Photometric observations and light curve solutions of the W UMa stars
NSVS 2244206, NSVS 908513, CSS J004004.7+385531 and
VSX J062624.4+570907

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Abstract Photometric observations in Sloan g′ and i′ bands of four W UMa stars, NSVS 2244206, NSVS 908513, CSS J004004.7+385531 and VSX J062624.4+570907, are presented. The light curve solutions reveal that all targets have overcontact configurations with fillout factors within 0.15–0.26. Their components are G-K spectral types and are almost in thermal contact. They are also relatively close in size and luminosity: the radius ratios \( \frac{r_2}{r_1} \) are within 0.75–0.90; the luminosity ratios \( \frac{l_2}{l_1} \) are within 0.53–0.63. The results of the light curve solution of CSS J004004.7+385531 imply the weak limb-darkening effect of its primary component and possible presence of additional absorbing features in the system.

Key words: methods: data analysis — stars: fundamental parameters — stars: binaries: eclipsing: individual (NSVS 2244206, NSVS 908513, CSS J004004.7+385531, VSX J062624.4+570907)

1 INTRODUCTION

W UMa-type binaries consist of two cool stars (F, G, K spectral type) in contact with each other, surrounded by a common convective envelope lying between the inner and outer critical Roche surfaces. As a result, their components possess almost identical surface brightness, i.e. temperature (Lucy 1968, 1976).

The periods of W UMa binaries are in the range 0.22–0.70 d. They form a large family representing around 1/500–1/130 of the main sequence (MS) stars in the solar neighborhood (Rucinski 2002). Although there are many studies on them (Liu et al. 2011; Qian et al. 2013; Liao et al. 2014, etc.), a complete theory of their origin, structure, evolution and future fate is still lacking.

The most recent theoretical models explain the formation of (short-period) contact systems by systematic angular momentum loss (AML) in initially detached binaries with orbital periods of a couple of days, due to magnetized stellar winds and tidal coupling (Vilhu 1981; Rahnen 1982; Stepien 1995). But according to Pribulla & Rucinski (2006), a third (distant) companion is necessary for formation of systems with a period under 1 d.

There are two models of evolution during the contact phase itself. The thermal relaxation oscillation (TRO) model assumes that each component of the binary is out of thermal equilibrium and its size oscillates around the inner Roche lobe (Lucy 1976; Flannery 1976; Webbink 1977; Yakut & Eggleton 2005). The binary spends a part of its present life in contact (when both stars fill their Roche lobes and mass flows from the secondary to the primary) and the rest as a semi-detached binary (when only the primary fills its Roche lobe and mass flows from the primary to the secondary), slowly evolving towards an extreme mass ratio system. The TRO model explains the geometry of W UMa-type stars well: the primary component is an ordinary MS star and the secondary is also an MS star but swollen to its Roche lobe by energy transfer. The main problem with the TRO model is the mechanism of energy transfer. The alternative model (Stepien 2004; Stepien 2006; Stepien 2009, 2011) assumes that mass transfer occurs with mass ratio reversal, similar to Algol-type binaries, following Roche lobe overflow by the massive component. The contact configuration is formed immediately after that or after some additional AML. Each component is then in thermal equilibrium and the large size of the currently less massive component results from its advanced evolutionary stage (its core is depleted of hydrogen).

The final products of W UMa-type evolution are also 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 as a result of the high rate of AML); two brown dwarfs (Li et al. 2007) or two stars with very low mass (if mass-loss rate is very high).

The existence of W-subtype systems is another unresolved problem of W UMa-type stars. They appear by the lower surface brightness of the more massive components of the binaries (Binnendijk 1970). The W-subtype systems are recognized by the primary minima which are occultations (indicating that the small components are the hotter ones). It was suspected that this effect is due to a large coverage of cool, dark spots on the primary, significantly reducing its apparent luminosity (Eaton et al. 1980; Stepien 1980; Hendry et al. 1992), but this explanation was not entirely convincing. Gazeas & Niarchos (2006) suggested that subtype A systems have higher total angular momentum and can evolve into subtype W which is the opposite of the earlier conclusion.

Besides their key role in understanding stellar evolution, contact binaries are natural laboratories to study important astrophysical processes: interaction of stellar winds; magnetic activity; mass, energy and angular momentum transfer and loss; the phenomenon of “mass ratio reversal”; and merging or fusion of the stars (Martin et al. 2011). The period-color-luminosity relation of contact binary stars is a useful tool for distance determination (Rucinski 1994, 1996; Rucinski & Duerbeck 1997; Klagyivik & Csizmadia 2004; Eker et al. 2008).

Hence, study of the properties and variety of W UMa stars is important for modern astrophysics. However, the statistics of the most interesting W UMa stars, those with short periods, is still quite poor (Terrell et al. 2012), mainly due to their faintness (they are late-type stars).

In this paper, we present photometric observations and light curve solutions of four short-period W UMa stars: NSVS 2244206, NSVS 908513, CSS J004004.7+385531 ≡ 2MASS J00400476+3855318 ≡ GSC 02797−00705 ≡ UCAC4—465−002474 and VSX J062624.4+570907 ≡ 2MASS J06262444+5709075 ≡ CSS J062624.5+570907 ≡ GSC 03772—01134. Table 1 presents their coordinates and available (preliminary) information about their light variability.

2 OBSERVATIONS

Our CCD photometric observations of the targets in Sloan $g'$, $i'$ bands were carried out at Rozhen Observatory with the 30-cm Ritchey-Chrétien Astrograph (located in the IRIDA South dome) using and ATIK 4000M CCD camera (2048×2048 pixels, 7.4 μm pixel$^{-1}$, field of view 35 × 35 arcmin). Information about our observations is presented in Table 2.

The photometric data were reduced by AIP4WIN2.0 (Berry & Burnell 2005). We performed aperture ensemble photometry with the software VPHOT using more than six standard stars in the observed field of each target. The coordinates and magnitudes of the standard and check stars (Table 3) were taken from the catalog UCAC4 (Zacharias et al. 2013).

We established that there are two close objects, CSS J004004.7+385531 and VSX J004004.4+385513, with the same periods and types of variability in the VSX database (Table 1). Our observations revealed that the true variable is CSS J004004.7+385531 while VSX J004004.4+385513 is a stationary star (Fig. 1).

We determined the times of the individual minima (Table 4) by the method of Kwee & van Woerden (1956).

3 LIGHT CURVE SOLUTIONS

We carried out modeling of the photometric data by the code PHOEBE (Prša & Zwitter 2005). It is based on the Wilson–Devinney (WD) code (Wilson & Devinney 1971;
### Table 1 Previous Information on Our Targets

| Name               | RA       | Dec      | Period [d] | Epoch [d] | $V$ [mag] | Ampl [mag] | Type     | Ref       |
|--------------------|----------|----------|------------|-----------|-----------|------------|----------|-----------|
| NSVS 2244206       | 06 06 20.21 | +65 07 21.0 | 0.280727  | –         | 11.997    | 0.32       | EB/EW    | [1]       |
| NSVS 908513        | 12 30 39.36 | +83 23 07.8 | 0.399592  | –         | 11.772    | 0.53       | EB/EW    | [1]       |
| CSS J004004.7+385531 | 00 40 04.73 | +38 55 31.9 | 0.251206  | –         | 13.95     | 0.72       | EW       | [2]       |
| VSX J062624.4+570907 | 06 26 24.43 | +57 09 07.4 | 0.280628  | 245135.756 | 13.42     | 0.34       | EW       | [3]       |

References: [1] Gettel et al. (2006); [2] Drake et al. (2014); [3] Wozniak et al. (2004)

### Table 2 Journal of the Rozhen Photometric Observations

| Target             | Date       | Exposure $(g', i')$ [s] | Number $(g', i')$ | Error $(g', i')$ [mag] |
|--------------------|------------|-------------------------|-------------------|-------------------------|
| NSVS 2244206       | 2015 Jan 8 | 60, 90                  | 64, 64            | 0.004, 0.004           |
|                    | 2015 Jan 11 | 60, 90                | 78, 78            | 0.003, 0.004           |
|                    | 2015 Jan 12 | 60, 90                | 91, 84            | 0.004, 0.004           |
|                    | 2015 Jan 15 | 60, 90                | 147, 171          | 0.003, 0.003           |
| NSVS 908513        | 2015 Mar 31 | 60, 90              | 55, 55            | 0.003, 0.004           |
|                    | 2015 Apr 11 | 60, 90               | 106, 144          | 0.002, 0.003           |
|                    | 2015 Apr 16 | 60, 90               | 138, 137          | 0.004, 0.005           |
| CSS J004004.7+385531 | 2014 Nov 10 | 120, 120            | 110, 112          | 0.014, 0.014           |
|                    | 2014 Nov 20 | 120, 120            | 16, 16            | 0.011, 0.015           |
|                    | 2014 Nov 22 | 120, 120            | 44, 60            | 0.012, 0.014           |
|                    | 2014 Nov 26 | 120, 120            | 74, 66            | 0.008, 0.010           |
| VSX J062624.4+570907 | 2014 Dec 24 | 150, 150           | 118, 117          | 0.003, 0.006           |

Fig. 3 Same as Fig. 2 but for NSVS 908513.

Wilson 1979). PHOEBE incorporates all the functionality of the WD code but also provides a graphical user interface alongside other improvements, including Sloan filters used in our observations. We apply the traditional convention that MinI (phase 0.0) is the deeper light minimum and the star that is eclipsed at MinI is the primary (hotter) component.

We determined in advance the mean temperatures $T_m$ of the binaries (Table 5) by their infrared color indices $(J - K)$ from the 2MASS catalog and the calibration color-temperature of Tokunaga (2000). In fact, the determination of stellar temperatures from the infrared flux is a method first developed by Binnendijk (1970).

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

At the first stage, we fixed $T_0^1 = T_m$ and searched for a fit by varying the secondary temperature $T_2$, orbital inclination $i$, mass ratio $q = m_2/m_1$ and potentials $\Omega_{1,2}$ (and thus relative radii $r_{1,2}$ and fillout factor $f$). The quality of the fit was estimated by the value of $\chi^2$.

Coefficients of gravity brightening and the reflection effect appropriate for stars with convective envelopes were adopted. Initially, we used a linear limb-darkening law.
with limb-darkening coefficients corresponding to the stellar temperatures and Sloan photometric system (Claret & Bloemen 2011).

In order to reproduce the light curve distortions of the targets, we added cool spots on the stellar surfaces and varied spot parameters: longitude $\lambda$, latitude $\beta$, angular size $\alpha$ and temperature factor $\kappa = T_{sp}/T_{st}$.

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

After reaching the best fit, we adjusted $T_{1}$ and $T_{2}$ around the value $T_{m}$ by the formulae (Kjurkchieva et al. 2015)

$$T_{1}^{c} = T_{m} + \frac{c \Delta T}{c + 1},$$

$$T_{2}^{c} = T_{1}^{c} - \Delta T.$$  

Here $c = l_{2}/l_{1}$ and $\Delta T = T_{1}^{0} - T_{2}^{0}$ are determined from the PHOEBE solution.
Finally, we slightly varied $T_1$, $T_2$, $i$ and $\Omega_{1,2}$ around their values $T_1^0$, $T_2^0$, $i^0$ and $\Omega_{1,2}^0$ and obtained the final PHOEBE solution.

The first part of Table 5 contains the parameters of our light curve solutions: mass ratio $q$; orbital inclination $i$; potentials $\Omega_{1,2}$; fillout factor $f$; stellar temperatures $T_1$, $T_2$; relative radii $r_1$, $r_2$; and ratio of relative luminosities $l_2/l_1$. The errors of these parameters are the formal PHOEBE errors. Table 6 gives the obtained spot parameters. The synthetic curves corresponding to our light curve solutions are shown in Figures 2–5.

Due to the lack of radial velocity measurements, we were not able to determine reliable values for the global parameters of the target components. However, we could obtain some estimations of these quantities by the following procedure.

The primary luminosity $L_1$ was determined by the empirical luminosity-temperature relation for MS stars. The secondary luminosity $L_2$ was calculated by the relation $L_2 = cL_1$ where $c = l_2/l_1$ is the luminosity ratio from our light curve solution.

We obtained the orbital separation $a$ (in solar radii) from the equation

$$\log a = 0.5 \log L_i - \log r_i - 2 \log T_i + 2 \log T_\odot,$$  \hspace{1cm} (3)$$

and then calculated the absolute stellar radii by $R_i = ar_i$.

The total target mass $M$ (in solar units) was calculated from Kepler’s third law

$$M = \frac{0.0134a^3}{P^2},$$ \hspace{1cm} (4)$$

where $P$ is in days while $a$ is in solar radii. Then the individual masses $M_i$ were determined by the formulae $M_1 = M/(1 + q)$ and $M_2 = M - M_1$.

The global parameters of the target components obtained by the foregoing procedure are given in the second part of Table 5. Their errors are calculated from the corresponding formulae by the errors in the quantities of the light curve solutions or by observations.

### Table 4

| Target          | MinI         | MinII       |
|-----------------|--------------|-------------|
| NSVS 2244206    | 2457038.42614| 2457034.51298|
| NSVS 908513     | 2457124.30454| 2457124.50608|
| CSS J004004.7+385531 | 2456972.34036| 2456972.46714|
| VSX J062624.4+570907 | 2457016.33657| 2457016.47792|

### 4 ANALYSIS OF THE RESULTS

The analysis of the light curve solutions of our short-period W UMa stars led to several important results.

(1) CSS J004004.7+385531 reveals total eclipses while the remaining three targets undergo partial eclipses.

(2) The temperatures of the stellar components of the targets correspond to G-K spectral type (Table 5). The temperature differences in their components do
not exceed 450 K and the components of CSS J004004.7+385531 are in thermal contact.

(3) The targets have overcontact configurations with fill-out factors \( f \) in the range 0.15–0.26 (Table 5). It should be pointed out that the preliminary classification of NSVS 2244206 and NSVS 908513 was EB/EW (Table 1) but our observations and light curve solutions led to the conclusion that they have overcontact configurations (Fig. 6).

(4) The target components are relatively close in size and luminosity: the size ratios \( r_2/r_1 \) are within 0.75–0.90; the luminosity ratios \( l_2/l_1 \) are within 0.53–0.63.

(5) We observed slightly different levels of the two quadratures (O’Connell effect) in three of our targets. They were reproduced by small cool spots (Table 6) on their primaries. We obtained solutions with the same quality of fit for slightly different combinations of spot sizes (within 1°) and latitudes (±25° around the stellar equator). Table 6 presents parameters of the equatorial spots whose angular sizes have minimum values.

(6) The residuals of CSS J004004.7+385531 are bigger than those of the other three targets, which is expected considering this totally-eclipsed binary is the faintest member of our sample (Table 1). However, the residuals are biggest at its primary eclipse because the synthetic eclipse is narrower than the observed one (Fig. 4). The reason for this discrepancy is that the observed primary eclipse of CSS J004004.7+385531 turns out to be slightly wider than the secondary one. This may be due to some additional structure in the system which cannot be accounted for with the software, for example an equatorial bulge around the less massive component (accretor) could have formed as a result of the transferred mass; the presence of a disk-like feature; or clouds at some Lagrangian points (as a result of previous nonconservative mass transfer, Stępień & Kiraga 2013).

(7) We managed to reproduce the almost flat bottom of the primary eclipse of CSS J004004.7+385531, especially in the \( i' \) band, with only a very small limb-darkening coefficient of 0.18, a value considerably smaller than that corresponding to its temperature. This formally means there is a faint limb-darkening effect, i.e. an almost homogeneous stellar disk associated with the primary component. There are two possible reasons for this effect. The first one is that the theory and corresponding codes for light curve synthesis cannot precisely take the limb-darkening effect into account when applied to overcontact binaries with strongly distorted components whose photospheres are deep inside the envelopes. The second reason for the flat bottom of the primary eclipse might be contribution of light from the optically thick region around L1 which is covered by the secondary component at the primary eclipse. Such an argument just refers to CSS J004004.7+385531 which undergoes an almost central eclipse.

(8) Quite often, photometric solutions of W UMa light curves appear to be ambiguous since both A and W configurations can fit the observations well (van Hamme 1982a; Lapasset & Claria 1986). The mass ratio of W UMa binaries is an important parameter for their W/A subclassification. However, the rapid rotation of their components does not allow us to obtain the precise spectral mass ratio from measurement of their highly broadened and blended spectral lines (Bilir et al. 2005; Dall & Schmidtobreick 2005). As a result, the W/A subclassification of W UMa binaries is mainly based on the widely-accepted empirical relation “spectral type – mass” (van Hamme 1982a; Lapasset & Claria 1986): the G-K binaries are W subtype while A and earlier F binaries are A subtype.

In particular, our targets are faint objects and we have only obtained their photometric mass ratios \( q \) by vary-

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### Table 5 Parameters of the Best Light Curve Solutions (top) and Global Parameters (bottom) of the Targets

| Star name   | q     | \( q \) (°) | \( T_\text{in} \) (K) | \( T_1 \) (K) | \( T_2 \) (K) | \( r_1 \) | \( r_2 \) | \( l_2/l_1 \) | \( L^\text{bol}_1 \) | \( L^\text{bol}_2 \) | \( a(R_\odot) \) | \( R_1(R_\odot) \) | \( R_2(R_\odot) \) | \( M_1(M_\odot) \) | \( M_2(M_\odot) \) |
|-------------|-------|-------------|------------------------|---------------|---------------|--------|--------|-------------|---------------------|---------------------|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| NSVS 2244206 | 0.735±0.003 | 76.42±0.07 | 5000 | 5157 ± 36 | 4702 ± 32 | 0.429±0.001 | 0.376±0.001 | 0.530±0.034 | 0.519±0.023 | 0.338±0.045 | 2.214±0.064 | 0.951±0.028 | 0.833±0.032 | 1.064±0.084 | 0.782±0.067 |
| NSVS 908513  | 0.709±0.002 | 75.15±0.03 | 5810 | 5923 ± 25 | 5615 ± 23 | 0.422±0.001 | 0.363±0.001 | 0.5946 | 1.031±0.023 | 0.646±0.046 | 2.312±0.066 | 0.976±0.03 | 0.839±0.033 | 0.607±0.051 | 0.430±0.038 |
| CSS J004004.7+385531 | 0.548±0.004 | 89.77±0.01 | 4560 | 4650 ± 37 | 4560 ± 38 | 0.449±0.003 | 0.344±0.004 | 0.5883 | 0.254±0.04 | 0.149±0.062 | 1.798±0.055 | 0.808±0.03 | 0.619±0.026 | 0.798±0.07 | 0.437±0.043 |
| VSX J062624.4+570907 | 0.777±0.002 | 78.88±0.11 | 5230 | 5350 ± 20 | 5044 ± 7 | 0.416±0.002 | 0.372±0.002 | 0.6314 | 0.604±0.073 | 0.421±0.096 | 2.23±0.067 | 0.927±0.032 | 0.829±0.027 | 1.061±0.094 | 0.825±0.077 |

| q     | \( q \) (°) | \( T_\text{in} \) (K) | \( T_1 \) (K) | \( T_2 \) (K) | \( r_1 \) | \( r_2 \) | \( l_2/l_1 \) | \( L^\text{bol}_1 \) | \( L^\text{bol}_2 \) | \( a(R_\odot) \) | \( R_1(R_\odot) \) | \( R_2(R_\odot) \) | \( M_1(M_\odot) \) | \( M_2(M_\odot) \) |
|-------|-------------|------------------------|---------------|---------------|--------|--------|-------------|---------------------|---------------------|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
Table 6 Parameters of the Cool Spots on the Targets

| Target | $\beta$ | $\lambda$ | $\alpha$ | $\kappa$ |
|--------|---------|-----------|---------|---------|
| NSVS 908513 | 90 | 330 | 13 | 0.90 |
| CSS J004004.7+385531 | 90 | 70 | 7 | 0.90 |
| VSX J062624.4+570907 | 90 | 270 | 10 | 0.90 |

5 CONCLUSIONS

We obtained light curve solutions of four short-period W UMa binaries. The main results are as follows.

1. The temperatures of the stellar components of the targets correspond to G-K spectral type and they are almost in thermal contact.

2. All targets are overcontact configurations with fillout factors within 0.15–0.26.

3. The target components are relatively close in size and luminosity: the size ratios $r_2/r_1$ are within 0.75–0.90; the luminosity ratios $l_2/l_1$ are within 0.53–0.63.

4. The results of the light curve solution of CSS J004004.7+385531 imply a weak limb-darkening effect of its primary component and possible presence of additional absorbing features in the system.

This study adds four new systems with estimated parameters to the family of short-period binaries. They could help to improve the statistical relations between the stellar parameters of low-massive stars and better understand the evolution of close binaries.

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