Observations and light curve solutions of the eclipsing stars CSS J075205.6+381909 and NSVS 691550

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Abstract. The paper presents observations and light curve solutions of the eclipsing stars CSS J075205.6+381909 and NSVS 691550. As a result their initial epochs were determined. The target periods turned out almost equal to the previous values. We found that NSVS 691550 is overcontact system whose components are close in temperature while CSS J075205.6+381909 has almost contact configuration and temperature difference of its components is around 2000 K. Both targets undergo partial eclipses. Their stellar components seem to obey the relations mass-temperature of MS stars.

Key words: binaries: eclipsing binaries: close binaries: contact stars: fundamental parameters; individual (CSS J075205.6+381909, NSVS 691550)

Introduction

Most of the W UMa stars consisting of solar-type components have orbital periods within $0.25 \, \text{d} < P < 0.7 \, \text{d}$. They are recognized by continuous brightness variations and nearly equal minima depth. The short orbital periods of these binaries mean small orbits and synchronized rotation and orbital revolution.

The investigation of the contact binary systems is important for the modern astrophysics because they are natural laboratories for study of the late stage of the stellar evolution connected with the processes of mass and angular momentum loss, merging or fusion of the stars (Martin et al., 2011).

The huge surveys ROTSE, MACHO, ASAS, Super WASP, Catalina, Kepler increased significantly the number of stars classified as W UMa type but small part of them are studied in details.

This paper presents our follow-up photometric observations of two W UMa stars, CSS J075205.6+381909 (further CSS 0752+38) and NSVS 691550, and their modeling. Table 1 presents the coordinates of our targets and available preliminary information for their light variability from VSX database (www.aavso.org/vsx/).

1. Observations

Our CCD photometric observations of the targets 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 CCD camera ATIK 4000M ($2048 \times 2048$ pixels, $7.4 \, \mu \text{m/pixel}$, field of view $40 \times 40$ arcmin). Information for our observations is presented in Table 2.
Table 1. Parameters of variability of the targets according to VSX database

| Target   | RA     | DEC     | mag    | ampl  | P    | type |
|----------|--------|---------|--------|-------|------|------|
| CSS 0752+38 | 07 52 05.68 | +38 19 09.8 | 14.35(CV) | 0.17  | 0.5493 | EW   |
| NSVS 691550 | 08 08 40.32 | +70 29 24.4 | 11.74(R1) | 0.26  | 0.334562 | EB/EW |

Table 2. Journal of the Rozhen photometric observations

| Target   | Date     | Exposure | Number | Error | Δg′ | Δi′ |
|----------|----------|----------|--------|-------|-----|-----|
| CSS 0752+38 | 2016 Feb 8 | 180, - | 4, - | 0.006, - |
|           | 2016 Feb 9 | 180, 240 | 40, 40 | 0.007, 0.014 |
|           | 2016 Feb 15 | 180, 240 | 63, 62 | 0.008, 0.017 |
|           | 2016 Feb 28 | 180, 240 | 36, 32 | 0.009, 0.018 |
|           | 2016 Mar 6 | 180, 240 | 35, 35 | 0.007, 0.016 |
|           | 2016 Feb 17 | 180, 240 | 48, 48 | 0.011, 0.017 |
|           | 2016 Feb 18 | 180, 240 | 50, 52 | 0.014, 0.023 |
| NSVS 691550 | 2014 Dec 19 | 60, 90 | 82, 81 | 0.006, 0.004 |
|           | 2014 Dec 20 | 60, 90 | 192, 187 | 0.003, 0.004 |

Table 3. List of the standard stars

| Label | Star ID | RA     | Dec     | g′ | i′ |
|-------|---------|--------|---------|----|----|
| Target | CSS 0752+38 | 07 52 05.68 | +38 19 09.8 | 14.35 | 13.68 |
| Chk    | UCAC4 643-044185 | 07 51 20.51 | +38 34 24.58 | 14.121 | 13.686 |
| C1     | UCAC4 643-044208 | 07 51 47.59 | +38 35 55.44 | 14.120 | 13.657 |
| C2     | UCAC4 643-044212 | 07 51 49.87 | +38 35 24.70 | 14.660 | 13.681 |
| C3     | UCAC4 643-044217 | 07 51 54.27 | +38 32 17.07 | 14.572 | 13.818 |
| C4     | UCAC4 643-044225 | 07 52 03.85 | +38 32 23.81 | 14.709 | 14.018 |
| C5     | UCAC4 643-044233 | 07 52 15.03 | +38 34 48.84 | 13.911 | 13.311 |
| C6     | UCAC4 643-044248 | 07 52 40.64 | +38 32 08.27 | 14.134 | 13.686 |
| C7     | UCAC4 643-044271 | 07 53 09.97 | +38 31 21.83 | 13.671 | 13.366 |
| C8     | UCAC4 643-044218 | 07 51 54.46 | +38 29 44.02 | 14.346 | 13.859 |
| C9     | UCAC4 643-044228 | 07 52 07.68 | +38 27 03.01 | 13.635 | 13.310 |
| C10    | UCAC4 643-044235 | 07 52 19.56 | +38 25 59.02 | 14.447 | 13.755 |
| C11    | UCAC4 643-044258 | 07 52 55.66 | +38 24 46.13 | 14.096 | 13.712 |
| C12    | UCAC4 642-042689 | 07 52 04.30 | +38 21 25.15 | 14.479 | 13.864 |
| Target | NSVS 691550 | 08 08 40.32 | +70 29 24.4 | 11.91 | 11.280 |
| Chk    | UCAC4-803-018811 | 08 08 11.10 | +70 31 24.30 | 13.893 | 12.897 |
| C1     | UCAC4-803-018819 | 08 08 35.27 | +70 27 34.33 | 12.235 | 11.135 |
| C2     | UCAC4-803-018792 | 08 07 14.92 | +70 29 38.18 | 13.617 | 13.227 |
| C3     | UCAC4-803-018788 | 08 06 53.73 | +70 24 34.73 | 13.703 | 13.357 |
| C4     | UCAC4-803-018845 | 08 09 52.06 | +70 26 47.75 | 12.788 | 12.350 |
| C5     | UCAC4-803-018826 | 08 08 56.41 | +70 25 32.22 | 13.536 | 12.918 |
| C6     | UCAC4-803-018829 | 08 09 05.15 | +70 24 34.93 | 13.981 | 13.230 |
| C7     | UCAC4-802-017856 | 08 09 29.07 | +70 23 33.50 | 13.721 | 13.218 |
| C8     | UCAC4-802-017853 | 08 09 27.67 | +70 21 39.78 | 12.754 | 12.180 |

Table 4. Parameters of variability of the targets according to the Rozhen data

| Target   | T0, -2450000 | Period | Δg′ | Δi′ | J − K | Tm |
|----------|--------------|--------|-----|-----|-------|----|
| CSS 0752+38 | 7428.3033(7) | 0.549284(4) | 0.283 | 0.281 | 0.306 | 6420(180) |
| NSVS 691550 | 7011.3033(4) | 0.334562(2) | 0.338 | 0.308 | 0.419 | 5650(80) |
The photometric data were reduced by \textit{AIP4WIN2.0} (Berry, Burnell 2006). We performed aperture ensemble photometry with the software \textit{VPHOT} using more than eight standard stars in the observed field of each target. Table 3 presents their coordinates and magnitudes from the catalogue UCAC4 (Zacharias \textit{et al.}, 2013).

We performed periodogram analysis of our data by the software \textit{PerSea}. It led to determination of initial epochs of the targets (Table 4) while the periods turned out almost equal to the previous values (Table 1). The amplitudes of variability of our observations (Table 4) are considerably larger than the preliminary values (Table 1). This is a result of higher precision of Rozhen observations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{light_curves.png}
\caption{The folded light curves of targets with their fits and the corresponding residuals (shifted vertically by different amount to save space).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{3D_configurations.png}
\caption{3D configurations.}
\end{figure}

\section*{2. Light curve solutions}
We carried out the modeling of our data by the package \textit{PHOEBE} (Prsa \& Zwitter 2005) based on the Wilson–Devinney code (Wilson \& Devinney 1971).
It is appropriate for our task because allows to model data in various filters, including Sloan ones. The observational data (Fig. 1) show that our targets are contact systems. That is why we modelled them using the mode "Overcontact binary not in thermal contact".

The target temperatures $T_m$ were determined in advance (Table 4) on the basis of their infrared color indices ($J-K$) from the 2MASS catalog and the calibration color-temperature of Tokunaga (2000).

The procedure of the light curve solutions consists of several steps. Firstly, we adopted primary temperature $T_1 = T_m$ and assumed that the stellar components are MS stars. Then we calculated initial (approximate) values of secondary temperature $T_2$, mass ratio $q$, relative stellar radii $r_1$ and $r_2$, based on the empirical relation of MS stars (Ivanov et al. 2010):

$$T_2 = T_1 (d_2/d_1)^{1/4},$$

$$q = (T_2/T_1)^{1.7},$$

$$k = r_2/r_1 = q^{0.75}.$$  

Further we searched for best fit varying: $T_2$ and $q$ around their initial values; orbital inclination $i$ in the range 60-90$^\circ$ (appropriate for eclipsing stars); potentials $\Omega_{1,2}$ in such way that the ratio $r_1/r_2$ to correspond to the initial value $k$. We adopted coefficients of gravity brightening 0.32 and reflection effect 0.5 appropriate for late stars (Table 4). The limb-darkening coefficients were chosen according to the tables of Van Hamme (1993).

After reaching the best solution (corresponding to the minimum of $\chi^2$) we adjusted the stellar temperatures $T_1$ and $T_2$ around the value $T_m$ by the formulae (Kjurkchieva & Vasileva 2015)

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

$$T_2^f = T_1^f - \Delta T$$

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.

**Table 5.** Fitted parameters

| Star          | $i$    | $q$   | $T_2$ | $\Omega$ |
|---------------|--------|-------|-------|----------|
| CSS 0752+38  | 58.5(0.2) | 0.36(0.01) | 4477(250) | 2.59(0.02) |
| NSVS 691550  | 60.4(0.1) | 0.845(0.001) | 5370(50) | 3.448(0.002) |

**Table 6.** Calculated parameters

| Star          | $T_1^f$ | $T_2^f$ | $r_1$   | $r_2$   | $l_2/l_1$ |
|---------------|---------|---------|---------|---------|-----------|
| CSS 0752+38  | 6525(195) | 4580(250) | 0.472(0.003) | 0.294(0.004) | 0.057(0.017) |
| NSVS 691550  | 5650(90)  | 5370(50)  | 0.404(0.002) | 0.374(0.002) | 0.681(0.077) |
Table 7. Parameters of the surface spots

| star                | $\beta$ | $\lambda$ | $\alpha$ | $k$     |
|---------------------|---------|-----------|----------|--------|
| CSS 0752+38         | 90(5)   | 110(2)    | 10(1)    | 0.9(0.02) |
| NSVS 691550         | 90(5)   | 11(2)     | 12(1)    | 0.87(0.02) |

Although PHOEBE works with potentials, it gives a 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 linear radius and $a$ is orbital separation). Moreover, PHOEBE yields as output parameters bolometric magnitudes $M^i_{bol}$ of the two components in conditional units (when radial velocity data are not available). But their difference $M^2_{bol} - M^1_{bol}$ determines the true luminosity ratio $c = L_2/L_1 = l_2/l_1$.

The formal PHOEBE errors of the fitted parameters were unreasonably small. That is why we estimated the parameter errors manually based on the following rule (Dimitrov & Kjurkchieva 2017). The error of parameter $b$ corresponded to that deviation $\Delta b$ from its final value $b^f$ for which the mean residuals increase by $3\bar{\sigma}$ ($\bar{\sigma}$ is the mean photometric error of the target).

Table 5 contains the final values of the fitted stellar parameters and their uncertainties: inclination $i$; mass ratio $q$; potentials $\Omega_{1,2}$; secondary temperature $T_2$. Table 6 exhibits the calculated parameters: stellar temperatures $T_{1,2}^f$; relative stellar radii $r_{1,2}$ (back values); ratio of relative stellar luminosities $l_2/l_1$. Their errors are determined from the uncertainties of fitted parameters used for their calculation.

The synthetic curves corresponding to the parameters of our light curve solutions are shown in Fig. 1 as continuous lines while Figure 2 exhibits 3D configurations of the targets. Table 7 shows the parameters (latitude $\beta$, longitude $\lambda$, angular size $\alpha$ and temperature factor $\kappa = T_{sp}/T_{st}$) of the spots which were necessary to reproduce the light curve asymmetries.

4. Analysis of the results

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

(a) NSVS 691550 is overcontact system while CSS 0752+38 is almost contact binary (Fig. 2).

(b) The components of CSS 0752+38 and NSVS 691550 are F – K stars.

(c) The difference between the component temperatures of the overcontact system is around 300 K, while that of CSS 0752+38 reaches almost 2000 K.

(d) The two targets undergo partial eclipses.

(e) The mass ratio of NSVS 691550 is near 0.84 while that of CSS 0752+38 is 0.35. This result means that the stellar components of our targets almost obey the relations mass-temperature of MS stars.

(f) Light curve asymmetries of the targets were reproduced by cool spots on their primary components.
Acknowledgements. This work was supported partly by projects DN 08/20 and DM 08/02 of the Foundation for Scientific Research of the Bulgarian Ministry of Education and Science as well as by project RD 08-102 of Shumen University.

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