Period Analysis, Photometry, and Astrophysical Modelling of the Contact Eclipsing Binary BC Gruis

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Abstract BC Gruis is a W UMa-type contact binary system of the W-subtype with the primary minimum 0.1 magnitude fainter than the secondary minimum. The period is currently 0.3073060 ± 0.0000001 day; it was 4 seconds longer between 1986 and 1991. There were small modulations of 0.001–0.002 day in the Observed–Calculated diagram due to asymmetry in the light curves, most likely caused by star spots. An astrophysical model of the system was developed with a mass ratio of 1.2 determined from light curve analysis. The best fit to light curves in B, V, and I pass bands in 2014 was given by including two large cool star spots on the more massive, cooler component and 1 cool spot on the hotter star. In 2015, the asymmetry in the light curves was different and was modelled best with a hot spot on the more massive component at the neck joining the stars and 1 cool spot on the other component.

1. Introduction

The W Ursae Majoris contact eclipsing binaries have been divided into two classes: A-subtype, in which the more massive and brighter component is the hotter star, and the W-subtype, in which the more massive and brighter component is the cooler star (Binnendijk 1970). The formation and evolution of short period contact binary stars is not well understood. They are old stars whose secondary components are at an advanced stage of evolution, burning hydrogen in the shell around a small helium core, according to an evolutionary model proposed by Stępień (2006). Pribulla and Rucinski (2006) comment that those with periods of less than 1 day should not exist, and suggest they may have formed in triple or larger multiple systems, where angular momentum could be transferred to the distant component, especially if it were in an eccentric orbit that brought it close to the binary.

BC Gruis is a short period W UMa-type contact system of the W-subtype with the components displaying uneven eclipse depths (Plewa and Kałużny 1992). Dall *et al.* (2007) found that it is a triple system with spectral types of approximately K0, K0, and K components. They reported rotational velocities (v sin i) = 165 ± 50 km s^{-1} and 142 ± 50 km s^{-1} for the binary, and (v sin i) = 6 ± 3 km s^{-1} for the third member of the system. An astrophysical model based on a mass ratio of 1.77 was developed by Plewa and Kałużny (1992) before the spectral types were determined and the third component was discovered.

In the *General Catalogue of Variable Stars* (GCVS) the period of BC Gru is listed as 0.26617 day (Kholopov *et al.* 1985). Plewa and Kałużny determined the period to be 0.307356 ± 0.000019 day from their 1986 data. Samec and Becker (1993) determined four times of minimum in 1991 and calculated the period to be 0.30735687 ± 0.00000004 day. They cited a 1988 report by Gomez and colleagues in Argentina of 15 unpublished epochs of minima and an ephemeris with a period of 0.30731 ± 0.00001 day.

The aims of the present study were to determine an accurate, current period from the times of minimum of both primary and secondary eclipses and update the ephemeris of BC Gru. An additional aim was to develop an astrophysical model based on detailed photometric light curves obtained in 2014 and 2015.

2. Methods, observations, and analysis

The instruments used for photometry were a 356-mm Schmidt-Cassegrain telescope with a Moravian G3-6303 charge-coupled device (CCD) camera with exposures of 40 seconds in the B, and 20 seconds in the V and I filters, respectively. The number of observations was usually about 240 each night in each filter. On some nights, only the V and I filters were used in order to obtain faster cadences for more accurate determinations of the times of minima. See Moriarty (2015) for full details of the imaging procedures and photometric analyses. Details of the comparison and check star positions and magnitudes are given

Table 1. Magnitudes and color indices of BC Gru, comparison, and check stars used in this work.

Star	R.A. (2000) h m s	Dec. (2000) ° ' "	B	V	Ic	B–V	V–Ic
TYC 8449 00652-1	22 44 48.725	–48 07 47.22	11.663	10.818	9.893	0.845	0.925
error			0.01	0.051	0.011	0.061	0.062
TYC 8449 00771-1	22 44 37.322	–47 59 38.22	11.879	11.355	10.757	0.524	0.598
error			0.009	0.041	0.02	0.029	0.061
BC Gru	22 44 49.11	–48 10 13.0	11.473	10.662	9.744	0.811	0.918
error			0.145	0.092	0.358	0.503	0.45

Source: APASS DR9 (Henden et al. 2015). The Ic magnitudes were calculated from the Sloan g and i values with the formula $Ic = i - 0.3645 - 0.0743 \times (g-i) + 0.0037 \times (g-i)^2$ (Munari et al. 2014).

in Table 1. The epochs and times of minima were determined from a 7-order polynomial fit to the light curves spanning about 1 hour each side of the minima in PERANSO (Vanmunster 2013). These values were analyzed by least squares linear regression in Microsoft EXCEL. Phase-magnitude light curves were produced in PERANSO and exported for modelling.

Values for the period of BC Gru were also determined by two methods using data collected during the All Sky Automated Survey (ASAS) (Pojmański 2002). Firstly, one epoch of minimum was determined from the ASAS data for each season between 2001 and 2008. All the ASAS A and B quality data were imported into PERANSO as a single set. Blocks of 1 season with > 50 observations each were activated and analyzed with the ANOVA period analysis routine. An epoch for a primary minimum within each season was calculated with the ephemeris determined in section 3.1 (Equation 2) and inserted into the Epoch value in the Info form shown in Figure 1. An actual value for the observed epoch of a primary minimum for that season was then obtained by altering the calculated value by small amounts (0.01–0.001 day) until the primary minimum was centered on phase 1.0 (Figure 1, top right). Secondly, a value for the period of BC Gru between 2001 and 2009 was determined in PERANSO by applying the ANOVA period analysis procedure to the full set of A and B quality ASAS data, that is, with all data points activated.

The epochs of minima determined in 2014 and 2015 together with the six times of minima from the ASAS data and the values for 1986–1991 published previously (section 1) were combined in an EXCEL spreadsheet for analysis (Table 2).

Astrophysical models of the BC Gru system for two complete light curves obtained on 2014-09-10 and 2015-09-08 were developed with BINARY MAKER 3.0 (Bradstreet and Steelman 2004). For the modelling process, the procedures described in the BINARY MAKER 3 manual, which is supplied with the software, and by Bradstreet (2005) were used. As the spectral types were reported by Dall *et al.* (2007) to be approximately K0 for both components, the effective temperature of the cooler component was set at 5040 K, as given for a K2V star by Pecaut and Mamajek (2013). The "q method" was used to find a probable mass ratio by trying a range of values for the mass ratio, inclination, fillout factor, and temperature of the hotter component.

3. Results

3.1. Period analysis

In 2014, 12 times of minima and in 2015, 18 times of minima were recorded (Table 2). The orbital period of BC Gru, determined from the times of minima in 2015 by a least squares linear regression, was 0.307305 (± 0.000002) day (Table 3). The following ephemeris was determined from the 2015 data set.

$$\text{HJD (Min I)} = 2457274.0791\ (0.0001) + 0.307305\ (0.000002) \times E \qquad (1)$$

Observed minus calculated (O–C) values for all epochs from 1959 to 2015 do not display a simple pattern, based on an ephemeris using the epoch and period in the GCVS (Figure 2a).

Table 2. BC Gru times of minima, observed minus calculated (O–C) differences in epochs, and photometric data, based on the ephemeris in Equation 2. The epoch from the GCVS was converted to heliocentric Julian days (HJD).

Year	*Cycle*	*Epoch HJD*	*Error*	*O–C*	*Error*	*Band*
1959[a]	–66578.0	2436814.29642	—	0.0313	—	—
1986[b]	–34452.5	2446686.65316	0.00007	0.0336	0.0068	V
1986[b]	–34452.0	2446686.80628	0.00027	0.0330	0.0068	V
1986[b]	–34449.0	2446687.72825	0.00019	0.0331	0.0068	V
1986[b]	–34445.5	2446688.80488	0.00019	0.0341	0.0068	V
1986[b]	–34439.5	2446690.64873	0.00032	0.0341	0.0068	V
1988[c]	–32210.0	2447375.78280	0.0001	0.0295	0.0064	V
1991[c]	–28637.0	2448473.77990	0.0004	0.0223	0.0057	V
1991[c]	–28634.0	2448474.70210	0.0003	0.0225	0.0057	V
1991[c]	–28621.0	2448478.69640	0.0003	0.0219	0.0057	V
1991[c]	–28617.5	2448479.77260	0.0003	0.0225	0.0057	V
2001[d]	–16725.0	2452134.69500	0.00211	0.0010	0.0039	V
2002[d]	–15516.0	2452505.92000	0.00211	0.0003	0.0037	V
2003[d]	–14462.0	2452829.82100	0.00211	0.0008	0.0036	V
2004[e]	–12713.0	2453367.29600	0.00211	–0.0024	0.0033	V
2005[d]	–12288.0	2453597.46700	0.00211	–0.0036	0.0032	V
2007[d]	–9631.0	2454314.41500	0.00211	–0.0005	0.0028	V
2008[d]	–8595.0	2454632.78100	0.00211	–0.0035	0.0027	V
2010[f]	–6103.0	2455398.58800	0.003	–0.0031	0.0032	V
2014	–1116.5	2456930.97436	0.00114	0.0019	0.0012	V
2014	–1116.5	2456930.97363	0.00106	0.0012	0.0011	B
2014	–1116.5	2456930.97445	0.00133	0.0020	0.0014	I
2014	–1116.0	2456931.12715	0.00115	0.0011	0.0012	V
2014	–1116.0	2456931.12722	0.00111	0.0011	0.0011	B
2014	–1116.0	2456931.12745	0.00121	0.0014	0.0012	I
2014	–1064.5	2456946.95300	0.00116	0.0007	0.0012	V
2014	–1064.5	2456946.95342	0.00128	0.0011	0.0013	B
2014	–1064.5	2456946.95355	0.00147	0.0012	0.0015	I
2014	–1064.0	2456947.10552	0.00097	–0.0005	0.0010	B
2014	–1064.0	2456947.10617	0.00112	0.0002	0.0012	V
2014	–1064.0	2456947.10676	0.00112	0.0008	0.0012	I
2015	–97.5	2457244.11610	0.00151	–0.0011	0.0015	I
2015	–97.5	2457244.11729	0.00126	0.0001	0.0013	V
2015	–97.5	2457244.11804	0.00171	0.0008	0.0017	B
2015	–97.0	2457244.27030	0.00133	–0.0006	0.0013	I
2015	–97.0	2457244.27043	0.00107	–0.0005	0.0011	V
2015	–97.0	2457244.27060	0.00143	–0.0003	0.0014	B
2015	–71.0	2457252.26003	0.00092	–0.0008	0.0009	V
2015	–71.0	2457252.26021	0.00107	–0.0006	0.0011	I
2015	–0.5	2457273.92547	0.00133	–0.0004	0.0013	I
2015	–0.5	2457273.92569	0.00136	–0.0002	0.0014	V
2015	–0.5	2457273.92648	0.00144	0.0006	0.0014	B
2015	0.0	2457274.07837	0.00090	–0.0012	0.0009	V
2015	0.0	2457274.07883	0.00104	–0.0007	0.0011	B
2015	0.0	2457274.07904	0.00107	–0.0005	0.0011	I
2015	0.5	2457274.23204	0.00136	–0.0012	0.0014	V
2015	0.5	2457274.23275	0.00133	–0.0005	0.0013	B
2015	0.5	2457274.23282	0.00134	–0.0004	0.0014	I
2015	91.0	2457302.04394	0.00113	–0.0005	0.0011	I
2015	91.0	2457302.04398	0.00118	–0.0004	0.0012	V

Source: (a) Kholopov et al. *1985; (b) Plewa and Kaluzny 1992; (c) Samec and Becker 1983; (d) ASAS, this work; (e) ASAS, Paschke and* Luboš Brat *2004; (f) Paschke 2010.*

Table 3. Orbital periods of BC Gru. The periods in rows 1 and 2 were determined by a least squares linear regression of the epochs and cycles given in Table 2, with the ephemeris in Equation 2. The period in row 3 was determined from the full set of ASAS A and B quality data for the years 2001–2009 (see section 2, Methods).

Years	*Period day/cycle*	*Standard error*	*Number of observations*
2015	0.307305	0.000002	18
2001–2015	0.3073060	0.0000001	36
2001–2009	0.307306	0.000001	510

With the updated ephemeris in Equation 1, a pattern is apparent that suggests there have been period changes (Figure 2b). (If there were no changes in the period, then all values would lie on a single straight line.) The O–C values for the 1986–1991 era have a negative slope, whereas the slope of the O–C values from 2001–2015 is positive (Figure 2b). When all the epochs of minima from 2001 to 2015 were analyzed with a linear regression the period was determined as 0.307306 day (Table 3).

The period calculated from the full set of ASAS A and B quality data was also 0.307306 day (Table 3). Thus the period of the binary system since 2001 is 0.307306 day. A revised ephemeris is shown in Equation 2. The O–C values for the 2001–2015 era differed from zero mostly by less than 0.0015 day, although the ASAS values had larger errors (Figure 2c and Table 2). In contrast, the O–C values from 1986 to 1991 differ from zero by more than 0.02 day (Table 2). The equations for linear regression lines fitted to the two sets of data are shown in Figure 2c.

$$\mathrm{HJD\ (Min\ I)} = 2457274.0796\ (0.0002) + 0.3073060\ (0.0000001) \times \mathrm{E} \quad (2)$$

A second order polynomial equation (Equation 3) was fitted to the O–C values for the 1986–2015 data as shown in Figure 2d.

$$y = 5 \times 10^{-11}\, x^2 + 7 \times 10^{-7}\, x + 0.0003 \quad (3)$$

The positive value for the quadratic coefficient indicates an apparent period increase of 1 second per 100 years.

3.2. Light curve analysis and modelling

Examples of the light curves in the B, V, and I pass bands are shown in Figure 3. The difference in magnitudes of the primary minima, which were 0.11 to 0.12 fainter than those of the secondary minima in the B and V bands, and 0.07 magnitude fainter in the I band, indicate that the primary star is the cooler star by several hundred degrees (Table 4). The magnitudes at phase 0.25 were brighter than those at phase 0.75 by 0.01 magnitude in B and I and 0.02 magnitude in the V band pass in 2014, but did not differ in 2015 (Table 4). The color index varied during the cycle with a noticeable asymmetry in reddening during and after the primary eclipse in 2015 compared to that in 2014; the asymmetry is enhanced in the B–I index (compare Figures 4a and 4b). The shape of the light curve and the differences in the B–V, B–I, and V–I indices between the primary eclipse (phase 0) and phase 0.25 suggest that the contact zone on the primary component was hotter in 2015 than in 2014. At phase 0 in 2015, BC Gru was 0.03 magnitude brighter in the B band than in 2014 (Table 4). The precision of the aperture photometry was generally ± 1–2 millimagnitudes in the V and I pass bands and 3–4 millimagnitudes in the B pass band.

An astrophysical model with a mass ratio of 1.2 and inclination of 69° gave the best fit to the light curves in the V pass band, with the lowest sums of squared residuals of 0.013 for the light curves in 2014 and 0.007 in 2015 (Figure 5). The residual values were larger with inclinations of 67°, 68°, or 70°. Details of the parameters for the models, including third light, are shown in Table 5. Star spots had to be included before good fits to the observed light curves were obtained. In 2014, the best fit was obtained with two cool spots on the secondary component and one cool spot on the primary component (Figure 6 and Table 6). In contrast, the best fit to the light curves in 2015 was given by a hot spot at the contact zone on the primary star and one cool spot on the secondary star (Figure 7 and Table 6). The model parameters in Table 5 also provided good fits to the light curves in the B and I bandpasses in 2014 and 2015, with one exception: a temperature factor of 0.84 for the B pass band in 2014 gave a better fit for the spot at 250° longitude. The noise in the 2014 light curves around phase 0.15–0.2 is due to the higher airmass of 1.5 at the end of the observing run, compared to 1.08 at the start.

Table 4. Magnitudes of BC Gru at different phases in the orbital cycle. The standard errors at each phase are shown below each magnitude.

Date y-m-d	*Phase*	*B*	*V*	*I*	*B–V*	*V–I*	*B–I*
2014-09-30	0.00	11.804	10.944	9.972	0.860	0.972	1.832
		0.002	0.04	0.003	0.042	0.043	0.005
	0.25	11.284	10.483	9.588	0.801	0.895	1.696
		0.003	0.002	0.001	0.005	0.003	0.004
	0.50	11.676	10.841	9.901	0.835	0.940	1.775
		0.004	0.003	0.004	0.007	0.007	0.008
	0.75	11.288	10.498	9.595	0.790	0.902	1.692
		0.003	0.002	0.002	0.005	0.004	0.005
2015-09-08	0.00	11.773	10.937	9.954	0.836	0.983	1.819
		0.003	0.002	0.002	0.005	0.004	0.005
	0.25	11.271	10.488	9.576	0.783	0.912	1.695
		0.003	0.001	0.003	0.004	0.004	0.006
	0.50	11.649	10.821	9.882	0.828	0.940	1.758
		0.003	0.002	0.003	0.005	0.005	0.006
	0.75	11.275	10.488	9.583	0.787	0.904	1.691
		0.004	0.001	0.002	0.005	0.003	0.006

Table 5. Light curve model data for the models shown in Figures 6 and 7. The convention used in Binary Maker 3 for W-subtype W UMa systems, where the more massive star is the cooler component, is to invert the mass ratio.

Parameter	*Star 1*	*Star 2*
Mass ratio	1.2	1.2
Fillout	0.08	0.08
Inclination	69°	69°
Third light (B)	0.09	0.09
Third light (V)	0.12	0.12
Third light (I)	0.19	0.19
Temperature (K)	5040	5480
Gravity coefficient	0.32	0.32
Limb darkening (B)	0.87	0.81
Limb darkening (V)	0.70	0.63
Limb darkening (I)	0.46	0.41

Table 6. Star spot parameters for the light curve solutions in Figures 6 and 7. In each case, star 1 is the cooler component.

Date and Pass Band	*Star*	*Co-Latitude*	*Longitude*	*Radius*	*Temperature Factor*
2014-09-30	1	90	140	28	0.82
2014-09-30	1	90	250	28	0.82
2014-09-30	2	110	198	28	0.80
2015-09-08	1	90	2	20	1.15
2015-09-08	2	90	170	10	0.94

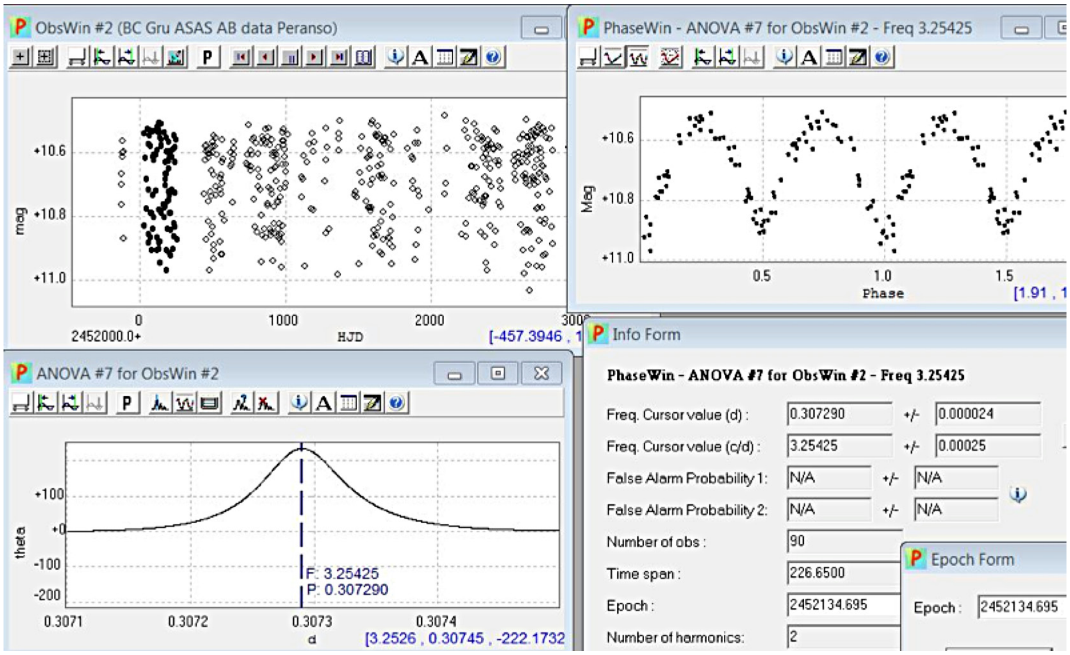


Figure 1. A composite view of 4 windows in PERANSO showing how epochs of primary eclipse minima were determined from the ASAS data (Pojmański 2002). Top right: Phase diagram for the activated 2001 dataset shown highlighted in the top left panel. The primary minimum was usually not centred on phase 1.0 by the frequency cursor in the ANOVA window (bottom left); therefore, an epoch was calculated and inserted into the Epoch tab in the Info form window (bottom right panel) and adjusted as described in section 2.

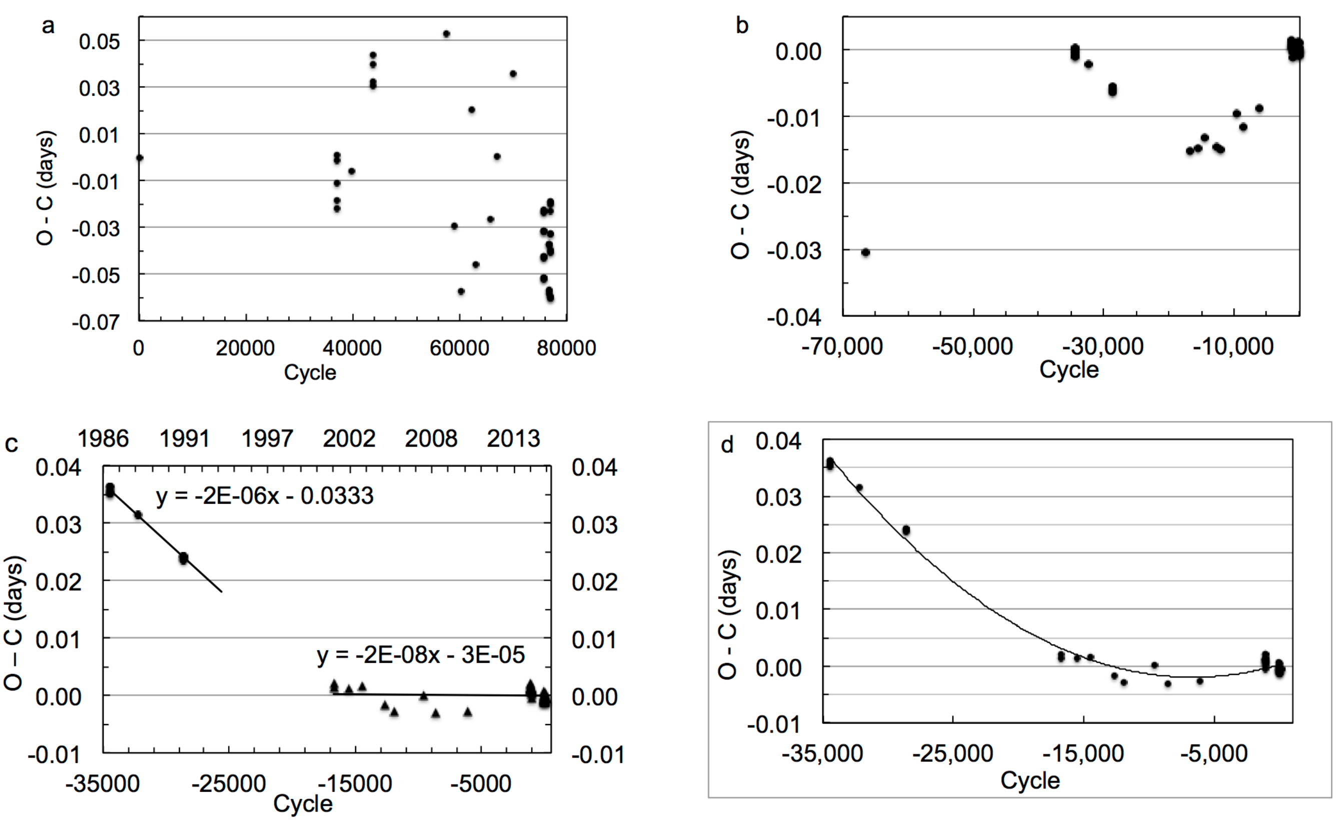


Figure 2. (a) The O–C diagram for BC Gru for the period 1959 to 2015, based on the GCVS ephemeris. (b) The O–C diagram for BC Gru for the period 1959 to 2015, based on the ephemeris in Equation 1. (c) The O–C diagram of the values given in Table 2 for the period 1986 to 2015 based on the ephemeris in Equation 2, with linear regression lines fitted for the periods of 1986–1991 and 2001–2015. (d) The O–C diagram shown in (c) with a second order polynomial fitted. See Table 2 for details of epochs and error values.

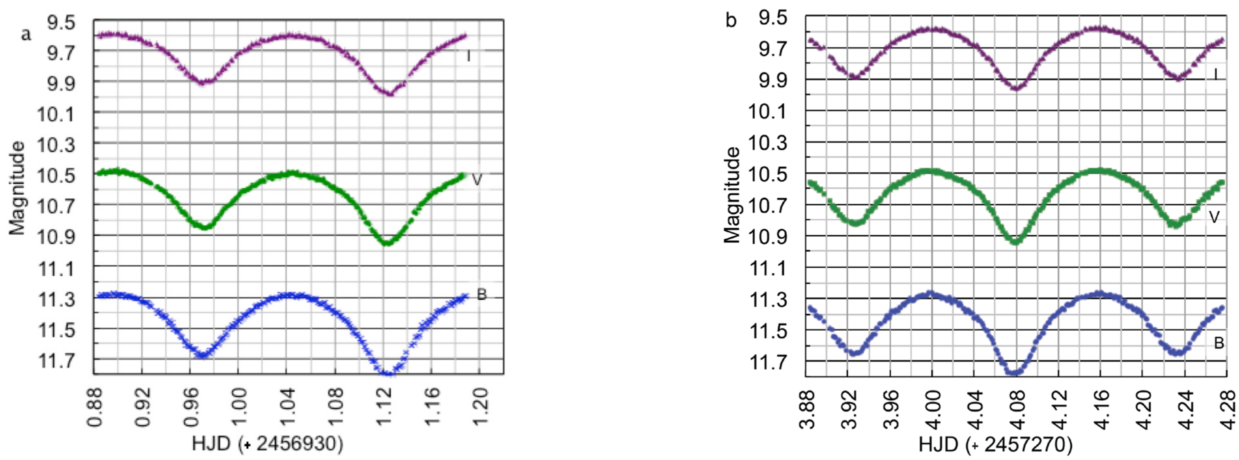


Figure 3. Light curves of BC Gru in B (x), V (●) and I (▲) pass bands on 2014-09-30 (a) and 2015-09-08 (b). Note the larger amplitude of the secondary eclipse in 2014 compared to 2015, particularly in the B pass band.

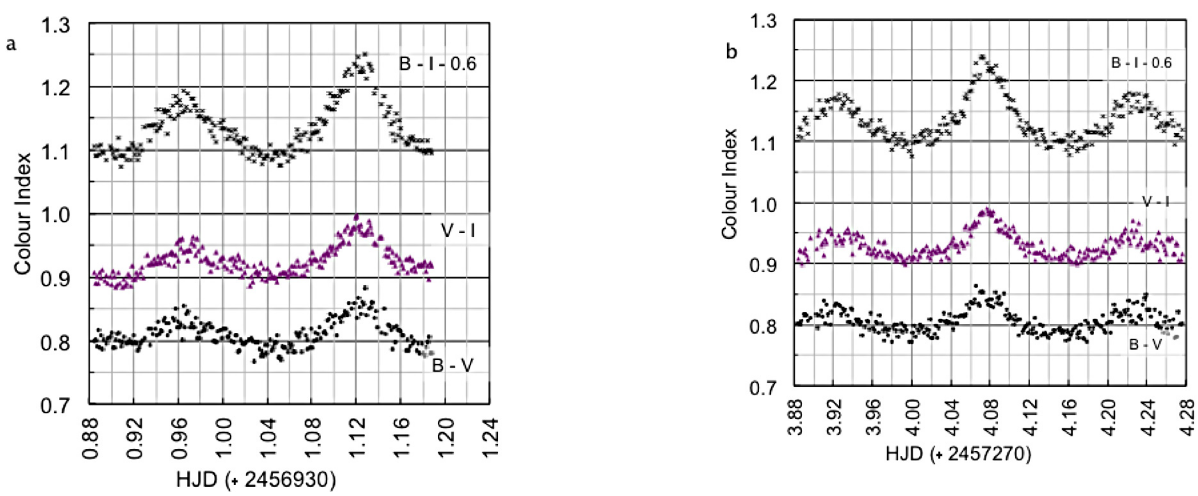


Figure 4. Color indices of the light curves observed on 2014-09-30 (a) and 2015-08-09 (b). The B–I index is offset by –0.6 magnitude.

4. Discussion

4.1. Period analysis

The period of BC Gruis is now 0.307306 day, but as described in the Introduction, the period was reported to be 0.26617 day in 1959 and then between 1986 and 1991, it was found to be 1 hour longer, at 0.307356 day. The period of BC Gru, determined by linear regression analysis of the epochs of minima that included both primary and secondary eclipses for the interval from 2001 to 2015, differs by more than two standard errors from the period reported by Plewa and Kałużny (1992) and Samec and Becker (1993) (see Table 3).

Orbital period changes are studied with the aid of O–C diagrams in which the differences between observed epochs of minima and calculated epochs of minima determined from linear ephemerides are plotted against eclipse cycles. The O–C diagrams based on the updated ephemerides (Equations 1 and 2) of BC Gruis also indicate that there was a change in the period in the interval between 1991 and 2001. The small variations in O–C values between 2001 and 2015 were not due to changes in period, but to the effect of star spots and to variability in the ASAS data sets. In contrast to the decrease in period from 0.0307356 day in 1991 to its present value, the positive value of the quadratic term in the second order polynomial fit implies that there was a smooth increase (Equation 3). However, as there are not sufficient data points in the interval between 1991 and 2001, and with the large variability inherent in the ASAS data, I conclude that it is not appropriate to analyze these O–C values with a quadratic function. Furthermore, residual values from calculations of linear or polynomial functions are not meaningful when the variability in O–C values is 0.01 day or less, due to asymmetry in the light curves caused by stellar spots (as discussed below), and in the case of ASAS data, the low precision of the photometry. The observational data for the photometry in 1986, 1991, 2014, and 2015 that were used to determine times of minimum are quite different from the ASAS data. The former data sets were a series of observations over individual light curve cycles from which times of minimum can be determined accurately (provided that the computer clocks were set accurately), whereas the ASAS light curves were a composite of observations over a whole season; for example, the 2001 light curves in Figure 1 comprised 90 data points taken

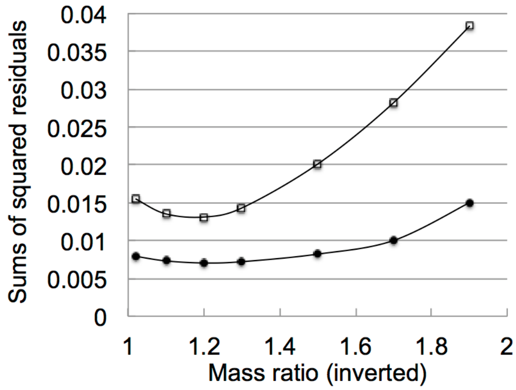


Figure 5. Graph showing the variations in best fit at an inclination of 69° to the light curves in 2014 and 2015: the sum of squared residuals for different mass ratios on 2015-09-08 (●) and 2014-09-30 (□).

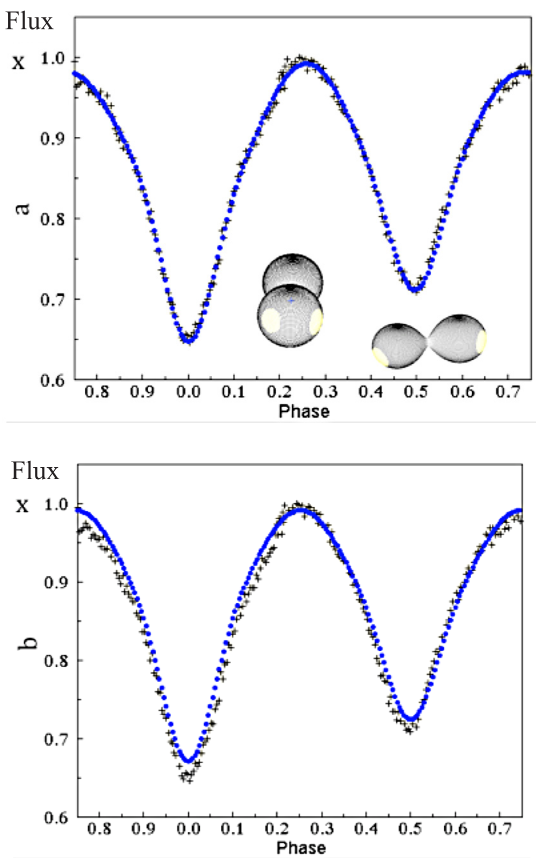


Figure 6. (a) Light curve (crosses) and model fit (blue line) of the V pass band for 2014-09-30. Insets: the binary model at phase 0 (left) showing 2 cool spots on star 1 and phase 0.3 (right) showing a cool spot on star 2. Star 1 is the larger star, on the right at phase 0.3. (b) Light curve (crosses) and model (blue line) with the same parameters as in (a), but without spots.

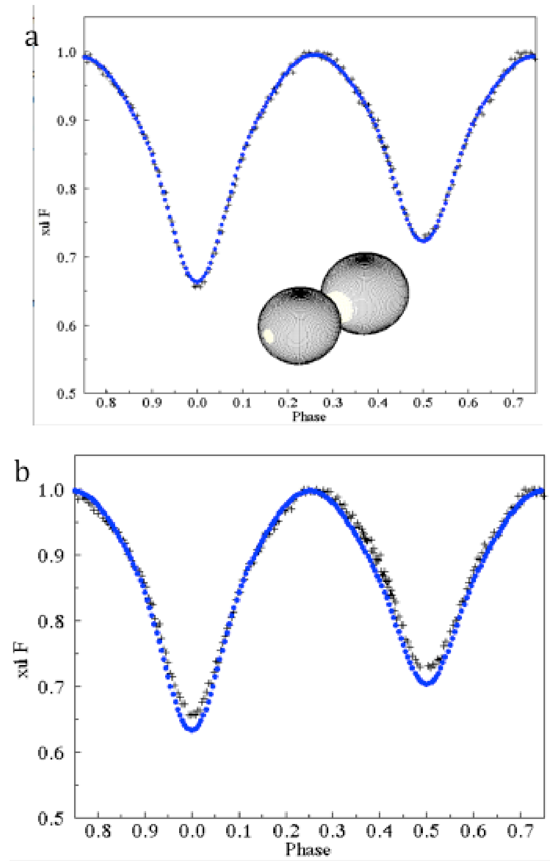
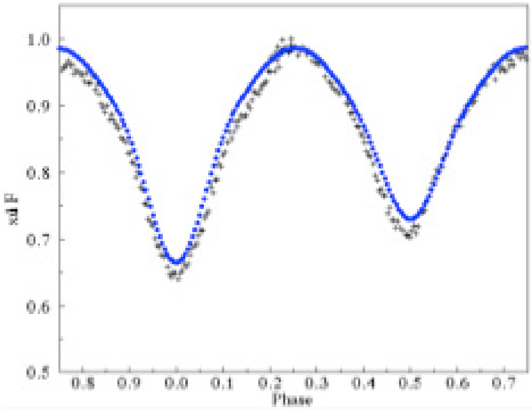


Figure 7. (a) Light curve (crosses) and best fit (blue line) of the V pass band for 2015-9-8 with 12% third light and a hot spot on star 1 around the contact zone and a cool spot on star 2. Inset: the binary model at phase 0.4. (b) Light curve (crosses) and best fit (blue line) of the V pass band for 2015-9-8 without the hot zone and zero third light.

from 735 cycles. In other words, from a statistical viewpoint, the populations of the 1986, 1991, 2014, and 2015 data are different from the populations of ASAS data.

Kalimeris *et al.* (2002) calculated the effect of star spots on O–C values and showed that they caused high frequency, low amplitude variability in the O–C diagram, generally less than 0.01 day. Thus the variability the O–C values of 0.001 to 0.002 day in 2014 and 2015 is a typical effect of star spots and similar to that found for TW Crucis (Moriarty 2015). The presence of star spots causes asymmetry in the light curves. The variability in the epochs of minima determined from some of the ASAS data was larger due to the small number of observations around the selected time of minimum (see section 2). Note that the minima shown in the top right panel in Figure 1 are a composite of minima over a time span of 226 days (Figure 1, bottom right panel). It was not possible for ASAS to provide detailed coverage of individual orbital cycles. For example, in 2001 the selected epoch was based on about 20 out of a total of 90 data points spanning about 780 cycles.

Plewa and Kałużny (1992) commented that the period of 0.26617 day, determined by Meinunger from 1959 photographic data, cannot be reconciled with the period they calculated in 1986, which is an hour longer. If the third star in the system is in a wide eccentric orbit (and not necessarily co-planar with the binary) it could affect the period during a close approach. As discussed below, the binary is a very active system in which



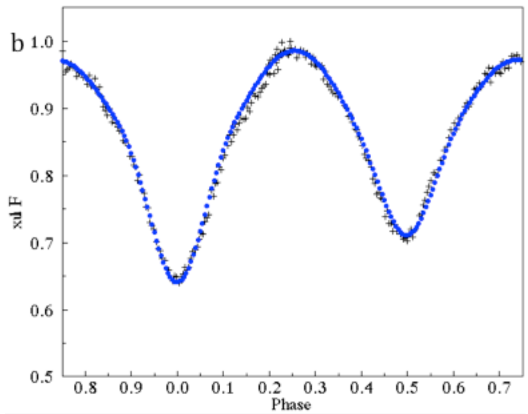


Figure 8. (a) Light curve (crosses) and model fit (blue line) of the V pass band for 2014-9-30 with mass ratio 1.77, fillout 0.011, inclination 66.9° and zero 3rd light (data from Plewa and Kałużny 1982). Teff and other factors are the same as those in Table 5. (b) Light curve (crosses) and model fit (blue line) of the V pass band for 2014-9-30 with mass ratio 1.77, fillout 0.07, inclination 69° and 8% third light and 3 spots (Table 6).

other processes could affect the period. Many more years of observations of this system are needed before more definitive conclusions can be drawn concerning period changes.

4.2. Light curve analysis and modelling

The differences in the light curves between 2014 and 2015, and in particular the probable higher temperature at the contact zone in 2015, suggest that mass or energy transfer is episodic, which would affect the period. Kałużny (1986) found that the asymmetry in the light curve of AU Ser could be explained by the presence of a hot zone at the neck between its components. If the epoch and period listed in the GCVS were correct, they provide further evidence of episodic or sudden changes in the period of BC Gru. Unfortunately, the original data and publication reference given in the GCVS are not available for study.

The analysis of O–C values over longer time scales can reveal period changes or modulations caused by other factors, including a light travel time effect due to a third component, mass transfers or loss, magnetic braking and angular momentum loss, and to gravitational quadrupole moment changes (Lanza and Rodonò 1999). Many more years of observation are required to determine the effects of these and of the third component on the orbital period of the BC Gru binary system. The differences between the light curves in 2014 and 2015 indicate that BC Gru is a chromospherically active system with stellar spots varying on short time scales. Angular momentum and mass loss through the effects of magnetic braking would be expected to occur in this late-type contact binary (see Hilditch (2001) for a discussion of this process). The model solutions derived here are not unique; they are preliminary analyses of the 2014 and 2015 light curves and await better data for the spectral types and spectroscopic mass ratio. The models are in agreement with the conclusion of Plewa and Kałużny (1992) that BC Gru is a W-subtype W-UMa binary. They developed a model with effective temperatures of 5430 K and 5072 K based on B–V values of 0.748 at quadrature phases and an inclination of 66.9 ± 2.8°. However, they determined that a mass ratio of 1.77 gave the best fit to their light curves. They commented that their modelling of BC Gru implied that the surface brightness of the components was not symmetrical, which would be expected when star spots are present.

Although Dall *et al.* (2007) reported the spectral types to be about the same for both components, the difference in V magnitudes of 0.11 between primary and secondary minima indicates a difference in their effective temperatures of several hundred degrees. Therefore, with the effective temperature set for the cooler component at 5040 K, typical of a K2 star on the main sequence, the model indicates that the temperature of the hotter component would be 5480 K, i.e. about type G8. As the best fits for third light to the model required a contribution of 10% greater flux in the infrared band than in the blue, the third component must be a later spectral type than the binary components (Table 5).

As the stars would be tidally locked, their rotational velocities are equal to their orbital velocities. The rotational velocities determined by Dall *et al.* (2007) have a large range of 165 ± 50 and 142 ± 50 km s^{-1}, thus giving a mass ratio of 1.16 with very wide limits. In fact, it is similar to the value of 1.2 determined photometrically for the modelling reported here. As Dall *et al.* (2007) pointed out, spectra at several different orbital phases are required to improve the spectral fitting and velocity determinations and thence improve the astrophysical model and determine absolute masses and radii.

5. Conclusions

BC Gru is a W-subtype W UMa-type contact binary system that is probably very active magnetically, as the best fits of the astrophysical models include star spots that changed in size, temperature, and number between 2014 and 2015. Its period is 0.307306 day now, but was 4 seconds longer between 1986 and 1991. Further time series observations are required to determine the effect of the third component in the system on the period of BC Gru. A longer time series of observations over several years is required to determine the influence of other causes of period change, including angular momentum and mass loss due to magnetic braking and stellar winds. High resolution spectra are needed to determine accurate and precise orbital radial velocities and thence the mass ratio in order to check and improve the models.

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