Contrib. Astron. Obs. Skalnaté Pleso **49**, 384 – 389, (2019)

A search for additional bodies in short period eclipsing binary stars

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Received: November 1, 2018; Accepted: February 25, 2019

Abstract. We describe here the formulation of our search for additional bodies in fifteen short period eclipsing binary stars and some results obtained by now. We intended to use two methods: transits across the surface of one or both stars (in order to detect planets) in the binary and a timing of eclipses of central binary stars (that can indicate the presence of a stellar mass body in the system). Observations were carried out using ground based photometry with 50-60 cm telescopes in 2013-2017. Until now no transits had been detected in our data. But at the same time we found several candidates for additional bodies in four systems. Further data processing will be performed.

Key words: eclipsing binary stars

1. Introduction

We present a list of eclipsing binary stars that are used to search for potentially existing planetary systems, or additional stellar components. The presence of eclipses increases the probability that the observer is in the orbital plane of the system, since it is natural to expect that protoplanetary disks and planets are located in, or close to this plane (Tutukov & Bogomazov, 2012). Our target binaries can be found in Table 1. Planets in them could be detected with the transit method using 1-meter class telescopes. Also there is a possibility to search for additional bodies using the light time effect, its precision for ground based telescopes allows us to find brown dwarfs or new stars in binary systems.

Table 1. A list of systems to explore. Data from the General Catalogue of Variable Stars (Samus' et al., 2017). "System" is the name of a target binary, "RA" is its right ascension, "Dec" is its declination, P_{orb} is the orbital period, m_{max} is the stellar magnitude at the maximum, m_{min} is the stellar magnitude at the primary minimum, "Type" is the light curve type.

System	RA	Dec	P_{orb}	m_{max}	m_{min}	Type
AC Boo	14 56 28.34	+46 21 44.1	0.3524485	10.14	10.67	EW
CV Boo	15 26 19.58	+36 58 53.6	0.8469938	10.65	11.48	EA
AR CrB	15 59 18.58	+27 52 15.1	0.397352	10.84	11.45	EW
GU Her	16 32 05.52	+30 23 09.7	4.342921	11.5	12.3	EA/DM
V1097 Her	17 33 27.97	+26 55 47.9	0.360847	10.76	11.30	EW
TZ Lyr	18 15 49.67	+41 06 37.9	0.5288269	10.87	11.85	EB/D
V0563 Lyr	18 45 06.63	+40 11 11.5	0.577639[a]	10.96	11.47	EW
V2364 Cyg	19 22 11.75	+49 28 34.4	0.5921376	11.20	11.84	EW
CG Cyg	20 58 13.45	+35 10 29.6	0.63114100	9.73	10.86	EA/SD/RS
SW Lac	22 53 41.66	+37 56 18.6	0.3207209	8.51	9.39	EW/KW
AB And	23 11 32.09	+36 53 35.1	0.3318912	9.49	10.46	EW
AP And	23 49 30.70	+45 47 21.3	1.5872910	11.3	11.9	EA
CO And	01 11 24.84	+46 57 49.4	1.8276678	11.1	12.1	EA
V0873 Per	02 47 08.21	+41 22 31.9	0.2949039	10.8	11.5	EW
HS Aur	06 51 18.47	+47 40 24.2	9.815377	10.16	10.90	EA

[a] By Beltraminelli et al. (1999).

For our photometric observations we used two 60-cm Zeiss-600 telescopes and one 50-cm AMT-1 telescope (the R filter was used everywhere): at the South Station of M. V. Lomonosov Moscow State University in Nauchnii, Crimea (Zeiss-600), and at the Maidanak observatory of the Ulugh Beg Astronomical Institute of Uzbek Academy of Sciences (AMT-1 and Zeiss-600). These sites have excellent (Maidanak) and good (Crimea) astronomical climate, so we were provided with very high quality observations, typical errors were about a few thousandths of stellar magnitude. Usual time of unbroken monitoring was 5-7 hours per night, that allowed us to find a lot of times of minima for our target objects.

2. First results

For V0873 Per, CV Boo, AR CrB, and AB And we obtained evidence in favour of the existence of additional bodies in them using the light time effect, see Table 2 for the summary of our results.

V0873 Per. The system was observed in September-November 2013 and in August-September 2014 at both observatories (Bogomazov et al., 2016a). We obtained 28 times of minima (more than 50% of times of minima existed for V0873 Per in January 2016 at the time of publication). Combining our times of minima with times of minima from the literature we found that the system contains a new body candidate with the lower limit of mass $m_3 \sin i_3 \approx 0.2 M_\odot$ (its orbital period is about 300 days), in addition to the body candidate with the lower mass limit $m_4 \sin i_4 \approx 0.06 M_\odot$ (its orbital period is about 4 years) found by Kriwattanawong & Poojon (2015).

According to Table 6 by Holman & Wiegert (1999), circumbinary bodies should have stable orbits on long timescales if their semi-major axes are $\gtrsim$ 4 separations of the central binary (i.e., the orbital period of the additional companion is $\gtrsim 8$ orbital periods of the central binary) in all models considered by them. This criterion was met for all third and fourth bodies suggested by us in this manuscript, except the candidate for the third body in CV Boo.

CV Boo. We obtained 14 times of minima during May-July 2014 with practically highest possible precision. The data showed a variation of times of minima on a timescale of about 70 days. We combined our times of minima with the data from the literature and found that the system possesses a secular variation of the orbital period (Figure 2 and Equation 2 by Bogomazov et al., 2016b). The $(O-C)_2$ values were calculated as the difference between observed (our+literature) times of minima and the theoretical curve for the secular variation, $(O-C)_2$ could be statistically satisfactory explained by the influence of a third star with a mass of $m_3 \sin i_3 \approx 0.4 M_\odot$ in an eccentric orbit ($e \approx 0.9$) with the orbital period of ≈ 75 days (Figures 3 and 4 by Bogomazov et al., 2016b).

This candidate can be in a chaotic zone, or near it (if the orbit is wider than its projection), see Figure 1 by Shevchenko (2015), the suggested third body's projection of the orbit has the following parameters for this Figure: $\mu = M_2/(M_1 + M_2) \approx 0.5$, $r_p = 2a_b$, where $M_{1,2}$ are masses of the primary and secondary stars correspondingly, r_p is the periastron distance of the third body, a_b is the semi-major axis of the central binary's orbit. At the same time it is far from the unlimited chaotic diffusion, see Figure 4 by Shevchenko (2015), the ratio of orbital periods of the candidate body and the central binary is about 80, whereas the body is expected to be possibly ejected from the system if it is $\lesssim 5$. So, CV Boo is an interesting example to test its dynamical evolution.

In a previous investigation Torres et al. (2008) claimed no orbital period variations in CV Boo, because they analysed a lot of times of minima with low precision (photo plates and visual observations), but later more CCD observation were made. Their radial velocity studies could miss this companion because of the following reasons. The orbital velocity of the binary's center of masses around the triple's center of masses is $\approx 170-190$ km s^{-1} in the periastron, its radial projection is $\approx 130-140$ km s^{-1}. In the apastron it is $\approx 8-10$ km s^{-1}, its radial projection is $\approx 6-8$ km s^{-1}. These quantities are valid for parameters obtained using both our times of minima and times of minima from the literature. Velocities of the binary's components are close to 300 km s^{-1} and their radial projections can be much higher than the radial velocities caused by the influence of the third body. In addition, almost all radial velocity points were obtained in different orbital phases of the central binary. Since the candidate's orbit is highly elliptical, most of the time the orbital velocity of the binary should be much less than during the periastron passage. The radial projection of the orbital velocity can be only less than the orbital velocity and in some positions within the orbit it can be almost zero. Only a few radial velocity measurements were made near the periastron passage of the suggested body, may be there are no such points, because the epoch of the passage was found with an uncertainty. If one takes into account parameters of the third body only from our observations, radial velocities are less than values above, therefore the third's companion influence could be missed even easier. It is essential to note that residuals of the radial velocity by Torres et al. (2008) in comparison to the model could be up to 16 km s^{-1}, see Table 3; potentially they could be attributed to the suggested influence of the tertiary companion, or to errors that exceed that influence. A new careful radial velocity investigation with a special attention to the periastron passages of the suggested candidate is very important to confirm/reject the existence of the body.

AB And. In October 2013 and August 2014 we observed 45 times of minima of AB And (Kozyreva et al., 2018b). Combining them with data from the literature we found and corrected errors in the treatment of old times of AB And minima made by Li et al. (2014). The correction helped us to arrange models concerning time variations of minima. We studied the secular evolution of the central binary's orbital period and also we found that the system possibly possesses two additional low mass stellar companions.

AR CrB. We collected times of minima from our observations of the system in 2013, 2014, 2016, 2017 (Kozyreva et al., 2018a). Combining them with times of minima from the literature we found that the orbital period of AR CrB could possess periodical variations that can be explained by the gravitational influence of a third companion in a highly eccentric orbit ($e \approx 0.7$) around the central binary. The period of mentioned variation is about 5000 days, it is comparable to the duration of all observations of AR CrB, so potentially there can not be a periodic variation, but a secular change of the orbital period. If our data are not included into consideration the orbital period can be accepted to be stable (Alton & Nelson, 2018) due to the lack of information about the system. Using their radial velocity estimates of the masses of the central binary components, the lower limit of the mass of the suggested third body can be estimated as $m_3 \sin i_3 = 0.07 M_\odot$. Future observations are required to clarify the character of the suggested variation of the orbital period of AR CrB.

3. Alternative explanations of variations of orbital periods in studied binaries

Photometric observations practically are able to find almost only candidates to additional bodies that should be confirmed or rejected using other methods, e.g. radial velocity studies. The O'Connell (1951) effect (whose nature has not been adequately studied yet) can complicate the precise determination of times

Table 2. Obtained results. "System" is the name of a target binary, "$m_{3,4} \cdot \sin i_{3,4}$" is the lower limit of a new companion's mass, "P" is the orbital period of a new companion, e is the eccentricity of its orbit.

System	$m_{3,4} \cdot \sin i_{3,4}$	P, days	e
V0873 Per (3rd)[a]	$0.2M_{\odot}$	297 ± 15	0-0.05
V0873 Per (4th)[b]	$0.06M_{\odot}$	1475 ± 113	0.19 ± 0.09
CV Boo[c]	$0.4\text{-}0.5M_{\odot}$	76.2 ± 1.5	0.90 ± 0.04
AB And (3rd)[d]	$0.1M_{\odot}$	21650 ± 100	0.87
AB And (4th)[e]	$0.4\text{-}05M_{\odot}$	38700 ± 1990	0.41
AR CrB[f]	$0.07M_{\odot}$	5360 ± 50	0.7

[a] Bogomazov et al. (2016a).
[b] Kriwattanawong & Poojon (2015).
[c] Bogomazov et al. (2016b).
[d] Kozyreva et al. (2018a).
[e] Kozyreva et al. (2018a).
[f] Kozyreva et al. (2018b).

of minima. Transits of planets, or partial eclipses by stars, can potentially be confused with each other and with star spots, binaries that possess one (or both) companions with high magnetic fields potentially can change their quadrupole gravitational momentum with time and, therefore, they are able to show quasi-periodic time variations (Applegate, 1992) that can look similar to the light time effect, and even a mass transfer between components can show quasi-periodical variations of the orbital period of the binary (Liu et al., 2018).

Remaining work over data obtained in our observations is under way, we are going to study the possible presence of additional bodies in all binaries from our target list. Our results can be used for subsequent observations using other methods, because in our photometric study we can find only candidates for such bodies, because mentioned processes can be confused with the gravitational influence of additional bodies.

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