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Revision of the photometric parameters of BS Cassiopeiae *

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Abstract Seven charge-coupled device (CCD) photometric times of light minimum of the overcontact binary BS Cas which were obtained from 2007 August to November and one CCD light curve in the R band which was observed on 2007 September 24 and October 15, are presented. It is found that the light curve of BS Cas has characteristics like a typical EW-type light variation. The light curve obtained by us is symmetric and shows total eclipses, which is very useful for determining photometric parameters with high precision. Photometric solutions were derived by using the 2003 version of the Wilson-Devinney code. It shows that BS Cas is a W-subtype overcontact binary ($f = 27.5\% \pm 0.4\%$) with a mass ratio of $q = 2.7188 \pm 0.0040$. The temperature difference between the two components is 190 K. Analysis of the O–C curve suggests that the period of AE Phe shows a long-term continuous decrease at a rate of $dP/dt = -2.45 \times 10^{-7}$ d yr^{-1}. The long-time period decrease can be explained by mass transfer from the primary to the secondary.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual: BS Cas

1 INTRODUCTION

The variability of BS Cassiopeiae (= GSC 03682–01152, $\alpha_{2000.0} = 01^{\rm h}21^{\rm m}38.6^{\rm s}$ and $\delta_{2000.0} = +59^\circ10'26.9''$) was first revealed by Beljawsky (1931). He first gave the coordinates of BS Cas from photographic observations. BS Cas is an EW-type eclipsing binary with a spectrum of A-F, a period of $0.4404832^{\rm d}$ and a magnitude varying in the V-band from $12.2^{\rm m}$ to $12.6^{\rm m}$ according to the fourth edition of the General Catalogue of Variable Stars (GCVS; Kholopov et al. 1987). Later, Pribulla et al. (2003) gave a period of $0.44046934^{\rm d}$ for BS Cas, while Kreiner (2004) revised it to $0.44046793^{\rm d}$. The first complete light curves in the B, V and R bands were published by Yang et al. (2008) (hereafter Y08). Their secondary maxima of light curves all show large scatters and typical

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O'Connell effects with Max.II (phase 0.75) – Max.I (phase 0.25) = $0.06^{\rm m}$, 0.05, and 0.04, for the B, V and R bands, respectively. Y08 analyzed the orbital period change of BS Cas neglecting the part of the O–C data prior to 1989, and revised its orbital period to $0.44046828^{\rm d}$. They found that the period of BS Cas shows a long-term continuous decrease at a rate of $dP/dt = -2.45 \times 10^{-7}$ d yr^{-1}. Using the Wilson-Devinney code (hereafter W-D code) (Wilson & Devinney 1971; Wilson 1990, 1994; Wilson & Van Hamme 2003), they analyzed the asymmetric light curves and published the first photometric parameters of BS Cas. The aforementioned photometric solutions obtained by Y08 may be not accurate because of asymmetries and the variability of the light curves. A better light curve should be obtained and the photometric solutions of BS Cas should be revised.

2 PHOTOMETRIC OBSERVATIONS

The observations of BS Cas were carried out on 2007 August 22 and 26, September 13 and 24, October 15 and November 19 in the V, R, and I bands at Ondřejov Observatory. One of the two available CCD cameras (SBIG ST-8 or Apogee AP-7) was used, while SBIG ST-10XME and ST-7 CCD cameras were employed at the ÇOMÜ and Brno Observatories, respectively. The variable star, the comparison star and the check star were kept on the same pixels of the frame throughout the observing run and their coordinates are listed in Table 1. The integration time for each image was 60 s. CCD frames were mostly reduced by the C-MuniPack code (Motl 2007), a well-known adaptation of the MuniPack code (Hroch 1998), based on DaoPhot routines (Stetson 1987, 1991). All frames were darkframe and flat-field corrected first before we applied the frames to further reduction steps. Seven epochs of times of light minimum were determined by the Kwee-van Woerden method using the AVE program (Barberá 1999) and these are listed in Table 2.

Table 1 Coordinates of BS Cas, the Comparison, and Check Stars

Stars	α_{2000} (h m s)	δ_{2000} (° ′ ″)
BS Cas	01 21 38.6	59 10 26.9
The comparison	01 22 35.94	59 08 35.9
The check	01 21 51.25	59 03 08.2

Table 2 New CCD Times of Light Minimum for BS Cas (Method: CCD)

No.	J.D. (Hel.) (d)	Error (d)	Min.	Filter
1	2454335.48561	±0.00014	II	R
2	2454339.44823	±0.00034	II	R
3	2454357.50817	±0.00021	II	R
4	2454368.51917	±0.00016	II	R
5	2454389.44068	±0.00050	I	V
	2454389.44076	±0.00036	I	R
	2454389.44031	±0.00035	I	I
6	2454389.65894	±0.00086	II	R
	2454389.65996	±0.00099	II	I
7	2454424.45812	±0.00036	II	R
	2454424.45887	±0.00028	II	I

Though we observed BS Cas in the V, R, and I bands for 6 nights from August to November in 2007, we obtained just one complete light curve in the R band. The CCD observations and the light curve data obtained on 2007 September 24 and October 15 in the R band, which can make up a complete light curve, are listed in Table 3 and shown in Figure 1, respectively. The magnitude differences of the comparison star and check star are also shown in the lower panel of Figure 1. The complete CCD light curve in the R band with respect to the linear ephemeris:

$$\mathrm{Min.\,I} = 2454389.44076 + 0.44047629^{\mathrm{d}} \times E, \qquad (1)$$

where the time of the light minimum is obtained by us and the period is obtained by Y08, which are shown in Figure 2 with open circles. As seen in the figure, the light curve obtained on 2007 September 24 and that obtained on October 15 in the R band can be joined well. Our light curve of BS Cas is symmetric and shows total eclipses, which is very useful for determining photometric parameters with high precision.

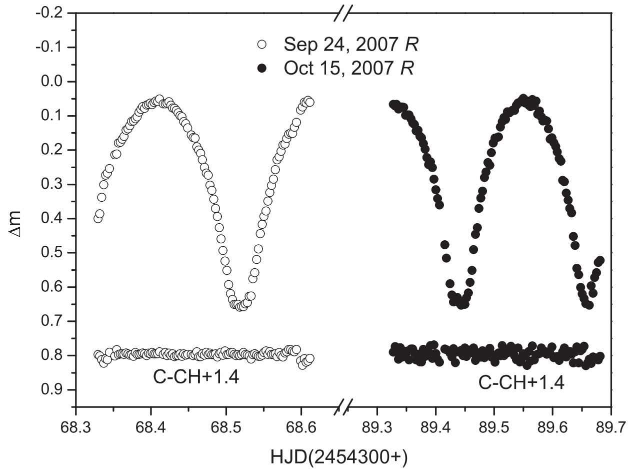

Fig. 1 CCD photometric observations for BS Cas in the R band observed on 2007 September 24 and 2007 October 15.

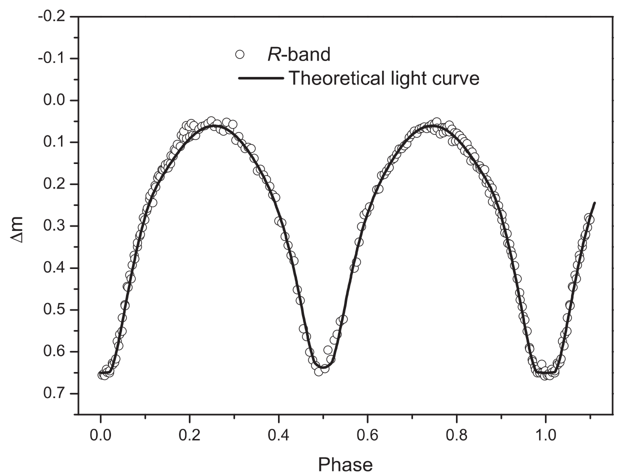

Fig. 2 Observed light curves of BS Cas in the R band and the fit by theoretical light curves by using the W-D code for BS Cas.

Table 3 Observations in the R Band for BS Cas Obtained on 2007 September 24 and 2007 October 15

J.D.(Hel.) 2454300+	ΔMag.	J.D. (Hel.) 2454300+	ΔMag.	J.D. (Hel.) 2454300+	ΔMag.	J.D.(Hel.) 2454300+	ΔMag.	J.D.(Hel.) 2454300+	ΔMag.
68.32948	0.400	68.43626	0.091	68.55044	0.393	89.41538	0.476	89.55615	0.056
68.33196	0.386	68.43875	0.099	68.55293	0.378	89.41842	0.515	89.55920	0.069
68.33447	0.338	68.44123	0.103	68.55541	0.349	89.42451	0.590	89.56224	0.073
68.33701	0.301	68.44370	0.117	68.55788	0.324	89.42755	0.623	89.56529	0.052
68.33954	0.273	68.44619	0.123	68.56037	0.303	89.43060	0.643	89.56833	0.070
68.34208	0.267	68.44868	0.135	68.56285	0.285	89.43364	0.641	89.57138	0.057
68.34464	0.254	68.45363	0.156	68.56534	0.257	89.43668	0.630	89.57442	0.095
68.35178	0.213	68.45612	0.163	68.56787	0.228	89.44050	0.646	89.57747	0.086
68.59898	0.083	68.45860	0.165	68.57040	0.219	89.44354	0.653	89.58051	0.103
68.35428	0.211	68.46109	0.190	68.57296	0.203	89.44658	0.642	89.58355	0.115
68.60147	0.074	68.46356	0.200	68.57552	0.185	89.44963	0.650	89.58660	0.112
68.35678	0.179	68.46606	0.209	68.57808	0.182	89.45267	0.631	89.58964	0.115
68.60396	0.060	68.46854	0.228	68.58065	0.166	89.45572	0.617	89.59269	0.138
68.35926	0.177	68.47102	0.250	68.58321	0.153	89.45876	0.586	89.59574	0.168
68.60644	0.062	68.47351	0.267	68.58576	0.150	89.46180	0.551	89.59878	0.164
68.36175	0.168	68.47598	0.273	68.58832	0.151	89.46484	0.490	89.60182	0.178
68.60892	0.055	68.47847	0.302	68.59087	0.133	89.46789	0.446	89.60486	0.189
68.36424	0.160	68.48095	0.318	68.59343	0.119	89.47093	0.426	89.60790	0.205
68.61140	0.060	68.48344	0.343	89.32756	0.066	89.47397	0.370	89.61095	0.225
68.36673	0.142	68.48591	0.370	89.33060	0.071	89.47702	0.340	89.61399	0.232
68.36920	0.138	68.48840	0.394	89.33323	0.066	89.48007	0.320	89.61703	0.288
68.37169	0.128	68.49088	0.426	89.33627	0.080	89.48311	0.280	89.62007	0.292
68.37417	0.116	68.49336	0.459	89.33932	0.077	89.48616	0.264	89.62312	0.325
68.37664	0.115	68.49584	0.493	89.34236	0.074	89.48920	0.236	89.62616	0.346
68.37913	0.108	68.49832	0.524	89.34540	0.075	89.49225	0.244	89.62921	0.370
68.38162	0.103	68.50080	0.551	89.34844	0.098	89.49529	0.207	89.63225	0.383
68.38410	0.089	68.50329	0.593	89.35149	0.097	89.49833	0.179	89.63529	0.452
68.38659	0.081	68.50576	0.619	89.35453	0.097	89.50138	0.165	89.63833	0.478
68.38906	0.073	68.50824	0.636	89.35757	0.108	89.50442	0.163	89.64138	0.545
68.39154	0.078	68.51073	0.650	89.36061	0.120	89.50746	0.161	89.64442	0.564
68.39403	0.068	68.51322	0.650	89.36366	0.125	89.51050	0.132	89.64746	0.601
68.39651	0.066	68.51569	0.650	89.36670	0.144	89.51354	0.117	89.65050	0.620
68.39899	0.063	68.51817	0.658	89.36974	0.142	89.51658	0.105	89.65355	0.633
68.40147	0.067	68.52066	0.656	89.37279	0.159	89.51962	0.110	89.65659	0.648
68.40396	0.061	68.52314	0.657	89.37583	0.164	89.52266	0.088	89.66267	0.653
68.40645	0.057	68.52561	0.649	89.37887	0.181	89.52570	0.091	89.66572	0.596
68.40894	0.058	68.52810	0.645	89.38191	0.197	89.52875	0.087	89.66876	0.618
68.41142	0.051	68.53058	0.627	89.38496	0.221	89.53179	0.083	89.67181	0.572
68.41641	0.065	68.53307	0.626	89.38800	0.242	89.53483	0.084	89.67485	0.558
68.41890	0.065	68.53554	0.575	89.39104	0.234	89.53788	0.069	89.67790	0.528
68.42138	0.063	68.53803	0.558	89.39408	0.251	89.54092	0.062	89.68094	0.522
68.42385	0.059	68.54051	0.519	89.39713	0.285	89.54397	0.060		
68.42634	0.069	68.54300	0.488	89.40017	0.316	89.54701	0.055		
68.42882	0.077	68.54548	0.444	89.40321	0.341	89.55006	0.049		
68.43131	0.078	68.54796	0.417	89.40625	0.360	89.55310	0.062		

3 PHOTOMETRIC ANALYSIS

There are no spectroscopic observations of BS Cas. In order to obtain photometric solutions and understand the evolutionary state of the binary system, we analyze the complete R band light curve with the fourth version of the W-D code. The temperature of star 1 (star eclipsed at primary light minimum) was chosen as $T_1 = 6250\,\mathrm{K}$ according to the $J - H = 0.276$ and $H - K = 0.088$ of

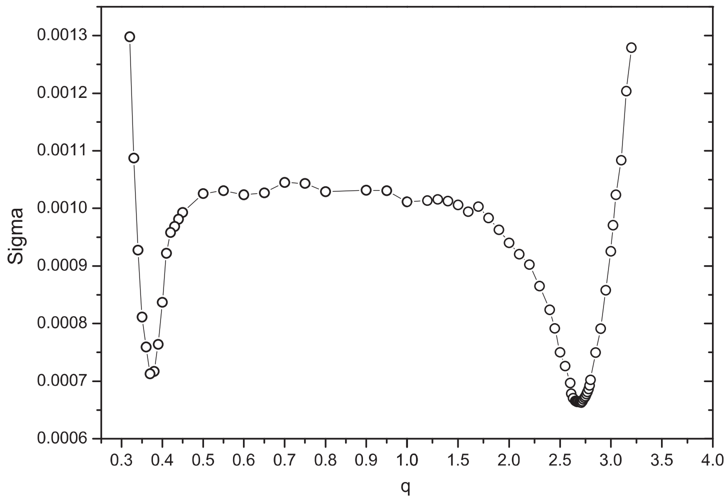

Fig. 3 Relation between sigma and q for BS Cas.

BS Cas from the CDS [1]. As shown in Figure 2, the light curves are of a typical EW type where the depths of both minima are nearly the same, indicating that the temperature of both components is nearly the same. Therefore, we take the same values of the gravity-darkening coefficients and the bolometric albedo for both components, i.e., $g_1 = g_2 = 0.32$ (Lucy 1967) and $A_1 = A_2 = 0.5$ (Ruciński 1969). The limb-darkening coefficients were used according to Claret & Gimenez (1990). The adjustable parameters were: the orbital inclination i; the mean temperature of star 2, T_2; the monochromatic luminosity of star 1, L_{1R}, and the dimensionless potential of star 1 ($\Omega_1 = \Omega_2$, mode 3 for overcontact configuration). A q-search method was used to determine the mass ratio of the system. Solutions were carried out for a series of values of the mass ratio. For each value of q, the calculation started at mode 2 (detached mode) and we found that the solutions usually converged to mode 3 (overcontact configuration). The relation between the resulting sum sigma of weighted square deviations and q is plotted in Figure 3.

A minimum value was obtained at $q = 2.71$. Therefore, we chose the initial value of q as 2.71 and set it as an adjustable parameter. Then we performed a differential correction until it converged and final solutions were derived. The solution converged at $q = 2.7188(\pm 0.0040)$. The photometric solutions are listed in Table 4 and the theoretical light curve, computed with those photometric parameters, is plotted in Figure 2. The solution reveals that BS Cas is a W-subtype contact binary system with a degree of overcontact of $f = 27.5\%(\pm 0.4\%)$.

4 DISCUSSION AND CONCLUSIONS

Comparing the light curve in the R band obtained by us with that by Y08, we found that the light curve of BS Cas shows many changes between the four months from 2007 September 24 to 2008 January 23. The main photometric parameters of the light curves of BS Cas obtained by us and Y08 are listed in Table 5. The light curve of BS Cas obtained by us shows symmetry and does not show an O'Connell effect. However, the light curve of Y08 presented a typical O'Connell effect with Max.II – Max.I= $0.04^{\rm m}$ for the R band. From Figure 1, we cannot see an obvious discrepancy between the Max.I and Max.II. The first minimum is almost equal to the secondary minimum, which means that almost equal temperatures of the two components were obtained on 2007 October 15 (see Fig. 1).

[1] CDS: *http://cdsweb.u-strasbg.fr/CDS.html*

Table 4 Photometric Solutions for BS Cas from This Paper and from Y08

Parameters	Photometric elements		
	This paper	Y08 (Unspotted)	Y08 (Spotted)
$g_1 = g_2$	0.32	0.32	0.32
$A_1 = A_2$	0.5	0.5	0.5
$x_{1\mathrm{bol}}$	0.144	–	–
$x_{2\mathrm{bol}}$	0.167	–	–
$y_{1\mathrm{bol}}$	0.577	–	–
$y_{2\mathrm{bol}}$	0.553	–	–
x_{1R}	0.037	–	–
x_{2R}	0.075	–	–
y_{1R}	0.689	–	–
y_{2R}	0.667	–	–
T_1(K)	6250	6100	6100
q (M_2/M_1)	2.7188(±0.0040)	0.2825(±0.0016)	0.2834(±0.0010)
Ω_{in}	6.2413	–	–
Ω_{out}	5.6270	–	–
T_2(K)	6060 (±14)	5540 (±13)	5637 (±12)
i	83.160 (±0.399)	80.7 (±0.5)	79.8 (±0.4)
$L_1/(L_1 + L_2)$ (R)	0.3161 (±0.0018)	0.6769 (±0.0054)	0.6919 (±0.0070)
$\Omega_1 = \Omega_2$	6.0723 (±0.0027)	2.3672 (±0.0101)	2.4291 (±0.0063)
r_1(pole)	0.2890 (±0.0023)	0.4735 (±0.0021)	0.4724 (±0.0014)
r_1(side)	0.3031 (±0.0029)	0.5137 (±0.0030)	0.5122 (±0.0019)
r_1(back)	0.3462 (±0.0053)	0.5430 (±0.0039)	0.5411 (±0.0024)
r_2(pole)	0.4516 (±0.0019)	0.2708 (±0.0027)	0.2700 (±0.0017)
r_2(side)	0.4861 (±0.0026)	0.2840 (±0.0033)	0.2830 (±0.0020)
r_2(back)	0.5170 (±0.0034)	0.3296 (±0.0066)	0.3276 (±0.0040)
f	27.5 % (±0.4 %)	33.9 % (±1.8 %)	31.6 % (±1.1 %)
$\Sigma\omega(O - C)^2$	0.00068	0.1485	0.1297

Table 5 Main Photometric Parameters of the Light Curves for BS Cas Obtained from This Paper and from Y08

Band	Max.I – Min.I (m)	Max.II – Min.II (m)	Min.II – Min.I (m)	Max.I – Max.II (m)	Ref.
R	−0.55	−0.41	−0.10	−0.04	Y08
R	−0.59	−0.59	−0.01	−0.00	this paper

However, the light curves obtained by Y08 showed Min.I – Min.II= 0.10^{m} for the R band. This may indicate that BS Cas is a strong active binary system with hot or dark spots.

We present 7 new times of light minimum of BS Cas and add them to calculate the period change, with the result that the period of BS Cas shows a long-term orbital decrease at a rate of $dP/dt = -2.45 \times 10^{-7}$ d yr^{-1}. This is the same as Y08. This can be seen more clearly from Figure 4. The long-term orbital period decrease suggests that BS Cas is undergoing mass transfer from the primary to the secondary. With the mass transfer and accompanying angular momentum loss, BS Cas will evolve into a deeper contact configuration.

As discussed in Section 3, the presented solutions are more reliable than those determined by Y08 because our solutions were based on the light curves being symmetric and showing total eclipses. The situation of BS Cas resembles those of RZ Com (He & Qian 2008), AD Cnc (Qian et al. 2007) and AE Phe (He et al. 2009). There are two minima in Figure 3. One is $q = M_2/M_1 = 0.37$ (or $q = M_1/M_2 \sim 2.70$), the other is $q = M_2/M_1 = 2.71$ (or $q = M_1/M_2 \sim 0.37$). The self-

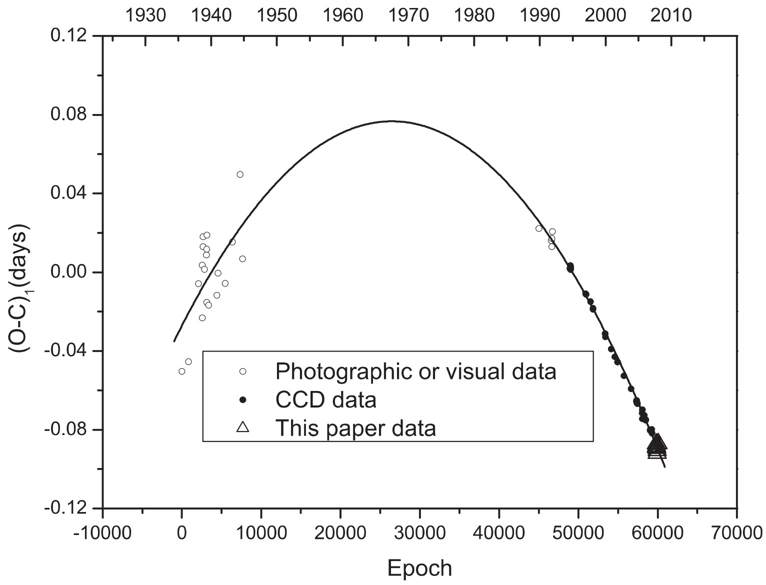

Fig. 4 (O–C)$_1$ curve for the eclipsing binary BS Cas. The open and filled circles represent photographic or visual observations and CCD data collected by Y08. The open triangles refer to the new times of light minimum obtained by us.

consistency of the two values indicates that our q-search method is credible. The $\sigma = 0.00066$ for $q = M_2/M_1 = 2.71$ is less than $\sigma = 0.00071$ for $q = M_2/M_1 = 0.37$. We can conclude that BS Cas is more like a W-subtype contact binary rather than an A-subtype one. For the advantage of comparing the photometric solutions from us and Y08, we also list the solutions obtained by Y08 in the third and fourth columns in Table 4 for unspotted and spotted solutions. Our solutions based on the photometric R band light curve analyzed by the W-D code indicate that BS Cas could be a W-subtype contact binary with a mass ratio of $q = M_2/M_1 = 2.7188(\pm 0.0040)$ (or $q = M_1/M_2 = 0.3678(\pm 0.0296)$). The mass ratio obtained by us is higher than the value $q = M_1/M_2 = 0.2825(\pm 0.0016)$ for the unspotted solutions or the value $q = M_1/M_2 = 0.2834(\pm 0.0010)$ for the spotted solutions obtained by Y08. The degree of geometrical contact, defined by $f = (\Omega_{\rm in} - \Omega)/(\Omega_{\rm in} - \Omega_{\rm out})$, is $27.5\%(\pm 0.4\%)$. The degree of contact $27.5\%(\pm 0.4\%)$ is less than $33.9\%(\pm 1.8\%)$ for the unspotted solutions or $31.6\%(\pm 1.1\%)$ for the spotted solutions obtained by Y08. However, this paper and Y08 only present photometric solutions of this contact binary system; to further understand the properties of the strong active binary and its associated physical parameters, spectroscopic and photometric observations are needed.

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