M_\odot$, $M_2 = 0.21 \pm 0.06M_\odot$, $R_1 = 1.40 \pm 0.07R_\odot$, $R_2 = 0.67 \pm 0.04R_\odot$, $L_1 = 3.2 \pm 0.2L_\odot$, and $L_2 = 0.72 \pm 0.04L_\odot$, with an estimated distance 459 ± 42 pc. These uncertainties mainly come from the errors of the color used to estimate the temperature of the primary star. By investigating all of the available times of light minima, it is found that the Observed-Calculated $[(O-C)]$ curve shows a long-term period increase, with a rate of $dP/dt = +(3.46 \pm 0.01) \times 10^{-7}$ day/year. As an extreme mass-ratio contact binary, AS CrB may merge into a single star, such as an FK Com-type star or a blue straggler, because of the orbital instability.

1. Introduction

Extreme mass-ratio, deep contact binaries whose mass ratios are less than 0.25 and whose fill-outs are greater than 50% (Samec et al., 2015a,b), almost without exception, are totally eclipsing binaries. Pribulla et al. (2003) had collected 80 contact binaries of which both the spectroscopic and photometric mass ratios have been derived and then they had concluded that 33 of 80 are totally eclipsing systems whose photometric mass ratios almost agreed with their spectroscopic results, while 47 of 80 are partly eclipsing systems whose photometric mass ratios deviate from the spectroscopic values. This work suggested that the absolute parameters of a contact binary derived by the photometric method should be acceptable if it is a totally eclipsing system. Extreme mass-ratio, deep contact binaries are also believed as highly evolved contact binary systems because they should have the smallest angular momentum for given total mass. These binaries are going to merge into fast rotating single stars (FK Com-type), or may become blue stragglers (BSs) (Guinan and Bradstreet, 1988; Eggleton and Kiseleva-Eggleton, 2001). Samec and his colleagues had studied on many extreme mass-ratio contact binaries. They had summarized 26 systems of this rare group (Samec et al., 2011) and had been adding fresh samples continuously (Samec et al., 2012, 2013, 2015a,b). We also have a series of studies about these i.e., Qian and Yang (2004); Qian et al. (2007); 2011); Liu et al. (2015). AS CrB is another individual extreme mass-ratio, deep contact binary in our observation schedule. For understanding its evolutional phase, we had observed its complete light curves in multiple filters. Multi-passband photometry is sensitive to detect cool/hot spots and irradiative tertiary companions which are very common in contact binary

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systems. Because the temperatures of the spots and the third bodies are different from the binary systems, the luminosity contributions of them are distinguished in different passbands. Hence, multi-passband photometry for contact binaries is helpful for finding such affections to the light curves, and for restoring the light curves to their original performances.

AS Coronae Borealis (AS CrB, ROTSE1 J160014.54+351228.4, GSC 2579-1125) was discovered as an EW type binary system by The Robotic Optical Transient Search Experiment I (ROTSE-I) (Akerlof et al., 2000). Subsequently, Blättler and Diethelm (2002) had observed AS CrB during 7 nights, obtaining 230 frames, then publishing an unfiltered light curve and several times of minima. They had derived a linear ephemeris,

$$Min.I(HJD) = 2452409.4467 + 0^{d}.380658 \times E. \quad (1)$$

In the later time, although some times of minima and another r-band normalized light curve (Devor et al., 2008) had been obtained, no photometric or orbital investigation had been done.

Terrell et al. (2012) had published the BVR_cI_c colors for 606 W Ursae Majoris binaries, including AS CrB. According to that, the $B-V$ color index is 0.463 with an uncertainty of 0.003. As we know, the color of an eclipsing binary system depends on the eclipsing phase. Our $\Delta(B-V)$ presents an amplitude of 0.05 mag (Fig. 4). So, this value could be taken as the uncertainty of the $B-V$ color, yielding $B-V = 0.463 \pm 0.05$. Based on the method of Worthey and Lee (2011), the effective temperature of the primary component can be estimate as 6500 ± 370 K. This value agrees with the temperature of the extreme mass-ratio contact binary GSC 3208-1986, which has a similar color and has been supported by its spectroscopic data (Samec et al., 2015a). In the paper, the first high- precision CCD light curves in *BVRI* bands for AS CrB were obtained and analyzed with the 2015 Version of the Wilson–Devinney (W-D) program (Wilson and Devinney, 1971; Wilson, 1979, 1990, 1993, 2008, 2012a,b; Van Hamme and Wilson, 2003, 2007; Wilson et al., 2010 and Wilson and Van Hamme, 2014). According to those photometric solutions and to the analysis of the orbital period, the evolutionary state of the AS CrB is discussed later.

2. New CCD photometric observations

To investigate the variation of the orbital period, we had observed AS CrB with the 1 m and 60 cm reflecting telescopes at the Yunnan Observatories (YNOs), and with the 85 cm reflecting telescope at the Xinglong Station, the National Astronomical Observatory (NAO). The 1 m and 60 cm telescopes were equipped with the same Andor DW436 CCD cameras, with a standard Johnson–Cousins filter system. The 85 cm telescope was equipped with a PI1024 BFT (Back-illuminated and Frame-Transfer) camera at the primary-focus (Zhou et al., 2009), whose effective field of view is $16.'5 \times 16.'5$. 2MASS 16003465 + 3511279 and 2MASS 16001451 + 3509452 were chosen as comparison and check star, respectively. The aperture photometry package PHOT which is for measuring magnitudes for a list of stars in IRAF was used to reduce the observed images, with the standard procedure of flat-fielding. The original data were observed by the 85-cm telescope which were used to yield the complete light curves. As the light curves are shown in Fig. 1, the phases were calculated with the equation of $2456011.24568 + 0.^{d}38065936 \times E$, where 2456011.24568 is one of the times of minima obtained by us, $0.^{d}38065936$ is our corrected linear orbital period, and E is the epoch number (Section 3). As it is seen, the light curves taken in the two nights phased up smoothly, suggesting little night-to-night variation. The magnitude differences between the two comparison stars, on the other hand, remained nearly constant, vindicating the variation nature of AS CrB. The standard deviations of the C-CH light curves (yielded by the magnitudes of the comparison minus those of the check star in the same phase) is less than 0.04 mag, which can be comparable to the standard deviations of the photometry for the target. Hence, the average precision of our photometry is about 0.04 mag.

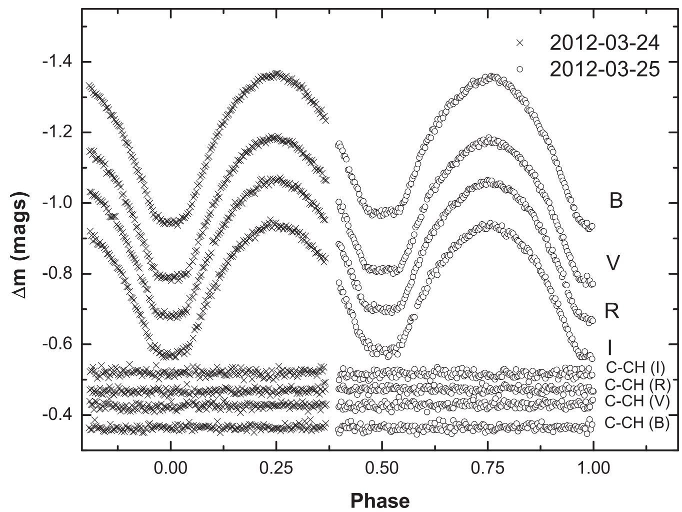

Fig. 1. Observed multi-color light curves in *BVRI* bands for AS CrB. The cross symbols denote the data observed in 2012-03-24 while the solid circles denote the data observed on 2012-03-25. The standard deviations of the C-CH light curves (yielded by the magnitudes of the comparison minus those of the check star in the same phase) can be comparable to the standard deviations of the photometry for the target.

3. Orbital period analysis

40 collected times of minima for AS CrB, including 8 of ours, are listed in Table 1, where "60 cm" and "1 m" refer to the data obtained by the 60 cm and the 1 m telescopes at YNOs, respectively, while the "85 cm" signifies the data observed by the 85 cm telescope at the Xinglong station. The second column of Table 1 is the filters used during the observations where "C" means clear filter while "N" means no filter. By using the ephemeris $2456011.24568 + 0.^{d}380658 \times E$, a linear correction was done. T_0 is one of our minima, and P_0 is obtained from Blättler and Diethelm (2002). The new linear ephemeris is,

$$\begin{aligned} \text{Min. I} = {} & 2456011.2452(\pm 0.0007) \\ & + 0.^{d}38065936(\pm 0.00000011) \times E. \end{aligned} \quad (2)$$

The $(O-C)$ values with respect to the linear ephemeris are listed in the fifth column of Table 1. The corresponding $(O-C)$ diagram is displayed in Fig. 2. The general $(O-C)$ trend of AS CrB shown in Fig. 2 indicates that the orbital period should long-term increase so that a parabola fitting for the $(O-C)$ values was used. The result is,

$$\begin{aligned} \text{Min. I} = {} & 2456011.24603(\pm 0.00003) \\ & +0.^{d}38066114(\pm 0.00000001) \times E \\ & +1.805(\pm 0.009) \times 10^{-10} \times E^{2}. \end{aligned} \quad (3)$$

With the quadratic term in this equation, a possible secular period increase rate is determined as $dP/dt = +(3.46 \pm 0.01) \times 10^{-7}$ days/year. The residuals shown in Fig. 2 may still show variations. To prove that a further monitoring is needed.

4. Photometric solutions

The *BVRI* multi-color light curves were analyzed with the 2015 version of the W-D code. As mentioned in Section 1, we applied the effective temperature of star 1 (T_1) as 6500 ± 370 K. Having

Table 1
Times of light minima for AS CrB.

JD (Hel.)	Filters	Min.	Epoch	$(O-C)$ (d)	Residuals (d)	Reference
51291.8339	C	p	−12398	0.00344	−0.00308	Akerlof et al. (2000)
51305.7310	C	s	−12361.5	0.00647	0.00004	Akerlof et al. (2000)
52360.5321	C	s	−9590.5	0.00049	0.00010	IBVS No.5295
52365.4792	C	s	−9577.5	−0.00098	−0.00134	IBVS No.5295
52368.3410	C	p	−9570	0.00587	0.00552	IBVS No.5295
52368.5276	C	s	−9569.5	0.00214	0.00179	IBVS No.5295
52395.3639	C	p	−9499	0.00196	0.00173	IBVS No.5295
52395.5523	C	s	−9498.5	0.00003	−0.00019	IBVS No.5295
52409.4459	C	p	−9462	−0.00044	−0.00060	IBVS No.5295
52415.5358	C	p	−9446	−0.00109	−0.00122	IBVS No.5295
52835.4036		p	−8343	−0.00056	0.00087	IBVS No.5543
53216.4409		p	−7342	−0.00328	−0.00078	IBVS No.5653
53541.5235		p	−6488	−0.00378	−0.00066	IBVS No.5653
53917.4231	R	s	−5500.5	−0.00529	−0.00180	IBVS No.5713
54197.4022		p	−4765	−0.00115	0.00239	IBVS No.5781
54587.1944	V	p	−3741	−0.00414	−0.00083	VSOLJ No.48
54684.4528		s	−3485.5	−0.00420	−0.00102	IBVS No.5781
54932.4535		p	−2834	−0.00308	−0.00031	IBVS No.5918
54945.7762	R	p	−2799	−0.00345	−0.00071	IBVS No.5929
54955.8638	V	s	−2772.5	−0.00333	−0.00061	IBVS No.5894
54968.4261		s	−2739.5	−0.00279	−0.00009	IBVS No.5959
55038.4675		s	−2555.5	−0.00271	−0.00016	IBVS No.5920
55067.3977		s	−2479.5	−0.00262	−0.00014	IBVS No.5959
55296.7443	V	p	−1877	−0.00328	−0.00140	IBVS No.5894
55657.9940	R_c	p	−928	0.00068	0.00135	VSOLJ No.53
55658.1831	R_c	s	−927.5	−0.00055	0.00012	VSOLJ No.53
55660.8457	V	s	−920.5	−0.00256	−0.00190	IBVS No.5894
56011.24568	$BVRI$	p	0	0.00048	−0.00034	The present paper (85cm)
56012.19800	$BVRI$	s	2.5	0.00115	0.00032	The present paper (85cm)
56018.0982	R_c	p	18	0.00113	0.00027	VSOLJ No.55
56018.2882	R_c	s	18.5	0.00080	−0.00005	VSOLJ No.55
56032.18187	N	p	55	0.00040	−0.00051	The present paper (60cm)
56038.8460	V	s	72.5	0.00299	0.00203	IBVS No.6029
56048.17021	N	p	97	0.00105	0.00005	The present paper (60cm)
56376.30127	R_cI_cN	p	959	0.00374	0.00104	The present paper (60cm)
56384.29490	R_cI_cN	p	980	0.00353	0.00078	The present paper (60cm)
56387.33931	R_cI_cN	p	988	0.00266	−0.00009	The present paper (60cm)
56390.7656		p	997	0.00302	0.00024	IBVS No.6092
56409.41860	VR_cI_c	p	1046	0.00371	0.00082	B.R.N.O. No.38
56746.30199	R_cI_c	p	1931	0.00356	−0.00136	The present paper (1m)

determined the temperature, we used q-search method to find a initial mass ratio q which could make the program converges much faster and to a stable value. The details are: we fixed q at a series of values of 0.1, 0.2, 0.3, and so on, then fitted the light curves with the W-D code for each q value, obtaining a series of corresponding fitting residuals and selected the final q value with minimal residuals. It was illustrated in Fig. 3. The optimal mass ratio should be $q = 0.18$. In next step, we derived the light curves with the temperature 6500 ± 370 K and $q = 0.18$. During whole solutions, the bolometric albedo $A_1 = A_2 = 0.5$ (Rucinski, 1969) and the values of the gravity-darkening coefficient $g_1 = g_2 = 0.32$ (Lucy, 1967) were used, which correspond to the common convective envelope of both components. Square root limb-darkening coefficients were used, according to Claret and Gimenez (1990). The adjustable parameters were: the mass ratio q; the orbital inclination i; the mean temperature of star 2, T_2; the monochromatic luminosity of star 1. Because the results always converged to the contact model, we adopted mode 3 for the final solution. The photometric solutions were listed in Table 2 and the theoretical light curves computed with those photometric elements were plotted in Fig. 4. The observed delta color indexes and their fittings are also shown in Fig. 4, where real subtle changes of the color indexes with phase. Such variations illustrate that the surface temperature/luminosity of components is not uniform, which may be caused by different visual lines to the limb darkening effect. The geometrical structure of AS CrB was displayed in Fig. 5.

Table 2
Photometric solutions for AS CrB.

Parameters	$BVRI$	uncertainties
$g_1 = g_2$	0.32	fixed
$A_1 = A_2$	0.50	fixed
$x_{1bolo} = x_{2bolo}, y_{1bolo} = y_{2bolo}$	0.123, 0.599	fixed
$x_{1B} = x_{2B}, y_{1B} = y_{2B}$	0.281, 0.604	fixed
$x_{1V} = x_{2V}, y_{1V} = y_{2V}$	0.108, 0.697	fixed
$x_{1R} = x_{2R}, y_{1R} = y_{2R}$	0.006, 0.706	fixed
$x_{1I} = x_{2I}, y_{1I} = y_{2I}$	−0.054, 0.671	fixed
T_1	6500K	±370 K
T_2	6498K	±376 K
q	0.172	±0.008
i (°)	78.4	±0.2
$\Omega_1 = \Omega_2$	2.0961	±0.0027
Ω_{in}	2.1619	–
Ω_{out}	2.0514	–
$L_1/(L_1+L_2)(B)$	0.8176	±0.0010
$L_1/(L_1+L_2)(V)$	0.8179	±0.0008
$L_1/(L_1+L_2)(R)$	0.8181	±0.0007
$L_1/(L_1+L_2)(I)$	0.8181	±0.0007
$r_1(pole)$	0.5147	±0.0007
$r_1(side)$	0.5693	±0.0011
$r_1(back)$	0.5962	±0.0014
$r_2(pole)$	0.2424	±0.0016
$r_2(side)$	0.2550	±0.0019
$r_2(back)$	0.3129	±0.0056
f	59.6%	±2.5%

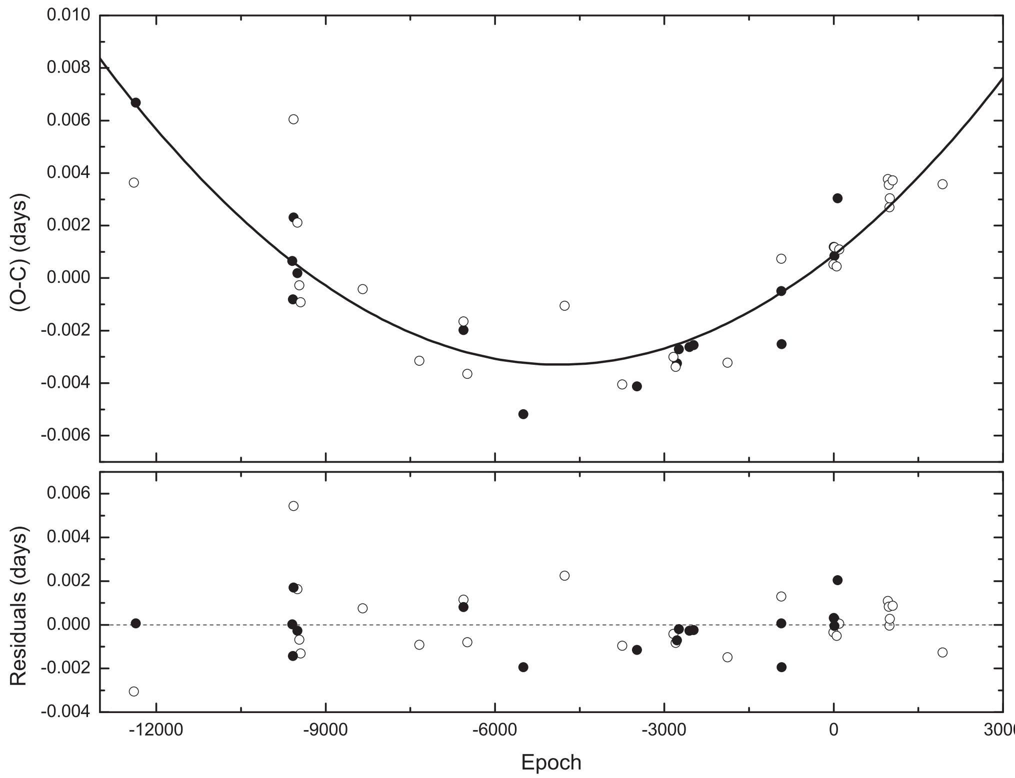

Fig. 2. $(O-C)$ diagram of AS CrB formed by all available measurements. The $(O-C)$ values were computed by using a newly determined linear ephemeris (Eq. 2). Full circles refer to the primary times of minima and open ones to the secondary times of minima. Solid line represents quadratic fitting (Eq. 3). Below the picture are residuals for Eq. 3. The dashed line in this panel is a zero level line.

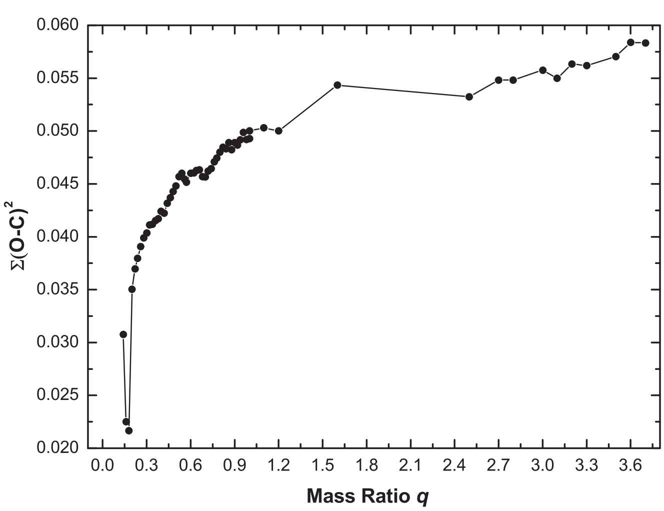

Fig. 3. The relationship between the mass ratio q and the fitting residuals. The optimal q is 0.18.

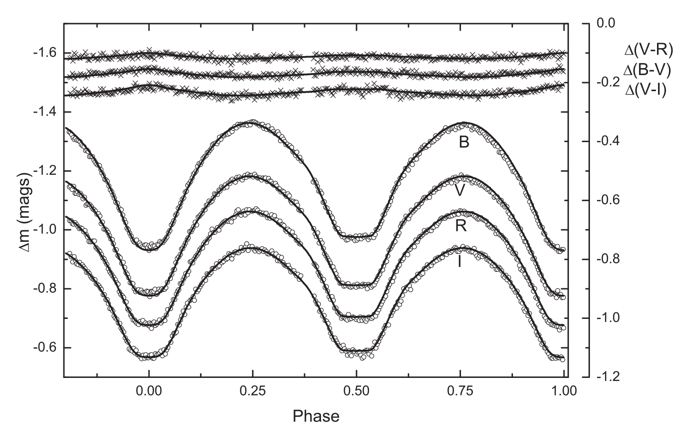

Fig. 4. Observed and theoretical light curves in *BVRI* bands of AS CrB. The solid lines are the theoretical light curves. Upside shows the observed delta color-magnitudes, while the corresponding solid fitting lines are computed from the theoretical light curves.

We also tried to solve the light curves with non-zero third light l_3. As we mentioned above, detecting third light would be easy with multi-color photometry especially it the star was of different spectral type. However, the resulting l_3 were always negative. It must be noted that the W-D code cannot solve a very faint l_3, or it can be thought as that the faint l_3 light is covered by photometric errors. For instance, assume that the typical photometric error of is 0.01 mag, and then the computed luminosity contribution error of the third light l_3 should be 0.92% according to the definition of magnitude. It means that if $l_3/(L_1+L_2+l_3) < 0.92\%$, we would not distinguish the l_3 from the photometric errors. Hence, the negative solutions of l_3 in the W-D code cannot eliminate tertiary companion exactly.

5. Discussions and conclusions

The geometric structure, depicted in Fig. 5, shows that AS CrB is a totally eclipsing binary system. We can see a very wide flat-bottom of the secondary minimum. The constant phase lasted for about 43.3 min. Moreover, compared the four bands, the best flat-bottom appeared in the B-Band, while the worst appeared in the R-Band, which would suggest that the main radiation come from the B-Band. The wide flat-bottom and the main radiation band agree with the totally eclipsing nature and the temperature of

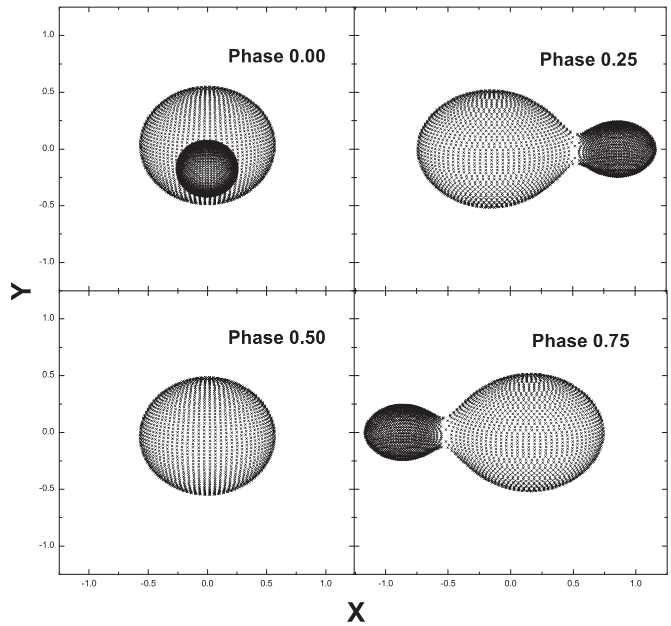

Fig. 5. Geometric structure of AS CrB at phase 0.00, 0.25, 0.50 and 0.75, suggesting that it is a totally eclipsing binary.

Table 3
Physical parameters of AS CrB.

T_1(K)	6500 ± 370
T_2(K)	6498 ± 376
$M_1(M_\odot)$	1.25 ± 0.15
$M_2(M_\odot)$	0.21 ± 0.06
$R_1(R_\odot)$	1.40 ± 0.07
$R_2(R_\odot)$	0.67 ± 0.04
$L_1(R_\odot)$	3.2 ± 0.2
$L_2(R_\odot)$	0.72 ± 0.04
$A(R_\odot)$	2.507
logg$_1$	4.24
logg$_2$	4.11
M_{bol1}	3.54
M_{bol2}	5.13
$M_{bol_{max}}$	3.312
B.C.	−0.020
Distance (pc)	459 ± 42

6500 K, respectively. The photometric solution shows that AS CrB is an extreme mass- ratio, deep contact binary, with a mass ratio as $q = 0.172 \pm 0.008$, and a fill-out factor as $f = 59.6\% \pm 2.5\%$. The totally eclipsing character and the four-band light curves suggest that the photometric solutions should be reliable.

The Dartmouth isochrones model (Dotter et al., 2008) was used to estimate the physical parameters of each component (for details, see Liu et al., 2014a,b). The mass of the primary inferred by the Dartmouth isochrones is $1.25 \pm 0.12 M_\odot$ with $T_1 = 6500$ K, assuming that the [Fe/H] and [α/Fe] are similar to those of the Sun. The maximum V mag of AS CrB is 11.64 mag (Terrell et al., 2012), with a V-Band bolometric correction $BCv = -0.020$ for 6500 K (Worthey and Lee, 2011). Combining the absolute bolometric magnitude derived by the photometric solution, the distance modulus of the system is estimated as 8.308 mag, or a distance of 458.8 pc. Because of the 370 K uncertainties of the temperature, the distance should have an uncertainty of 42.1 pc. The physical parameters and the associated errors of the system are given in Table 3. The errors mainly come from the estimated error of the primary's temperature. It must be noted that the estimated absolute parameters depend on input condition parameters of the Dartmouth isochrones model. To obtain precise ones, spectrographic data will be needed.

Based on all available CCD eclipse times, the possible period change of AS CrB was discussed in the previous section. The orbital period was revised as 0.38065936 days by using the 40 CCD timings which are listed in Table 1. We also found a long-term period increase with a rate of $dP/dt = +(3.46 \pm 0.01) \times 10^{-7}$ days/year. If this period increase is due to a conservative mass transfer from the less massive component to the more massive one, then with the absolute parameters derived by the present paper and by using the well-known equation of Tout and Hall (1991),

$$\frac{\dot{P}}{P} = 3\frac{\dot{M}_2}{M_2}\left(\frac{M_2}{M_1} - 1\right), \tag{4}$$

the mass transfer rate is estimated to be, $dM_2/dt = -7.68 \times 10^{-8} M_\odot/year$. The negative sign implies less massive component M_2 loses matter. The timescale of mass transfer is $\tau \sim M_2/\dot{M}_2 \sim 2.73 \times 10^6$ years which is the same order as the thermal time scale of the less massive component ($t_{th} = 2 \times 10^7 M^2 R^{-1} L^{-1} \sim 8.7 \times 10^6$ years, where the M, R, L are all in solar unit).

The evolutionary status of the components can be inferred from their mean densities (i.e., Mochnacki, 1981, 1984). By using the following formulae (Kopal, 1959),

$$\overline{\rho_1} = \frac{0.079}{V_1(1+q)P^2}, \quad \overline{\rho_2} = \frac{0.079q}{V_2(1+q)P^2}, \tag{5}$$

where $V_{1,\,2}$ are the volumes of the components using the separation A as the unit of length, we determined the mean densities ($\overline{\rho_1}$, $\overline{\rho_2}$) of the two components to be 0.0520 $\rho_\odot$ and 0.0058 $\rho_\odot$. Both of the mean densities are quite lower than either that of the Sun or those of zero-age main sequence (ZAMS) stars of the same spectral type. It implies that both components have already moved far away from the ZAMS line to a greater or lesser extent, and then

Table 4
Some short period contact binaries where the period is around 0.38 days.

Name	Period (days)	q	f(%)	T_1(K)	ΔT (K)	dP/dt ($\times 10^{-7}$day/year)	Reference
AH Cnc	0.36044	0.1682	58.5	6300	+35	+3.99	(1)(2)
DZ Psc	0.3661	0.136	79	6210	−77		(3)(4)
V410 Aur	0.36634699	0.144	52.4	6040	+125	+8.22	(5)
XY Boo	0.3705524	0.1855	55.9	6324	+17	+6.25	(6)(7)(5)
YY CrB	0.37656	0.241	64	6121	+126	−11.94	(8)
V857 Her	0.38223	0.06532	83.8	8300	−213	+2.9	(9)(10)
V710 Mon	0.40519638	0.183	59.5	6145	+86	+1.95	(11)
CU Tau	0.41253776	0.177	50.1	5900	−38	−18.1	(12)(13)
Y Sex	0.41982	0.18	64	6210	+117		(14)
AS CrB	0.38065937	0.172	62.6 ± 2.6	5800	−38	+3.46	(15)

Reference: (1) Sandquist and Shetrone, 2003; (2) Qian et al., 2006; (3) Gazeas et al., 2005; (4) Rucinski et al., 2003; (5) Yang et al., 2005; (6) McLean and Hilditch, 1983; (7) Winkler, 1977; (8) Essam et al., 2010; (9) Gomez-Forrellad and Garcia-Melendo, 1996; (10) Qian et al., 2005a; (11) Liu et al., 2014b; (12) Qian et al., 2005b; (13) Yang and Liu, 2004 (14) Yang and Liu, 2003; (15) The present paper.

illustrates that extreme mass-ratio, deep contact binaries have further evolutional stages.

We collected some extreme mass-ratio, deep contact binary systems whose periods are around 0.38 days and listed them in Table 4. Most members of the group have similar mass ratio q and contact factor f with a long-time period increase, indicating a similar evolution stage of them. As the mass transfer continues, like the other deep contact binaries whose orbital period long-term increase (e.g., V728 Her, (Nelson et al., 1995); V345 Gem, (Yang et al., 2009); V1191 Cyg, (Zhu et al., 2011); CK Boo, (Yang et al., 2012)), AS CrB will finally merge into a fast rotating single star when the dynamics unstable occurred (i.e., Jorb < 3Jrot, (Hut, 1980)). The spin angular momentum can be calculated with the formula of $J_{spin} = M_i(k_iR_i)^2\omega$, where k_iR_i is the radius of gyration while ω is the spin angular velocity of components. Because the rotation of components is bound, the spin angular velocity equals to the orbital angular velocity. Meanwhile, the orbital momentum can be obtained by:

$$J_{orb} = (GA)^{1/2}\frac{M_1M_2}{(M_1+M_2)^{1/2}}. \quad (6)$$

For a solar-type contact binary, gyration coefficients of k_i^2 could be taken as 0.07 (i.e., Van't Veer, 1979). So, the total spin angular momentum of AS CrB is $3.33 \times 10^{43}\mathrm{kg{\cdot}m^2{\cdot}s^{-1}}$, and the corresponding orbital angular momentum is $2.10 \times 10^{44}\ \mathrm{kg{\cdot}m^2{\cdot}s^{-1}}$, respectively. Consequently, $J\mathrm{orb}/3J\mathrm{rot} = 2.1$. The system is close to the merge condition.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.newast.2016.08.003

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