Global parameters of the W UMa binaries NSVS 3777464, NSVS 5810460 and ASAS J212236+0657.3

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Abstract. Photometric observations in Sloan filters g', i' of the short-period eclipsing stars NSVS 3777464, NSVS 5810460 and ASAS J212236+0657.3 are presented. Their goal was determination of the targets' parameters by light curve solutions. We found the three targets to be overcontact binaries of W subtype: NSVS 3777464 and NSVS 5810460 undergo partial eclipses while ASAS J212236+0657.3 reveals total eclipses. The masses, radii and luminosities of the components of NSVS 3777464 and ASAS J212236+0657.3 were obtained using the results of our light curve solutions and the *GAIA* distances. The total-eclipsing binary ASAS J212236+0657.3 with well-determined parameters turned out shallow contact binary whose components differ almost 5 times in mass and twice in radius. Due to the lack of *GAIA* distance for NSVS 5810460, we proposed a procedure for determination of the global parameters of its components based on the results of our light curve solution and the empirical relation period–axis of short-period binaries.

Key words: binaries: close – binaries: eclipsing – methods: data analysis – stars: fundamental parameters – stars: individual
(NSVS 3777464, NSVS 5810460, ASAS J212236+0657.3)

Introduction

W UMa-type binaries consist of two cool stars, surrounded by a common envelope lying between the inner and outer critical Roche surfaces. This result is a consequence of almost identical surface brightness of their components (Lucy 1968, Lucy 1976).

Although the W UMa stars present a numerous family (around of 1/500–1/130 MS stars in the solar neighborhood, Rucinski 2002) and there are many studies of them (Qian et al. 2013), the theory of their origin, structure, evolution and future fate is still not complete.

The final products of the W UMa-type evolution are debatable (Li et al. 2007, Eker et al. 2008). It is supposed that they may become: single blue stragglers (by merging of the W UMa components); two brown dwarfs or two stars with very low mass. The W-phenomenon is another unresolved problem and an interesting peculiarity appearing by the lower apparent surface brightness of the more massive components of the most W UMa-type systems (Binnendijk 1970).

Besides their key role for understanding of the stellar evolution, the W UMa stars are natural laboratories to study important astrophysical processes: interaction of stellar winds; magnetic activity; mass, energy and angular momentum transfer and loss; the phenomenon "mass ratio reversal"; the merging or fusion of the stars (Martin et al. 2011). The investigation of these processes requires knowledge of the fundamental parameters of as many W UMa stars as possible. Nowadays, the *GAIA* distances of billion stars give a possibility for precise determination of the global parameters of eclipsing binaries.

This paper presents photometric observations of the W UMa systems NSVS 3777464, NSVS 5810460 and ASAS J212236+0657.3 (further on assigned as ASAS 2122+06). The goal of our study was to determine the target parameters by light curve solutions of our data and *GAIA* distances.

Table 1 presents information for the target coordinates and variability from the VSX database.

Table 1. Parameters of targets from the VSX database

Target	RA [h, m, s]	DEC [^{o},$'$,$''$]	mag	ampl [mag]	P [d]	References
NSVS 3777464	00 34 24.89	+39 02 17.2	13.3(CV)	0.45	0.319938	Wozniak et al. 2004
NSVS 5810460	20 53 53.36	+47 55 18.0	12.871(R1)	0.278	0.24719	Hoffman et al. 2009
ASAS 2122+06	21 22 35.44	+06 57 14.1	13.47(V)	0.50	0.293946	Pojmanski 2002, Drake et al. 2014

Table 2. Log of our photometric observations

Star	Date	Exposure i', g'	Number i', g'	error i', g'
NSVS 3777464	2016 Oct 2	120, 120	75, 75	0.009, 0.012
	2016 Oct 6	120, 120	31, 30	0.009, 0.012
	2016 Oct 7	120, 120	33, 34	0.009, 0.012
	2016 Oct 12	120, 120	23, 23	0.009, 0.012
	2016 Oct 13	120, 120	125, 124	0.009, 0.012
	2016 Oct 14	120, 120	41, 42	0.009, 0.012
NSVS 5810460	2017 Sept 16	60, 90	38, 37	0.006, 0.007
	2017 Sept 17	60, 90	109, 109	0.006, 0.007
	2017 Sept 18	60, 90	36, 37	0.006, 0.007
ASAS 2122+06	2017 Aug 31	150, 150	36, 36	0.006, 0.008
	2017 Sept 1	150, 150	70, 69	0.006, 0.008
	2017 Sept 2	150, 150	13, 15	0.006, 0.008

1. Observations

The CCD photometric observations of the targets in the Sloan g', i' filters were performed at the Rozhen Observatory using the 30-cm Ritchey Chretien Astrograph (located in the IRIDA South dome) with an ATIK 4000

M CCD camera (2048 $\times$ 2048 pixels, 7.4 μm/pixel, field of view 35 $\times$ 35 arcmin). Table 2 shows information about our observations.

The data were obtained during photometric nights. Twilight flat fields were obtained for each filter, as well as dark and bias frames. The frames were combined into a single master bias, and dark, and flat frames. The reduction of the photometric data was done using the standard procedure (de-biasing, dark-frame subtraction and flat-fielding) with the software AIP4WIN v.2.0 (Berry & Burnell 2006).

The light curve variability of each target was estimated by comparing it with nearby constant (comparison) stars. A check star served to determine the observational accuracy and to verify the constancy of the comparison stars. The comparison and check stars were chosen to be: (i) constant in the framework of the photometric error during all nights; (ii) close in magnitude to the variable star; (iii) not at the periphery of the frames; (iv) with known magnitudes in APASS DR9 catalog. Table 3 shows the coordinates of the comparison and check stars, taken from the UCAC4 catalogue (Zacharias et al. 2013) while their magnitudes were taken from the APASS DR9 catalogue (Henden et al. 2016).

We performed ensemble photometry with the software VPHOT (https://www.aavso.org/vphot). It 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). The procedure of transformation of the instrumental magnitudes into standard ones is described in Kjurkchieva et al. (2017).

We determined the observed times of minima of the three binaries (Table 4) using the method of Kwee & van Woerden (1956). These timings would be useful for future investigation of changes of the targets' orbital periods.

2. Light curve solutions

The modeling of our data (Figs. 1–3) was carried out using the package PHOEBE (Prsa & Zwitter 2005).

The targets' temperatures T_m were determined by the relation of Covey et al. (2007). To achieve this, we measured the targets' color indices $(g' - i')$ at the quadratures and corrected them for reddening. The galactic latitudes of NSVS 3777464 and ASAS 2122+06 are -23° and -29°, respectively, and their reddening were taken from the NASA/IPAC EXTRAGALACTIC DATABASE (NED) (Schlafly & Finkbeiner 2011). As a result we determined temperature of 5200 K for NSVS 3777464 and 5550 K for ASAS 2122+06. The LAMOST temperature for NSVS 3777464 is also 5200 K (Luo et al. 2015). Hence, the T_m values of NSVS 3777464 and ASAS 2122+06 may be adopted with confidence. However, the galactic latitude of NSVS 5810460 is around 2° and the extinction values in g' and i' from NED are unreliably large. The IR colors are less influenced by the extinction and are more appropriate for the estimation of the temperature. The color index J–K = 0.53 of NSVS 5810460 leads to a temperature of 5240 K (Tokunaga 2000).

Table 3. List of standard stars.

Label	Star ID	RA	Dec	g'	i'
Target	NSVS 3777464	00 34 24.89	+39 02 17.02	13.87	12.93
Chk	UCAC4 646-002238	00 34 47.34	+39 09 02.00	13.491	12.231
C1	UCAC4 646-002211	00 34 29.27	+39 02 33.46	13.122	12.284
C2	UCAC4 646-002252	00 34 58.81	+39 03 29.60	13.214	12.733
C3	UCAC4 645-002140	00 34 43.19	+38 59 21.78	13.646	13.245
C4	UCAC4 645-002095	00 34 07.65	+38 57 11.85	13.785	13.087
C5	UCAC4 645-002153	00 34 51.94	+38 58 25.02	14.128	13.404
C6	UCAC4 645-002149	00 34 47.22	+38 54 14.10	13.751	13.126
C7	UCAC4 646-002197	00 34 21.57	+39 08 40.19	13.305	12.668
C8	UCAC4 645-002125	00 34 29.90	+38 51 47.90	12.892	12.226
C9	UCAC4 645-002091	00 34 02.30	+38 49 03.74	13.216	12.307
C10	UCAC4 645-002074	00 33 47.73	+38 51 20.10	12.721	12.125
C11	UCAC4 645-002072	00 33 46.06	+38 53 14.11	12.823	11.770
Target	NSVS 5810460	20 53 53.36	+47 55 18.00	13.14	12.19
Chk	UCAC4 690-087474	20 53 56.97	+47 55 30.11	14.219	13.484
C1	UCAC4 690-087576	20 54 18.45	+47 59 50.59	12.757	12.118
C2	UCAC4 690-087238	20 53 17.32	+47 58 35.87	13.407	12.514
C3	UCAC4 690-087257	20 53 19.97	+47 58 10.76	12.736	12.116
C4	UCAC4 690-087342	20 53 34.81	+47 53 58.44	12.906	11.771
C5	UCAC4 690-087425	20 53 46.08	+47 54 24.01	12.482	12.079
C6	UCAC4 690-087554	20 54 12.62	+47 51 49.31	12.035	9.338
Target	ASAS 2122+06	21 22 35.46	+06 57 14.10	13.79	12.95
Chk	UCAC4 485-130730	21 22 52.13	+06 55 29.33	13.347	12.925
C1	UCAC4 485-130709	21 22 43.54	+06 56 23.55	13.710	12.838
C2	UCAC4 485-130755	21 23 07.91	+06 57 49.60	13.791	13.461
C3	UCAC4 485-130753	21 23 07.30	+06 59 40.56	12.799	12.633
C4	UCAC4 485-130705	21 22 40.74	+06 59 04.63	13.466	13.561
C5	UCAC4 485-130665	21 22 09.34	+06 54 05.57	13.292	12.522
C6	UCAC4 485-130668	21 22 09.83	+06 54 32.21	14.022	13.234
C7	UCAC4 485-130686	21 22 26.37	+06 59 59.20	13.820	13.088

Table 4. Times of the observed light curve minima (I - primary, II - secondary) at Rozhen.

Target	Type	Times of minima, HJD
NSVS 3777464	I	2457664.40873(24)
	I	2457668.56647(6)
	II	2457674.49457(4)
	I	2457675.28775(8)
	II	2457675.45754(5)
	I	2457675.60607(6)
NSVS 5810460	I	2458013.50129(4)
	II	2458014.36538(5)
	I	2458014.48973(11)
ASAS J2122+06	I	2457997.460600(12)
	I	2457998.343270(9)
	II	2457998.490740(6)

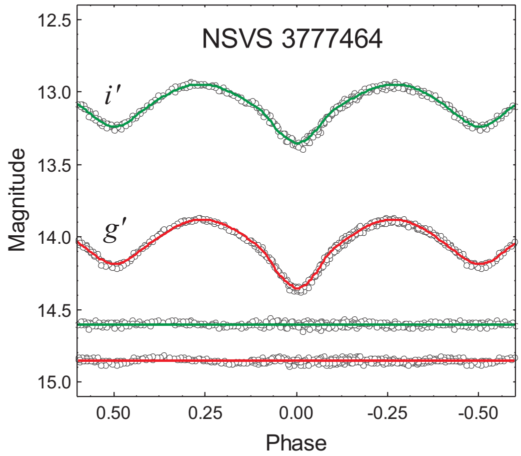

Fig. 1. Top: the folded light curves of NSVS 3777464 and their fits; Bottom: the corresponding residuals (shifted vertically).

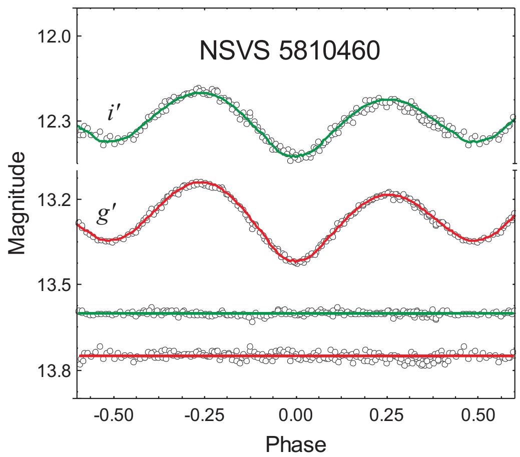

Fig. 2. The same as Fig.1 for NSVS 5810460.

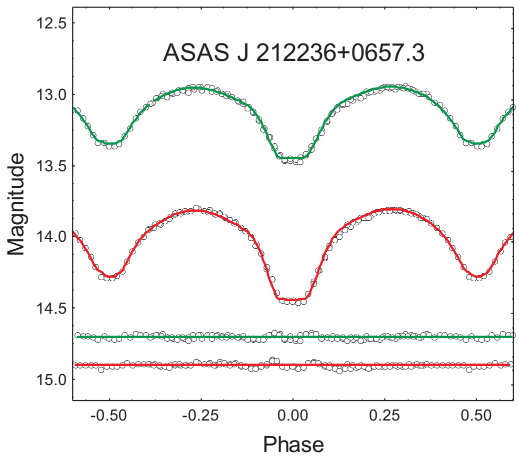

Fig. 3. The same as Fig.1 for ASAS 2122+06.

We adopted a linear limb-darkening law. The limb-darkening coefficients were interpolated according to the tables of Van Hamme (1993).

The light curve minima of NSVS 3777464 and NSVS 5810460 do not contain flat part which means that these targets undergo partial eclipses. Then, their photometric mass ratios are poorly determined (Rucinski 2001, Terrell & Wilson 2005) and require q-search analysis. For this aim we searched for the best solutions for fixed mass ratios in the range 0.1–18.0, varying Ω. The q-search curves of NSVS 3777464 and NSVS 5810460 (Fig. 4) exhibit wide, almost flat minima in the range $0.5 < q < 10$ with several narrower minima superposed on them. We adopt as acceptable those solutions whose χ^2 values differ from that of the absolute minimum by up to 10 %. For NSVS 3777464, with absolute minimum at $q = 1.82$, this is fulfilled for $1.6 < q < 1.95$, while for NSVS 5810460, with absolute minimum at $q = 1.49$, this range is $1.1 < q < 1.6$.

In order to limit the possible mass ratios of NSVS 3777464 and NSVS 5810460, we also mapped the χ^2 dependence on the mass ratio q and orbital inclination i (Fig. 5). The obtained values of q and i were used further as initial values in the light curve solutions of NSVS 3777464 and NSVS 5810460. For the totally-eclipsing binary ASAS 2122+06 we adopted as initial value $q = 4.8$, which corresponds to the deeper minimum of its q-search curve (Fig. 4).

We fixed the primary temperature of the targets as $T_1 = T_m$ and searched for the best fit varying initial epoch T_0, period P, secondary temperature T_2, mass ratio q and inclination i around their initial values while the potential Ω was varied freely.

We added a cool spot to reproduce the O'Connell effect of NSVS 5810460 (Fig. 2). On the other hand, we had to use a hot spot to reproduce the deviations (up to 0.03 mag) of the synthetic curves of ASAS 2122+06 from the observed points in the phase ranges 0.10–0.25 and 0.30–0.47. Such surface inhomogeneities are acceptable for W UMa stars (Berdyugina 2005).

The solution of the light curves in respect to all configuration and spot parameters (longitude λ, latitude β, angular size α and temperature factor κ) is ambiguous. Only the spot's longitude can be determined unambiguously. That is why we used the following considerations to reduce the fitted spot parameters: (i) due to lack of additional knowledge (for instance spectral or polarimetric data) the spots were put on the secondary (larger) component; (ii) we used equatorial spots, i.e. the spot latitude was fixed; (iii) the temperature factor $\kappa = T_{sp}/T_{ph}$ of the cool spot of NSVS 5810460 was varied in the range 0.8–0.9 appropriate for the stellar temperature (Berdyugina 2005), while the temperature factor and size of the hot spot of ASAS 2122+06 were varied freely.

Finally, we adjusted the stellar temperatures T_1 and T_2 around the value T_m by the formulae (Kjurkchieva & Vasileva, 2015):

$$T_1^f = T_\mathrm{m} + \frac{c\Delta T}{c+1}; \quad T_2^f = T_1^f - \Delta T \tag{1}$$

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

We estimated the precision of the fitted parameters using the method described in Dimitrov et al. (2017).

Table 5 contains the final values of the fitted parameters and their uncertainties.

Table 6 shows the calculated (output) parameters: relative (volume) radius $r_i = R_i/a$ of each component (R_i is linear radius and a is orbital separation); fill-out factor f; luminosity ratio $c = L_2/L_1 = l_2/l_1$ (determined from $M_{bol}^2 - M_{bol}^1$); and the final component temperatures T_i^f.

Table 5. Values of the fitted parameters from the final light curve solutions.

Star	T_0 - 2450000 [d]	P [d]	i [°]	q	T_2 [K]	Ω
NSVS 3777464	7664.407512(2)	0.319938(1)	64.8(1)	1.818(4)	4484(21)	4.938(2)
NSVS 5810460	8013.499558(2)	0.24719(1)	51.7(1)	1.499(3)	4566(29)	4.403(2)
ASAS 2122+06	3480.700807(2)	0.293945(1)	79.5(1)	4.825(9)	5100(32)	8.863(6)

3. Global parameters

The distances, d, to NSVS 3777464 and ASAS 2122+06 (Table 7) were measured by *GAIA* (Bailer-Jones etal 2018). Based on our solutions and these distances, we calculated the luminosities, radii and masses of the

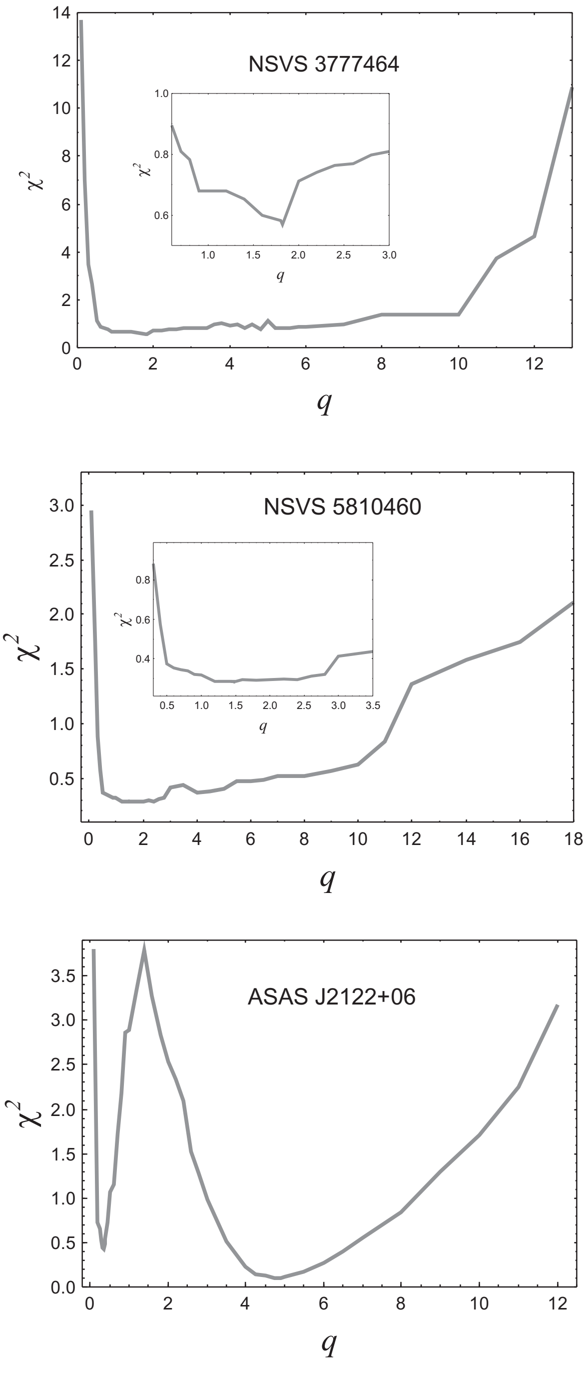

Fig. 4. q-search curves for the three targets.

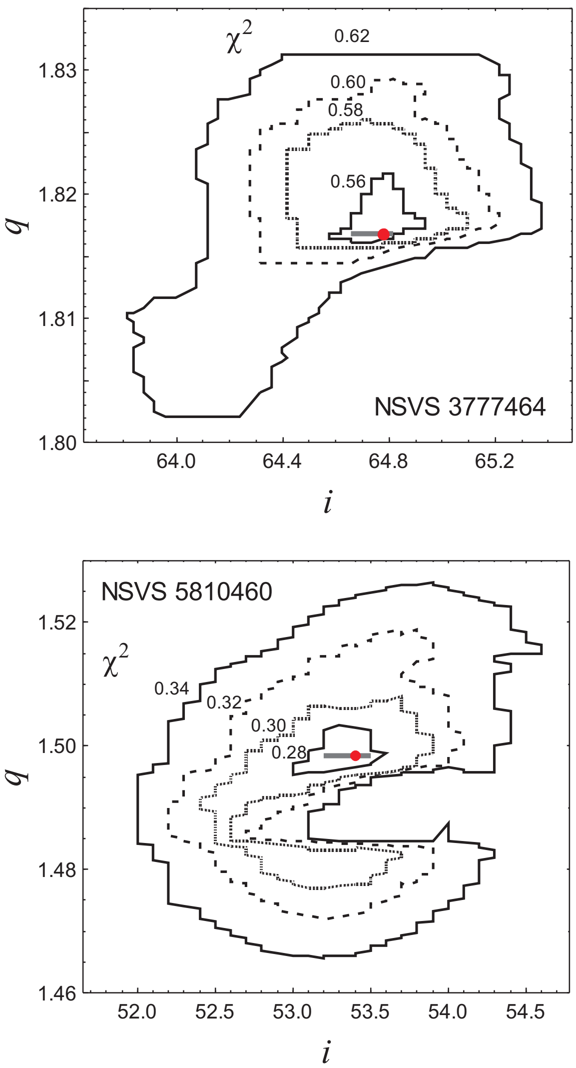

Fig. 5. The χ^2 dependencies of mass ratio q and inclination i for NSVS 3777464 and NSVS 5810460: the different isolines describe the areas whose normalized χ^2 are smaller than the marked values; the circle corresponds to the minimum of the χ^2.

Table 6. Calculated parameters.

Star	r_1	r_2	f	l_2/l_1	T_1^f	T_2^f
NSVS 3777464	0.336(5)	0.440(4)	0.091	0.973	5553(32)	4820(21)
NSVS 5810460	0.363(6)	0.433(5)	0.213	0.786	5596(27)	4811(29)
ASAS 2122+06	0.260(3)	0.526(7)	0.132	2.951	5886(34)	5423(32)

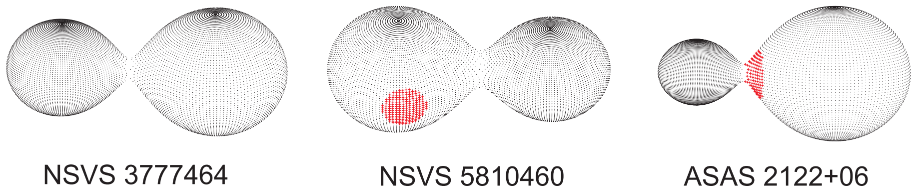

Fig. 6. 3D configurations of the targets made using Binary Maker 3 by Bradstreet & Steelman (2002).

Table 7. Global parameters.

Star	d [pc]	L $[L_\odot]$	L_1 $[L_\odot]$	L_2 $[L_\odot]$	R_1 $[R_\odot]$	R_2 $[R_\odot]$	a $[R_\odot]$	M_{tot} $[M_\odot]$	M_1 $[M_\odot]$	M_2 $[M_\odot]$
NSVS 3777464	490	1.038	0.526	0.512	0.786	1.029	2.339	1.674	0.594	1.080
ASAS 2122+06	455	1.020	0.312	0.708	0.567	1.151	2.187	1.623	0.278	1.345
NSVS 5810460	243	0.691	0.389	0.302	0.665	0.793	1.830	1.344	0.537	0.807

components of NSVS 3777464 and ASAS 2122+06 (Table 7), using the procedure described in Kjurkchieva et al. (2018).

The distance to NSVS 5810460 is unknown. For determination of its global parameters we used the following procedure.

(i) The orbital axis $a = 1.83$ R$_\odot$ was estimated from the empirical relation period–axis of short-period binaries (Dimitrov & Kjurkchieva 2015).

(ii) Total mass of 1.344 M$_\odot$ is determined by the third Kepler law. Then the individual stellar masses are $M_1 = 0.537$ M$_\odot$ and $M_2 = 0.807$ M$_\odot$.

(iii) The stellar radii (Table 7) were calculated by the formula $R_i = ar_i$.

(iv) The individual luminosities L_i were calculated by the radii R_i and temperatures T_i^f. Then, the total luminosity $L = 0.691$ L$_\odot$, and bolometric magnitude $M_{bol} = 5.16$, were obtained. Taking into account the appropriate BC, we determined the magnitude $M_V = 5.39$.

(v) The targets visual magnitude $V = 12.68$ was taken from the NOMAD catalog (Zacharias et al. 2004). Then the distance was obtained by the formula distance modulus, together with the extinction A_V from the model of Arenou et al. (1992).

The values of all global parameters of NSVS 5810460 (temperatures, masses, radii and luminosities) should be considered as approximate (preliminary) ones due to the unknown distance and large extinction.

4. Results and conclusion

Our study of the W UMa-type binaries NSVS 3777464, NSVS 5810460 and ASAS 2122+06 led to the following results:

(1) We determined the timings of light curve minima (Table 4) and the initial epochs (Table 5).

(2) The three targets are shallow contact binaries.

(3) NSVS 3777464 and NSVS 5810460 undergo partial eclipses, while ASAS 2122+06 reveals total eclipses.

(4) The temperature differences of the targets' components (Table 6) are larger than the typical values of 100–300 K for W UMa stars.

(5) The three targets are of W subtype because their larger components are the cooler ones.

(6) ASAS 2122+06 is an interesting target because its components differ almost 5 times in mass, and twice in radius, but its configuration is shallow contact. This result could be explained by the conclusion of Liu et al. (2018) that during the evolution of W UMa-type binaries the orbital period decreases while the fillout factor oscillates between 0 and 1.

(7) The O'Connell effect of NSVS 5810460 required a cool spot with radius $\alpha = 20°$, while the light curve distortions of ASAS 2122+06 were fitted by a hot spot with radius $\alpha = 18°$.

(8) The masses, radii and luminosities of the stellar components of NSVS 3777464 and ASAS J212236+0657.3 were calculated using the results of our light curve solutions and $GAIA$ distances.

(9) The global parameters of NSVS 5810460, as well as its distance were estimated based on our light curve solution and the empirical relation period–axis of short-period binaries.

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