Photometric Study of the W UMa-type Eclipsing Binary GM Bootis*

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2017-09-26

ChinaRxiv

Abstract

GM Boo is a short-period (approximately 0.36 days) contact binary that has been known for more than a decade. This study obtained newly observed multi-band time-series photometric data and low-dispersion spectra for GM Boo from 2010 to 2015. Nineteen new epochs of minimum light were extracted from the light curves, and the orbital period increase rate of this binary system was derived in combination with historical data. The Wilson-Devinney program was employed to analyze the photometric orbital solution of GM Boo. It is found to be a typical W-type overcontact binary system, with a mass ratio of approximately q~1.22 and a fill-out factor of approximately f~11%. Two spots were incorporated in the model to fit the asymmetric light curves, indicating that this system exhibits strong activity.

Full Text

Photometric Study of the W UMa-type Eclipsing Binary GM Bootis*

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Abstract: GM Boo is a contact binary with a short period (about 0.36 d) that was discovered more than 10 years ago. In this study, we obtained newly observed multiband time-series photometric data of GM Boo from 2010 to 2015, as well as its low-resolution spectrum. From the light curves, 19 new times of light minima were extracted, and, combined with historical data, the rate of increase of the orbital period of this binary was derived to be $dP/dt = 1.06 \times 10^{-7}\,\mathrm{d} \cdot \mathrm{yr}^{-1}$. The Wilson–Devinney program was used to analyze the photometric orbital solution of GM Boo. It is found to be a typical W-subtype overcontact binary system, with a mass ratio of about $q \sim 1.22$ and a contact degree of about $f \sim 11\%$. Two dark spots were added to the model to fit the asymmetric light curves, indicating that this system has relatively strong activity.

Keywords: eclipsing binary; orbital period; light curve

Chinese Library Classification No.: P144 **Document identification code:** A **Article No.:** 1672-7673

GM Boo (also known as GSC 02016-00830, ROTSE1 J144726.56+224515.0) was identified as an eclipsing binary system in the ROTSE survey (2000)[1], with an orbital period of $0.36110300 \pm 0.00001787$ d and a V magnitude of 12.230 mag. Subsequently, Blattler and Diethelm (2001) carried out CCD photometric observations of several binary stars, including GM Boo. They obtained the light curve of GM Boo and, for the first time, gave the linear ephemeris of GM Boo:

$$Min.I = HJD2{,}452{,}001.4032 + (0^d.361112) \times E \quad (1)$$

Reference [2] used ROTSE-I data combined with 2MASS J, H, K and near-infrared data to identify 1022 bright close binary systems from ROTSE-I, and gave for GM Boo an $I-H$ color index of 0.192, an $H-K$ color index of 0.057, an orbital period of 0.361112 d, and a heliocentric distance of $586 \pm 7pc$. Reference [3] considered GM Boo to be a W Ursae Majoris-type close binary, and gave its orbital period as 0.36108 d.

Because, up to now, there has been no further detailed study of this eclipsing binary, we carried out CCD photometric observations of this eclipsing binary in the V and R bands from 2010 to 2015, with the aim of analyzing the orbital-period variation of GM Boo and obtaining its photometric orbital solution.

1 Observations and Data Reduction

From 2010 May 16 to 2015 February 3, photometric observations of GM Boo were carried out on a total of 16 nights using three telescopes. Among them, the data from 5 nights were obtained with the 60 cm reflecting telescope at the Xinglong Station of the National Astronomical Observatories. This telescope has a primary-focus focal ratio of $F/4.23$, an effective field of view of $18' \times 18'$, and the CCD at the primary focus has 1024×1024 pixels with a pixel resolution of $1.056''/pixel$. The data from 10 nights were obtained with the 60 cm reflecting telescope of Yunnan Observatories. This telescope uses a Cassegrain focus, with a focal ratio of $F/12.5$ and an effective field of view of $12'.5 \times 12'.5$; the CCD model is Andor' s DW 436. The CCD has 2048×2048 pixels, and the pixel resolution is $0.37''/pixel$.

* Fund projects: supported by the National Natural Science Foundation of China (11673003); the National Key Basic Research and Development Program (973 Program) (2014CB845700 and 2013CB834900).
Received: 2017-06-02; revised: 2017-06-19
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Only one night of data was obtained using remote observations with the Tzec Maun telescope in New Mexico, USA. This telescope is a reflecting telescope with an aperture of 16 inches; its effective field of view is $26'.1 \times 17'.4$, the focal ratio is $F/9$, and the CCD model is SBIG STL-6303. The corresponding number of pixels and pixel resolution are 3072×2048 and $0.51''/pixel$, respectively. The photometric observation log is given in Table 1. Figure 1 shows an image of GM Boo taken with the Xinglong 60-cm telescope. UCAC4 564-052034 was selected

CCD image of GM Boo observed with the XL 60-cm telescope

Figure 1: CCD image of GM Boo observed with the XL 60-cm telescope

as the comparison star, and TYC 2016-1086-1 as the check star. Table 2 lists their coordinates and V magnitudes. The IRAF program was used

Fig. 1 A CCD image of GM Boo observed with the XL 60-cm telescope

to process the photometric data for this binary. The main procedures included bias subtraction, flat-field correction, and aperture photometry.

Table 1 Photometric observations of GM Boo

Date	Telescope	Filter	Frames
2010-05-16	TM16-in	VR	139
2011-05-08	YN60-cm	VR	228
2011-05-09	YN60-cm	VR	254
2011-05-18	XL60-cm	VR	137
2011-05-21	XL60-cm	VR	260
2011-05-22	XL60-cm	VR	330
2012-02-07	YN60-cm	VR	152
2013-01-23	YN60-cm	VR	102
2013-01-31	YN60-cm	VR	112
2013-05-05	XL60-cm	VR	155
2014-02-17	XL60-cm	VR	34
2015-01-25	YN60-cm	VR	352
2015-01-28	YN60-cm	VR	187
2015-01-29	YN60-cm	VR	420
2015-02-02	YN60-cm	VR	213

2012 May 14, using the 2.16-m telescope at Xinglong Station, a low-dispersion spectrum of GM Boo was obtained. This spectrum was taken with the BFOSC low-dispersion spectrograph; the grating was G7, the slit width was 1.8″, the dispersion was 95 Å$/mm$, the central wavelength was 530 nm, and the wavelength range was 380–680 nm. The IRAF program was used to process the original spectral data, yielding a low-resolution spectrum of this binary star (see Fig. 2). By comparison with the Pickles spectral flux library [4], the spectral type of GM Boo was preliminarily identified as $F3V - F5V$, with a temperature range of approximately $6800 \sim 7000K$.

Table 2 Coordinates and magnitudes of the object, the check star, and the comparison star

Spectrum of GM Boo observed with XL 2.16-m telescope

Figure 2: Spectrum of GM Boo observed with XL 2.16-m telescope

	Name	R.A. (J2000)	Dec. (J2000)	V magnitude /mag
Object	GM Boo	14 47 26.520	+22 45 14.49	11.89
Comparison star	UCAC4 564-052034	14 47 18.607	+22 43 53.27	12.34
Check star	TYC 2016-1086-1	14 47 20.948	+22 47 40.07	11.96

Fig. 2 The spectrum of GM Boo observed with XL 2.16-m telescope

2 Orbital-period variation

Using differential photometry, all light curves of GM Boo were extracted. At the same time, a least-squares method was used to perform quadratic fits near the minima of the light curves, determining 19 new times of minima. To study the orbital-period variation, 43 times of minima were collected from historical data. All times of minima are listed in Table 2. Using the least-squares method, new linear and quadratic ephemerides for GM Boo were obtained:

$$Min.I = HJD2,455,332.9007(3) + 0^d.36111863(7) \times E \tag{2}$$

$$Min.I = HJD2,455,332.9005(2) + 0^d.3611193(1) \times E + 1^d.05(2) \times 10^{-10} \times E^2 \tag{3}$$

Therefore, based on the new linear and quadratic ephemerides, the $O-C$ values of this binary star (the differences between the observed and calculated times of minima) are listed in Table 3. Using the $(O-C)_1$ values and epoch number E listed in Table 3, the $O-C$ diagram of GM Boo was plotted (see Fig. 3), with the aim of analyzing the long-term orbital-period variation of this binary. In Fig. 3, the red filled circles represent the data from this paper, and the black open circles represent data from the literature. A quadratic fit to all data points in Fig. 3 gives an upward-opening parabola, indicating that the orbital period of GM Boo is increasing. According to the quadratic term of the quadratic ephemeris, the orbital ⋯

The rate of period increase is $dP/dE = 1.05 \times 10^{-10}\ d \cdot cycle^{-1}$ or $dP/dt = 1.06 \times 10^{-7}\ d \cdot yr^{-1}$. The increase in the orbital period of a contact binary indicates that matter is being transferred from the less massive component to the more massive component[5].

Fig. 3 O–C diagram of GM Boo. The solid points represent our data, and the open circles represent the data from the literature. The solid curve shows the quadratic fitting.

Figure 3: Fig. 3 O–C diagram of GM Boo. The solid points represent our data, and the open circles represent the data from the literature. The solid curve shows the quadratic fitting.

Fig. 4 Light curves of GM Boo. The open circles represent the observational data, and the solid lines are the theoretical light curves.

Figure 4: Fig. 4 Light curves of GM Boo. The open circles represent the observational data, and the solid lines are the theoretical light curves.

Fig. 3 O–C diagram of GM Boo. The solid points represent our data, and the open circles represent the data from the literature. The solid curve shows the quadratic fitting.

3 Orbital Solution of the Photometric Data

The 2015 version of the Wilson–Devinney (W–D) program[6–9] was used to obtain an orbital solution for the photometric data of GM Boo.

The photometric data used for the solution were the 3 nights of data observed with the Xinglong 60-cm telescope in 2011 (see Table 1), because the data quality on these 3 nights was relatively high. The light curves with complete phase coverage in the V and R bands were obtained by combining the phases of these 3 nights of photometric data (see Fig. 4).

Fig. 4 Light curves of GM Boo. The open circles represent the observational data, and the solid lines are the theoretical light curves.

Fig. 4 Light curves of GM Boo. The open circles represent observational data and the solid lines show theoretical light curves.

GM Boo is classified as a W UMa-type eclipsing binary[^4]. Therefore, Mode 3 of the W–D program (overcontact binary not in thermal contact) was used to search for the initial orbital solution. According to the spectral type of GM Boo, $F3V - F5V$, the temperature of the primary star was assumed to be $T_1 = 6900K$; the gravity-darkening coefficients of the two components were taken as $g_1 = g_2 = 0.32$[^10]; the bolometric albedos of the two components were taken as $A_1 = A_2 = 0.50$[^11]; and the bolometric limb-darkening coefficients of the two components and the limb-darkening coefficients in each passband were taken from Ref. [12] (see Table 3). The above parameters were held fixed during the solution process. The adjustable free parameters in the W–D solution include the orbital inclination i, the secondary-star temperature T_2, the surface potentials of the two components Ω_1 and Ω_2, the mass ratio of the two components $q = m_2/m_1$, and the relative monochromatic luminosity of the

Fig. 5 The residual sigma versus mass ratio q = m2/m1.

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Fig. 6. The geometry configurations of GM Boo at the phases 0.0, 0.25, 0.5 and 0.75, respectively.

Figure 6: Fig. 6. The geometry configurations of GM Boo at the phases 0.0, 0.25, 0.5 and 0.75, respectively.

primary in the VR passbands.

Because there is, so far, no information about the mass ratio ($q = m_2/m_1$) of this binary, a q-search procedure was carried out to find the best mass ratio. The specific procedure of the q-search was to select a series of q values between 0.3 and 2, with an interval step of 0.1, and then, for each q value, to run the W-D program separately, adjusting the other free parameters until their corrections were smaller than the standard errors and the residual σ between the fitted light curve and the observed curve reached a minimum. Finally, a corresponding residual σ was obtained for each q value. Figure 5 plots the relationship between residual σ and mass ratio q, showing that the minimum residual σ occurs at $q = 1.2$. Therefore, the best mass ratio was sought near $q = 1.2$; the q value was released for fine adjustment, and the final best mass ratio was determined to be $q = 1.22$. The final orbital solution indicates that the component with the smaller mass but higher temperature is occulted by the component with the larger mass at primary minimum. Therefore, GM Boo is a typical W-subtype overcontact binary system[^13].

图 5 残差 σ vs 质量比 $q = m_2/m_1$

Fig. 5 The residual σ versus mass ratio $q = m_2/m_1$.

From the light curve in Figure 4, it can be seen that the primary maximum of the binary at phase 0.25 is fainter than the secondary maximum at phase 0.75; that is, an O' Connell effect is present[1]. This effect indicates that dark spots or bright spots may exist on the surfaces of the binary components. Here it is assumed that two dark spots exist on the surface of the more massive component, and then the longitude, latitude, angular radius, and temperature coefficient of the spots were adjusted to fit the maxima of the light curve. The final best orbital solution for the photometric data is listed in Table 4. The solid lines in Figure 4 show the theoretical light curves in the V and R passbands obtained from the orbital-solution fit. The geometrical structure of GM Boo is shown in Figure 6.

Fig. 6 The geometry configurations of GM Boo at the phase 0.0, 0.25, 0.5 and 0.75, respectively.

[1] http://adsabs.harvard.edu/full/1951PRCO···.2···85O

4 Summary and Discussion

Through CCD photometric observations, 19 new times of light minima of GM Boo were obtained, and its linear and quadratic ephemerides were derived. In addition, comparison with the light curve and ephemeris of Blattler and Diethelm (2001) shows that, in the observations of this paper, the times of primary and secondary minima of GM Boo are reversed; that is, the phase of the primary minimum in the light curve corresponds to the phase of the secondary minimum in the light curve of Blattler and Diethelm. Similar phenomena have also appeared in some eclipsing binaries observed by the Kepler satellite

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; this phenomenon may be caused by the migration of dark spots on the surfaces of the binary components.

The O-C diagram shows an upward-opening parabola, indicating that the orbital period of GM Boo has been increasing over the past several decades. The corresponding rate of period increase is $dP/dE = 1.05 \times 10^{-10}\ d \cdot cycle^{-1}$, or $dP/dt = 1.06 \times 10^{-7}\ d \cdot yr^{-1}$. This is consistent with the results given in recent studies of period changes in contact binaries

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. It is considered that the period increase of this binary may be due to mass transfer from the less massive component to the more massive component, but the presence of a third body cannot be completely excluded; further photometric observations are still needed.

Using the W-D program, a photometric orbital solution for GM Boo was obtained, thereby confirming that GM Boo is a typical W-subtype contact binary system. The surface potentials of the two components of GM Boo are $\Omega_1 = \Omega_2 = 4.0288(\pm 0.0025)$. Using $f = (\Omega - \Omega_{in})/(\Omega_{out} - \Omega_{in})$, the fill-out factor is obtained as $f = 11.11(\pm 0.39)\%$, i.e., the degree of contact of the two components is about 11%. The asymmetry of the maximum light in the light curve of GM Boo indicates the presence of the O' Connell effect. The W-D solution shows that there are two dark spots on the surface of the more massive component. The existence of spots indicates active magnetic activity on its surface, showing that, as an F-type star, it also has relatively strong surface magnetic activity, like later-type stars (G and K types).

Acknowledgements: JNF acknowledges the support from the National Natural Science Foundation of China (NSFC) through the grant 11673003 and the National Basic Research Program of China (973 Program 2014CB845700 and 2013CB834900). The authors acknowledge the support of the staff of the Xinglong 2.16m telescope. This work was partially supported by the Open Project Program

of the Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences.

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Photometric study of WUMa type eclipsing binary GM Bootis

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Abstract: GM Boo is a short-period ($\sim$ 0.36 days) contact binary system discovered for over 10 years. In this work, new multi-color photometric light curves from 2010 to 2015 and low-resolution spectra of GM Boo are obtained. We extracted 19 new eclipse timings of GM Boo from the light curves, deriving a long-term increasing rate of the orbital period $dP/dt = 1.06 \times 10^{-7}$ d $\cdot$ yr^{-1} combined with historical data. Photometric solution is derived with the Wilson-Devinney Code, which shows that GM Boo is a typical W-type contact binary with mass ratio of $q \sim 1.22$ and contact degree of $\sim$ 11%. Two cool spots are assumed in the model in order to fit the asymmetrical light curves, which indicated that GM Boo is an active system.

Key words: eclipsing binary; orbital period; light curves

Table 3 Minimum times and O-C residuals of GM Boo

HJD (2,400,000+)	Min.	E	$(O-C)_1$	$(O-C)_2$	Reference[2]
51996.5287	I	-9239	0.0092	0.0004	BBS 125
52001.4034	II	-9225.5	0.0088	0.0001	BBS 125
52001.5836	I	-9225	0.0084	-0.0003	BBS 125
52022.3507	II	-9167.5	0.0112	0.0026	BBS 125
52022.5291	I	-9167	0.0090	0.0004	BBS 125
52033.3584	I	-9137	0.0047	-0.0038	BBS 125
52041.4856	II	-9114.5	0.0068	-0.0018	BBS 125
52367.3979	I	-8212	0.0089	0.0020	BBS 128
52763.3562	II	-7115.5	-0.0001	-0.0052	BBS 129
53081.5055	II	-6234.5	0.0031	-0.0008	BBS 130
53445.5102	II	-5226.5	-0.0005	-0.0031	IBVS 5653
53815.4769	I	-4202	-0.0005	-0.0022	BAVM 186
53900.8800	II	-3965.5	-0.0021	-0.0036	OEJV 0162
53936.4531	I	-3867	0.0007	-0.0006	IBVS 5781
54174.4301	I	-3208	0.0001	-0.0008	IBVS 5781
54186.5265	II	-3174.5	-0.0010	-0.0018	BAVM 186
54201.5136	I	-3133	-0.0003	-0.0012	BAVM 186
54213.4318	I	-3100	0.0009	0.0001	BAVM 186
54570.3954	II	-2111.5	-0.0019	-0.0022	BAVM 201

HJD (2,400,000+)	Min.	E	$(O-C)_1$	$(O-C)_2$	Reference[2]
54570.5776	I	-2111	-0.0003	-0.0005	BAVM 201
54631.0653	II	-1943.5	0.0000	-0.0002	VSB 48
54888.9036	II	-1229.5	-0.0009	-0.0009	IBVS 5929
54933.5024	I	-1106	-0.0004	-0.0003	BAVM 209
54961.8511	II	-1027.5	0.0005	0.0006	IBVS 5894
54968.5305	I	-1009	-0.0008	-0.0007	BAVM 209
55015.4787	I	-879	0.0019	0.0020	IBVS 5920
55315.3853	II	-48.5	-0.0011	-0.0009	BAVM 214
55315.5660	I	-48	-0.0010	-0.0008	BAVM 214
55332.7195	II	−0.5	−0.0006	−0.0004	This paper
55332.9005	I	0	−0.0002	0.0000	This paper
55398.4414	II	181.5	−0.0025	−0.0023	IBVS 5960
55625.5890	II	810.5	0.0011	0.0012	OEJV 0160
55644.9063	I	864	−0.0015	−0.0014	IBVS 5992
55649.6020	I	877	−0.0004	−0.0003	OEJV 0160
55654.4777	II	890.5	0.0003	0.0004	BAVM 220
55671.4512	II	937.5	0.0012	0.0013	BAVM 220
55672.5338	II	940.5	0.0004	0.0005	OEJV 0160
55690.0428	I	989	−0.0049	−0.0048	This paper
55690.2275	II	989.5	−0.0007	−0.0007	This paper
55695.8251	I	1005	−0.0005	−0.0004	IBVS 5992
55700.1582	I	1017	−0.0008	−0.0007	This paper
55703.0484	I	1025	0.0004	0.0005	This paper
55703.2292	II	1025.5	0.0007	0.0007	This paper
55704.1316	I	1028	0.0003	0.0003	This paper
55704.3134	II	1028.5	0.0015	0.0016	This paper
55965.3968	II	1751.5	−0.0044	−0.0045	This paper
56008.5570	I	1871	0.0021	0.0020	OEJV 0160
56009.4585	II	1873.5	0.0008	0.0006	BAVM 228
56009.6398	I	1874	0.0015	0.0014	BAVM 228
56015.4167	I	1890	0.0005	0.0003	BAVM 228
56015.5986	II	1890.5	0.0019	0.0017	BAVM 228
56316.4089	II	2723.5	−0.0002	−0.0008	This paper
56324.3527	II	2745.5	−0.0010	−0.0016	This paper
56355.5875	I	2832	−0.0031	−0.0037	OEJV 0160
56418.0657	I	3005	0.0015	0.0008	This paper
56418.2485	II	3005.5	0.0037	0.0030	This paper
57048.4044	II	4750.5	0.0065	0.0043	This paper
57051.2930	II	4758.5	0.0061	0.0039	This paper
57052.3763	II	4761.5	0.0061	0.0039	This paper

[2]References.

57056.3468	II	4772.5	0.0042	0.0020	This paper
57057.4284	II	4775.5	0.0025	0.0003	This paper
57186.7186	II	5133.5	0.0120	0.0094	JAAVSO 44-1

[1] BBS = Bulletin der Bedeckungsveränderlichen-Beobachter der Schweizerischen Astronomischen Gesellschaft.;
BAVM = BAV-Mitteilungen (Berliner/Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne); IBVS = Information Bulletin on Variable Stars; OEJV = Open European Journal on Variable Stars; VSB = Variable Star Bulletin (Japan);
JAAVSO = Journal of the American Association of Variable Star Observers.

Table 4 Orbital solution of GM Boo

Parameter	Best-fit value	Error
$q = m_2/m_1$	1.220	$\pm$0.002
T_1 (K)	6900[a]	
$T_2(K)$	6725	$\pm$11
$g_1 = g_2$	0.32[a]	
$i(^\circ)$	64.452	$\pm$0.072
$A_1 = A_2$	0.50	
$\Omega_1 = \Omega_1$	4.0288	$\pm$0.0025
$X_1 = X_2$(bolo)	0.172[a]	
$Y_1 = Y_2$(bolo)	0.553[a]	
$x_1 = x_2(V)$	0.061[a]	
$x_1 = x_2(R)$	0.033[a]	
$y_1 = y_2(V)$	0.726[a]	
$y_1 = y_2(R)$	0.725[a]	
$L_1/(L_1 + L_2)$ (V)	0.485	$\pm$0.002

Parameter	Value	Error
$L_1/(L_1 + L_2)(R)$	0.477	$\pm$0.001
r_1(pole)	0.3477	$\pm$0.0002
r_1(side)	0.3657	$\pm$0.0003
r_1(back)	0.4019	$\pm$0.0005
r_2(pole)	0.3811	$\pm$0.0004
r_2(side)	0.4029	$\pm$0.0005
r_2(back)	0.4371	$\pm$0.0008
Spot1 latitude (rad)	1.4835	
Spot1 longitude (rad)	4.7124	
Spot1 radius (rad)	0.1745	
Spot1 temp factor	0.9	

Parameter	Value	Error
Spot2 latitude (rad)	1.2217	
Spot2 longitude (rad)	1.3962	
Spot2 radius (rad)	0.349	
Spot2 temp factor	0.93	
f	0.1111	$\pm$0.0039
$\sum(O-C)^2$	0.013	

Note. ^{a} Assumed

Note: Figure translations are in progress. See original paper for figures.