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O-C diagrams of Algol-type binary stars

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We present the analysis of O-C diagrams for six detached eclipsing binary systems with 3rd and/or 4th body solutions. These solutions were obtained by the fitting of O-C diagrams using genetic algorithms and Monte-Carlo simulation. O-C diagrams were formed using times of minima collected from publications and our observations.

Key words: stars: planetary systems, brown dwarfs, binaries: eclipsing

INTRODUCTION

Eclipsing binaries are systems with orbital inclination about 90°, so the both components during the orbital movement undergo mutual periodic eclipses. The orbital period can be determined with high precision, which allows us to study its long-term changes. These changes are caused by one or by combination of several of reasons: (1) – the presence of additional, not visible bodies in the system (stars or planets), (2) – mass transfer between components, (3) spin-orbital interactions in the system, (4) – magnetic braking, (5) – angular momentum loss **via** stellar winds (see e. g. [30]).

In this work we present analysis of period changes for six eclipsing binary systems UU And, AD And, BD And, TW Cas, IW Cas, CL Aur, caused by mass transfer and the presence of the 3rd and the 4th body in the systems.

STUDIED BINARY SYSTEMS OVERVIEW

UU And is EA-type eclipsing binary. It contains the F5-type primary and a cool sub-giant secondary component with spectral type K5IV [1]. After its discovery, UU And was frequently observed visually and photographically by various authors. They determined many quite precise visual and photographic times of minima estimations, which enabled the study of the period changes of this star system in details (e. g., [28, 43]). An O-C diagram of UU And in the time interval 1973–1986 was published in [27], who pointed out two distinct period jumps, the first was roughly in 1976 and the second in 1983. The study of period variations of the system was made in [35], a period decrease of the order of $\mathrm{d}P/\mathrm{d}t = 4.76 \cdot 10^{-7}$ d/yr was reported in [26].

AD And is an interesting system with two nearly identical components with spectral types of A0V [10]. The light variability of AD And was discovered in 1927 [8]. It was found that the photographic magnitude changes in the range from 10.8^{m} to 11.7^{m} with almost the same primary and secondary minima. The first photoelectric lightcurve in yellow light was obtained in [36], where five minima times were also determined. The lightcurve obtained in [36] was reanalysed in [5] with Wood's lightcurve synthesis computer model [44]. They found that the photometric elements of the AD And components are practically identical with equal sizes, masses, temperatures, and luminosities, with an orbital inclination $i = 81.9 \pm 0.4$. The period variations of AD And had been investigated in [4, 36, 42]. Based on all visual or photographic times of minima derived before 1973 and only five photoelectric light minima obtained in [4, 36] the period of the triple system 16.8 yr with an amplitude of $A_3 = 0.0275$ days, and a mass function of $f(m) = 0.382\mathfrak{M}_\odot$ were determined [24]. Basing on all visual or photographic times of minima derived before 1973 and only five photoelectric light minima obtained in [4, 36], authors of [24] determined the period of the triple system 16.8 yr with an amplitude of $A_3 = 0.0275$ days, and a mass function of $f(m) = 0.382\mathfrak{M}_\odot$. Samolyk [?], however, carried out a new period study, based on the most modern times of minima, and found no period change. On the other hand, the authors of [24] conducted further O–C analysis and reported LITE variation with a 14.38 yr period [23].

BD And, according to the catalogue of parameters for eclipsing binaries [1], is a β Lyr type eclipsing binary, which has a spectral type of F8, with a period of 0.462902 day. The binary system BD And was mainly observed to derive times of minima in [12, 13, 14, 15, 17]. BD And was included to the

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catalogue of near-contact binary systems [39], while authors of [6, 29] both listed the system in their tables of Algol systems. BD And has a blue magnitude $B = 11.^{m}6$ as reported in the SIMBAD database and an interesting lightcurve variation. BD And is a system with an interesting lightcurve variation, its blue magnitude from SIMBAD database is $B = 11.^{m}6$. Its properties are relatively poorly known compared to those of other short-period binaries. There is no spectroscopic study for BD And in the literature [40]. The photometric lightcurves of BD And in the BVR-bands were observed in 2008 and 2009 [40]. Using these observations authors determined the photometric solution of BD And. The orbital period changes were also analysed with all photometric light times of minima. Authors also analysed period changes using times of minima for all photometric lightcurves.

TW Cas was discovered in 1907 [34] and classified as an Algol-type eclipsing binary. Zinner in [49] confirmed the variability type and determined the linear light elements, in particular, the period $P = 1.4283^{d}$ from photographic observations. McDiarmid [32] derived a period that was twice as long from his own visual observations. His light elements were subsequently used by many observers, until Struve [41] found that McDiarmid's period [32] did not agree with spectroscopic observations that were consistent with the period estimated by Zinner [49], that has been repeatedly confirmed and refined since then. The spectral type of TW Cas in the HD catalog is B9. Authors of [48] confirmed the B9 classification for the brighter component, and determined the spectral type of the fainter component to be A0. Struve [41] plotted a radial-velocity curve for the TW Cas primary and derived the mass function. He also confirmed the spectral type B9 for the primary, but was not able to confirm the A0 spectral type for the secondary. The most recent photoelectric observations of TW Cas were obtained in [33]. Authors plotted the binary's lightcurve, and determined the orbital parameters and absolute characteristics of the components of a model, according to which the secondary fills its Roche lobe. However, they remark that the secondary's radius may be slightly smaller than the corresponding Roche lobe. From the primary's spectral type and the lightcurve solution obtained earlier, they estimated the component masses to be $M_1 = 2.65M$ and $M_2 = 1.15M$. Later, in [2] orbital parameters of TW Cas were redetermined using the photoelectric observations of McCook [31]. The masses they found virtually exactly coincide with those determined in [33]: $M_1 = 2.66M$ and $M_2 = 1.15M$. The first studies of the behaviour of the eclipsing binary TW Cas period were based on sparse photographic observations, which were not sufficiently accurate to enable any firm conclusions [3]. Kreiner [20] used all the available times of minima for TW Cas, but could draw no definite conclusions concerning the period variations. Note, that the wrong binary period from [32] was used in both these papers. In [33] the period variations of TW Cas were studied using the correct period; they assumed that the period was slowly decreasing. It was confirmed in [25]. However, the recent photoelectric times of minima of TW Cas demonstrate that the bulging part of the O–C diagram is the part of a sinusoid, rather than part of a parabola. Thus, we are probably observing cyclic variations of the period due to the presence of a third body in the system, rather than a secular period decrease [16].

IV Cas has been known as a semidetached Algol-type eclipsing binary in the GCVS catalogue [38]. The oEA-type pulsating features of IV Cas were discovered in photometric survey of [19]. In work [45] authors examined the orbital period change of IV Cas and found a sinusoidal variation in the O-C diagram. They interpreted the variation as a light-travel time effect by the third component with minimum mass of $0.96\mathfrak{M}_{\odot}$. Although a few tens of eclipsing minimum epochs were reported by many observers, a detailed lightcurve analysis of IV Cas has not been presented yet. The probable reason is that its orbital period is close to 1.0 day, requiring a very long observation time at a single site in order to cover full orbital phases. Eclipsing lightcurve analysis of IV Cas and the pulsation characteristics of the primary component in detail, based on dualsite photometric observations and high-resolution spectroscopic data were presented in [18].

CL Aur was discovered to be a variable star by authors of [11] based on photographic plate estimates. In work [21] authors presented the first (partial) photographic lightcurve of the star and the original light elements. The value of the period positions for this object toward the short period limit for Algols. The spectral type of the primary star was classified to be A0 in [7]. Since then, times of minimum light have been published assiduously by numerous researchers but, to our knowledge, a complete lightcurve and the fundamental parameters for the binary system have not been made so far. Changes of the orbital period have been considered in [9, 46]. In [9] this system was selected as a possible candidate for the study of apsidal motion. However, the later authors ruled out this possibility from CCD timings for primary and secondary eclipses. They suggested the cause of period variation to be a light-travel-time (LTT) effect due to the presence of a third body in the binary system. Most recently, in [47] it was reported that a longterm period increase is superimposed on an LTT orbit with a period of $P_3 = 21.7$ yr, a semi-amplitude of $K = 0.014$ day, and an eccentricity of $e = 0.32$. In the SIMBAD database, the system is described as an eclipsing binary of β Lyr type. At present, CL Aur is known only as a neglected eclipsing system composed of an A-type primary and a cooler companion. In order to derive photometric solutions and to examine whether the [47] suggestion is appropriate for the orbital period change, lightcurves with multi-band photometry were obtained in [22].

RESULTS

Our results are presented in O–C diagrams (see Fig. 1–2) of selected binary systems and tables with determined orbital parameters (see Tables 2–4).

To form the whole O–C diagram, understand the properties of the period change and determine parameters of further bodies, for all eclipsed binary systems, all minima timings were compiled from the literature, mainly all data were available at B.R.N.O. database of times of minima and maxima web-page[1]. Super WASP project lightcurves were processed with method described in [50], obtained times of minima are presented in Table 1. Own observations can be found in [51]. Some times of light minima with large residual values were excluded, most of such minima were visual or photographic. Method that we use to determine parameters of further bodies will be described in a separate paper.

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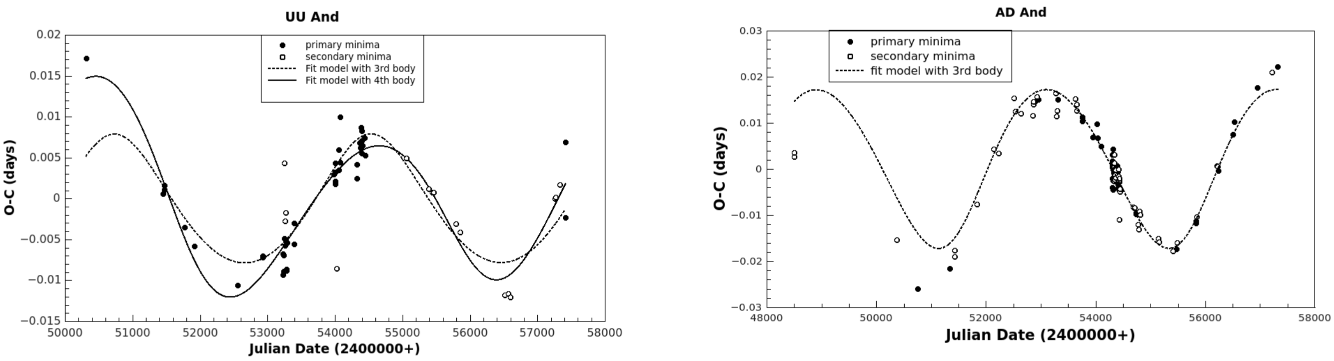

Fig. 1: UU And, AD And eclipsed binary systems fit.

Table 1: Times of minima calculated from SuperWASP project lightcurves

UU And		AD And	
HJD 2400000+		HJD 2400000+	
53231.60529	± 0.00116	54348.59854	± 0.00248
53271.73594	± 0.00181	54304.71489	± 0.00096
53228.63478	± 0.00059	54303.72376	± 0.00202
53237.55252	± 0.00215	54303.72951	± 0.00267
53240.52723	± 0.00421	54305.70074	± 0.00028
53260.59469	± 0.00140	54438.34054	± 0.00019
53245.73860	± 0.00186	54427.48392	± 0.01345
53219.71434	± 0.00054	54437.35396	± 0.00021
53263.56834	± 0.00203	54439.32717	± 0.00021
53274.70879	± 0.00206	54381.63487	± 0.00036
54074.36493	± 0.00063	54382.62155	± 0.00031
54068.41413	± 0.00048	54383.60851	± 0.00031
54021.58231	± 0.00160		
54050.57986	± 0.00173		
53998.55620	± 0.00047		
53980.72016	± 0.00040		
53995.58465	± 0.00044		
54056.52264	± 0.00027		
54004.49999	± 0.00044		
54001.52774	± 0.00091		
54438.50853	± 0.00048		
54383.51633	± 0.00055		
54389.45997	± 0.00072		
54362.70616	± 0.00050		
54392.43386	± 0.00167		
54444.45166	± 0.00084		
54368.65083	± 0.00077		
54319.59879	± 0.00200		
54322.57313	± 0.00211		

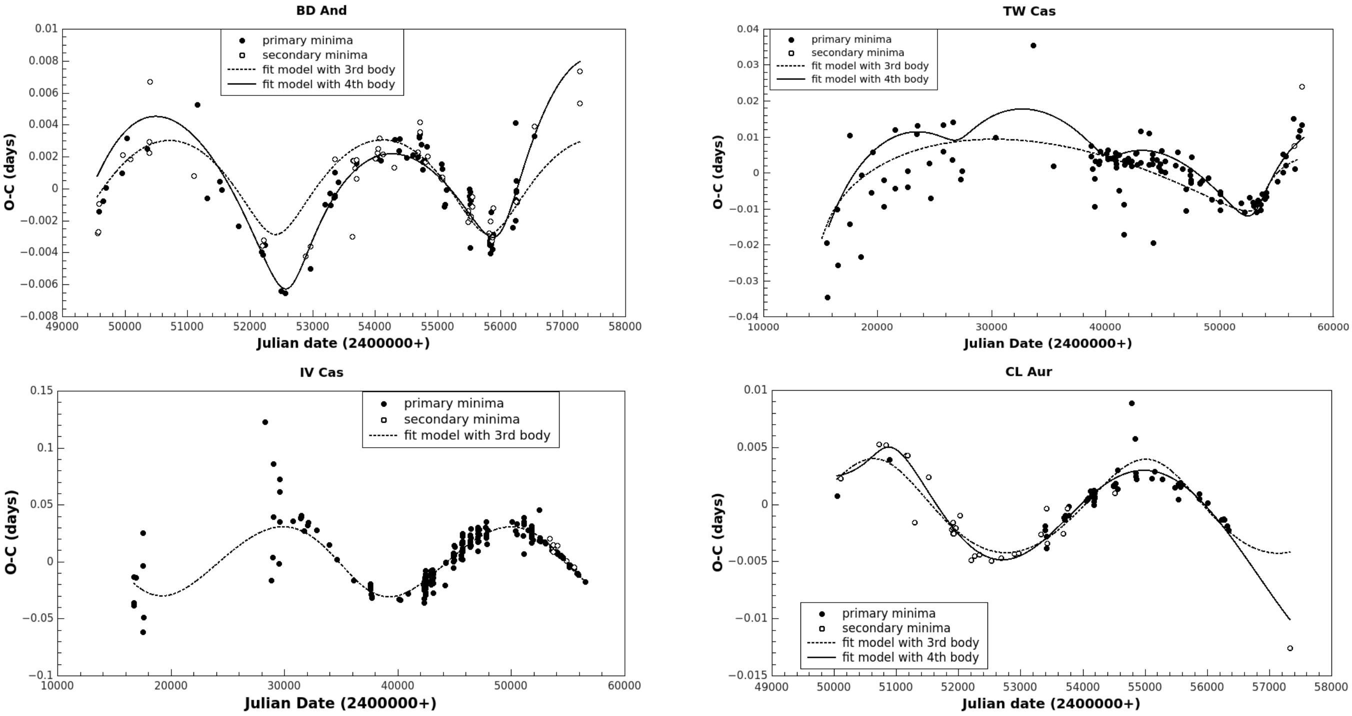

Fig. 2: BD And, TW Cas, IV Cas and CL Aur eclipsed binary systems fit.

Table 2: The parameters of UU And and AD And systems.

	UU And		AD And
fitted minima	61		140
	3rd	3rd and 4th	3rd
P (d)	1.48639497(5.7e-09)	1.48639497(5.7e-09)	0.98618776(4.7e-09)
P_3(d)	3802(104)	4210(117)	4174(28)
P_4(d)		7180 (520)	
Q (d)	9e-13(6e-13)	2e-12(1.7e-12)	1.08e-12(1e-12)
$a \sin i_3$ (AU)	1.390(148)	1.882(145)	2.959(89)
$a \sin i_4$ (AU)		0.832(179)	
e_3	0.188(98)	0.176(81)	0.101(27)
e_4		0.295(141)	
$T0$ (HJD)	41649.92442(2)	41649.92442(2)	39002.99314(3)
$T0_3$ (HJD)	54850(705)	55874(477)	42613(151)
$T0_4$ (HJD)		58695(1333)	
w_3 (°)	117(65)	208(39)	257(11)
w_4 (°)		136(67)	
$f(M_3)$ ($\mathfrak{M}_\odot$)	0.0245(79)	0.050(12)	0.198(18)
$f(M_4)$ ($\mathfrak{M}_\odot$)		0.00149(98)	
χ^2	55.548	49.481	132.073

Table 3: The parameters of BD And and TW Cas systems.

	BD And		TW Cas	
fitted minima	143		124	
	3rd	3rd and 4th	3rd	3rd and 4th
P (d)	0.92581516(4.5e-10)	0.92581516(4.5e-10)	1.42832399(8.0e-09)	1.42832399(8.0e-09)
P_3(d)	3349(56)	3326(59)	38665(1021)	38235(1236)
P_4(d)		10843(1182)		13118(1140)
Q (d)	5.097e-13(5e-13)	1.460e-12(1.2e-12)	linear	linear
$a \sin i_3$ (AU)	0.5164(36)	0.716(43)	2.711(153)	2.57(22)
$a \sin i_4$ (AU)		0.494(73)		0.67(23)
e_3	0.283(94)	0.475(54)	0.808(34)	0.721(79)
e_4		0.317(120)		0.482(111)
$T0$ (HJD)	34962.30938(0.04)	34962.30938(0.04)	42008.38414(0.5)	42008.38414(0.5)
$T0_3$ (HJD)	48994(402)	56049(63)	54104(351)	53044(1283)
$T0_4$ (HJD)		58375(1918)		53073(1761)
w_3 (°)	254(39)	294(8)	332(5)	320(16)
w_4 (°)		102(67)		276(42)
$f(M_3)$ ($\mathfrak{M}_\odot$)	0.0016(3)	0.0044(8)	0.00178(31)	0.00155(41)
$f(M_4)$ ($\mathfrak{M}_\odot$)		0.00013(7)		0.00023(24)
χ^2	124.877	128.116	120.831	118.966

Table 4: The parameters of IV Cas and CL Aur systems.

	IV Cas	CL Aur	
fitted minima	233	84	
	3rd	3rd	3rd and 4th
P (d)	0.99851732(8.4e-09)	1.24426348(4.4e-09)	1.24426348(4.4e-09)
P_3(d)	20037(341)	4390(61)	6872 (304)
P_4(d)			9632(270)
Q (d)	1.838e-12(1.69e-12)	-5e-13(3.8e-13)	8.45e-13(4.95e-14)
$a \sin i_3$ (AU)	5.343(142)	0.715(45)	1.715(185)
$a \sin i_4$ (AU)			1.865(295)
e_3	0.135(44)	0.173(70)	0.093(33)
e_4			0.597(108)
$T0$ (HJD)	40854.62467(4)	32968.08775(1)	32968.08775(1)
$T0_3$ (HJD)	56452(631)	37838(302)	39412(599)
$T0_4$ (HJD)			60544(430)
w_3 (°)	213(13)	124(21)	330(16)
w_4 (°)			55(20)
$f(M_3)$ ($\mathfrak{M}_\odot$)	0.0506(44)	0.00254(49)	0.0142(47)
$f(M_4)$ ($\mathfrak{M}_\odot$)			0.00933(445)
χ^2	226.500	80.380	52.183