COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS

Number 6119

Konkoly Observatory
Budapest
8 November 2014

HU ISSN 0374 – 0676

LIGHT TIME EFFECT IN THE SYSTEM V2294 Cyg

LIŠKA, J.

Department of Theoretical Physics and Astrophysics, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic, e-mail: jiriliska@post.cz

The eclipsing binary star V2294 Cyg (GSC 03564-03059, 2MASS J19402932+5025522, KIC 12019674, ROTSE1 J194028.86+502554.7, ASAS J194029+5026.0) was discovered as a variable object by Akerlof et al. (2000) in data from the ROTSE all-sky survey. They found a preliminary, but incorrect period of variability of 0.26168(4) d. Follow-up observations were performed by Blättler & Diethelm (2000). They detected brightness changes in the range of 13.25–13.58 mag (unfiltered). Subsequently, they determined a better period of 0.35436(4) d, and found the star to be a W UMa type eclipsing binary. The binary star was included in a catalogue of contact binary stars (Pribulla, Kreiner & Tremko 2003) and in the same year it obtained the name V2294 Cyg in the GCVS (Kazarovets et al. 2003). Several different periods have been published up to now, e.g. 0.354317(3) d (Kreiner 2004) or 0.3544890 d (Pigulski et al. 2009). The latter value is taken from a catalogue of variable stars in the Kepler field of view, which is based on ASAS measurements. This catalogue contains information about average brightness in the V-band of 13.158 mag (amplitude 0.37 mag) and in the I-band of 12.210 mag (amplitude 0.31 mag), respectively.

The system V2294 Cyg was measured by the Kepler Space Telescope and the most information about the eclipsing binary come from this great project. Preliminary parameters from the first 44 days of Kepler operations, e.g. period 0.35450 d, effective temperature 5841 K, ratio of temperatures $T_2/T_1 = 0.91126$ and mass ratio 1.06290, were published by Prša et al. (2011). Updated values from a larger dataset (125 days) include the period 0.354492 d, ratio of temperatures $T_2/T_1 = 1.047$ and mass ratio $M_2/M_1 = 0.760$ (Slawson et al. 2011).

The eclipsing binary V2294 Cyg shows fast and irregular changes with an amplitude of about 2.5 hours in its O–C diagram (Fig. 1). This variability is supported by different published periods. Better orbital elements provided information about cyclic changes in the O–C diagram, which can be explained by the Light Time Effect (LiTE) with an ~ 8 yr period (see below).

The latest results from the Kepler project (Conroy et al. 2014) also describe the variability of the period of the V2294 Cyg in terms of LiTE. Unfortunately their results from LiTE modelling are based on measurements obtained over only a short time interval (4 years), therefore the parameters that they found (period of LiTE $P_3 = 1088.4(34.7)$ d $= 2.980(95)$ yr, eccentricity $e_3 = 0.346(1)$ and semi-amplitude of LiTE $A = 198(4)$ s $= 0.00229(5)$ d) are less reliable.

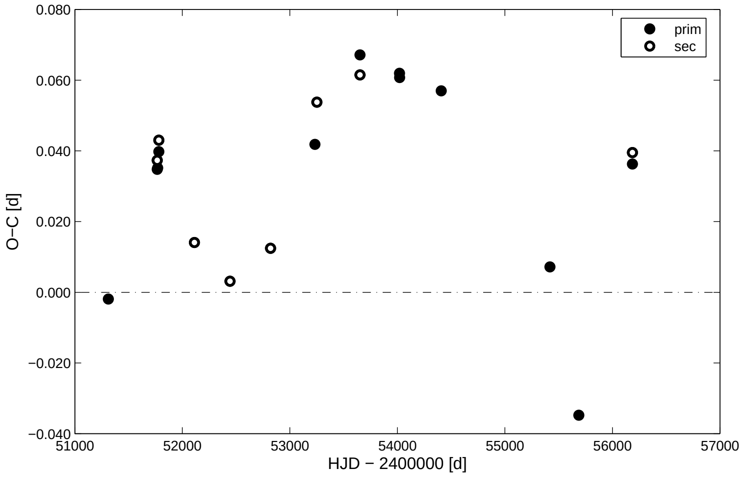

Figure 1. O–C diagram of V2294 Cyg constructed with elements $E_0 = 2451781.365$ and $P = 0.354328\,\mathrm{d}$ adopted from O–C Gateway (Paschke & Brát 2006).

For our study of LiTE in the system, the non-linear least squares method described in Liška et al. (2014) was used. All the mid-eclipse timings were used from the O–C Gateway (Paschke & Brát 2006) and are listed in Table 2 with the corrected types of minima according to our model and original source. All the minima were obtained from CCD light curves and the same value of weights were used for this reason. The best found solution, with the lowest sum of squares of residuals $R = 0.000122$ and corresponding average uncertainty of individual measurement ($0.0024\,\mathrm{d}$), is shown in Fig. 2. Individual parameters together with their uncertainties, determined by the bootstrap method, are summarized in Table 1.

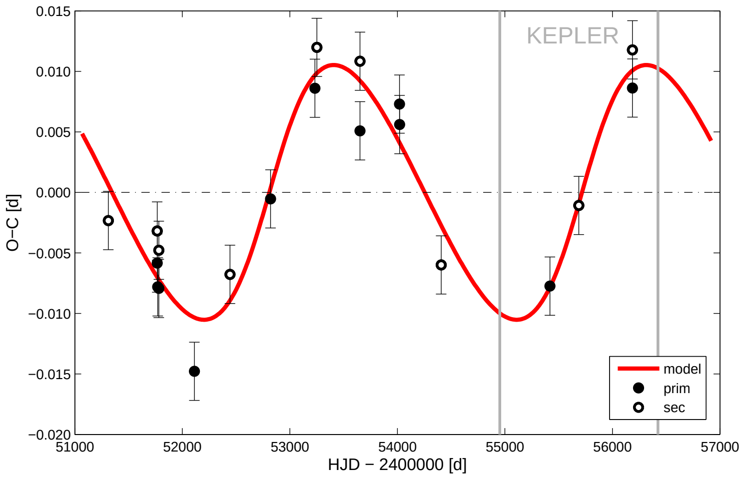

Figure 2. O–C diagram of V2294 Cyg with model of 8 years long LiTE according to parameters from Table 1. Baseline of Kepler observations from JD 2454953 to 2456424 is displayed (area between gray lines).

Despite the fact that our preliminary solution is based on only 20 times of minima from ground-based observations, it seems that our solution for the three-body system is more convincing than the solution based on the parameters from Conroy et al. (2014). The middle ephemeris for eclipses of the binary system in Heliocentric Julian Date (HJD) can be expressed in the form

$$T_{\min} = 2453363.5350^{+17}_{-20} + 0.35449748^{+21}_{-24}\,\mathrm{d} \cdot E. \tag{1}$$

The orbit of the third body with a period of $P_3 \sim 8$ years can be described by parameters from Table 1; time of periastron passage T_0, eccentricity e_3, argument of periastron ω_3 and semi-amplitude of LiTE A. The estimation of the lowest limit of a third body mass from the mass function $f(M_3)$ was performed for an assumed total mass of the eclipsing system of $M_{1+2} = 0.982^{0.173}_{0.111}\,\mathrm{M}_\odot$ (Huber et al. 2014). Unfortunately, the total mass of the star V2294 Cyg was determined only from its total brightness in different bands without taking into account that this is a multiple star system. Therefore, the value of $M_{3\,\min}$ of about $0.66\,\mathrm{M}_\odot$ is only a rough estimate. All three stars could have similar masses and contributions to the total flux.

LiTE allows us to estimate the shape of variations in γ-velocity of an eclipsing binary system caused by the orbit of a third body. Based on our model, the semi-amplitude of these changes is about 8 $\mathrm{km\,s^{-1}}$. Unfortunately no value for radial velocity for V2294 Cyg has been published yet. High-resolution spectroscopic measurements are necessary for a correct analysis of this system.

Table 1: Determined parameters from LiTE model for the three-body system V2294 Cyg. Mass limit of the third body was estimated from mass function $f(M_3)$, inclination of orbit ($i_3 = 90°$) and mass of eclipsing binary $M_{1+2} = 0.982^{0.173}_{0.111}\,\mathrm{M}_\odot$ adopted from Huber et al. (2014).

Parameter	Value
P_{ecl} [d]	0.35449748^{+21}_{-24}
E_0 [HJD]	2453363.5350^{+17}_{-20}
P_3 [y]	7.96^{+30}_{-28}
T_0 [d]	2452820^{+320}_{-390}
e_3	0.27^{+26}_{-5}
ω_3 [°]	2^{+42}_{-52}
A [light day]	0.0109^{+20}_{-8}
R	0.000122
$a_{12}\sin i$ [AU]	1.89^{+34}_{-14}
$f(M_3)$ [$\mathrm{M}_\odot$]	0.107^{+63}_{-27}
$M_{3\,\min}$ [$\mathrm{M}_\odot$]	0.66^{+16}_{-10}
K_{12} [$\mathrm{km\,s^{-1}}$]	$7.6^{+2.2}_{-0.5}$

Our results suggest that the use of the short-time interval data from Kepler could lead to misinterpretations as in Conroy et al. (2014). As in the case of similar projects, this high-accuracy photometric project is limited by the length of its time baseline. The approximately 4-year-long interval was insufficient to cover the whole LiTE cycle (see Fig. 2). In addition, the part of the cycle (from minimal value O–C to maximal) covered by the available Kepler data caused confusion in the determination of the length of the orbital period of the third body. We propose that other systems from the publication (Conroy et al. 2014) be investigated as well. Suspect systems occur in the second or third part of their Table 4 which therefore have LiTE periods longer than half of the baseline of Kepler observations (more than 2 years). Based on our multi-colour photometry of V2294 Cyg (initiated in 2010) together with high-accuracy Kepler measurements, a more comprehensive study on V2294 Cyg is being prepared.

Table 2: Minima used from the O–C Gateway together with information about corrected minimum-type and used publication.

HJD	Type	Source
2451311.8785	sec	Blättler & Diethelm (2000)
2451766.3434	sec	BBSAG 123[a]
2451766.5180	prim	BBSAG 123[a]
2451771.4790	prim	BBSAG 123[a]
2451781.4048	prim	BBSAG 123[a]
2451781.5852	sec	BBSAG 123[a]
2452112.4986	prim	BBSAG 126[a]
2452443.4300	sec	BBSAG 128[a]
2452820.4443	prim	Diethelm (2004)
2453233.4430	prim	Diethelm (2005)
2453251.3485	sec	Diethelm (2005)
2453652.2840	sec	Diethelm (2006)
2453652.4555	prim	Diethelm (2006)
2454019.3626	prim	Diethelm (2007)
2454020.4244	prim	Hübscher & Walter (2007)
2454407.3468	sec	Diethelm (2008)
2455418.5491	prim	Hübscher (2011)
2455687.4421	sec	BAVM 220[b]
2456186.4070	prim	BAVM 231[b]
2456186.5874	sec	BAVM 231[b]

Notes: [a]BBSAG Bulletins from http://www.astroinfo.ch/bbsag/bbsag_e.html,
[b]BAV Mitteilungen from http://www.bav-astro.de/rb/mitteilungen.php

Acknowledgements: This work was supported by the grant MUNI/A/0773/2013. The author thanks Miloslav Zejda for useful comments and Stephan N. de Villiers for carefully reading and language corrections.

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