Ultrashort-period MS eclipsing systems. New observations and light curve solutions of six NSVS binaries

Dinko P. Dimitrov$^1$ and Diana P. Kjurkchieva$^2$

$^1$Institute of Astronomy and NAO, Bulgarian Academy of Sciences, Tsarigradsko shossee 72, 1784 Sofia
$^2$Department of Physics, Shumen University, 9700 Shumen, Bulgaria

Accepted 2015 January 19. Received 2015 January 12; in original form 2014 November 17

ABSTRACT
We carried out photometric and low-resolution spectral observations of six eclipsing ultrashort-period binaries with MS components. The light curve solutions of the Rozhen observations show that all targets are overcontact systems. We found well-defined empirical relation “period – semi-major axis” for the short-period binaries and used it for estimation of the global parameters of the targets. Our results revealed that NSVS 925605 is quite interesting target: (a) it is one of a few contact binaries with M components; (b) it exhibits high activity (emission in Hα line, X-ray emission, large cool spots, non-Planck energy distribution); (c) its components differ in temperature by 700 K. All appearances of high magnetic activity and huge fillout factor (0.7) of NSVS 925605 might be assumed as a precursor of the predicted merging of close magnetic binaries. Another unusual binary is NSVS 2700153 which reveals considerable long-term variability.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: late-type – stars: individual: NSVS 925605

1 INTRODUCTION
The short-period binaries with non-degenerate components are important objects for the astrophysics, especially for the understanding of the very late evolutionary stages of the binaries connected with the processes of mass and angular momentum loss, merging or fusion of the stars, etc. But their structure and evolution remains unsolved problem in stellar astrophysics due to poor statistics. There are two reasons for this insufficiency.

Firstly, the period distribution of binaries reveals a very sharp decline in the number of short period systems below 0.27 days (Drake et al. 2014). Systems with periods around the short-period limit of 0.22 day (Rucinski 1992) were extremely rare: the fraction of ultrashort period objects was estimated to only 0.26 % of the total number of the large number of contact systems (Drake et al. 2014). Secondly, the faintness of the late short binaries makes them difficult targets for detailed study. As a result, although M-dwarfs form the most common stellar population in our Galaxy (∼ 70 % by number, Henry et al. 1999), their intrinsic faintness is barrier to study their binary characteristics.

Lately, a hypothesis appeared 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 planets could be produced, particularly hot Jupiters (Martin et al. 2011).

Fortunately, the modern large stellar surveys during the last decade allowed to discover binaries with shorter and shorter periods (Rucinski 2007; Pribulla et al. 2009; Weltevrede et al. 2004; Maceroni & Rucinski 1997; Dimitrov & Kjurkchieva 2010; Norton et al. 2011; Nels et al. 2012; Davénport et al. 2013; Lohr et al. 2014; Qian et al. 2014; Drake et al. 2014 etc.).

This paper presents our observations and light curve solutions of six ultrashort-period binaries (whose periods are below 0.23 d).

2 SELECTION OF TARGETS
Using own approach (Dimitrov 2009) for searching for stellar variability we reviewed the NSVS database (Wozniak et al. 2004) and found around 300 ultrashort-period candidates with W UMa-type light curves. More than 100 of them were removed as probable δ Sct stars due to their small infrared colors (temperatures T > 6000 K). We carried out short test observations of the rest candidates and established that most of them were not variable stars. In such a way we managed to separate sample of about forty ultrashort-period candidates from the NSVS survey appropriate for follow-up observations at Rozhen observatory (δ > −10°). Our study

* E-mail: dinko@astro.bas.bg; d.kyurkchieva@shu-bg.net
of one of them (BX Tri) was already published (Dimitrov & Kjurkchieva 2010).

Table 1 reveals the coordinates and magnitudes of six other targets from this sample: four of them are newly discovered eclipsing stars while two of them are identified with objects from the lists of ultrashort-period binaries of Norton et al. (2011) and Lohr et al. (2014) based on the SuperWASP photometric survey (Pollacco et al. 2006).

Besides photometric data for all six targets in the NSVS database we found also data of four of them in the SuperWASP archive (Butters et al. 2010). The periodogram analysis of these low-precise but numerous data allowed us to determine their ephemeris (Table 1). Figure A1 presents the folded curves of the targets corresponding to their old photometric data.

3 ROZHEN OBSERVATIONS AND DATA REDUCTION

The follow-up CCD photometry of the targets in VRI bands was carried out with the three telescopes of Rozhen National Astronomical Observatory (Table 2). The 2-m RCC telescope is equipped with VersArray CCD camera (1340 \times 1300 pixels; 20 \mu m/pixel, field of 5.35 \times 5.25 arcmin). The 60-cm Cassegrain telescope is equipped with FLI PL09000 CCD camera (3056 \times 3056 pixels, 12 \mu m/pixel, field of 17.1 \times 17.1 arcmin). The 50/70-cm Schmidt telescope has FoV around 1° and is equipped with CCD camera FLI PL 16803, 4096 \times 4096 pixels, 9 \mu m/pixel size.

Standard stars of Landolt (1992) and standard fields of Stetson (2000) were used for transition from instrumental photometric system to standard photometric system.

The standard IDL procedures (adapted from DAOPHOT) were used for reduction of the photometric data. More than 5 standard stars were chosen in the observed fields of each target by the requirement to be constant within 0.015 mag during the all observational runs and in all filters. Table A1 presents their V, B − V, V − R, and V − I determined by our observations (for the targets they correspond to phase 0.25) as well as their J − K colors from the 2MASS catalog.

Figures 1-6 present the follow-up Rozhen photometry of our targets. Table A2 presents a sample of the Rozhen photometric data (the full table is available in the online version of the article, see Supporting Information).

We calculated times of the observed light minima by the method described in Fribilla et al. (2012). Table A3 contains their HJD(Min), Epoch, and O − C.

We obtained low-resolution spectra (Fig. 7) during 5 nights in Feb-May 2011 by the 2-m RCC telescope equipped with focal reducer FoReRo-2. We used grism with 300 lines/mm that allows resolution 5.223 \AA/pixel in the range 5000-7000 \AA. These low-resolution spectra do not allow radial velocity measurement but are useful indicators of the temperature and stellar activity.

4 LIGHT CURVE SOLUTIONS

The photometric data (Figs. 1-6) implied that our targets are contact or overcontact systems that was expected for their ultra-short orbital periods.

We carried out modeling of the Rozhen photometric data by the code PHOEBE (Prša & Zwitter 2005) using the following procedure.

| Table 2. Journal of the Rozhen photometric observations |
|---------------------------------------------|
| Date | Filter | Exp. [s] | Number | Telescope |
|------|--------|---------|--------|-----------|
| 2010 Feb 24 | V | 120,60 | 0.16 | 60-cm |
| 2010 Dec 08 | V | 120,60 | 0.90 | 60-cm |
| 2011 Jan 08 | V | 120,60 | 0.87 | 60-cm |
| 2009 Sept 29 | R | 120 | 0.40 | 60-cm |
| 2009 Sept 30 | R | 120 | 1.32 | 60-cm |
| 2009 Oct 23 | V | 120,120,120 | 50,50,50 | 60-cm |
| 2010 Mar 06 | R | 120 | 0.95 | 60-cm |
| 2010 Mar 12 | I | 120 | 3.10 | 60-cm |
| 2011 Jan 01 | V | 1 | 4.43 | 2-m |
| 2009 Nov 19 | R | 120 | 0.50 | 60-cm |
| 2011 Jan 01 | V | 120,60 | 1.03,103 | 60-cm |
| 2011 Jan 06 | V | 120,60 | 0.85 | 60-cm |
| 2011 Jan 13 | V | 120,60 | 1.86 | 60-cm |
| 2010 May 16 | V | 120,120 | 0.82 | 60-cm |
| 2010 June 20 | V | 120,120 | 0.86 | 60-cm |
| 2010 Nov 21 | V | 120,120 | 0.21 | 60-cm |
| 2011 Jan 17 | V | 120,120 | 0.82 | Schmidt |
| 2011 Jan 18 | V | 120 | 0.12 | Schmidt |
| 2011 Jan 19 | I | 120 | 0.15 | Schmidt |
| 2009 June 05 | R | 120 | 0.10 | 60-cm |
| 2009 June 06 | R | 120 | 0.10 | 60-cm |
| 2009 July 27 | V | 120 | 0.91 | 60-cm |
| 2009 Aug 26 | V | 120,60,60 | 50,50,50 | 60-cm |
| 2009 Aug 27 | V | 120,60,60 | 60,60,60 | 60-cm |
| 2009 Aug 26 | V | 120,60,60 | 50,50,50 | 60-cm |
| 2009 Aug 27 | V | 120,60,60 | 50,50,50 | 60-cm |
Table 1. List of our ultrashort-period targets

| Target | NSVS ID | α  [2000] | δ  [2000] | $R_{\text{NSVS}}$ [mag] | Period [d] | References          |
|--------|---------|-----------|-----------|----------------|----------|---------------------|
| 1      | 4484038 | 05 54 16.99 | +44 25 34.1 | 12.50 | 0.2185 | Norton et al. (2011) |
| 2      | 7179685 | 06 46 06.47 | +36 20 21.1 | 14.90 | 0.2097 | new                 |
| 3      | 4761821 | 08 01 50.03 | +47 14 33.8 | 13.10 | 0.2175 | Norton et al. (2011) |
| 4      | 2700153 | 13 43 51.43 | +63 04 22.8 | 12.48 | 0.2285 | new                 |
| 5      | 925605  | 14 01 46.37 | +77 16 38.7 | 13.73 | 0.2176 | new                 |
| 6      | 8626028 | 21 16 26.81 | +25 17 36.2 | 13.78 | 0.2174 | new                 |

Table 3. The 2MASS color indices $J - K$ and corresponding mean temperatures $T_m$ of the targets

| Target | NSVS 4484038 | NSVS 7179685 | NSVS 4761821 | NSVS 2700153 | NSVS 925605 | NSVS 8626028 |
|--------|---------------|---------------|--------------|--------------|--------------|--------------|
| $J - K$ | 0.590 ± 0.030 | 0.798 ± 0.033 | 0.651 ± 0.033 | 0.635 ± 0.037 | 0.363 ± 0.028 | 0.769 ± 0.028 |
| $T_m$   | 4950 ± 150    | 4040 ± 190    | 4690 ± 130   | 4730 ± 200   | 3490 ± 250   | 4200 ± 180   |

Figure 2. Same as Fig. 1 for NSVS 7179685.

Figure 3. Same as Fig. 1 for NSVS 4761821.

We determined in advance the mean temperatures $T_m$ of the binaries (Table 3) by their infrared color indices $(J - K)$ from the 2MASS catalog and the calibration color-temperature of Tokunaga (2000). The "spectral" temperatures of the targets obtained by comparison of their low-resolution spectra (Fig. 7) with those of standard stars with known temperatures, were almost the same as those of the values of $T_m$ in Table 3.

Firstly we assumed $T_1 = T_m$ and searched for solutions for fixed $T_2$, $i^0$ and $q^0 = 1$ varying the ephemeris, secondary temperature $T_2$, orbital inclination $i$ and potentials $\Omega_{1,2}$.

We adopted coefficients of gravity brightening 0.32 and reflection 0.5 appropriate for late stars. The linear limb-darkening coefficients were interpolated from the values of Van Hamme (1993). In order to reproduce the O’Connell effect we added cool spots on the components and varied their parameters: longitude $\beta$, latitude $\lambda$, angular size $\alpha$ and temperature factor $k = T_{\text{sp}}/T_1$. To obtain a good fit in all colors a third light was necessary for some targets.

As a result of the first stage of the light curve solution we obtained initial values $T_2^0$, $i^0$ and $\Omega_{1,2}^0$ as well as the ephemeris and spot parameters for each target. Further we determined the mass ratio applying $q$-search method. We calculated the normalized $\chi^2$ for two-dimensional grid $(i, \log q)$ consisting of values of $i$ within the $10^\circ$-range around the value $i^0$ with step $0.5^\circ$ and $q$ values 0.15, 0.20, ..., 0.95, 1.00, 1/0.95, 1/0.90, ..., 1/0.20, 1/0.15 ($T_2^0$, $i^0$ and spot parameters were fixed). In this way we obtained $\chi^2_{\text{min}}(1)$ corresponding to the first approximation $(i^1, q^1)$. Further this procedure was repeated around the pair $(i^1, q^1)$ for finer grid corresponding to 10 times smaller step of $q$ and 5 times smaller step of $i$. The obtained $\chi^2_{\text{min}}(2)$ corresponded to the second approximation $(i^2, q^2)$, etc.
we reach to the absolute minimum with $\chi^2_{\text{min}}(\text{abs}) \sim 1$ corresponding to the final values $(i^*, q^*)$.

The diagrams $(i, \log q)$ exhibit that the solution ambiguity rapidly increases with the decreasing of the orbital inclination (Fig. 8). Maceroni et al (1985) has reached to the same result by other procedure.

Further we searched for the best fit for fixed $i^*$, $q^*$, ephemerides and spot parameters, varying $T_2$, $\Omega_1$, and third light $l_3(V, R, I)$. Finally, we calculated $T_1$ and $T_2$. For this aim we developed the approach of Coughlin et al. (2011)

\begin{align*}
T_1 &= T_m + \frac{\Delta T}{c + 1} \\
T_2 &= T_1 - \Delta T
\end{align*}

where $c = l_2/l_1$ and $\Delta T$ (difference of temperatures of the components) are determined from the PHOEBE solution.

Table 4 contains the final values of all determined parameters: period $P$; initial epoch $HJD_0$; orbital inclination $i$; temperatures of the components $T_1, T_2$; potentials of the components $\Omega_1, \Omega_2$; fill-out factor $FF$; spot parameters; third light contribution in the different colors $l_3(V, R, I)$. The er-
5 ANALYSIS OF THE RESULTS

The analysis of the light curve solutions led us to several conclusions.

(a) All targets are overcontact (OC) binaries. The fill-out factor of NSVS 925605 is huge (Fig. 9).

(b) The mass ratios of four targets are within the narrow range 0.68–0.8 while NSVS 7179685 and NSVS 4761821 have components which masses differ around 2 times. Just they are with total eclipses and thus with most precise photometric mass ratio.

(c) The differences between the temperatures of the components of the targets are up to 220 K, that is expected for overcontact systems. The only exception is NSVS 925605 which cool components differ by nearly 700 K (although the big fill-out factor).

(d) NSVS 7179685 is the only target which more massive star is the cooler component. We do not know overcontact binary with orbital period below 0.21 d with such a property.

(e) NSVS 925605 is rare case of overcontact ultrashort period binary consisting of M dwarfs.

(f) NSVS 2700153 revealed considerable long-term variability during our observations (Fig. 4): the secondary minimum was shallower than the primary one in June 2010, but they became almost equal in depth in Jan 2011. Parameters in Table 4 correspond to the light curve solution from Jan 2011.

(g) NSVS 925605 shows high activity: emission in Hα line (Fig. 7) from its chromosphere; X-ray emission from the corona (it is the only X-ray source among our six targets identified as 1RXS J140139.8+771643); large cool photospheric spot. The considerable contribution of third light, especially in I color (Table 4), cannot be explained by blurring because there is not nearby star within 1 arcsec from this target. The reason could be non-Planck distribution of its energy. All appearances of high magnetic activity and huge fillout factor of NSVS 925605 might be interpreted in the light of the hypothesis of Martin et al. (2011) as a precursor of the merging of close magnetic binaries.

6 GLOBAL PARAMETERS OF THE TARGETS

Due to lack of RV-curve solutions we had to use empirical relations for determination of the global characteristics of our targets. For this aim we built a diagram period–semi-major axis ($P,a$) on the base of 14 binaries with $P < 0.27$ d which have radial velocity solution and modern light curve solution (Table 5). Their distribution was approximated by parabola

$$a = -1.154 + 14.633 \times P - 10.319 \times P^2 \quad [R\odot]$$

where $a$ is in solar radii and $P$ in days. The standard deviation of the fit is 0.05 R\odot and we assume this value as a mean error of $a$ for our targets with periods around 0.22 days.
Such a relation is expected for contact and overcontact binaries of MS late stars for which \( R_1 + R_2 \approx a \) and \( R \sim M^k \) where \( k \approx 1 \). Then the third Kepler law leads to \( a \sim P \) that is similar to the almost linear dependence (3) for periods of about 0.22 d (Fig. 10).

The \((P, a)\) relation (3) corresponds to the following relation “period – mass” for short-period binaries

\[
M = \frac{0.0134}{P^2} \left( -1.154 + 14.633 \times P - 10.319 \times P^2 \right)^3 [M]\]

where \( M \) is the total mass of the binary.

It is important to know is there a lower limit of the period-axis relation (3). Very recently Drake et al. (2014) modeled binaries with extremely short periods by configurations consisting of white dwarf and DM star. They are stable non-accreting WD+MS systems which differ from the accretion induced variability in CV variables. We added these five systems (Table 5) on our diagram \((P, a)\). It is interesting that their semi-axes, and respective masses, are almost the same (within the errors) while the orbital periods are quite different. The WD+DM models (blue asterisk) of four of these binaries fall away from the line approximating the relation \((P, a)\) of binaries with MS components (red line). It is visible that the dependence of the semi-axis of these extremely short-period binaries on the period (blue continuous line) is considerably weaker. One of them, CSS J001242.4+130809, has 2 models: WD+DM and DM+DM (Table 5). Its DM+DM model as well as the longest-period target, CSS J090119.2+114254, fall just on the line period-axis of our MS binaries (Fig. 10). This may imply that such configurations are more appropriate for these two targets. The low-resolution spectroscopy of the extremely short-period binaries Drake et al. 2014 revealed the presence of Balmer emission and Ca H+K emission typical for late dwarfs and strong local magnetic fields.

We used the empirical relation (3) to obtain the semi-major axes \( a \) of our targets and further the masses \( M_{1,2} \), radii \( R_{1,2} \), and luminosities \( L_{1,2} \) of their components in solar units; bolometric and visual absolute magnitudes \( M_{bol} \) and \( M_V \) of the targets; distance \( d \) in parsecs and orbital angular momenta \( J_{orb} \) (by the expression of Popper & Ulrich 1977). Table 6 contains the values of the obtained global parameters.

The orbital angular momenta of the targets (Table 6) are considerably smaller than those of the RS CVn binaries and detached systems which have \( \log J_{orb} \) ≥ +0.08. They are smaller also than those of the ordinary contact systems which have \( \log J_{orb} \) ≥ −0.5. The obtained \( J_{orb} \) values are bigger only than those of the shortest-period CVs of SU UMa type.

### Table 4. Results from the light curve solutions

| Parameter | NSVS 4484038 | NSVS 7179685 | NSVS 4761821 | NSVS 2700153 | NSVS 925605 | NSVS 8626028 |
|-----------|--------------|--------------|--------------|--------------|--------------|--------------|
| \( P \) [d] | 0.218493 | 0.209740 | 0.217513 | 0.228456 | 0.217629 | 0.217407 |
| \( HJD_0 \) [d] | 5539.479711 | 5104.528662 | 5563.438743 | 5368.312230 | 4988.575181 | 5070.408406 |
| \( q = M_2/M_1 \) | 0.792 | 2.128 | 0.432 | 0.775 | 0.678 | 0.805 |
| \( T_1 \) [K] | ±0.00035 | ±0.008111 | ±0.009020 | ±0.000114 | ±0.000028 | ±0.000051 |
| \( r_1 \) | ±0.41 | ±0.67 | ±0.80 | ±0.90 | ±0.50 | ±0.70 |
| \( r_2 \) | ±0.364 | ±0.456 | ±0.318 | ±0.364 | ±0.408 | ±0.380 |
| \( i_2/I_1 \) | ±0.727 | ±1.731 | ±0.479 | ±0.709 | ±0.221 | ±0.592 |
| \( \Omega \) | ±0.004 | ±0.006 | ±0.006 | ±0.007 | ±0.010 | ±0.004 |
| \( F \) | 0.0857 | 0.193 | 0.136 | 0.071 | 0.702 | 0.207 |

7 CONCLUSIONS

We found well-defined empirical relation “period – semi-major axis” for the short-period binaries and used it for estimation of the global parameters of six ultrashort-period targets.

One of them, NSVS 925605, with huge fill-out factor and another peculiar characteristics (consisting of M components with high activity and non-Planck energy distribution) probably is at stage of merging.

Our results revealed that all six ultrashort-period tar-
Table 5. Semi-major axes of short-period binaries from spectral studies

| Star                  | $P_{\text{orb}}$ | $M_1 + M_2$ | $a$  | References       |
|-----------------------|------------------|-------------|------|------------------|
| CSS J090826.3+123648* | 0.1392           | 0.80        | 1.049| Drake et al. 2014|
| CSS J111647.8+294602* | 0.1462           | 0.75        | 1.061| Drake et al. 2014|
| CSS J081158.6+311959* | 0.1562           | 0.70        | 1.083| Drake et al. 2014|
| CSS J001242.4+130809* | 0.1641           | 0.80        | 1.171| Drake et al. 2014|
| CSS J001242.4+130809* | 0.1641           | 0.41        | 0.937| Drake et al. 2014|
| CSS J090119.2+114254* | 0.1867           | 0.70        | 1.222| Drake et al. 2014|
| BX Tri                | 0.1926           | 0.77±0.03   | 1.28±0.022| Dimitrov & Kyurkchieva 2010|
| BW3 V38               | 0.1984           | 0.85±0.11   | 1.356±0.085| Maceroni & Montalban 2004|
| SDSS J001641-000925   | 0.1986           | 0.88±0.08   | 1.372±0.057| Davenport et al. 2014|
| GSC 1387-475          | 0.2178           | 0.94±0.03   | 1.492±0.019| Rucinski & Pribulla 2008|
| CC Com                | 0.2211           | 1.09±0.02   | 1.585±0.011| Pribulla et al. 2007|
| ISWASP J160156.04+202821.6 | 0.2265 | 1.43±0.06 | 1.761±0.033| Lohr et al. 2014|
| V523 Cas              | 0.2337           | 1.13±0.04   | 1.663±0.025| Rucinski et al. 2003|
| RW Com                | 0.2373           | 1.18±0.03   | 1.704±0.060| Pribulla et al. 2009|
| BI Vul                | 0.2518           | 1.45        | 1.899 |
| ISWASP J150822.80-054236.9 | 0.2601 | 1.62±0.10 | 2.013±0.065| Lohr et al. 2014|
| VZ Psc                | 0.2612           | 1.46±0.06   | 1.950±0.040| Dimitrov & Kjurkchieva 2010|
| V803 Aql              | 0.2634           | 1.58        | 2.014 |
| FS Cra                | 0.2636           | 1.51        | 1.984 |
| 44 Boo=i Boo          | 0.2678           | 1.47        | 1.987 |

Note: Stars with WD+dM model are marked with asterisk.

Table 6. Global parameters of the targets

| Name     | $a$  | $R_1$ | $R_2$ | $M$  | $M_1$ | $M_2$ | $L_1$ | $L_2$ | $M_{\text{bol}}$ | $V_{\text{max}}$ | $d$   | $J_{\text{orb}}$ |
|----------|------|-------|-------|------|-------|-------|-------|-------|------------------|------------------|------|------------------|
| NSVS 4484038 | 1.55 | 0.63±0.02 | 1.01  | 0.56±0.06 | 0.23±0.02 | 5.73±0.11 | 200  | 0.151 |
| ±0.05  | 0.57±0.02 | ±0.10  | 0.45±0.04 | 0.17±0.02 | 5.928 | ±12 | ±0.034 |
| NSVS 7179685 | 1.461 | 0.48±0.02 | 0.95  | 0.30±0.03 | 0.06±0.01 | 6.68±0.13 | 428  | 0.118 |
| ±0.05  | 0.67±0.02 | ±0.09  | 0.65±0.06 | 0.10±0.01 | 7.284 | ±26 | ±0.027 |
| NSVS 4761821 | 1.541 | 0.71±0.02 | 1.04  | 0.72±0.07 | 0.23±0.02 | 6.00±0.10 | 248  | 0.137 |
| ±0.05  | 0.49±0.02 | ±0.10  | 0.32±0.03 | 0.11±0.01 | 6.397 | ±12 | ±0.030 |
| NSVS 2700153 | 1.650 | 0.67±0.02 | 1.15  | 0.65±0.06 | 0.22±0.02 | 5.81±0.11 | 267  | 0.190 |
| ±0.05  | 0.60±0.02 | ±0.11  | 0.50±0.05 | 0.16±0.02 | 6.060 | ±14 | ±0.042 |
| NSVS 925605 | 1.542 | 0.73±0.02 | 1.04  | 0.62±0.06 | 0.11±0.01 | 6.82±0.12 | 154  | 0.155 |
| ±0.05  | 0.64±0.02 | ±0.10  | 0.42±0.04 | 0.024±0.005 | 8.020 | ±9 | ±0.034 |
| NSVS 8626028 | 1.540 | 0.63±0.02 | 1.04  | 0.57±0.06 | 0.13±0.01 | 6.40±0.10 | 184  | 0.159 |
| ±0.05  | 0.57±0.02 | ±0.10  | 0.47±0.04 | 0.09±0.01 | 7.904 | ±9 | ±0.035 |

ACKNOWLEDGEMENTS

The authors gratefully acknowledge observing grant support from the Institute of Astronomy and Rozhen National Astronomical Observatory, Bulgarian Academy of Sciences. The research was supported partly by funds of project RD-08-244 of Shumen University.

This research make use of the SIMBAD, Vizier, and Aladin databases, operated at CDS, Strasbourg, France, and NASA’s Astrophysics Data System Abstract Service. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research also has made use of the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (http://www.nofs.navy.mil/data/fchpix/).

This research was based on data obtained with the telescopes at Rozhen National Astronomical Observatory, the Northern Sky Variability Survey (http://skydot.lanl.gov/nsvs/nsvs.php), and SuperWASP Public Archive first public data release DR1 (http://www.wasp.le.ac.uk/public/).

The authors are grateful to anonymous referee for the valuable notes and propositions.
Figure 10. Diagram period – semi-major axis for short-period binaries. The thin black lines represent the isolines of binary (total) mass. The positions of the stars from Table 6 are marked by red diamonds while those of our targets are marked by black pluses. The red line exhibits the empirical relation described by equation (3). The blue line presents empirical relation for WD+dM binaries, marked with blue asterisk. Color version of this figure is available in the online journal.

REFERENCES

Bilir S., Karatas Y., Demircan O., Eker Z., 2005, MNRAS, 357, 497
Butters O.W., et al., 2010, A&A, 520L, 10
Coughlin J.L., Lo’pez-Morales M., Harrison T.E., Ule N., Hoffman D.I., 2011, AJ, 141, 78
Dall T., Schmidtobreick L., 2005, A&A, 429, 625
Davenport J.R.A., et al., 2013, ApJ, 764, 62
Dimitrov D.P., 2009, Bulg. AJ, 12, 49
Dimitrov D.P., Kjurkchieva D.P., 2010, MNRAS, 406, 2559
Drake A.J., et al., 2014, ApJ, 790, 157
Hrivnak B.J., Guinan E.F., Lu W., 1995, ApJ, 455, 300
Henry T.J., et al., 1999, ApJ, 512, 864
Landolt A., 1992, AJ, 104, 340
Lohr M.E., Hodgkin S.T., Norton A.J., Kolb U.C., 2014, A&A 563A, 34
Lu W., Rucinski S.M., Ogloza W., 2001, AJ, 122, 402
Maceroni C., Montalban J., 2004, A&A, 426, 577
Maceroni C., Rucinski S.M., 1997, PASP, 109, 782
Maceroni C., van’t Veer F., 1996, A&A, 311, 523
Maceroni C., Milano L., Russo G., 1985, MNRAS, 217, 843
Martin E.L., Spruit H.C., Tata R., 2011, A&A, 535, 50
Nefs S.V., et al., 2012, MNRAS 425, 950
Norton A.J., et al., 2011, A&A, 528A, 90
Pollacco D.L., et al. 2006, PASP, 118, 1407
Popper D., Ulrich R., 1977, ApJ, 212, L131
Pribulla T., et al., 2007, AJ, 133, 1977
Pribulla T., et al., 2009, AJ 137, 3646
Pribulla T., et al., 2012, AN 333, 754
Prša A., Zwitter T., 2005, ApJ, 628, 426
Qian S.-B., Jiang L.-Q., Zhu L.-Y., Zejda M., Mikulášek Z., Fernández-Lajús E., Liu N.-P., 2014, CoSka, 43, 290
Rucinski S.M., 1992, AJ, 103, 960
Rucinski S.M., 2007, MNRAS, 382, 393
Rucinski S.M., Pribulla T., 2008, MNRAS, 388, 1831
Rucinski S.M. et al, 2003, AJ, 125, 3258
Stetson P., 2000, PASP, 112, 925
Tokunaga A.T., in Allen’s astrophysical quantities, 4th ed.

Figure A1. Folded light curves based on the NSVS and Super-WASP observations of the targets

Edited by Arthur N. Cox, New York, AIP Press, Springer, 2000, p. 143
Van Hamme W., 1993, AJ, 106, 2096
Weldrake D.T.F., Sackett P.D., Bridges T.J., Freeman K.C., 2004, AJ, 128, 736
Woźniak P.R., et al., 2004, AJ, 127, 2436

APPENDIX A: ADDITIONAL INFORMATION
Table A1. Colors of the targets and their standard stars

| Star  | ID         | GSC1.2(2.3) | $V$   | $B - V$  | $V - R$  | $V - I$  | $J - K$  |
|-------|------------|-------------|-------|----------|----------|----------|----------|
| Var   | 2924-0179  | 12.43       | 0.71  | 0.25     | 1.17     | 0.59     |
| St1   | 2924-2161  | 12.86       | 1.00  | 0.40     | 1.31     | 0.69     |
| St2   | 2924-1407  | 12.68       | 2.23  | 0.70     | 1.93     | 1.08     |
| St3   | 2924-1435  | 13.23       | 0.60  | 0.16     | 0.78     | 0.37     |
| St4   | 2924-0641  | 12.02       | 1.87  | 0.68     | 1.88     | 1.07     |
| St5   | 2924-1202  | 11.79       | 0.86  | 0.13     | 0.69     | 0.34     |
| St6   | 2924-1069  | 12.94       | 0.97  | 0.46     | 1.40     | 0.75     |

Table A2. Rozhen photometric data. This is a sample of the full table, which is available with the online version of the article (see Supporting Information). The number of the target is the same as in Table 1.

| Target | Filter | $HJD$(Min) [d] | Magnitude [mag] | Error [mag] |
|--------|--------|----------------|----------------|-------------|
| 1      | $V$    | 2455252.207213 | 12.8632        | 0.0059      |
| 2      | $I$    | 2455252.209054 | 11.6127        | 0.0054      |
| 3      | $V$    | 2455252.201868 | 12.2977        | 0.0059      |
| 4      | $I$    | 2455252.272028 | 11.5911        | 0.0053      |

Table A3. Times of the observed eclipse minima.

| $HJD$(Min) [d] | Filter | Type of Epoch | Epoch | $O - C$ [d] |
|----------------|--------|---------------|-------|-------------|
| 2455539.497830 | $V$    | Min I         | 0     | 0.005063    |
| 2455539.597669 | $I$    | Min I         | 0     | -0.001747   |
| 2455539.589299 | $V$    | Min II        | 0     | 0.015772    |
| 2455539.598193 | $I$    | Min II        | 0     | 0.001041    |
| 2455570.287555 | $V$    | Min I         | 1     | -0.010548   |
| 2455570.287666 | $I$    | Min I         | 1     | -0.000540   |
| 2455570.397084 | $V$    | Min II        | 1     | 0.000236    |
| 2455570.397060 | $I$    | Min II        | 1     | 0.000126    |

* Standard stars used for the observations with the 2-m telescope.