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OBSERVATIONS AND LIGHT CURVE SOLUTIONS OF FOUR ULTRASHORT-PERIOD BINARIES

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SUMMARY: The paper presents light curve solutions of our observations of four new ultrashort-period eclipsing binaries with MS components. Two of them have periods almost at the upper limit (0.22 days) of the ultrashort-period binaries, while the periods of around 0.18 days of CSS J171508.5+350658 and CSS J214633.8+120016 are amongst the shortest known orbital periods. CSS J171410.0+445850, CSS J214633.8+120016 and CSS J224326.0+154532 are overcontact binaries with fillout factors around 0.25 while CSS J171508.5+350658 is a semidetached system. The two targets with shortest periods consist of M dwarfs.

Key words. binaries: close – binaries: eclipsing – methods: data analysis – stars: fundamental parameters – stars: individual: CSS J171410.0+445850, CSS J171508.5+350658, CSS J214633.8+120016, CSS J224326.0+154532

1. INTRODUCTION

Most of the contact binaries consisting of solar-type components have orbital periods within 0.25 days < P < 0.7 days. Rucinski (1992) found that they show a short-period limit at about 0.22 days. But ultrashort binaries with period below 0.22 days were found lately (Maceroni and Rucinski 1997, Maceroni and Montalban 2004, Weldrake 2004, Rucinski 2006, 2007, Pribulla et al. 2009, Lohr et al. 2014, Qian et al. 2014, etc.).

The binaries consisting of main sequence (MS) components with periods around and below the cut-off limit are important objects for the astrophysics, especially for understanding the very late evolutional stages of the binaries connected with the processes of mass and angular momentum loss, merging or fusion of the stars, etc. Recently, it is supposed that the very short period low-mass binaries could merge via "magnetic braking" and, if a substantial amount of mass remains in orbit around the primary, it would form a disk in which hot Jupiters could be produced (Martin et al. 2011).

Table 1. Journal of our photometric observations.

Target	Date	Exposure (g', i') [sec]	Number (g', i')	Error (g', i') [mag]
CSS J171410.0+445850	2015 Jul 22	150, 180	15, 14	0.015, 0.028
	2015 Aug 2	150, 180	53, 53	0.041, 0.035
	2015 Jan 12	150, 180	47, 48	0.031, 0.032
	2015 Jan 15	150, 180	51, 51	0.026, 0.028
CSS J171508.5+350658	2015 Jul 8	-, 300	-, 27	-, 0.026
	2015 Jul 9	-, 300	-, 45	-, 0.030
	2015 Jul 10	-, 300	-, 15	-, 0.032
	2015 Jul 11	-, 300	-, 55	-, 0.027
CSS J214633.8+120016	2015 Jul 12	-, 300	-, 39	-, 0.066
	2015 Jul 16	-, 300	-, 43	-, 0.072
	2015 Jul 17	-, 300	-, 48	-, 0.072
	2015 Jul 18	-, 300	-, 40	-, 0.063
	2015 Jul 19	-, 300	-, 43	-, 0.064
	2015 Jul 21	-, 300	-, 28	-, 0.063
CSS J224326.0+154532	2015 Aug 14	120, 120	74, 73	0.006, 0.008
	2015 Aug 15	120, 120	8, 6	0.006, 0.007
	2015 Aug 16	120, 120	62, 62	0.005, 0.007
	2015 Aug 17	120, 120	73, 73	0.006, 0.007

However, the statistics of short and ultrashort binaries is poor due to two reasons. Firstly, the period distribution of binaries reveals a very sharp decline in the number of short period systems below 0.27 days (Drake 2014). Secondly, the faintness of the late short binaries makes them difficult targets for detailed study. In the recent decades the huge surveys ROTSE, MACHO, ASAS, SuperWASP, Catalina, *Kepler* led to considerable increasing of the number of ultrashort binaries (around 140), but only a small part of them (few dozens) are better studied, i.e. with follow-up observations and determined parameters.

This paper presents our observations and light curve solutions of four ultrashort-period binaries from the Catalina Surveys Periodic Variable Star Catalog.

2. OBSERVATIONS

Our CCD photometric observations of the targets in Sloan *g', i'* bands were carried out at the Rozhen Observatory with the 30-cm Ritchey Chretien Astrograph (located into the *IRIDA South* dome) using the CCD camera ATIK 4000M (2048 × 2048 pixels, 7.4 μm/pixel, field of view 40 × 40 arcmin). Information for our observations is presented in Table 1.

The photometric data were reduced by AIP4WIN2.0 (Berry and Burnell 2005). We performed aperture ensemble photometry with the software VPHOT using more than six standard stars in the observed field of each target whose coordinates were taken from the catalogue UCAC4 (Zacharias et al. 2013) and their magnitudes from the catalogues SDSS DR9 (Ahn et al. 2012) and APASS DR9.

Our data are accessible at: `http://www.irida-observatory.org/Observations/irida3.zip` in the form of tables whose samples A1-A4 are shown in the Appendix.

The times of our light minima (Table 2) were determined by the method of Kwee and van Woerden (1956).

Table 2. Times of the observed light minima at Rozhen.

Target	Min I [HJD]	Min II [HJD]
CSS J171410.0+445850	2457237.39610	2457237.50570
	-	2457238.39320
	2457238.50274	-
	2457239.39160	2457239.50115
CSS J171508.5+350658	-	2457212.39982
	2457213.38129	2457213.47224
	-	2457214.36594
	-	2457215.43708
	2457215.52635	-
CSS J214633.8+120016	2457216.39482	2457216.47988
	2457220.42657	-
	2457221.41086	2457221.49934
	-	2457222.39863
	2457222.48450	-
	2457223.38286	2457223.47631
	2457224.46315	-
CSS J224326.0+154532	2457249.31521	2457249.42749
	2457249.53772	2457251.43690
	2457251.54672	2457252.32920
	2457252.44030	2457252.55268

Table 3 contains the available information for the targets from the Catalina Surveys Periodic Variable Star Catalog (Drake et al. 2009, Drake et al. 2014): *CV* magnitude, period, amplitude, configuration type. Two of them are with periods almost at the upper limit (0.22 days) of the ultrashort-period binaries, while the periods of around 0.18 days of CSS J171508.5+350658 and CSS J214633.8+120016 are amongst the shortest known orbital periods of binaries with MS components.

Table 3. Parameters of the targets from the Catalina Surveys Periodic Variable Star Catalog.

Target	CV [mag]	amplitude [mag]	P [days]	Type	Reference
CSS J171410.0+445850	15.38	0.45	0.221462	EW	Drake et al. (2014)
CSS J171508.5+350658	16.58	0.30	0.178549	EW	Drake et al. (2014)
CSS J214633.8+120016	17.25	0.24	0.179327	EW	Drake et al. (2009)
CSS J224326.0+154532	13.28	0.23	0.223228	EW	Drake et al. (2014)

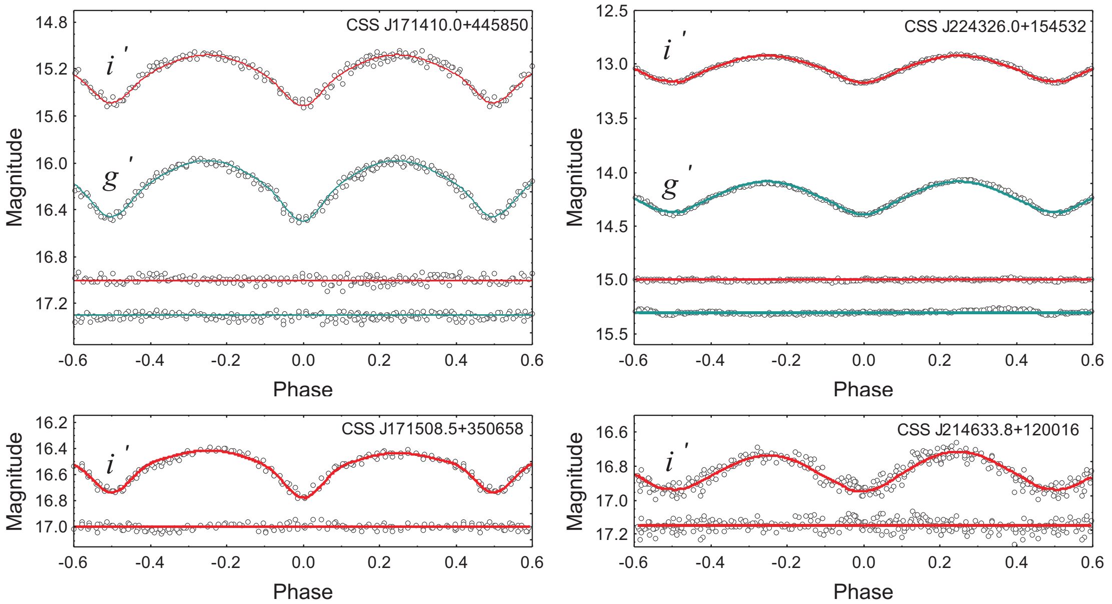

Fig. 1. *Top: the folded light curve of the targets and their fits; Bottom: the corresponding residuals.*

3. LIGHT CURVE SOLUTIONS

We carried out the modeling of our data by the binary modelling package PHOEBE (Prsa and Zwitter 2005). It is based on the Wilson–Devinney (WD) code (Wilson and Devinney 1971) but provides also a graphical user interface and other improvements, including modeling of data in Sloan filters.

The observational data (Fig. 1) show that our targets are nearly contact or overcontact systems that was expected for their ultrashort orbital periods. That is why we modeled them using the modes "overcontact binary not in thermal contact" and "semi-detached binary".

We determined in advance the mean temperatures T_{m} of the binaries (Table 4) by their infrared color indices from the 2MASS catalog (Skrutskie et al. 2006) and the calibration color-temperature of Tokunaga (2000).

Our procedure of the light curve solutions was carried out in several stages.

At the first stage we fixed primary temperature $T_1^0 = T_{\mathrm{m}}$ and searched for the fit by varying the following parameters: the epoch T_0, secondary temperature T_2, mass ratio q, orbital inclination i and potentials $\Omega_{1,2}$ (and simultaneously relative radii $r_{1,2}$ and fillout factor f). In order to reproduce the O'Connell effect we added cool spots on the primary and varied their parameters (longitude λ, latitude β, angular size α and temperature factor κ).

We adopted coefficients of gravity brightening 0.32 and reflection effect 0.5 appropriate for late stars. The limb-darkening coefficients were chosen according to the tables of Van Hamme (1993).

As a result of the first stage of the light curve solution we obtained initial values T_2^0, q^0, i^0 and $\Omega_{1,2}^0$ as well as the initial epoch and spot parameters for each target.

Further, we determined the mass ratio applying the q-search method (similar to that in Dimitrov and Kjurkchieva 2015). For this aim we fixed T_1^0, T_2^0, $\Omega_{1,2}^0$ and spot parameters and calculated the normalized χ^2 for a two-dimensional grid (i, q) consisting of values of i within the 10°-range around the value i^0 with step 1^0 and q values in the range 0.1–2.0 with step 0.1. In this way we obtained the first approximation (i^1, q^1) corresponding to $\chi^2_{\mathrm{min}}(1)$. Then the procedure was repeated around (i^1, q^1) for a finer grid and the second approximation (i^2, q^2) was obtained for $\chi^2_{\mathrm{min}}(2)$. The same procedure was repeated until reaching $\chi^2_{\mathrm{min}}(f) \sim 1$ corresponding to the final values ($i^{\rm f}, q^{\rm f}$). Fig. 2 exhibits the result from the q-search method.

After that, we adjusted the stellar temperatures T_1 and T_2 around the value $T_{\rm m}$ by the formulae (Ivanov et al. 2010, Dimitrov and Kjurkchieva 2015)

$$T_1^c = T_{\rm m} + \frac{c\Delta T}{c+1} \quad (1)$$

$$T_2^c = T_1^c - \Delta T \quad (2)$$

where the quantities $c = l_2/l_1$ (the ratio of relative luminosities of the stellar components) and $\Delta T = T_1^0 - T_2^0$ are determined from the first stage of the PHOEBE solution.

Finally, we varied slightly T_1, T_2 and $\Omega_{1,2}$ around their values T_1^c, T_2^c and $\Omega_{1,2}^0$ and obtained the final PHOEBE solution.

The derived parameters of the targets corresponding to our light curve solutions and their formal PHOEBE errors are given in Table 4 while Table 5 gives information for the spot parameters reproducing the light curve distortions of two targets. The synthetic curves corresponding to parameters of our light curve solutions are shown in Fig. 1 as continuous lines.

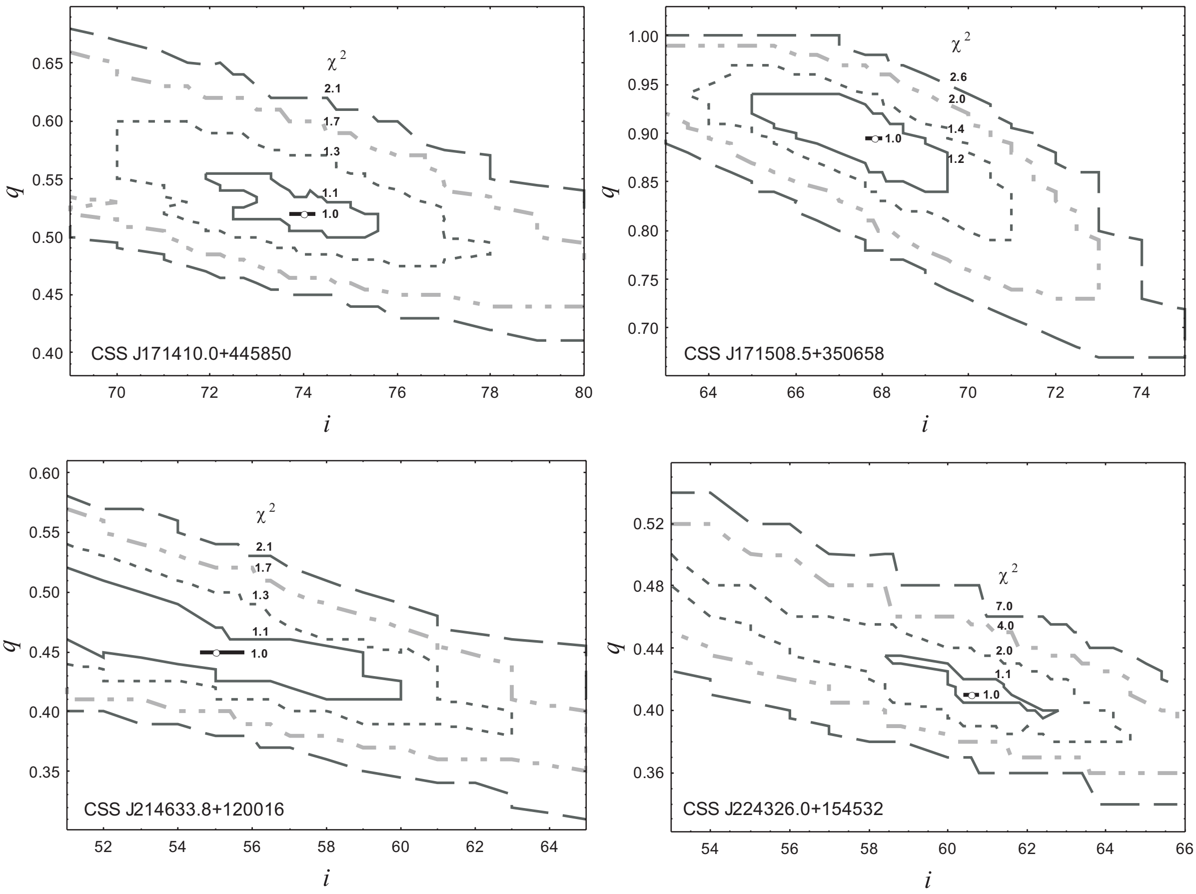

Fig. 2. *Q-search method: the different isolines circumscribe the areas whose χ^2 are smaller than their marked values; the empty circles correspond to the final values of the mass ratio and orbital inclination given in Table 4.*

Table 4. Parameters of the light curve solutions: the initial epoch T_0; average temperature $T_{\rm m}$; temperatures of components T_i; relative radii of components r_i; mass ratio q; orbital inclination i; configuration; fillout factor f; primary relative luminosity l_1; ratio of relative luminosities l_2/l_1; $\chi^2_{\rm min}$.

Target	T_0-2400000	$T_{\rm m}$	T_i	r_i	q	i	type	f	l_1	l_2/l_1	$\chi^2_{\rm min}$
CSS J171410.0+445850	57238.5045	5120	5150 ± 100	0.454	0.519 ± 0.005	74.1 ± 0.1	OC	0.249	0.64	0.55	0.998
			5080 ± 100	0.344							
CSS J171508.5+350658	57213.3828	3650	3700 ± 50	0.384	0.895 ± 0.005	67.9 ± 0.1	SD	-0.007	0.61	0.64	0.997
			3600 ± 30	0.329				-0.068			
CSS J214633.8+120016	53480.472145	3600	3600 ± 60	0.471	0.450 ± 0.005	55.0 ± 0.3	OC	0.262	0.67	0.49	0.995
			3600 ± 60	0.329							
CSS J224326.0+154532	57249.53868	4500	4500 ± 40	0.474	0.410 ± 0.005	60.6 ± 0.1	OC	0.246	0.68	0.47	0.986
			4500 ± 40	0.323							

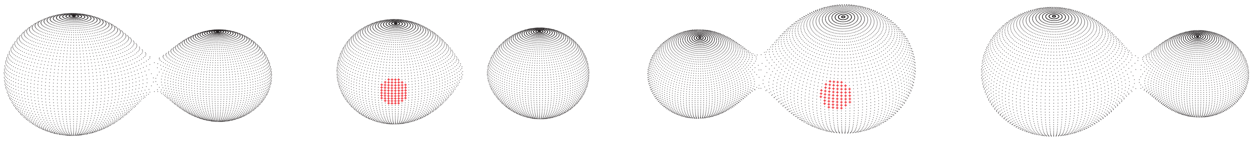

Fig. 3. *From left to right: 3D configurations of CSS J171410.0+445850, CSS J171508.5+350658, CSS J214633.8+120016 and CSS J224326.0+154532.*

Table 5. Spot parameters.

Target	β	λ	α	κ
CSS J171508.5+350658	90	270	15	0.9
CSS J214633.8+120016	80	80	14	0.9

4. RESULTS AND CONCLUSIONS

The main results from the analysis of our light curve solutions of the ultrashort-period binaries are as follows.

(1) Three of the targets, CSS J171410.0+445850, CSS J214633.8+120016 and CSS J224326.0+154532, are overcontact (OC) binaries with nearly the same configurations and fillout factors around 0.25 (Fig. 3). The sum of their relative radii $r_1 + r_2 \simeq 0.8$ and their mass ratios $q \sim 0.5$ correspond indeed to overcontact configurations between the inner and outer critical surfaces (see Fig. 2 in Lucy 1976).

Our model reveals that CSS J171508.5+350658 is a semidetached (SD) system (Table 4). This result differs from its previous EW classification (Table 3). The sum of the relative radii $r_1 + r_2 \simeq 0.71$ and its mass ratio $q \sim 0.9$ correspond indeed to configuration below the inner critical surface (see Fig. 2 in Lucy 1976).

(2) The different light levels of CSS J171508.5+350658 and CSS J214633.8+120016 at the quadratures were reproduced by a cool, almost equatorial spot on the lateral side of their primaries with angular radius of around 15° (Fig. 3). The photospheric activity is expected characteristic for these cool stars.

(3) All targets (Table 4) undergo partial eclipses corresponding to their relatively small eclipse depths.

(4) The components of CSS J171410.0+445850 and CSS J224326.0+154532 are K stars while CSS J171508.5+350658 and CSS J214633.8+120016 consist of two early M dwarfs.

Our study adds new four members to the small family (few dozens) of the studied ultrashort-period binaries with MS components. Two of them, CSS J171508.5+350658 and CSS J214633.8+120016, are with periods of only 0.18 days and consist of M dwarfs.

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APPENDIX

Table A1. Photometric data of CSS J171410.0+445850.

HJD	*g'*	error *g'*
2457226.355455	16.121	0.017
2457226.359395	16.092	0.018
2457226.363285	16.051	0.019
...	...	...
HJD	*i'*	error *i'*
2457226.357435	15.149	0.030
2457226.361335	15.159	0.031
2457226.365225	15.175	0.036
...	...	...

*The complete table is available at `http://saj.math.rs/192/TableA1.dat`.

Table A2. Photometric data of CSS J171508.5+350658.

HJD	*i'*	error *i'*
2457212.327861	16.548	0.024
2457212.331550	16.535	0.023
2457212.335210	16.527	0.024
...	...	...

*The complete table is available at `http://saj.math.rs/192/TableA2.dat`.

Table A3. Photometric data of CSS J214633.8+120016.

HJD	*i'*	error *i'*
2457216.384473	16.865	0.080
2457216.388123	16.893	0.093
2457216.391793	16.926	0.087
...	...	...

*The complete table is available at `http://saj.math.rs/192/TableA3.dat`.

Table A4. Photometric data of CSS J224326.0+154532.

HJD	*g'*	error *g'*
2457249.299321	14.302	0.007
2457249.302511	14.329	0.007
2457249.305701	14.353	0.008
...	...	...
HJD	*i'*	error *i'*
2457249.300921	13.090	0.009
2457249.304101	13.130	0.009
2457249.307281	13.154	0.009
...	...	...

*The complete table is available at `http://saj.math.rs/192/TableA4.dat`.

ПОСМАТРАЊА И РЕШЕЊА ЗА КРИВЕ СЈАЈА ЧЕТИРИ ДВОЈНА СИСТЕМА СА УЛТРАКРАТКИМ ПЕРИОДИМА

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Оригинални научни рад

У овом раду представљена су решења за криве сјаја четири нова посматрана система еклипсних двојних звезда ултракраткког периода који садрже компоненту на главном низу. Два система имају периоде скоро на горњој граници периода (0.22 дана) двојних звезда ултракратког периода, док су периоди CSS J171508.5+350658 и CSS J214633.8+120016 од 0.18 дана међу најкраћим познатим орбиталним периодима. CSS J171410.0+445850, CSS J214633.8+120016 и CSS J224326.0+154532 су контактни двојни системи са фактором попуњености 0.25, док је CSS J171508.5+350658 полуконтактни систем. Два система са најкраћим периодима се састоје од патуљака M класе.