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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: $M_1 = 1.25 \pm 0.15 M_\odot$, $M_2 = 0.21 \pm 0.06 M_\odot$, $R_1 = 1.40 \pm 0.07 R_\odot$, $R_2 = 0.67 \pm 0.04 R_\odot$, $L_1 = 3.2 \pm 0.2 L_\odot$, and $L_2 = 0.72 \pm 0.04 L_\odot$, 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.

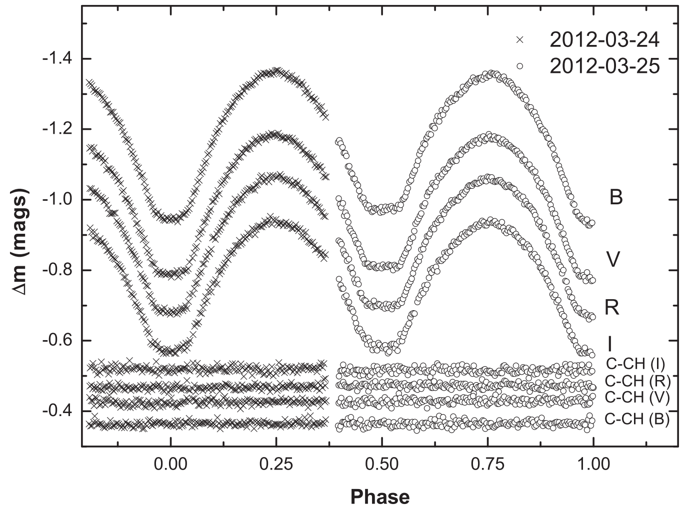

Fig. 1. Observed multi-color light curves in *BVRI* bands for AS CrB. The cross symbols denote the data observed in 2012-03-24 while the solid circles denote the data observed on 2012-03-25. The standard deviations of the C-CH light curves (yielded by the magnitudes of the comparison minus those of the 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