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Photometric study of the eclipsing binary GR Bootis

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HIGHLIGHTS

- We present time-series CCD photometry and low-resolution spectra for the eclipsing binary GR Boo.
- We analyze the variations of the orbital period and determine a new ephemeris formula.
- We firstly perform photometric analysis of GR Boo using the W-D program.
- The evolutionary status and physical nature of GR Boo are briefly discussed.

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ABSTRACT

We present CCD photometry and low-resolution spectra of the eclipsing binary GR Boo. A new ephemeris is determined based on all the available times of the minimum light. The period analysis reveals that the orbital period is decreasing with a rate of $dP/dt = -2.05 \times 10^{-10} d\ yr^{-1}$. A photometric analysis for the obtained light curves is performed with the Wilson–Devinney Differential Correction program for the first time. The photometric solutions confirm the W UMa-type nature of the binary system. The mass ratio turns out to be $q = 0.985 \pm 0.001$. The evolutionary status and physical nature of the binary system are briefly discussed.

1. Introduction

GR Boo was found in the ROTSE survey project by Akerlof et al. (2000) and identified as W UMa type eclipsing binary. Based on the survey data, Blattler and Diethelm (2001) provided light curves of GR Boo for the first time, and gave the linear epoch formula,

$$Min.I(HJD) = 2,451,996.5840 + 0^d.376670 \times E$$

Woźniak et al. (2004) compiled the NSVS catalog based on the ROTSE survey, in which GR Boo is number NSVS 7788990, and gave the light curve of GR Boo. Gettel et al. (2006) compiled 1022 contact binaries which were found in the ROTSE survey project into the catalog GGM2006, in which GR Boo is numbered as GGM2006 7788989. The parameters of GR Boo were given as : the period of 0.376675 days, the dimmest average magnitude in V band of 11.891 mag, the amplitude of variation of 0.439 mag, the absolute V magnitude of 4.462 mag ,the distance of 253 pc. Hoffman et al. (2009) derived the color index and a period of 0.37672 days based on the NSVS catalog. Pi et al. (2013) calculated an updated ephemeris and the change rate of the orbital period of GR Boo, and gave the new linear and quadratic ephemerides:

$$\begin{aligned} Min.I(HJD) &= 2,451,996.5849(\pm 0.0005) \\ &\quad + 0^d.37666986(\pm 0.00000008) \times E \\ Min.I(HJD) &= 2,451,996.5838(\pm 0.0003) \\ &\quad + 0^d.376671(\pm 0.000001) \times E \\ &\quad - 1^d.2(\pm 0.1) \times 10^{-10} \times E^2 \end{aligned}$$

However, no photoelectric study of the binary system has been available. The physical nature of the star system is not known. In order to get the photometric orbit solution, and further analyze the period change of this binary system, CCD photometric observations were carried out from 2011 to 2015. Light curves in V and R bands and new minimum times were obtained. In addition, we also obtained a low resolution spectrum of this eclipsing binary. In this paper, we present our study of GR Boo based on these observations.

2. Observations and data reduction

The CCD photometric observations were carried out using three telescopes from 2011 to 2015. Two nights of data in V and R bands were obtained with the 85 cm telescope located at the Xinglong station of the National Astronomical Observatories of China(NAOC), which was equipped with a PI 1024 × 1024 CCD camera at the main

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Table 1
Coordinates and brightness in *V* of the variable, comparison and check stars.

Star	Name	R.A.(J2000)	DEC.(J2000)	m_V
Obj	GR Boo	14 59 54.54	+25 54 33.62	11.51
Comp	GSC 02020–00659	14 59 40.45	+25 51 44.90	10.96
Check	GSC 02020–00910	15 00 19.54	+25 49 48.90	12.32

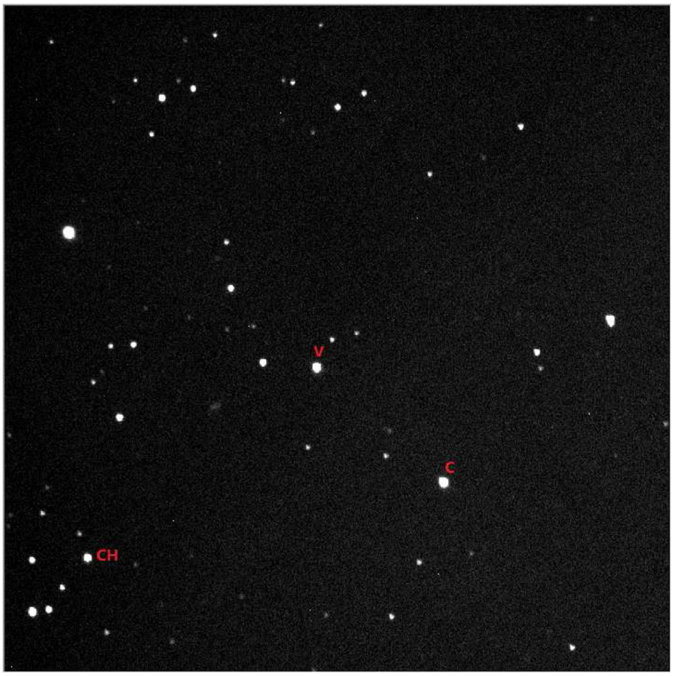

Fig. 1. A CCD image of GR Boo in V observed with the 85 cm telescope of Xinglong station. GR Boo, the comparison star and the check star are indicated.

focus, based on Zhou et al. (2009), corresponding to an image scale of 0.96 arcsec per pixel. The other three nights of data in *V* and *R* bands were obtained with the 60 cm telescope located at Xinglong station. The image scale is 1.056 arcsec per pixel. The last two nights of data in *V* and *R* bands and one night of data in *B*, *V*, *R* bands were collected with the 60 cm telescope located at the Yunnan Astronomical Observatory (YNAO), equipped with a *DW*436 2048 × 2048 CCD camera, with an image scale of 0.37 arcsec per pixel. We selected GSC 02020–00659 and GSC 02020–00910 as the comparison star and check star, respectively. The coordinates and brightness in *V* of GR Boo, the comparison star and the check star are listed in Table 1. Fig. 1 shows a CCD image of GR Boo in *V* with the 85 cm telescope. Table 2 lists the information of the new photometric observations for GR Boo. The preliminary processing of the CCD frames (bias substraction and flatfield correction) was performed with the standard routines of CCDPROC in the IRAF software. Photometry was made using the DAOPHOT package. We applied a series of apertures to make the photometry. The best aperture was determined according to the least of the deviations of the magnitude differences between the comparison star and the check star.

Spectroscopic observations for GR Boo were made on May 14, 2012 using the 2.16m telescope located at Xinglong station. The BFOSC low-dispersion spectrometer was used during the observations. The used grating was *G*7 with a slit width of 1.8" and a line dispersion of 95 *x*00*C*5; /*mm*. The center wavelength was at 530 nm with the wavelength range of 380–680 nm. The data were reduced with IRAF and the obtained low-resolution spectrum is shown in Fig. 2. Comparing with the spectrum flow library from Pickles (1998), the spectral type of GR Boo was preliminarily identified as $G3V - G4V$.

Table 2
Photometric observations for GR Boo.YN60 = Yunnan Astronomical Observatory 60 cm telescope, XL60 = Xinglong Astronomical Observatory 60 cm telescope, XL85 = Xinglong Astronomical Observatory 85 cm telescope.

Date	Telescope	Filter	Frames	Hours
2011 May 07	YN60	V	80	4.4
2011 May 07	YN60	R	80	4.4
2011 May 15	XL60	V	155	4.9
2011 May 15	XL60	R	154	4.9
2012 Feb 13	YN60	V	65	4.9
2012 Feb 13	YN60	R	65	4.9
2013 May 03	XL60	V	218	7.6
2013 May 03	XL60	R	218	7.6
2013 May 06	XL60	V	122	4.9
2013 May 06	XL60	R	122	4.9
2013 Jun 12	XL85	V	147	3.3
2013 Jun 12	XL85	R	147	3.3
2013 Jun 13	XL85	V	263	5.8
2013 Jun 13	XL85	R	263	5.8
2015 Jan 27	YN60	V	133	2.0
2015 Jan 27	YN60	R	132	2.0
2015 Jan 27	YN60	B	132	2.0

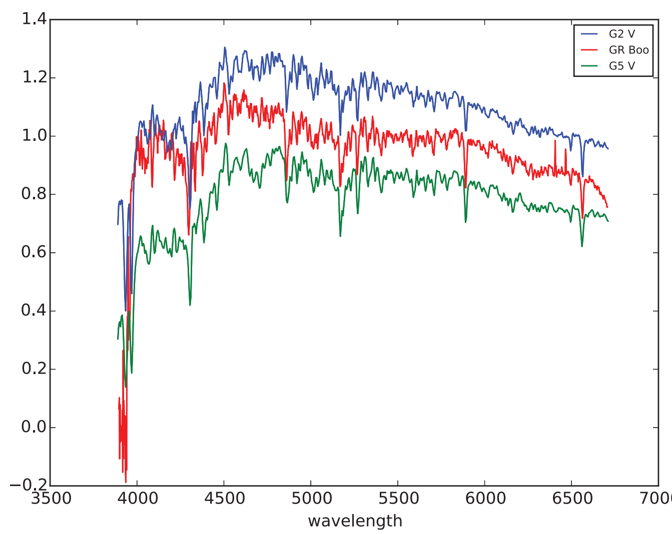

Fig. 2. The red: The spectrum of GR Boo, observed with the 2.16 m telescope of Xinglong station. The blue and green line are G2V and G5V from the Pickles (1998). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

3. Period changes

8 new minimum times were obtained in total from the obtained light curves. We also collected minimum times from the literature since 1999. Table 3 lists all the minimum times we have obtained, with which one can perform period analysis of the system. Using the method of least square fitting, we determined the new linear and quadratic ephemerides, as:

$$\begin{aligned} Min.I(HJD) &= 2,451,996.5462(\pm 0.0003) \\ &\quad + 0^d.37666954(\pm 0.00000004) \times E \end{aligned} \tag{1}$$

$$\begin{aligned} Min.I(HJD) &= 2,451,996.5838(\pm 0.0002) \\ &\quad + 0^d.37666954(\pm 0.00000006) \times E \\ &\quad - 1^d.126(\pm 0.005) \times 10^{-10} \times E^2 \end{aligned} \tag{2}$$

The $O - C$ residuals for all the times of minimum light according to the linear and quadratic ephemerides were calculated and listed in Table 3. According to the quadratic ephemeris, we plot the $O - C$

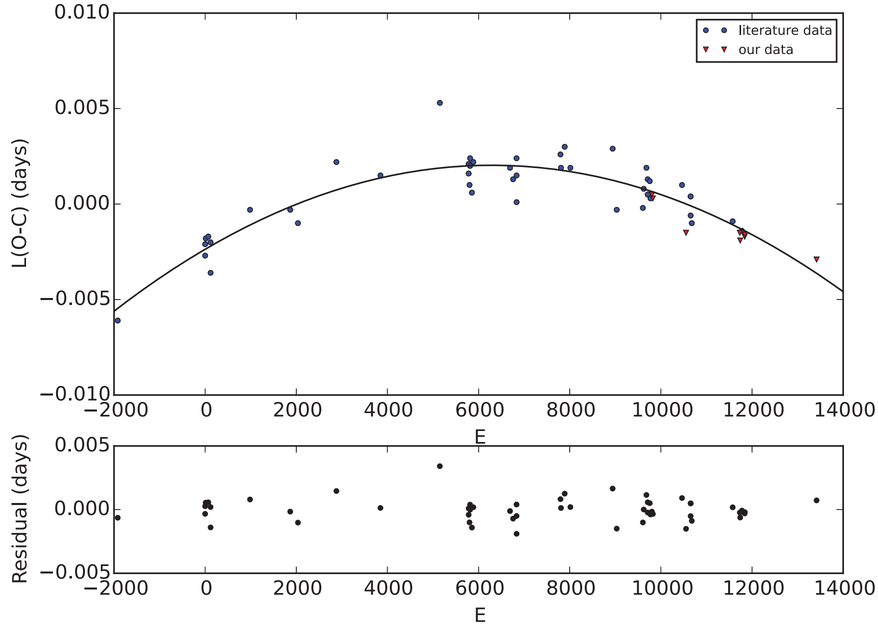

Fig. 3. The $O-C$ diagram of GR Boo. Filled circles represent the data collected from the literature, and the triangles represent the data from our observations. The quadratic fit is illustrated by the solid curve. The lower panel shows the residuals as the quadratic fit as Eq. (2).

diagram of GR Boo in Fig. 3, where the data from the literature are plotted as circles, our own data are plotted as triangles. The residuals of the fit are shown in the lower panel of Fig. 3. The scatter of the residuals is smaller than 0.0035 d. Hence, one finds that the orbital period of GR Boo appears to be decreases during last decade. We determined the rate of the period change of the binary system as $dP/dE = -1.12 \times 10^{-10} d\ cycle^{-1}$ or $dP/dt = -2.05 \times 10^{-10} d\ yr^{-1}$ from the quadratic ephemerides. The period decrease indicates mass transfer from the more massive component to the less massive component.

4. Photometric solution

In order to derive the photometric solution of GR Boo, we used the 2007 version of the WD code (Van Hamme and Wilson (2007);Wilson and Devinney (1971);Wilson (1979);Wilson (1990);Wilson (1994)) to analyze the data we observed in 2013. The photometric accuracy of the four nights data are 0.0033, 0.0071, 0.0060, 0.0103 in R band and 0.0028, 0.0050, 0.0063, 0.0113 in V band, respectively. With the derived linear ephemeris Eq. (1), we calculated the phases of all the measurements, and plotted the light curves in the form of differential magnitude versus phase in V and R band, respectively, in Fig. 4.

As can be seen in Fig. 4, the nearly equal minima reveal that GR Boo belongs to the W UMa type. The depths of the primary eclipse are 0.433 *mag* and 0.464 *mag*, in V and R band, respectively, which are slightly deeper than the depths of the secondary eclipses. With the complete light curves in V, R band, the photometric solution of the system was computed by means of the WD code. According to the spectral type determined from the spectrum, we take the effective temperature of the primary component(the star eclipsed at the primary minimum) of $T_1 = 5770$ K; the gravity-darkening coefficients of $g_1 = g_2 = 0.32$ for the two stars following Lucy (1967), and the bolometric albedos of $A_1 = A_2 = 0.5$ from Ruciński (1969). The initial bolometric (X_1, X_2, Y_1, Y_2) and monochromatic (x_1, x_2, y_1, y_1) limb-darkening coefficients of the components were adopted from van Hamme (1993). The adjustable parameters are listed as follows: the phase shift $x00F8;\ _0$, the orbital inclination i, the mean temperature of Star 2 T_2, the surface potentials Ω_1 and Ω_2 for both

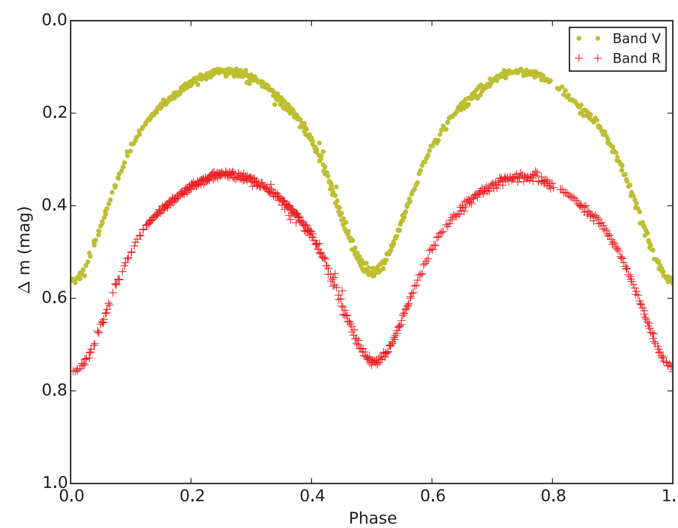

Fig. 4. Phase diagram of GR Boo in the V and R in 2013. The measurements are combined according to the linear ephemeris.

components, and the monochromatic luminosities of Star 1 L_{1V} and L_{1R} in V and R, respectively, and the mass ratio $q = m_2/m_1$.

Although the mass ratio of the two component stars q is a sensitive parameter, we have no information of it neither from photometry nor spectroscopy. Hence, a set of test solutions has been made to approximate this value. Taking into account characteristics of the light curves, we assumed the q values ranging between 0.2 and 2 ,with an interval step of 0.1. As GR Boo is a contact system from the light curves, the dc program was run with the trial mass ratio in mode 3, and a converged solution was then reached. After an iteration process, we got a series of q values and the residuals, among which the smallest residual is discovered when the q value is around 0.9. Fig. 5 shows the sum of weighted residuals versus the value of the mass ratio q. Then the dc program was run with mass ratio q varying slightly around 0.9 with the smaller steps. Finally we obtained the best-fitting result at $q = 0.985 \pm 0.001$. The photometrical solution is given in Table 4. The theoretical light curves in V and R bands are plotted in

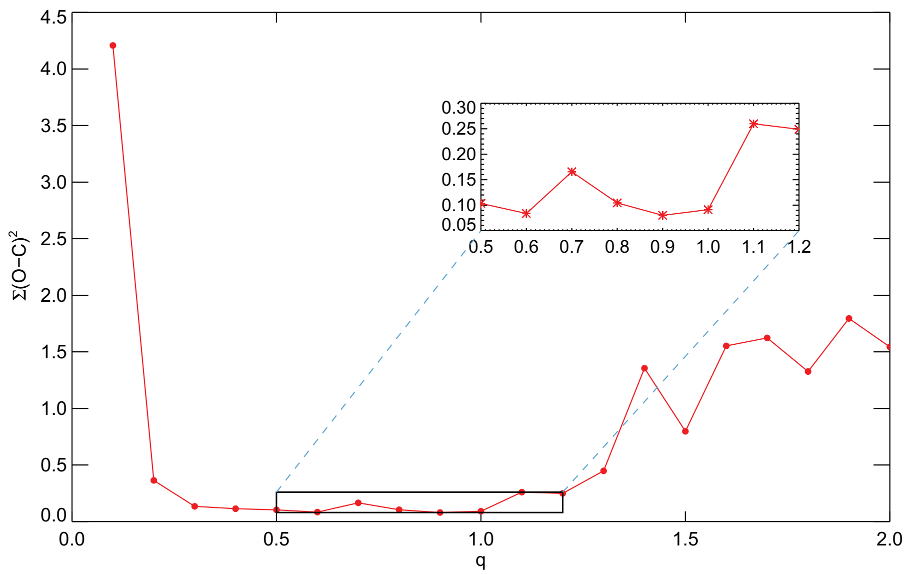

Fig. 5. The q values from 0 to 2.0, sum of weighted residuals $\sum(O-C)^2$ versus the mass ratio q, up right panel: Zoom-in of the inset rectangle domains.

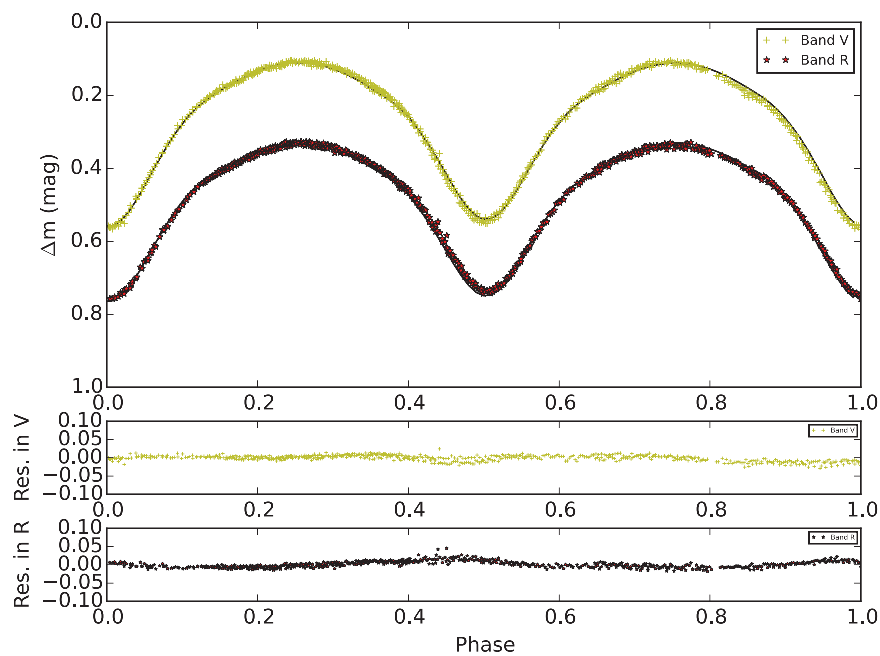

Fig. 6. Upper panel: The observed light curves in V, R bands (the circle dots) and theoretical light curves (the solid lines). Lower panel: the residual diagram.

the upper panel of Fig. 6, and the residuals are plotted in the lower panel.

5. Conclusions and discussion

According to the result of the period analysis and the photometric solutions, we arrived at following conclusions:

1. Based on Pi's research on the orbital period analysis of GR Boo, we added some new times of minimum light, and derived the new linear and quadratic ephemeris. It turns out that the orbital period of the binary system is decreasing at a rate of $dP/dE = -1.12 \times 10^{-10} d\ cycle^{-1}$ or $dP/dt = -2.05 \times 10^{-10} d\ yr^{-1}$ during last decades. One possible explanation for this phenomenon is that there is mass transfers from the more massive component to the less massive component. However, with all the available data we collected, it is not possible to identify whether there is any influence from the third body. More observations are needed to confirm this.
2. With the Wilson-Devinney code, a photometric solution of GR Boo was obtained for the first time. We thus confirm that GR Boo belongs to the W UMa-type. The temperature and the mass of the primary component are slightly higher than the values of the secondary, which indicates that GR Boo is an A-type contact system. The two components both fill in the Roche lobes.
3. A no-spot synthesis of the theoretical light curves of GR Boo fits the observed light curves which reveals that there was no spot on the system. This suggests that the system might be in a quiet phase of the magnetic activity as a Sun-like star. The decreasing period change does not look related with the conclusion of magnetic activity, which agrees with Yan-Ping et al. (2015), as well as Liao and Qian (2010). To examine this hypothesis, more observations are needed.

Table 3
Times of light minima of GR Boo and residuals calculated according to the new ephemerides. E = Cycle number.

HJD (2,400,000+)	E	$(O-C)_1$ (d)	$(O-C)_2$ (d)	Ref.
51,274.1280	−1918.0	−0.0061	−0.0005	1
51,996.3952	−0.5	−0.0027	−0.0003	2
51,996.5841	0.0	−0.0021	0.0003	2
52,001.4811	13.0	−0.0018	0.0006	2
52,022.5747	69.0	−0.0017	0.0006	2
52,041.4079	119.0	−0.0020	0.0002	2
52,041.5946	119.5	−0.0036	−0.0014	2
52,367.4171	984.5	−0.0003	0.0008	2
52,699.8280	1867.0	−0.0003	−0.0001	1
52,763.4844	2036.0	−0.0010	−0.0010	3
53,081.3967	2880.0	0.0022	0.0015	4
53,445.4471	3846.5	0.0015	0.0001	5
53,936.4397	5150.0	0.0053	0.0034	6
54,174.4911	5782.0	0.0016	−0.0004	7
54,174.4916	5882.0	0.0021	0.0001	6
54,181.8356	5801.5	0.0010	−0.0010	8
54,186.3570	5813.5	0.0024	0.0004	9
54,186.5450	5814.0	0.0020	0.0001	9
54,201.4220	5853.5	0.0006	−0.0014	9
54,213.4770	5885.5	0.0022	0.0002	9
54,516.5074	6690.0	0.0019	−0.0001	10
54,541.9320	6757.5	0.0013	−0.0007	11
54,570.3716	6833.0	0.0024	0.0004	12
54,570.5591	6833.5	0.0015	−0.0004	12
54,570.7460	6834.0	0.0001	−0.0019	23
54,933.4813	7797.0	0.0026	0.0009	10
54,937.8123	7808.5	0.0019	0.0002	13
54,968.5119	7890.0	0.0030	0.0013	10
55,015.4062	8014.5	0.0019	0.0002	14
55,364.7682	8942.0	0.0029	0.0017	15
55,398.4769	9031.5	−0.0003	−0.0015	16
55,614.4970	9605.0	−0.0002	−0.0010	17
55,621.6547	9624.0	0.0008	0	23
55,643.8793	9683.0	0.0019	0.0012	18
55,654.4247	9711.0	0.0005	−0.0001	19
55,654.6138	9711.5	0.0013	0.0006	19
55,671.5638	9756.5	0.0012	0.0005	23
55,677.4013	9772.0	0.0003	−0.0003	17
55,689.0783(9)	9803.0	0.0005	−0.0001	24
55,697.1765(1)	9824.5	0.0004	−0.0001	24
55,938.0573	10464.0	0.0010	0.0009	20
55,971.3898(4)	10552.5	−0.0016	−0.0016	24
56,009.4346	10653.5	−0.0006	−0.0005	21
56,009.6239	10654.0	0.0004	0.0005	21
56,009.6239	10654.0	0.0004	0.0005	23
56,018.8509	10678.5	−0.0010	−0.0009	22
56,356.9120	11576.0	−0.0009	0.0003	20
56,416.0485(1)	11733.0	−0.0015	−0.0001	24
56,419.0614(1)	11741.0	−0.0019	−0.0006	24
56,433.3754	11779.0	−0.0014	0	23
56,456.1636(1)	11839.5	−0.0017	−0.0002	24
56,457.1054(2)	11842.0	−0.0016	−0.0001	24
57,050.3586(3)	13417.0	−0.0029	0.0008	24

Notes. 1. Paschke and Brat (2006) 2. Blattler and Diethelm (2001) 3. Bulut et al. (2001) 4. Nomen-Torres and Escola-Sirisi (2001) 5. Simon et al. (2001) 6. Henden and Landolt (2001) 7. Hubscher et al. (2009a) 8. Nelson (2007) 9. Moschner et al. (2001) 10. Hubscher et al. (2010) 11. Nelson (2009) 12. Hubscher et al. (2009b) 13. Nelson (2010) 14. Diethelm (2010a) 15. Diethelm (2010b) 16. Diethelm (2011a) 17. Hubscher and Lehmann (2012) 18. Diethelm (2011b) 19. Hubscher et al. (2012) 23. Hoňková et al. (2013). 17. Hubscher and Lehmann (2012) 19. Hubscher et al. (2012) 20. Nelson (2013) 21. Hubscher et al. (2013) 22. Diethelm (2012) 23. Hoňková et al. (2013) 24. this study.

Table 4
Photometric solution of GR Boo.

Parameter	Best-fit value	Error
$q = m_2/m_1$	0.985	0.001
$T_1(K)$	5770[a]	
$T_2(K)$	5696	±9
$g_1 = g_2$	0.32[a]	
i	70.43	±0.07
$A_1 = A_2$	0.50[a]	
$\Omega_1 = \Omega_2$	3.726	±0.004
$X_1 = X_2(bolo)$	0.370[a]	
$Y_1 = Y_2(bolo)$	0.303[a]	
$x_1 = x_2$(V)	0.249[a]	
$x_1 = x_2$(R)	0.122[a]	
$y_1 = y_2$(V)	0.590[a]	
$y_1 = y_2$(R)	0.633[a]	
$L_1/(L_1+L_2)(V)$	0.520	±0.001
$L_1/(L_1+L_2)(R)$	0.520	±0.001
r_1(pole)	0.3572	±0.0005
r_1(side)	0.3752	±0.0164
r_1(back)	0.4060	±0.0009
r_2(pole)	0.3547	±0.0005
r_2(side)	0.3724	±0.0006
r_2(back)	0.4033	±0.0009
$\sum(O-C)^2$	0.083	

Notes. [a]Assumed.

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