MODELLING OF THE SEMI-DETACHED BINARY STAR WZ CORVI

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ABSTRACT. We present results from modeling of multicolor light curves of the semi-detached, algol-type binary system WZ Corvi. We analyzed VR data gathered in 2010 and new BVR_cI_c observations collected in 2012. Two models for WZ Crv are considered: the first was derived under the assumption that the temperature of the primary component, having the dominant contribution to total system light, corresponds to spectral type F7, and the second model, in which the temperature of the secondary was estimated from the colors observed at the flat bottom of the primary minimum. The new set of observations shows almost no difference in maxima heights, obvious in the earlier, 2010 data. However, primary minimum in V and R is deeper than in the 2010 light curve. We explain the variable shape of the system light curve as spot(s) present on primary or secondary component(s) due to their magnetic activity. Based on the derived solutions, we calculate relative physical (assuming the primary component to be a Main Sequence star) parameters of WZ Crv for both models.

Key words: Stars: binary; stars: individual: WZ Crv.

1. Introduction

Eclipsing binary WZ Corvi ($\alpha_{J2000.0} = 12^h44^m15.2^s$, $\delta_{J2000.0} = -21°25'35''$) is a poorly studied Algol-type system, discovered by Luyten (1937). During the Edinburg-Cape Blue Object Survey (Kilkenny et al., 1997), from five spectra, the spectral classes of components have been determined to be F7 and late G.

Since its discovery, multicolor observations of WZ Crv have been obtained only in 2010 (Virnina et al. 2011). They collected and subsequently analyzed VR_c observations and discovered that the phase curve is asymmetric: the second maximum is brighter than the first one.

Virnina et al. (2011) also noticed the flat bottom of the primary minimum, and from $V-R$ color index they estimated the temperature of 5650±66 K for

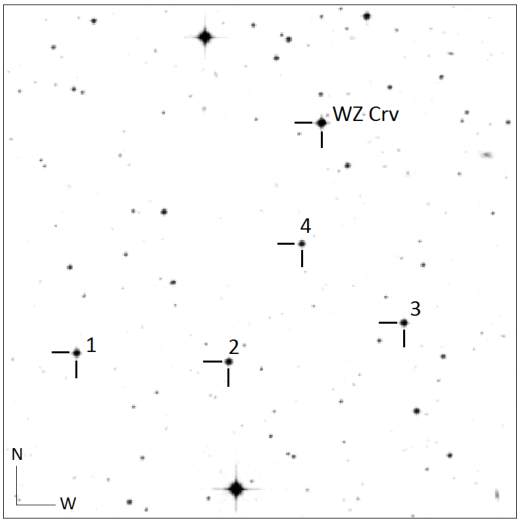

Figure 1: The position of WZ Crv and comparison stars. Field of view is $10' \times 10'$

the secondary (cooler) star. In the present paper we analyse new observations obtained in 2012, and illustrate variable magnetic activity of WZ Crv.

2. New Observations and Data Reduction

New observations of WZ Crv were obtained using the Schmidt-Cassegrain AAVSONet telescope Wright 28 (W28), D = 280mm, F = 1717mm, equipped with the 765 × 510 pixels CCD camera SBIG ST-7XME. With the scale of 1.074″/pixel, that gives a field of view of $13.7' \times 9.1'$. In the period between February 18th and May 5th, 2012, twenty three runs were gathered in BVR_cI_c filters and the exposure times were: B = 150 s, V = 70 s, R_c = 50 s and I_c = 70 s. Altogeather, in 2012 we have collected 396, 409, 414 and 381 single points in B, V, R_c and I_c filters, respectively. Scientific images have been calibrated for bias, flatfield and dark frames in a standard way.

Since the field of view of the W28 telescope is significantly smaller than that of TOA-150, used to

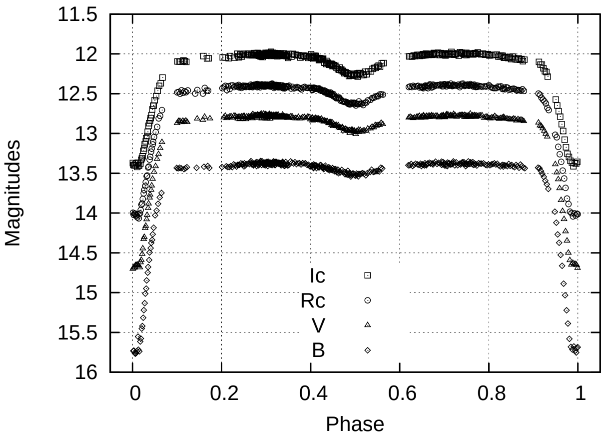

Figure 2: Phase curves, obtained from W28 robotic telescope of AAVSONet observatory in 2012.

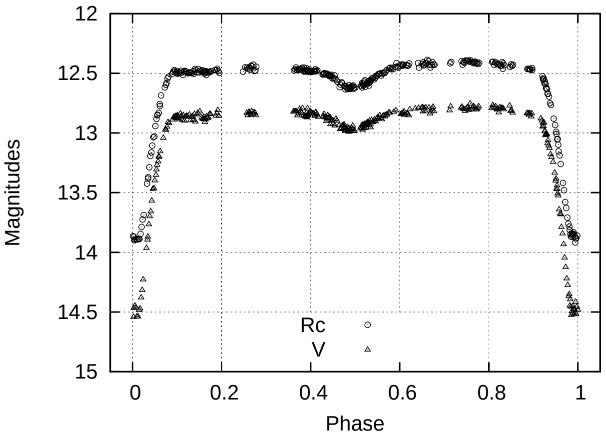

Figure 3: Phase curves, obtained on TOA-150 telescope of Tzec Maun observatory in 2010.

perform observations of WZ Crv in 2010, we had to choose other comparison stars to process photometry. We used the AAVSO software *SeqPlot* (`http://www.aavso.org/seqplot`), written by S. Beck, which is based on an original program by A. Henden, to extract from the AAVSO database the standard magnitudes of constant stars in the field of WZ Crv. Four comparison stars were chosen for "ensemble photometry" with the *MaxIm DL* software package. The coordinates and BVR_cI_c magnitudes of these stars are given in Table 1; their positions, together with the position of WZ Crv itself, are marked in Figure 1.

For direct comparison of the two sets of data, we recalibrated the VR_c observations collected in 2010, by using the same comparison stars as these for 2012 observations.

Making use of both datasets and *Peranso* (Vanmunster 2010) software, we have improved the ephemeris of WZ Crv:

$$\text{Min.I} = \text{HJD } 2455978.91668(45) + 1\overset{d}{.}78878(87) \cdot E$$

The period was calculated using the Lafler & Kinman method (1965); the initial epoch was measured from an individual minimum, observed in 2012, by approximating it with the algebraic polynomial of optimal degree $s = 6$ (MCV software, Andronov & Baklanov, 2004). The light curves phased with the above ephemeris are shown in Figures 2 and 3.

Table 1: Magnitudes of comparison stars.

♯	USNO-B1.0	B	V	R_c	I_c
1	0684-0300004	14.356	13.688	13.299	12.934
2	0684-0299934	14.605	14.028	13.648	13.360
3	0685-0281718	14.486	13.826	13.458	13.112
4	0685-0281767	15.185	14.561	14.176	13.815

We measured instrumental magnitudes of 45 constant stars in the fields of WZ Crv, W Crv and V881 Per. The results have been compared with the standard magnitudes from the AAVSO database. We found the following transformation formulae for obtaining the standard magnitudes:

$$B - v = 1.081(\pm 0.018) \cdot (b - v) - 0.060(\pm 0.015)$$

$$V - r = 0.951(\pm 0.016) \cdot (v - r) + 0.018(\pm 0.008)$$

$$R_c - i = 0.968(\pm 0.055) \cdot (r - i) + 0.026(\pm 0.024)$$

$$r - I_c = 1.022(\pm 0.061) \cdot (r - i) - 0.034(\pm 0.027)$$

where B, V, R_c and I_c denote standard magnitudes, while b, v, r and i are instrumental. The effective wavelengths for each filter have been calculated to be: λ_b = 447nm, λ_v = 546nm, λ_r = 649nm and λ_r = 777nm.

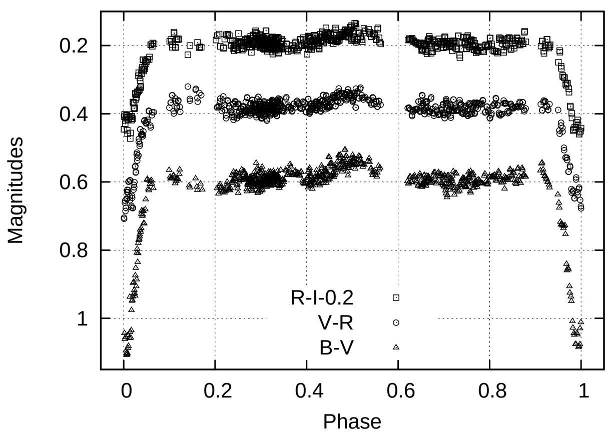

Figure 4: Phase curves of $b-v$, $v-r$ and $r-i$ color indices of WZ Crv, 2012.

In order to transform the instrumental measurements of the TOA-150 telescope to the standard system, we chose 58 constant stars in the field of WZ Crv. The resulting transformation formulae are:

$$V - r = 1.017(\pm 0.022) \cdot (v - r) - 0.026(\pm 0.010)$$

$$v - R_c = 0.950(\pm 0.041) \cdot (v - r) + 0.007(\pm 0.019)$$

where the meaning of V, R_c, v and r is the same as above. The effective wavelengths of the TOA-150 telescope are: $\lambda_v = 552$nm and $\lambda_r = 636$nm. We applied transformation formulae to smoothed magnitudes in minima and maxima and the results are shown in Table 2.

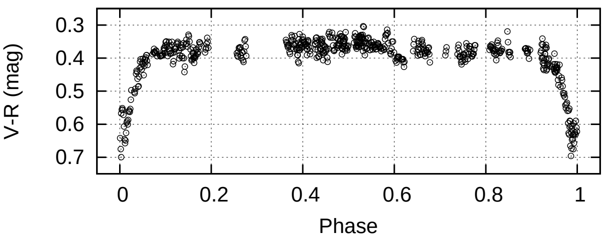

Figure 5: Variability of $v - r$ color index, 2010.

The asymmetry of the phase curves in maxima $\Delta max_V = max_{II} - max_I = -0\overset{m}{.}033(\pm 0\overset{m}{.}009)$ and $\Delta max_R = max_{II} - max_I = -0\overset{m}{.}050(\pm 0\overset{m}{.}004)$, which was clearly visible in 2010, in 2012 almost disappeared. However, the depth of the primary minimum in the new light curve is deeper both in V and R_c filters. Moreover, the $V - R_c$ color index in the primary minimum has changed - while in 2010 it was $(V - R_c)_{2010} = 0\overset{m}{.}548(14)$, we measured it to be $(V - R_c)_{2012} = 0\overset{m}{.}634(11)$ two years later.

We plotted the instrumental $b - v$, $v - r$ and $r - i$ colors observed in 2012 in Figure 4, while the $v - r$ instrumental color index derived from the 2010 data is shown in Figure 5. For phasing these data we used the same ephemeris as that for light curves. As it can be seen, there is rather high reddening in the primary minimum and WZ Crv becomes somewhat bluer at the secondary one.

Table 2: Standard magnitudes in minima and maxima with corresponding errors estimates.

	B	V	R_c	I_c
		2012		
min_I	15.750(9)	14.649(9)	14.015(6)	13.407(6)
max_I	13.363(1)	12.782(2)	12.411(1)	12.030(2)
min_{II}	13.502(4)	12.974(3)	12.643(3)	12.291(3)
max_{II}	13.366(2)	12.779(1)	12.406(2)	12.021(2)
		2010		
min_I		14.482(12)	13.934(7)	
max_I		12.803(8)	12.481(3)	
min_{II}		12.955(4)	12.647(3)	
max_{II}		12.770(4)	12.431(3)	

Additional evidence for the changing shape of WZ Crv light curve can be found in the SuperWASP project database (`http://www.wasp.le.ac.uk/public/`). There have been more than 11000 points gathered by this project, after deleting bad points, 10462 points were left, which were divided into three subsets for observational seasons 2006, 2007 and 2008. The light curves (flux versus phase) are shown in Figures 4-6. We marked the original data by grey circles, while black points represent a smoothed light curve.

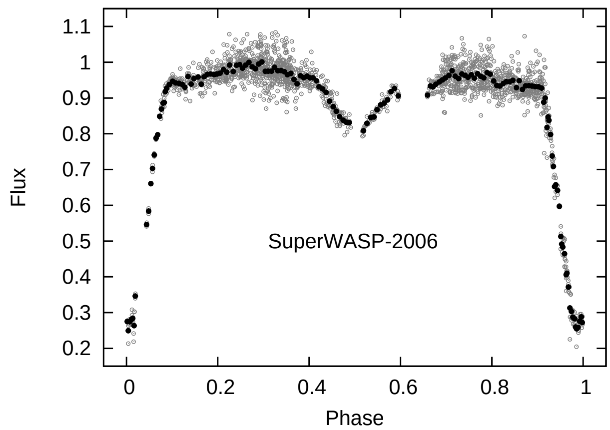

Figure 6: SuperWASP data, 2006.

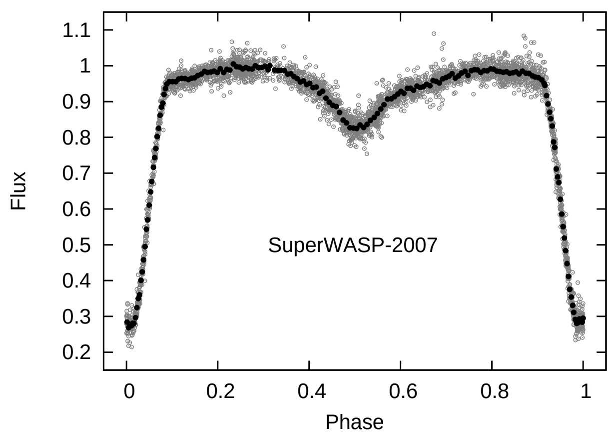

Figure 7: SuperWASP data, 2007.

3. Modeling the light curve

We used Wilson-Devinney code (Wilson & Devinney 1971; Wilson 1979; Wilson 1993) appended with Monte Carlo search algorithm (Zola 1997; Zola et al. 2010 and references therein) to obtain physical parameters of WZ Crv.

The light curves of this system are aparently unstable. The instability of the curve in close binary systems is usually explained by the presence of spots, caused by

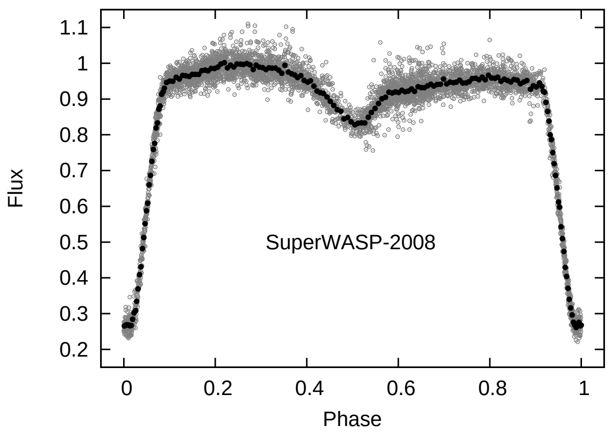

Figure 8: SuperWASP data, 2008.

magnetic activity of one or both components of the system. The main goal of this study was to determine the physical parameters of WZ Crv and to find a common solution for both 2010 and 2012 seasons. According to the spectral classification, obtained by Kilkenny et al. (1997), one may suggest, that the temperature of the hotter (primary) component should be 6200 K.

However, the flat bottom primary minimum indicates that at phase $\varphi = 0.0$ we see a total eclipse of the primary star, and only the rear face of the secondary (cooler) star is visible at that time. Therefore, the temperature of the secondary component could be independently evaluated from the color indices. In 2012 we collected four-color observations, thus the temperature determined from the color indices should be more reliable. However, in 2012, as it had been already shown, the primary minimum is deeper than that in 2010, and the color index $V - R_c$ is redder, indicating a lower temperature. To explain this, we assumed that in 2012 the depth and color at primary minimum could have been affected by a cool spot. Therefore, we eventually decided to determine the temperature of the secondary star from $V - R_c$ color index observed in 2010. According to Cox (2000), $V - R_c = 0\overset{m}{.}548(14)$ corresponds to temperature of $T_2 = 5510(\pm 87)$ K.

For each year we performed simultaneous computations in all available filters. The diference between color indices in minima indicates that the temperature difference between components should be significantly higher than 700 K. While searching for the common solution for both years, we applied two different approaches to light curve modeling. The first model (*Solution 1*) had been computed with a fixed temperature of the primary component to be $T_1 = 6200$ K as follows from the F7 spectral type and temperature of the secondary was adjusted. The second model assumed that the temperature of the secondary component is $T_2 = 5510$ K (*Solution 2*). In both cases we searched for a dark region in the photosphere of each component to account for visible asymmetries and changes of the shape of light curves.

3.1. Solution 1

With the primary star temperatire fixed at $T_1 = 6200$ K, the ranges for the other parameters were set up for four-color observations as follows: temperature of the secondary component between 3000K and 6000K, inclination between 70° and 90°, the mass ratio $q = M_2/M_1$ in the range of 0.1 - 0.9,and the luminosity of the primary component L_1 between 7 and 12.6. Following Lucy (1967) and Rucinski (1973), the gravity darkening exponents of both components and the bolometric albedo coefficients were set to the values of $g_{1,2} = 0.32$ and $A_{1,2} = 0.5$, respectively, which are appropriate for stars with convective envelopes. The limb-darkening coefficients were interpolated from the tables published by Claret et al. (1995) and Díaz-Cordovés et al. (1995).

Initially, we assumed that the third light could be present, but since its contribution in every band turned out to be negligible we proceeded with no third ligth solutions.

Parameters of the WZ Crv, including the position of the spot and its radius, are listed in Table 3. The resulting theoretical curves for 2012 are shown on Figure 9 with a solid line. The configuration of the system and the position of the dark spot were visualised at phase $\varphi = 0.11$ with the *Binary Maker* software (Figure 10). The theoretical and observed light curves for 2010 are plotted in Figure 11 while the configuration of the system (at phase $\varphi = 0.24$) is shown in Figure 12. The parameters of the system are listed in Table 3 for both 2010 and 2012.

Modeling yielded the temperature of the secondary star to be $T_2 = 4220$ K. The potential of the secondary star was $\Omega_2 = 3.56$ and this corresponds to filling the Roche lobe by the secondary component. The primary star was within its Roche lobe. The best fit was found for a dark spot to be on the secondary star.

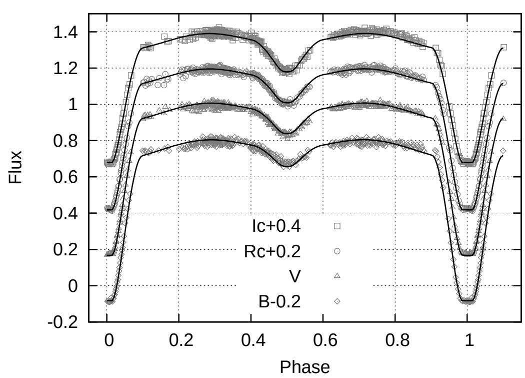

Figure 9: *Solution 1*: Synthetic curves (2012) are presented in solid lines, the grey symbols represent the original data.

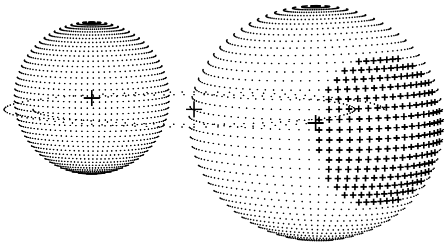

Figure 10: *Solution 1*: Configuration of the system (2012) at the phase $\varphi = 0.11$.

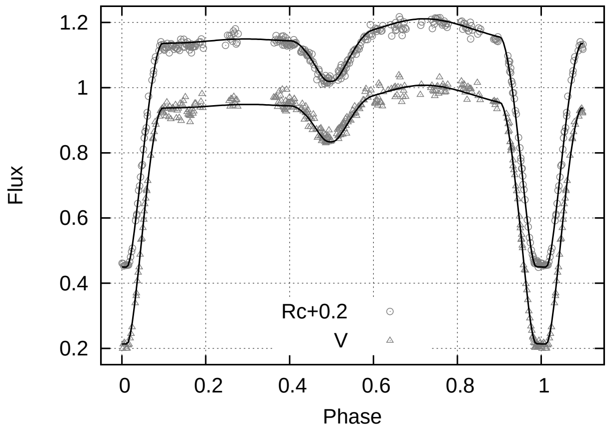

Figure 11: *Solution 1*: Synthetic curves (2010) are presented in solid lines, while the grey symbols represent the original data.

3.2. Solution 2

In the second solution, the temperature of the secondary star was fixed as $T_2 = 5510$K. The search range for the temperature of the primary star was between 7200 K and 13000 K. According to Lucy (1967) and Rucinski (1973) the gravity darkening exponents were set at $g_1 = 1.0$ and $g_2 = 0.32$, the bolometric albedo coefficients were set to be $A_1 = 1.0$ and $A_2 = 0.5$, for the primary and secondary, respectively. The same ranges as those for Solution 1 we set for inclination, potentials and the mass ratio. A dark spot was placed on the surface of the secondary component.

From the preliminary solution we found that the mass ratio was close to 0.75, and the secondary star filled its Roche lobe. Since this star is very distorted and the color corresponded to its back side, for the final solution the temperature of the secondary has been corrected to account for such a shape and resulted in a new T_2 value of 5630 K. From new computations we derived a model with the same parameters describing stars in 2010 and 2012. They are listed in Table 4. Figure 13 presents the synthetic light curves for 2012, while the configuration of the system ($\varphi = 0.10$) is shown in Figure 14. The resulting ligh curve and data for 2010 and the configuration of the system ($\varphi = 0.24$) in that year could be seen in Figures 15 and 16, respectively.

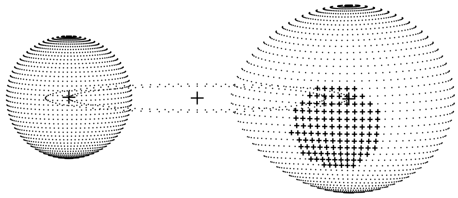

Figure 12: *Solution 1*: Configuration of the system (2010) at the phase $\varphi = 0.24$.

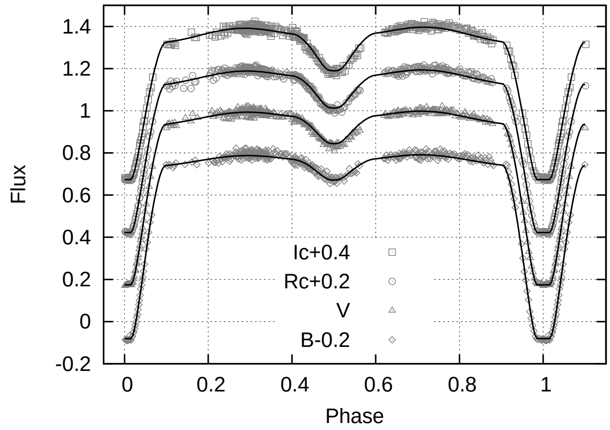

Figure 13: *Solution 2*: Synthetic curves (2012) are presented as solid lines, while grey symbols represent the observed data.

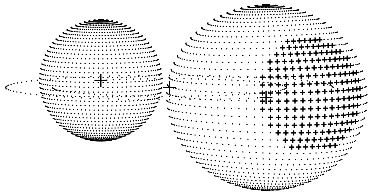

Figure 14: *Solution 2*: Configuration of the system (2012) at the phase $\varphi = 0.10$.

Table 3: Parameters of WZ Crv derived from modeling, *Solution 1.* Given uncertainties are those derived from the fit at the 90% confidence level. Stars radii are given in orbital separation units.

Parameter	2012	2010
i (deg)	84.7±0.1	84.7±0.1
T_1 (K)	*6200	*6200
T_2 (K)	4220±5	4220±5
Ω_1	5.413±0.015	5.413±0.015
Ω_2	3.561±0.011	3.561±0.011
$q(M_2/M_1)$	0.847±0.005	0.847±0.005
$L_1/(L_1+L_2)$ (b)	0.7929±0.0017	
$L_1/(L_1+L_2)$ (v)	0.7475±0.0015	0.7448±0.0017
$L_1/(L_1+L_2)$ (r)	0.6990±0.0017	0.7052±0.0018
$L_1/(L_1+L_2)$ (i)	0.6363±0.0035	
$L_2/(L_1+L_2)$ (b)	0.2071±0.0004	
$L_2/(L_1+L_2)$ (v)	0.2525±0.0005	0.2552±0.0006
$L_2/(L_1+L_2)$ (r)	0.3010±0.0007	0.2948±0.0008
$L_2/(L_1+L_2)$ (i)	0.3637±0.0014	
r_p (pole)	0.2181	0.2181
r_p (point)	0.2240	0.2240
r_p (side)	0.2203	0.2203
r_p (back)	0.2230	0.2230
r_s (pole)	0.3341	0.3341
r_s (point)	0.4199	0.4199
r_s (side)	0.3490	0.3490
r_s (back)	0.3765	0.3765
	Spot parameters	
Star	2	2
longitude (°)	90±6	103±10
latittude (°)	178±2	85±1
radius (°)	37.2±0.5	27.9±1.7
temperature	0.925±0.002 T_2	0.751±0.022 T_2

*-not adjusted

Table 4: Parameters of WZ Crv derived from modeling, *Solution 2.* Given uncertainties are those derived from the fit at the 90% confidence level. Stars radii are given in orbital separation units.

Parameter	2012	2010
i (deg)	85.7±0.1	85.7±0.1
T_1 (K)	10390±26	10390±26
T_2 (K)	*5630	*5630
Ω_1	5.321±0.014	5.321±0.014
Ω_1	3.270±0.007	3.270±0.007
$q(M_2/M_1)$	0.715±0.004	0.715±0.004
$L_1/(L_1+L_2)$ (b)	0.8160±0.0015	
$L_1/(L_1+L_2)$ (v)	0.7516±0.0015	0.7480±0.0020
$L_1/(L_1+L_2)$ (r)	0.6941±0.0018	0.7009±0.0023
$L_1/(L_1+L_2)$ (i)	0.6338±0.0022	
$L_2/(L_1+L_2)$ (b)	0.1840±0.0003	
$L_2/(L_1+L_2)$ (v)	0.2484±0.0005	0.2520±0.0007
$L_2/(L_1+L_2)$ (r)	0.3059±0.0008	0.2991±0.0010
$L_2/(L_1+L_2)$ (i)	0.3662±0.0013	
r_p (pole)	0.2164	0.2164
r_p (point)	0.2213	0.2213
r_p (side)	0.2183	0.2183
r_p (back)	0.2205	0.2205
r_s (pole)	0.3284	0.3284
r_s (point)	0.4626	0.4626
r_s (side)	0.3437	0.3437
r_s (back)	0.3756	0.3756
	Spot parameters	
Star	2	2
longitude (°)	84±3	102±11
latittude (°)	175±2	81±2
radius (°)	35.0±0.2	29±2
temperature	0.897±0.016 T_2	0.751±0.025 T_2

*-not adjusted

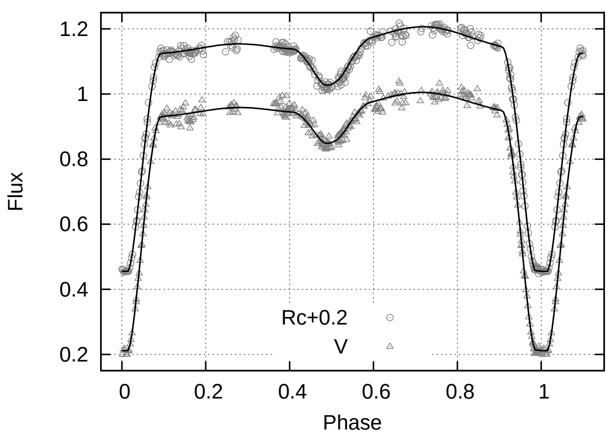

Figure 15: *Solution 2*: Synthetic curves (2010) are presented as solid lines, while grey symbols represent the original data.

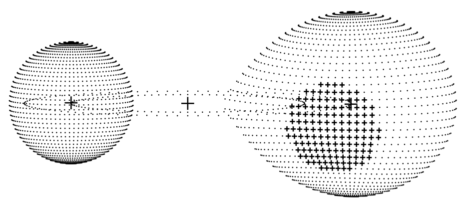

Figure 16: *Solution 2*: Configuration of the system (2010) at the phase $\varphi = 0.24$.

4. Results and Discussion

We analysed multicolor observations of the binary system WZ Crv, collected in 2012 and 2010. We noticed that the primary minimum has a flat bottom. We found differences in the shape of the light curve and in depth of the primary minimum. We assumed that magnetic activity, manifesting by the presence of a dark spot, is reponsible for the observed changes. These light curve variations could be easily noticed also in the combined SuperWASP data and confirm a strong magnetic activity of one or both components of this system.

The ligth curves taken at the two seasons were modeled using the Wilson-Devinney code. Two alternative solutions were considered: (1) in the first one the temperature of the primary was assumed to be 6200 K as corresponding to the F7 spectral class; (2) in the second solution we determined the temperature of the secondary, the only component visible at the primary eclipse, from its $V-R$ color measured at flat bottom phases. We were able to obtain models within both solutions that have the same stellar parameters but differ only in these describing a cool spot on the surface of the secondary. Our solution indicated that the cool spot was located at longitude of about 80 degrees in 2010 while in 2012, its longitude position was about 180 degrees. We conclude, that the magneticaly active component in WZ Crv is the secondary star.

Spectroscopic observations are needed to confirm the photometric mass ratio derived in this paper. Further photometric observations are required to monitor the magnetic activity of WZ Crv.

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