Possible substellar companions in low-mass eclipsing binaries: GU Bootis and YY Geminorum

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ABSTRACT

We present the next results of our long-term observational project to analyze the variations in the orbital periods of low-mass eclipsing binaries. About 70 new precise mid-eclipse times recorded with a CCD were obtained for two eclipsing binaries with short orbital periods: GU Boo ($P = 0^d.49$) and YY Gem ($0^d.81$). Observed-minus-calculated diagrams of the stars were analyzed using all reliable timings, and new parameters of the light-time effect were obtained. We derived for the first time or improved the short orbital periods of possible third bodies of 11 and 54 years for these low-mass binaries, respectively. We calculated that the minimum masses of the third components are close to $50 M_{\text{Jup}}$, which corresponds to the mass of brown dwarfs. The multiplicity of these systems also plays an important role in the precise determination of their physical parameters.

Key words. binaries: eclipsing – stars: late-type – stars: individual: GU Bootis – stars: individual: YY Geminorum – stars: fundamental parameters

1. Introduction

Low-mass stars and their multiple systems play an important role in stellar astrophysics. The origin of low-mass stars and brown dwarfs is still an unresolved question in star formation theory. Moreover, observations of low-mass stars show a discrepancy between estimated and modeled parameters, where the models give 5–10% smaller radii than observations (Chabrier & Baraffe 2000; Morales et al. 2010; Mann et al. 2015). The identification and characterization of low-mass multiples is also highly relevant to exoplanet studies.

Searching for substellar companions to short-period low-mass eclipsing binaries (LMB) sheds more light on the formation and evolution of planets and brown dwarfs. Because of the small size of the binary components, the eclipse times of this type of binary system can be determined with high precision, and very small amplitude variations in the orbital period can be detected by analyzing the observed-minus-calculated (O–C) diagram. This makes them very promising targets to search for circumbinary brown dwarfs or giant planets by analyzing the light-time effect (LITE). To date, several substellar companions to LMBs have been discovered using this efficient method (Lee et al. 2009; Hinse et al. 2012; Pribulla et al. 2012). Moreover, low-mass stars frequently exhibit phenomena

associated with magnetic activity, such as flares and star spots.

We here report on a long-term mid-eclipse time campaign of two selected LMBs. These systems are all relatively well-known low-mass objects in the northern hemisphere. Their orbital periods are up to 20 h, and spectroscopic observations have been published for both LMBs. This paper is a continuation of our previous period study of LMB presented in Wolf et al. (2016).

2. Observations of mid-eclipses

Long-term photometric observations for accumulating the mid-eclipse times are necessary when the O–C method is used to analyze the period variation. Short-period and detached LMBs with deep and symmetric eclipses enable us to obtain individual minimum times of eclipses with high accuracy. Moreover, this observing program is suitable for small amateur telescopes connected with modern detectors.

Since 2006, we have accumulated nearly 10^4 photometric observations during primary and secondary eclipses and derived about 80 precise times of minimum light for both systems. New CCD photometry was obtained mostly at the Ondřejov Observatory, Czech Republic, using the 0.65 m ($f/3.6$) reflecting telescope with the CCD cameras Apogee AP7p or the Moravian

Instruments G2-3200 and *VRI* photometric filters. The next precise CCD photometry was carried out at the Valašské Meziříčí Observatory, Czech Republic, using the 0.3 m Celestron Ultima telescope with the CCD camera SBIG ST-7 or G2-1600 and *VRI* filters, and with the Jan Šindel Telescope (JST) reflector (0.40 m $f/5$) and G2-1600 CCD camera with a set of *VR* bandpass filters operated at the observing house of the Astronomical Society in Hradec Králové. Additional measurements were obtained at the Prostějov and Mladá Boleslav observatories, where a 0.2 m Newtonian telescope and the CCD camera Atik 320E and MII G2-8300 without filter were used, respectively.

A standard calibration (dark frame, flat field) was applied to the observed CCD frames. *APHOT*, a synthetic aperture photometry and astrometry software, was routinely used for data obtained at Ondřejov observatory. *C-MUNIPACK*¹ was used to reduce our CCD time series obtained at Valašské Meziříčí, Hradec Králové, Mladá Boleslav and Prostějov. Differential photometry was performed using suitable comparison stars.

The computers at the telescope are synchronized using the time-server provided by `tick.usno.navy.mil` every two minutes. These corrections are usually on the order of 10^{-3} s. The new times of primary and secondary minima and their errors were generally determined by fitting the light curve by Gaussians or polynomials of the third or fourth order; we used the least-squares method. All new times are given in Tables A.1 and 3. The columns are self-explaining. If necessary, the times for the mid-eclipses are the averages of times obtained in two or three bandpasses.

All of the new timings we used in this analysis were first converted into barycentric Julian date dynamical time (BJD_{TBD}) using the time utilities of the Ohio State University² (Eastman et al. 2010). Our new timings were combined with previously published times of minima, and where appropriate, the historic times were converted into BJD_{TBD} before analyses.

All new precise CCD times of minima were used with a weight of 10 in our computation. Some of our less precise measurements were weighted by a factor of 5, while the earlier visual times or times determined from sky surveys were given a weight of 1 or 0 because of the large scatter in these data. We found this traditional weighting scheme more reliable than using sometimes overestimated formal errors of individual mid-eclipse times obtained from different telescopes and light curves. We tested the stability of the results with respect to our somewhat arbitrarily chosen weighting scheme. The results show some dependence on the weighting, but this is mainly related to the less ideal distribution of available observations. For this reason, the results must be considered preliminary.

3. Period variations

An unseen circumbinary body can be detected by observing the timings of the mid-eclipse times of the eclipsing binary. The presence of an additional body causes a change in the relative distance of the eclipsing pair to the observer depending on the motion of the third body around the common barycenter of the system. As a result, the eclipses present delays or advances in the timings of minimum light. This well-known light-time effect (LITE) was introduced by Irwin (1952, 1959), who also gave a graphical fitting procedure for determining the elements of the light-time orbit. Later, the LITE was improved by Mayer (1990).

See also Sterken (2005) for a short review on the application of O–C diagrams in the analysis of period variations of different variable stars. If the orbital period of the third star is short (usually up to one year), then additional dynamical perturbations of the inner orbit can occur that also create changes in the mid-eclipse times (see Borkovits et al. 2011, 2016). The precise mid-eclipse time estimation enable us to find small apparent period changes and derive the physical parameters of the next orbiting bodies that are of a substellar size and mass.

We propose LITE in both systems studied by means of an O–C diagram analysis. For an accurate calculation, the method originally described by Irwin (1952) and later extended by Mayer (1990) was applied. The least-squares method was used. Seven independent variables (T_0 , P_s , P_3 , e_3 , A , ω_3 , and T_3) are determined in this procedure, where P_s is the orbital period of the binary, P_3 is the orbital period of the third body, A is the semi-amplitude of LITE, e_3 represents the eccentricity of the outer orbit, and T_3 is the periastron passage time of the third body. The zero epoch is given by T_0 , and the corresponding position of the periastron is represented by ω_3 .

3.1. GU Boo

The detached eclipsing binary GU Boo (also NSVS 7820507, GSC 02566-00776, $V_{\max} = 13^m11$, Sp. M0/1.5, *Gaia* parallax 6.146 ± 0.015 mas) is a relatively well-known northern low-mass binary and double-lined system with a short orbital period ($P = 0.49$ d). It was discovered as a variable object by Diethelm (2001) in the Robotic Optical Transient Search Experiment database (ROTSE I, Akerlof et al. 2000). Later, López-Morales & Ribas (2005) derived the first precise absolute dimensions and physical parameters. They identified this system as a low-mass binary composed of two similar stars of about $0.6 M_{\odot}$. The following linear light elements were derived by these authors:

$$\text{Pri.Min.} = \text{HJD}2452723.^d9811(3) + 0.^d488728(2) \cdot E.$$

von Braun et al. (2008) presented a set of *Spitzer* 24 micron MIPS time series and confirmed the previously derived system parameters from optical studies. The effect of star spots on accurate radius determination was measured by Windmiller et al. (2010), who also confirmed the previous results of López-Morales & Ribas (2005) at the level $\sim 2\%$.

The additional measurements were obtained at Úpice observatory (0.2 m telescope without filter) and Prostějov observatory, where a 0.4 m telescope and the *V* filter were used. The flare activity on this LMB was also captured during the monitoring of the secondary eclipse at Prostějov observatory on June 14, 2017 (see Fig 1). The brightness in *V* band has suddenly increased by 0.37 mag in BJD 2457919.4073.

The next timing of GU Boo was derived from the ASAS database (Pojmanski 2002) with lower precision. The Bootes-2 telescope³ in Spain (0.6 m RC telescope and CCD camera Andor iXon, Jelinek et al. 2016) was also used for the photometry of this object. All mid-eclipse times are listed in Table A.1, where epochs are calculated from the ephemeris given in Table 2. The data from Brát et al. (2009, 2011), Diethelm (2009, 2011, 2012), Zasche et al. (2011), and Hubscher (2017) were also included. A total of 125 times of minimum light were taken into our analysis, with 57 secondary eclipses among them. Several published times of amateur observers were omitted due to large scatter of

¹ <http://c-munipack.sourceforge.net/>

² <http://astroutils.astronomy.ohio-state.edu/time/>

³ <http://bootes.iaa.es/>

Table 1. New times of minimum light for GU Boo.

JD Hel.- 2400 000	BJD(TDB)- 2400 000	Error (day)	Epoch	Weight	Source observatory
53818.49237	53818.49311	0.00008	2239.5	10	Ondřejov
53846.59395	53846.59469	0.00007	2297.0	10	Ondřejov
53860.52315	53860.52389	0.00012	2325.5	10	Ondřejov
53866.38769	53866.38843	0.00013	2337.5	10	Ondřejov
53898.39943	53898.40017	0.00010	2403.0	10	Ondřejov

Notes. This table is available in its entirety in Appendix A.

Fig. 1. V light curve of the secondary eclipse of GU Boo obtained in Prostějov observatory on June 14, 2017. The flare is clearly visible on the descending branch of the light curve on BJD 2457919.4073.

Fig. 2. Current O-C diagram for the eclipse times of GU Boo. The sinusoidal curve represents the LITE with a period of 11.1 years. The individual primary and secondary minima are denoted by circles and triangles, respectively. Larger symbols correspond to the CCD measurements, which were given higher weights in the calculations.

these less precise data. The O-C diagram is shown in Fig. 2, the computed LITE parameters and their internal errors of the least-squares fit are given in Table 2. It also lists the period ratio P_s^2/P_3 , which indicates possible dynamical interactions between the orbits that could be observed. a_{12} is the semi-axis of the eclipsing-pair orbit around the common center of mass with the third body. The reduced chi-square value, χ_{red}^2 , is also calculated. The nonlinear prediction, corresponding to the fitted parameters, is plotted as a continuous blue curve.

3.2. YY Gem

The detached eclipsing binary YY Geminorum (also Castor C, Gliese 278C, BD+32 1582, ADS 6175C, HD 60179C, $V_{\text{max}} = 9^{\text{m}}27$, Sp. dM1e, *Gaia* parallax 66.23 ± 0.05 mas and the distance 15.1 pc) is a frequently studied low-mass and double-lined spectroscopic binary and a member of the nearby Castor multiple stellar system. It contains two nearly identical components with a well-known flare activity. It was discovered spectroscopically in 1916 by Adams & Joy (1917); later, van Gent (1926) discovered eclipses and presented the first photographic light curve. YY Gem has been extensively studied in the past. The very precise absolute dimensions were obtained by Torres & Ribas (2002; $M = 0.5992 \pm 0.0047 M_{\odot}$, $R = 0.6191 \pm 0.0057 R_{\odot}$ and $T_{\text{eff}} = 3820 \pm 100$ K) for two practically identical components. See also the investigation history of the Castor multiple system presented in that paper. Qian et al. (2002) later found that the orbital period shows a secular decrease with a rate $\sim 10^{-10}$ day yr $^{-1}$. They conclude that the system is undergoing secular mass and angular momentum loss through a magnetic stellar wind. They also presented the improved light elements

$$\text{Pri. Min.} = \text{HJD}2424595.^{\text{d}}8172 + 0.^{\text{d}}81428254 \times E.$$

Recently, a multiwavelength study of YY Gem was presented by Butler et al. (2015). They included broad-band optical, near-infrared, ultraviolet, and radio data to determine the physical parameters and transient spots located near quadrature longitudes. New observations of eclipses were obtained at Mladá Boleslav and Prostějov observatories, where a 0.2 m Newtonian telescopes, Atik 320E, and the MII G2-8300 CCD camera were used, respectively. All mid-eclipse times of YY Gem given in Torres & Ribas (2002, their Table 3) as well as in Agerer & Hubscher (1999, 2002), Tas et al. (2004), Hubscher et al. (2009a,b, 2012), Hubscher (2011), Hubscher & Lehman (2015), Hubscher (2016), Zasche et al. (2014), and new timings published on the O-C Gateway of the Variable Star and Exoplanet Section, Czech Astronomical Society⁴, were included in our calculation with different weights. A total of 194 times of minimum light were used in our analysis, including 87 secondary eclipses. Many older visual mid-eclipse times were omitted due to the large scatter of these points. The computed LITE parameters are given in Table 2, the complete O-C diagram is shown in Fig. 3.

4. Discussion

The detection of the LITE in LMBs enables us to test the stellar multiplicity in low-mass stars and also prove current models of stellar evolution. The derived parameters of the third-body orbit allow us to determine the mass function $f(M)$

⁴ <http://var2.astro.cz/EN/>

Table 2. LITE parameters for selected LMBs (with errors of the last digit in parentheses).

Element	Unit	GU Boo	YY Gem
T_0	BJD	24 54723.98337(12)	24 24595.82174(18)
P_s	days	0.48872947(5)	0.81428219(1)
P_3	days	4040(60)	19785(200)
P_3	years	11.1(2)	54.2(5)
e_3	–	0.10(3)	0.11(3)
A	days	0.00126(7)	0.0034(2)
ω_3	deg	14.5(32)	37.6(25)
T_3	BJD	2454 090(20)	2454 805(50)
P_s^2/P_3	days	6×10^{-5}	3×10^{-5}
$a_{12} \sin i$	au	0.22(1)	0.58(3)
$\Sigma (O-C)^2$	day ²	6.2×10^{-5}	6.4×10^{-4}
χ^2_{red}	–	2.45	27.5

Notes. We used the SI definition of the speed of light $c = 299\,792\,458\text{ m s}^{-1}$ in our calculation.

$$f(M) = \frac{M_3^3 \sin^3 i_3}{(M_1 + M_2 + M_3)^2} = \frac{1}{P_3^2} \left[\frac{173.15 A}{\sqrt{1 - e_3^2 \cos^2 \omega_3}} \right]^3,$$

where P_3 is the period of the third body (in years) and M_i are the component masses. The systemic radial velocity of the eclipsing pair has an amplitude (in km s^{-1}) of

$$K = \frac{A}{P_3} \frac{5156}{\sqrt{(1 - e_3^2)(1 - e_3^2 \cos^2 \omega_3)}}.$$

Assuming a coplanar orbit ($i_3 \sim 90^\circ$), we can obtain a lower limit for the mass of the third component $M_{3,\text{min}}$. These values for the third body of individual systems were calculated by iteration and are collected in Table 4. The amplitude of the dynamical contribution of the third body A_{dyn} is given approximately by (Borkovits et al. 2016)

$$A_{\text{dyn}} = \frac{1}{2\pi} \frac{M_3}{M_1 + M_2 + M_3} \frac{P_s^2}{P_3} (1 - e_3^2)^{-3/2}$$

and is also given in Table 4. The value of A_{dyn} is on the order of seconds and is comparable with the precision of individual mid-eclipse time estimation.

Another possible mechanism for cyclical period variation is a magnetic activity cycle for systems with a late-type secondary star (Applegate 1992). However, the newly derived LITE periods for GU Boo (~ 11 yr) are too short for the magnetic cycle when compared with a mean value of about 40–50 yr in Algols and RS CVn binaries (Lanza & Rodono 1999). This mechanism can contribute significantly to the observed period changes in YY Gem.

The reduced chi-square value, χ^2_{red} , is satisfactory for GU Boo. This value is substantially higher than unity for YY Gem, caused very probably by the large scatter of older mid-eclipse times. For both LMBs we expect the brown dwarfs that are well below the mass limit of $0.075 M_\odot$ as the unseen third body orbiting the eclipsing pair. Moreover, the Castor stellar system could be at least septuple.

Additional timing variations with small amplitudes might be produced by the asymmetries of the eclipse light curves through stellar activity, such as star spots or small flares. The effect of star spots on the O–C diagrams was studied by Kalimeris et al. (2002). They found that star spots modulate the O–C values and

Fig. 3. O–C graph for YY Gem. See legend to Fig. 2. The sinusoidal curve represents the LITE with a period of about 55 yr and an amplitude of 5 min.

can introduce high-frequency and low-amplitude disturbances of less than 0.01 d. These variations are caused by the change in the surface density and center of light over the visible hemisphere. Barros et al. (2013) showed that observed transit time variations in the hot-Jupiter WASP-10b system are also due to spot occultation features. Recently, Korda et al. (2017) tested the spot variability on the light curve of low-mass binaries and found a difference in mid-eclipse times of about 95 s.

It is possible that circumbinary companions may be detected to transit these binary systems, especially if their orbital plane is closely aligned with the orbital plane of the binary system. Our predicted circumbinary companions have orbital periods measured in years and orbital distances in au, giving them a low probability of detecting a transit.

On the other hand, the probable brown dwarf could be confirmed spectroscopically using modern precise spectrographs connected to medium-size telescopes. The derived amplitudes of the systemic radial velocity of both LMB are on the order of hundreds of m/s (Table 4). For YY Gem the previous measurements of radial velocity were obtained by Torres & Ribas (2002) in the phase of the third-body orbital period near 0.8. Their result $\gamma = 0.54 \pm 0.26 \text{ km s}^{-1}$ is close to the value $\gamma = 1.97 \pm 0.24 \text{ km s}^{-1}$ obtained by Ségransan et al. (2000) in practically the same phase. In 2019, we start at phase 0.2 of the long third-body orbit, which promises that we may be able to discover a detectable change in the systemic velocity of the binary. The previous radial-velocity curve of GU Boo was obtained in the phase 0.675 of the third-body orbital period (López-Morales & Ribas 2005) and resulted in $\gamma = -24.57 \pm 0.36 \text{ km s}^{-1}$. After 2019, we can measure in phase up to 0.1, thus it will be also possible to determine a change in the γ -velocity with a precision on the order of several hundreds of m/s.

5. Conclusions

Our analysis of O–C diagrams has led to the identification of the next two probable triples in the known low-mass eclipsing binaries. The sinusoidal term in the orbital period is interpreted as the LITE being caused by a third body as the more likely scenario, most probably brown dwarfs of a similar mass about $50 M_{\text{Jup}}$. In both systems the whole third-body orbital period is now practically covered by the precise mid-eclipse times.

Our results contribute to this class of rare triple systems in our Galaxy (Tokovinin 2004; Raghavan et al. 2010). The sample of well-known LMB needs to be increased, and observations of additional systems would be very useful.

Table 3. New times of minimum light for YY Gem.

JD Hel.- 24 00000	BJD(TDB)- 24 00000	Error (day)	Epoch	Weight	Source observatory
53461.3113	53461.31204	0.0020	35449.0	1	Brát et al. (2007)
53744.6817*	53744.68216	0.0009	35797.0	10	Brát et al. (2007)
56630.50029	56630.50105	0.00012	39341.0	10	Zasche et al. (2014)
57735.48124	57735.48204	0.00019	40698.0	10	Mladá Boleslav
57737.51762	57737.51848	0.00005	40700.5	10	Mladá Boleslav
57739.55179	57739.55259	0.00013	40703.0	10	Mladá Boleslav
58198.40145	58198.40228	0.00012	41266.5	10	Prostějov

Table 4. Physical properties of the selected LMBs and parameters of their third bodies (with errors of the last digit in parentheses).

Parameter	Unit	GU Boo	YY Gem
M_1	$M_\odot$	0.6041(36)	0.5992(47)
M_2	$M_\odot$	0.5905(50)	0.5992(47)
R_1	$R_\odot$	0.6372(42)	0.6191(57)
R_2	$R_\odot$	0.5998(68)	0.6191(57)
Source		Windmiller et al. (2010)	Torres & Ribas (2002)
$f(m_3)$	$M_\odot$	$8.6(17) \times 10^{-5}$	$6.4(9) \times 10^{-5}$
$M_{3,\min}$	$M_\odot$	0.052(10)	0.047(6)
$M_{3,\min}$	M_{Jupiter}	54(11)	49(7)
K	km s^{-1}	0.56	0.3
A_{dyn}	s	8	4

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Appendix A: Tables of mid-eclipse times

Table A.1. Minima timings of GU Boo.

BJD(TDB)– 24 00000	JD Hel.– 24 00000	Error (day)	Epoch	Weight	Source observatory
53818.49311	53818.49237	0.00008	2239.5	10	Ondřejov
53846.59469	53846.59395	0.00007	2297.0	10	Ondřejov
53860.52389	53860.52315	0.00012	2325.5	10	Ondřejov
53866.38843	53866.38769	0.00013	2337.5	10	Ondřejov
53898.40017	53898.39943	0.00010	2403.0	10	Ondřejov
53988.32688	53988.32614	0.00009	2587.0	10	Ondřejov
54175.51030	54175.50956	0.00007	2970.0	10	Ondřejov
54210.45430	54210.45356	0.00009	3041.5	10	Ondřejov
54231.46973	54231.46899	0.00011	3084.5	10	Ondřejov
54237.33434	54237.33360	0.00018	3096.5	10	Ondřejov
54888.56736	54888.5666	0.0001	4429.0	5	AAVSO
54935.48536	54935.4846	0.0001	4525.0	5	Brát et al. (2011)
54936.46313	54936.4624	0.0020	4527.0	1	Brát et al. (2011)
54937.44064	54937.4399	0.0020	4529.0	1	Brát et al. (2011)
54943.54907	54943.5483	0.0001	4541.5	1	Hradec Králové
54965.78527	54965.7845	0.0005	4587.0	1	Diethelm (2009)
55231.65585	55231.6551	0.0001	5131.0	1	Brát et al. (2011)
55258.53534	55258.53457*	0.00012	5186.0	5	Brno
55309.36368	55309.3629	0.0005	5290.0	1	Brát et al. (2011)
55357.50258	55357.5018*	0.0002	5388.5	1	Brno
55382.42750	55382.4267	0.0002	5439.5	1	Brát et al. (2011)
55392.44700	55392.44622	0.00008	5460.0	10	Ondřejov
55599.66813	55599.6673*	0.0002	5884.0	5	Hoňková et al. (2013)
55640.47689	55640.47611	0.00012	5967.5	10	Ondřejov
55654.89548	55654.8947	0.0009	5997.0	1	Diethelm (2011)
55662.46940	55662.4686	0.0009	6012.5	1	Hoňková et al. (2013)
55687.39468	55687.3939*	0.0002	6063.5	1	Hoňková et al. (2013)
55700.34633	55700.34555	0.0001	6090.0	10	Zasche et al. (2011)
55798.33584	55798.33506	0.00008	6290.5	10	Ondřejov
55963.52593	55963.52515*	0.0003	6628.5	1	Hoňková et al. (2013)
55968.65828	55968.6574*	0.0002	6639.0	10	Hoňková et al. (2013)
55991.62868	55991.62790	0.00008	6686.0	10	Ondřejov
55996.51611	55996.5153	0.0002	6696.0	5	Hoňková et al. (2013)
56009.46638	56009.4656*	0.0004	6722.5	1	Hoňková et al. (2013)
56019.48607	56019.48529	0.00011	6743.0	10	Ondřejov
56036.34678	56036.3460	0.0002	6777.5	1	Hoňková et al. (2013)
56071.77978	56071.779	0.005	6850.0	1	Paschke (2014)
56100.37000	56100.36922	0.00012	6908.5	1	Ondřejov
56268.49272	56268.492	0.001	7252.5	1	ASAS
56318.58825	56318.58746	0.00011	7355.0	10	Ondřejov
56356.46489	56356.4641*	0.0003	7432.5	1	Hoňková et al. (2013)
56400.45014	56400.44935	0.00012	7522.5	10	Ondřejov
56431.48488	56431.4841*	0.0001	7586.0	1	Hoňková et al. (2013)
56683.66788	56683.6671*	0.0003	8102.0	1	Hoňková et al. (2015)
56692.71016	56692.70938	0.00009	8120.5	10	Ondřejov
56701.50778	56701.5070*	0.0002	8138.5	1	Hoňková et al. (2015)
56711.52510	56711.5243	0.0003	8159.0	1	Ondřejov
56712.50228	56712.5015*	0.0002	8161.0	5	Hoňková et al. (2015)
56730.58579	56730.5850	0.0001	8198.0	1	Hoňková et al. (2015)
56731.56358	56731.5628	0.0001	8200.0	5	Ondřejov

Notes. (*) Mean value of *VR*, *RI*, or *VRI* measurements.

Table A.1. continued.

BJD(TDB)– 24 00000	JD Hel.– 24 00000	Error (day)	Epoch	Weight	Source observatory
56773.59411	56773.593	0.001	8286.0	1	ASAS
56773.83930	56773.839	0.001	8286.5	1	ASAS
56827.35451	56827.35373	0.00011	8396.0	5	Ondřejov
56845.43763	56845.4369	0.0001	8433.0	1	Hoňková et al. (2015)
57074.65176	57074.6510	0.0005	8902.0	5	ASAS
57089.55798	57089.55721	0.00007	8932.5	10	Ondřejov
57089.55805	57089.55728	0.00012	8932.5	10	Bootes-2
57125.47972	57125.4790*	0.0002	9006.0	5	Juryšek et al. (2017)
57139.40847	57139.4077*	0.0002	9034.5	5	Juryšek et al. (2017)
57143.31826	57143.31749	0.00014	9042.5	10	Ondřejov
57153.33738	57153.33661	0.00009	9063.0	10	Ondřejov
57208.56288	57208.562	0.001	9176.0	1	ASAS
57441.44317	57441.442	0.001	9652.5	1	ASAS
57464.41337	57464.4126	0.0001	9699.5	1	Hubscher (2017)
57464.65667	57464.6559	0.0001	9700.0	1	Hubscher (2017)
57562.40414	57562.40337	0.00008	9900.0	10	Ondřejov
57567.29112	57567.290	0.001	9910.0	1	ASAS
57567.53600	57567.5352	0.0005	9910.5	5	ASAS
57607.36737	57607.3666	0.0001	9992.0	10	Ondřejov
57654.28557	57654.28480	0.00009	10088.0	10	Ondřejov
57780.62277	57780.62199	0.00007	10346.5	10	Ondřejov
57813.61148	57813.611	0.001	10414.0	1	ASAS
57813.85608	57813.8553	0.0005	10414.5	5	ASAS
57824.60863	57824.60785	0.00013	10436.5	10	Ondřejov
57864.43918	57864.43840	0.00015	10518.0	5	Úpice
57864.43940	57864.43862	0.00015	10518.0	5	Prostějov
57868.34900	57868.34822*	0.00012	10526.0	5	Valašské Meziříčí
57868.59433	57868.59355*	0.00014	10526.5	5	Hradec Králové
57880.32406	57880.3233	0.0003	10550.5	5	Ondřejov
57918.44468	57918.4439	0.0002	10628.5	5	Prostějov
57929.43984	57929.4391	0.0005	10651.0	1	Valašské Meziříčí
57929.44028	57929.4395*	0.0001	10651.0	5	Hradec Králové
57938.48247	57938.4817	0.0001	10669.5	10	Prostějov
57938.72598	57938.725	0.001	10670.0	1	ASAS
57938.97208	57938.971	0.001	10670.5	1	ASAS
57941.41493	57941.4142	0.0002	10675.5	5	Ondřejov
57948.50060	57948.4998	0.0001	10690.0	5	Valašské Meziříčí
57954.36566	57954.3649	0.0001	10702.0	5	Valašské Meziříčí
57989.31054	57989.30976	0.00018	10773.5	5	Ondřejov
58113.69187	58113.69109	0.00012	11028.0	10	Ondřejov
58184.06798	58184.067	0.001	11172.0	1	ASAS
58184.31248	58184.312	0.001	11172.5	1	ASAS
58198.48684	58198.4861	0.0001	11201.5	5	Prostějov
58207.52840	58207.5276	0.0002	11220.0	5	Ondřejov
58219.50242	58219.5016	0.0002	11244.5	5	Ondřejov
58229.52114	58229.52036*	0.00014	11265.0	5	Hradec Králové
58229.52125	58229.52047	0.00013	11265.0	5	Prostějov
58245.40538	58245.4046*	0.0001	11297.5	5	Hradec Králové
58246.38297	58246.3822	0.0001	11299.5	5	Valašské Meziříčí
58258.35632	58258.3555	0.0002	11324.0	5	Prostějov
58269.35313	58269.35235	0.00018	11346.5	5	Ondřejov
58300.38731	58300.3865	0.0002	11410.0	10	Ondřejov
58323.35760	58323.3568	0.0002	11457.0	5	Valašské Meziříčí
58347.30564	58347.30485	0.00017	11506.0	10	Ondřejov
58366.36629	58366.3655	0.0002	11545.0	10	Ondřejov