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OBSERVATIONS AND LIGHT CURVE SOLUTIONS OF THE ECLIPSING W UMA BINARIES CSS J071813.2+505000, NSVS 2459652, NSVS 7178717 AND NSVS 7377875

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RESUMEN

Presentamos observaciones en las bandas *g'* e *i'* del Sloan de cuatro binarias eclipsantes tipo W UMa, que permitieron mejorar las efemérides de los sistemas. Con las soluciones para las curvas de luz obtuvimos los siguientes resultados: (i) CSS J071813.2+505000 es un sistema escasamente en sobre-contacto, NSVS 2459652 y NSVS 7377875 son binarias en sobre-contacto con un factor de llenado intermedio, y NSVS 7178717 está en una configuración de contacto profundo. (ii) NSVS 7178717 presenta eclipses totales, mientras que las otras tres binarias tienen eclipses parciales. (iii) Las componentes de cada binaria tienen casi la misma temperatura: las de CSS J071813.2+505000 son estrellas G tempranas, mientras que las de los otros tres sistemas son estrellas K. (iv) Las binarias con componentes tardías presentan actividad de manchas. (v) NSVS 2459652 y NSVS 7377875 son binarias tipo W UMa, subtipo H. (vi) La relación cociente de masas-cociente de luminosidad de nuestros sistemas confirma los resultados de análisis estadísiticos previos de sistemas tipo W UMa.

ABSTRACT

Photometric observations in Sloan *g'* and *i'* bands of four eclipsing W UMa binaries are presented. They allowed the improvement of system ephemerides. The light curve solutions led to the following results: (i) CSS J071813.2+505000 is barely an overcontact system, NSVS 2459652 and NSVS 7377875 are overcontact binaries with an intermediate fillout factor, while NSVS 7178717 has a deep-contact configuration; (ii) NSVS 7178717 undergoes total eclipses while the other three targets exhibit partial eclipses; (iii) The components of each target are almost the same in temperature: those of CSS J071813.2+505000 are early G stars while those of the other three targets are of K spectral type; (iv) The targets with late components reveal spot activity; (v) NSVS 2459652 and NSVS 7377875 are W UMa binaries of H subtype; (vi) The relation mass ratio – luminosity ratio of our targets confirms the results from previous statistical analysis of W UMa systems.

Key Words: binaries: eclipsing — stars: fundamental parameters — stars: individual (CSS J071813.2+505000, NSVS 2459652, NSVS 7178717, NSVS 7377875)

1. INTRODUCTION

Many W UMa stars consist of solar-type components and are easily recognized by their continuous brightness variations and nearly equal depths of eclipse minima. Their orbital periods are within 0.25 d $< P <$ 0.7 d which means small orbits, and synchronized rotation and orbital revolution. The W UMa systems are a result of the evolution of wide binaries by angular momentum loss and mass-ratio reversals (Stepien 2006, Qian 2003).

It is supposed that components of some W UMa binaries (those with fillout factor around zero) alternate between configurations of full and marginal contact (Flannery 1976; Lucy 1976; Robertson & Eggle-

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TABLE 1

PARAMETERS FOR OUR TARGETS FROM THE VSX DATABASE

Target	RA	Dec	P [d]	m [mag]	A [mag]	Type
CSS J071813.2	07 18 13.26	+50 50 00.6	0.38635	14.29(CV)	0.21	EW
NSVS 2459652	08 16 13.03	+64 54 23.0	0.251730	12.539(R1)	0.312	EW
NSVS 7178717	06 45 01.21	+34 21 54.9	0.248616	14.110(V)	0.35	EW
NSVS 7377875	08 40 00.61	+36 39 28.6	0.26498067	13.38(R1)	1.02	EW

TABLE 2

LOG OF PHOTOMETRIC OBSERVATIONS

Target	Date	Exposure g' [s]	Exposure i' [s]	Number g'	Number i'
CSS J071813.2	2016 Jan 28	180	240	46	46
	2016 Jan 29	180	240	18	17
	2016 Feb 3	180	240	37	37
	2016 Feb 6	180	240	67	68
	2016 Feb 7	180	240	72	70
NSVS 2459652	2015 Dec 23	90	90	185	186
	2015 Dec 26	90	90	183	181
	2015 Dec 27	90	90	120	119
	2015 Dec 28	90	90	169	168
NSVS 7178717	2015 Jan 16	150	150	95	95
	2015 Jan 17	150	150	64	62
NSVS 7377875	2016 Apr 4	150	150	52	51
	2016 Apr 5	150	150	63	62
	2016 Apr 6	150	150	65	65

ton 1977). According to the contact model (Lucy 1968), the energy generated in the cores of their components is redistributed to the common gaseous envelope. As a result, the relations between the stellar parameters of W UMa binaries are different from those of detached configurations.

The W UMa binaries are important targets for the modern astrophysics, because they give information about the late stage of the stellar evolution related to the processes of mass and angular momentum loss, merging or fusion of the stars (Martin et al. 2011). Moreover, they are useful tracers of distance and galactic structure due to their period-color-luminosity relation (Rucinski 1994; Rucinski 1996; Rucinski & Duerbeck 1997; Klagyivik & Csizmadia 2004; Gettel et al. 2006).

This paper presents photometric observations and light curve solutions of four W UMa binaries: CSS J071813.2+505000 (UCAC4 705-045020, 2MASS J07181325+5050000, CSS J071813.2), NSVS 2459652 (UCAC4 775-028323, GSC 04129-01031), NSVS 7178717 (1SWASP J064501.21+342154.9; 2MASS J06450122+3421546; UCAC4 622-035881), NSVS 7377875 (GSC 02490-01074; UCAC4 634-043109; 2MASS J08400055+3639287). Table 1 presents the coordinates of our targets and available information about their light variability.

2. OBSERVATIONS

The CCD photometric observations in Sloan g', i' bands were carried out at Rozhen Observatory with the 30-cm Ritchey-Chretien Astrograph (located into the IRIDA South dome) using a CCD camera ATIK 4000M (2048 × 2048 pixels, 7.4 μm/pixel, field of view 35 x 35 arcmin). The information about our observations is presented in Table 2.

The data were obtained during photometric nights with seeing within 1.1–1.9 arcsec and humidity below 70 %. The airmass during observations of all targets was within the range 1.01–2.01.

Twilight flat fields were obtained for each filter, dark and bias frames were also taken throughout the runs. The frames were combined respectively into a single master bias, dark and flat frames. The standard procedure was used for the reduction of the photometric data (de-biasing, dark frame subtraction and flat-fielding) by the software AIP4WIN2.0 (Berry & Burnell 2006).

We used aperture photometry with a radius of 1.5 FWHM of the star image, along with sky background measurements with annuli enclosing a comparable area.

The light variability of the targets was estimated with respect to nearby comparison (constant) stars in the observed field of each target, so called ensemble photometry. A check star served to determine the observational accuracy and to check the constancy of comparison stars. The CCD ensemble photometry calculates the difference between the instrumental magnitude of the target and a comparison magnitude obtained from the mean of the intensities of the chosen comparison stars. The use of numerous comparison stars increases considerably the statistical accuracy of the comparison magnitude (Gilliland & Brown 1988, Honeycutt 1992).

We performed the ensemble aperture photometry with the software VPHOT. Table 3 presents the coordinates of the comparison and check stars from the catalogue UCAC4 (Zacharias et al. 2010) and their magnitudes from the catalogue APASS DR9 (Henden et al. 2016). The values in brackets correspond to the standard deviations of the standard stars during the observational nights. The choice of comparison and check stars in the same field of view of the targets means practically equal extinctions for all stars.

The transformation of the obtained instrumental magnitudes to standard ones was made manually. For this aim we used the mean color of the ensemble comparison star $\overline{(g'-i')}_{comp}$ and the transformation coefficients of our equipment (calculated earlier using standard star field M67). Their values, applicable to the presented $g'i'$ observations, are: $T_{g',g'i'} = -0.002 \pm 0.012$, $T_{i',g'i'} = -0.061 \pm 0.017$, $T_{g'i'} = 1.063 \pm 0.011$. They show that our local photometric system is very close to the standard Sloan system (especially in the g' band). The calculated corrections of the instrumental magnitudes for our targets were from -0.0008 mag to 0.0003 mag in the g' filter (within the observational precision) and from -0.0258 mag to 0.0085 mag in the i' filter.

3. LIGHT CURVE SOLUTIONS

The IRIDA light curves of the targets were solved using the code PHOEBE (*PH*ysics *O*f *E*clipsing *B*inariEs). It is a modeling package for eclipsing binary stars, built on top of the widely used WD program (Wilson & Devinney 1971) that has undergone many expansions and improvements (Wilson & Sofia 1976; Wilson 1979, 1990; Milone et al. 1992; Kallrath et al. 1998; Van Hamme & Wilson 2003). PHOEBE was presented firstly in 2005 (Prsa & Zwitter 2005). It retains 100 % WD compatibility, but introduces new computational and physical extensions to WD (proper handling of color indices and therefore temperatures in absolute units; interstellar reddening effects, new minimization schemes aiming at stability and convergence improvements). PHOEBE also provides a graphical user interface alongside with updated filters (as the Sloan ones used in our observations). PHOEBE itself was improved several times and rewritten recently as a whole (Prsa et al. 2016).

We used the traditional convention MinI (phase 0.0) to be the deeper light minimum and the star that is eclipsed at MinI to be the primary component.

Target temperatures T_m were determined in advance (see Table 5 further) on the basis of their infrared color indices *(J-K)* from the 2MASS catalog and the calibration color-temperature of Tokunaga (2000).

The initial runs revealed that all targets were overcontact systems. Hence, we applied mode "Overcontact binary not in thermal contact" of the code. The fit quality was estimated by the χ^2 value.

Firstly, we fixed $T_1 = T_m$ and varied the initial epoch T_0 and period P to try to fit the phases of light minima and maxima. After that we fixed their values and varied simultaneously secondary temperature T_2, orbital inclination i, mass ratio q and potential Ω to try to reproduce the whole light curves. The data in *i'* and *g'* bands were modelled simultaneously.

We adopted coefficients of gravity brightening $g_1 = g_2 = 0.32$ and reflection effect $A_1 = A_2 = 0.5$ appropriate for late-type stars, while the linear limb-darkening coefficients for each component and each color were updated according to the tables of Van Hamme (1993). A solar metallicity was assumed for the targets, because they consist of late stars from the solar vicinity.

In order to reproduce the light curve anomalies we used cool spots, whose parameters (longitude λ, angular size α and temperature factor κ) were adjusted within reasonable ranges (but not varied si-

TABLE 3

LIST OF STANDARD STARS

Label	Star ID	RA	Dec	g'	i'
Target	CSS J071813.2+505000	07 18 13.26	+50 50 00.60	14.479	13.936
Chk	UCAC4 705-045055	07 18 53.59	+50 49 30.10	14.492(0.008)	14.200(0.015)
C1	UCAC4 704-044503	07 18 43.01	+50 45 03.92	13.902(0.012)	13.004(0.012)
C2	UCAC4 704-044543	07 19 41.02	+50 42 56.07	13.529(0.017)	12.832(0.016)
C3	UCAC4 704-044539	07 19 38.17	+50 46 54.09	14.138(0.020)	13.742(0.020)
C4	UCAC4 705-045015	07 18 00.28	+50 52 25.05	13.113(0.013)	12.523(0.013)
C5	UCAC4 705-045065	07 19 05.66	+50 53 59.35	12.989(0.017)	12.572(0.014)
C6	UCAC4 704-044484	07 18 13.70	+50 38 22.77	13.689(0.027)	12.650(0.022)
Target	NSVS 2459652	08 16 13.03	+64 54 23.00	12.822	11.818
Chk	UCAC4 775-028328	08 16 21.45	+64 56 46.54	13.526(0.008)	12.962(0.011)
C1	UCAC4 774-029263	08 15 14.36	+64 47 36.64	12.502(0.012)	11.811(0.010)
C2	UCAC4 775-028310	08 15 37.28	+64 49 50.62	13.316(0.008)	12.934(0.012)
C3	UCAC4 775-028318	08 16 01.65	+64 48 43.69	12.657(0.006)	12.264(0.010)
C4	UCAC4 775-028338	08 16 40.11	+64 50 13.54	13.480(0.008)	13.072(0.013)
C5	UCAC4 775-028341	08 16 43.64	+64 52 44.64	13.487(0.013)	12.375(0.010)
C6	UCAC4 776-027238	08 15 56.50	+65 06 02.71	13.484(0.012)	13.069(0.014)
C7	UCAC4 776-027232	08 15 45.05	+65 06 20.17	12.839(0.009)	11.996(0.014)
Target	NSVS 7178717	06 45 01.21	+34 21 54.90	14.564	13.254
Chk	UCAC4-622-035913	06 45 15.06	+34 21 49.61	14.786(0.008)	14.555(0.018)
C1	UCAC4-622-035872	06 44 58.07	+34 23 52.05	14.341(0.006)	13.747(0.012)
C2	UCAC4-623-036530	06 44 54.57	+34 24 09.67	13.874(0.006)	13.184(0.010)
C3	UCAC4-623-036514	06 44 46.08	+34 24 17.22	14.148(0.007)	13.520(0.010)
C4	UCAC4-622-035820	06 44 36.81	+34 22 52.45	15.217(0.012)	14.037(0.015)
C5	UCAC4-622-035834	06 44 41.87	+34 17 47.50	14.715(0.009)	14.074(0.016)
C6	UCAC4-622-035948	06 45 33.45	+34 21 22.64	15.050(0.008)	13.958(0.014)
C7	UCAC4-623-036641	06 45 44.36	+34 24 57.26	14.813(0.011)	13.956(0.016)
C8	UCAC4-622-035827	06 44 38.52	+34 23 17.39	14.393(0.006)	13.859(0.013)
C9	UCAC4-622-035908	06 45 13.97	+34 15 26.03	14.549(0.008)	14.068(0.014)
C10	UCAC4-622-035941	06 45 28.20	+34 17 29.17	13.397(0.005)	12.330(0.006)
C11	UCAC4-622-035969	06 45 41.86	+34 18 19.91	14.454(0.006)	13.128(0.011)
C12	UCAC4-622-035967	06 45 39.42	+34 21 22.64	14.792(0.009)	14.313(0.017)
Target	NSVS 7377875	08 40 00.50	+36 39 28.30	13.551	12.464
Chk	UCAC4 633-044666	08 40 09.68	+36 33 22.14	14.116(0.007)	13.007(0.008)
C1	UCAC4 634-043123	08 40 31.57	+36 47 09.08	14.854(0.011)	14.025(0.013)
C2	UCAC4 634-043112	08 40 10.25	+36 47 13.54	13.130(0.005)	12.270(0.007)
C3	UCAC4 634-043122	08 40 28.27	+36 40 28.26	13.577(0.005)	12.594(0.007)
C4	UCAC4 634-043110	08 40 04.30	+36 40 43.13	13.795(0.007)	13.304(0.009)
C5	UCAC4 634-043126	08 40 37.71	+36 39 13.58	14.449(0.007)	13.239(0.010)
C6	UCAC4 634-043121	08 40 21.16	+36 39 09.98	13.701(0.008)	12.523(0.008)
C7	UCAC4 634-043103	08 39 51.33	+36 37 54.57	13.712(0.005)	13.041(0.010)
C8	UCAC4 634-043096	08 39 36.26	+36 36 05.25	13.945(0.007)	12.861(0.009)
C9	UCAC4 633-044662	08 39 59.84	+36 35 42.44	13.768(0.005)	13.054(0.009)
C10	UCAC4 633-044690	08 40 57.08	+36 35 59.73	13.793(0.007)	13.028(0.008)
C11	UCAC4 633-044661	08 39 59.19	+36 32 11.51	13.295(0.009)	11.875(0.007)
C12	UCAC4 633-044641	08 39 19.57	+36 33 30.90	13.911(0.012)	13.407(0.015)

TABLE 4

VALUES OF THE FITTED PARAMETERS

Star	T_0	P	q	i	Ω	T_2^{PH}
CSS J071813.2	2457416.24065(9)	0.386324(3)	0.485(5)	58.9(4)	2.845(3)	6123(75)
NSVS 2459652	2457380.33148(74)	0.251730(2)	0.786(6)	63.5(3)	3.315(1)	4565(19)
NSVS 7178717	2457039.33000(31)	0.248616(2)	0.549(6)	89.8(4)	2.770(1)	4535(45)
NSVS 7377875	2457483.40716(21)	0.26498578(3)	0.898(7)	84.9(4)	3.528(6)	4579(24)

TABLE 5

CALCULATED PARAMETERS

Target	T_m	T_1	T_2	r_1	r_2	f	l_2/l_1
CSS J071813.2	6350	6420(81)	6193(75)	0.445(2)	0.319(2)	0.009	0.452
NSVS 2459652	4682	4731(10)	4614(10)	0.417(6)	0.375(6)	0.176	0.727
NSVS 7178717	4560	4569(45)	4544(45)	0.481(6)	0.379(6)	0.600	0.614
NSVS 7377875	4655	4689(25)	4613(24)	0.399(7)	0.381(7)	0.109	0.837

multaneously along other configuration parameters). Due to the ambiguous solution of this inverse problem we chose equatorial spots on the side surfaces of the primaries, because they have the smallest size and temperature contrast required to fit a given light curve distortion.

After reaching the best solution, we varied together all parameters (including period P and initial epoch T_0) around the values from the last run and obtained the final values of the fitted quantities: T_2^{PH}, i, q, Ω, T_0 and P.

In order to obtain the stellar temperatures T_1 and T_2 around the target value T_m we used the formulae (Kjurkchieva et al. 2016):

$$T_1 = T_m + \frac{\Delta T}{c+1}, \tag{1}$$

$$T_2 = T_1 - \Delta T, \tag{2}$$

where $c = l_2/l_1$ (luminosity ratio) and $\Delta T = T_m - T_2^{PH}$ were taken from the final PHOEBE fitting.

Although PHOEBE (as WD) works with potentials, it offers the possibility to calculate directly all values (polar, point, side, and back) of the relative radius $r_i = R_i/a$ of each component (R_i is the linear radius and a is the orbital separation). In the absence of radial velocity curves we used as default $a = 1$. Moreover, PHOEBE yields as output parameters bolometric magnitudes M_{bol}^i of the two components in conditional units (when radial velocity data are not available). But their difference $M_{bol}^2 - M_{bol}^1$ determines the true luminosity ratio $c = L_2/L_1 = l_2/l_1$. The fillout factor $f = [\Omega - \Omega_{crit}^{L_1}]/[\Omega_{crit}^{L_2} - \Omega_{crit}^{L_1}]$ can be also calculated from the output parameters of the PHOEBE solution ($\Omega_{crit}^{L_1}$ and $\Omega_{crit}^{L_2}$ are the Roche potentials at inner/outer Lagrangian point L_1 and L_2).

Table 4 contains the final values of the fitted stellar parameters and their PHOEBE uncertainties: initial epoch T_0; period P; mass ratio q; inclination i; potential Ω; secondary temperature T_2^{PH}. Table 5 exhibits the calculated parameters: stellar temperatures $T_{1,2}$; relative stellar radii $r_{1,2}$; fillout factor f; ratio of the relative stellar luminosities l_2/l_1. The errors were determined from the uncertainties of the output parameters used for their calculations. Table 6 gives information on the spot parameters and the steps of their adjusting (in brackets).

The synthetic light curves corresponding to our solutions are shown in Figures 1-2 as continuous lines. The mean (g', i') residuals for the final fittings are: (0.0196, 0.0267) for CSS J071813.2; (0.0125, 0.0126) for NSVS 2459652; (0.0346, 0.0288) for NSVS 7178717; (0.0220, 0.0188) for NSVS 7377875.

In order to check the effect of the correlation between the mass ratio and the orbital inclination (suspected from the correlation matrix) we carried out a q-search analysis (Kjurkchieva et al. 2016). For this aim we fixed all configuration parameters except i and q. The last ones were varied by a fine grid and the corresponding normalized χ^2 values were calculated. Figure 3 illustrates the q-search procedure for the target NSVS 7377875. It reveals the correctness of the obtained uncertainties of i and q.

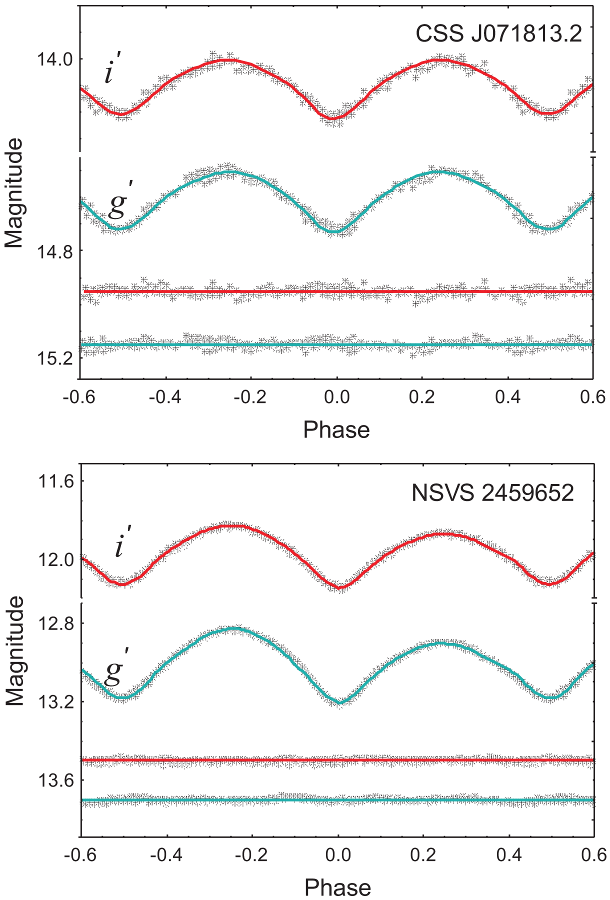

Fig. 1. The folded light curves of CSS J071813.2 and NSVS 2459652 with their fits and the corresponding residuals (shifted vertically by different number to save space). The observational data are accessible at: `http://www.irida-observatory.org/Observations/IRIDA-7.zip`.

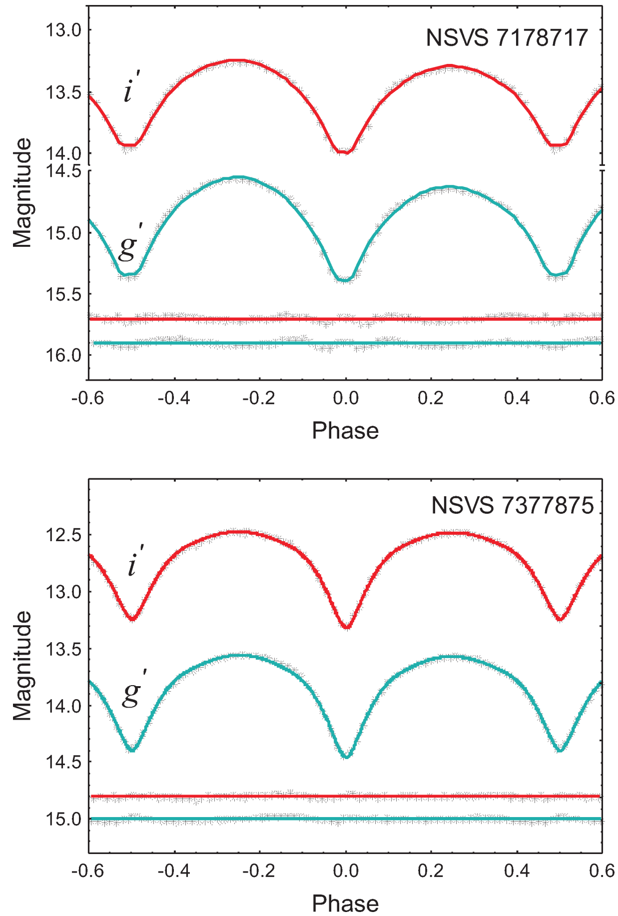

Fig. 2. The same as Figure 2 for NSVS 7178717 and NSVS 7377875.

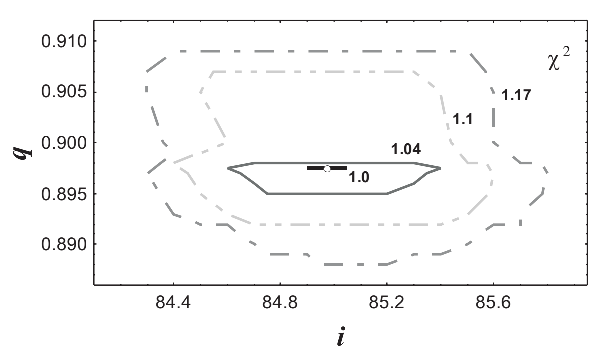

Fig. 3. Illustration of the q-search analysis for NSVS 7377875: the different isolines circumscribe the areas whose normalized χ^2 are smaller than the marked values; the empty circle corresponds to the final values of the mass ratio and orbital inclination given in Table 4.

4. CONCLUSIONS

The main results of the light curve solutions of our photometric data are as follows.

(1) We determined the initial epochs T_0 of the four targets (Table 4).

(2) The periods of CSS J071813.2 and NSVS 7377875 were improved (Table 4) on the basis of all photometric data: CRTS, NSVS, SWASP and IRIDA.

(3) The amplitudes of the IRIDA light curves of CSS J071813.2, NSVS 2459652 and NSVS 7178717 are larger than the previous values (Table 1) correspondingly by around 25%, 20% and 220% while that of NSVS 7377875 is smaller by 15% than the previous value. The differences are probably due to the low precision of the previous observations.

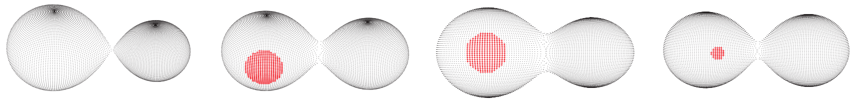

Fig. 4. From left to right 3D configurations of CSS J071813.2, NSVS 2459652, NSVS 7178717, NSVS 7377875.

(4) We found that NSVS 7178717 undergoes total eclipses while the other three targets exhibit partial eclipses.

(5) CSS J071813.2 is barely an overcontact system, NSVS 2459652 and NSVS 7377875 are overcontact binaries with an intermediate fillout factor, while NSVS 7178717 has a deep-contact configuration (Figure 4, Table 5).

(6) The components of CSS J071813.2 are early G stars while those of the remaining three targets are of K spectral type (Table 5). The equally deep minima of the light curves of all targets were reproduced by almost the same (within 230 K) temperatures of the components (Table 5). This result was expected taking into account their overcontact configurations. In such cases the terms primary and secondary component as well as A and W subtype (Binnendijk 1970) are quite conditional.

(7) The cool spots (Table 6) are manifestations of magnetic activity of the targets with late components (Table 5).

(8) Two of our targets, NSVS 2459652 and NSVS 7377875, have a mass ratio $q \geq 0.72$ (Table 4), i.e. they belong to the H subtype W UMa systems (introduced by Csizmadia & Klagyivik 2004).

(9) The relation between the mass ratio and luminosity ratio for CSS J071813.2 and NSVS 7178717 (with $q \approx 0.5$) is $l_2/l_1 = q^{0.95}$, i.e. almost the same as that of Lucy (1968). The relation for the H subtype targets NSVS 2459652 and NSVS 7377875 is approximately $l_2/l_1 = q^{1.5}$. These results confirmed the conclusion of Csizmadia & Klagyivik (2004) that the W UMa stars with intermediate mass ratios are farthest from the line $l_2/l_1 = q^{4.6}$ representing the empirical relation of the detached MS binaries.

This study adds four new systems to the family of W UMa binaries with estimated parameters. They could help to develop and improve our empirical knowledge about these stars and the statistical relations between their parameters.

TABLE 6

SPOT PARAMETERS

Star	λ	α	k
NSVS 2459652	270(5)	27(1)	0.90(2)
NSVS 7178717	270(5)	25(1)	0.90(2)
NSVS 7377875	290(5)	10(1)	0.90(2)

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