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ROTSE1 J164341.65+251748.1: A NEW W UMA-TYPE ECLIPSING BINARY

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RESUMEN

ROTSE1 J164341.65+251748.1 fue observada fotométricamente en la banda V durante tres épocas con el telescopio de 0.84-m del Observatorio de San Pedro Mártir en México. Con base en fotometría BVR adicional, encontramos que la estrella primaria tiene un tipo espectral cercano a G0V. La curva del luz del sistema es característica de los sistemas binarios del tipo W UMa y tiene un periodo orbital de ≈ 0.323 días. Con el propósito de entender mejor a este sistema binario, hemos analizado su curva de luz con ayuda del método de Wilson y Devinney. Hemos encontrado que ROTSE1 J164341.65+251748.1 tiene una razón de masas de ≈ 0.34 y que la componente menos masiva es ≈ 230 K más caliente que la estrella primaria. La inclinación del sistema es ≈ 84.6 grados y el sobre-contacto es de 11%. El análisis también mostró la presencia de manchas brillantes variables sobre la estrella primaria.

ABSTRACT

ROTSE1 J164341.65+251748.1 was photometrically observed in the V band during three epochs with the 0.84-m telescope of the San Pedro Mártir Observatory in Mexico. Based on additional BVR photometry, we found that the primary star has a spectral type around G0V. The light curve of the system is typical of a W UMa type binary stars and has an orbital period of ≈ 0.323 days. In an effort to gain a better understanding of the binary system and determine its physical properties, we analyzed the light curve with the Wilson and Devinney method. We found that ROTSE1 J164341.65+251748.1 has a mass ratio of ≈ 0.34 and that the less massive component is about 230 K hotter than the primary star. The inclination of the system is ≈ 84.6 degrees, and the degree of over-contact is 11%. The analysis shows the presence of variable bright spots on the primary star.

Key Words: binaries: eclipsing — techniques: photometric — stars: individual (ROTSE1 J164341.65+251748.1)

1. INTRODUCTION

The ROTSE-I survey for variable stars (Akerlof et al. 2000) has identified nearly 2000 new variables. Among them is ROTSE1 J164341.65+251748.1 (hereinafter J1643+2517), reported by these authors as a variable source with a V magnitude of around 14.2, varying with an amplitude of 0.69 mag and a periodicity of 0.32343200 days. No further information was given about the nature of its variability. While conducting a spectroscopic and photometric study in the V band on AH Herculis, J1643+2517 was detected as a serendipitous source in the field. Our extensive photometric coverage revealed that J1643+2517 has the typical light curve of W UMa-type systems.

Since the pioneer work by Lucy (1968) on contact stars, it is now well established that W UMa-type systems are over-contact binary stars, which consist of two late type main sequence stars sharing a common connecting envelope (Rucinski 2010). There is a considerable number of publications about this kind of objects, both observational and theoretical, since

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TABLE 1

LOG OF PHOTOMETRIC OBSERVATIONS OF J1643+2517

Date yyyymmdd	Filter	Exp. Time (secs)	Images	Obs. Time (hours)
20130530	V	30	439	4.85
20130531	V	30	709	8.27
20130601	V	30	263	2.93
20130602	V	30	683	7.87
20130603	V	30	376	4.57
20130604	V	30	281	3.65
20130605	V	30	340	4.57
20130606	V	30	267	2.90
20130607	V	30	223	2.42
20130613	V	30	603	7.19
20130614	V	30	479	7.03
20130617	V	30	574	6.64
20130618	V	30	373	4.52
20140214	V	180	43	3.25
20140215	V	180	28	2.30
20140216	V	60	42	1.526
20140220	V	120	17	0.64
20140308	V	20	532	4.66
20140312	V	20	475	4.86
20140519	V	60	208	4.26
20140520	V	20	210	1.80
20150630	V	30	264	3.33
20150702	B, V, R	30,20,15	106,106,106	4.47
20150703	B, V, R	30,20,15	47,47,47	3.13
20150729	B, V, R	30,20,15	151,151,151	5.79
20150730	B, V, R	30,20,15	51,51,51	2.01

the early work by Eggen (1961), who recognized that binaries with orbital periods of less than a day and with continuous light variations could be considered stars in full contact. Among these studies are the reviews published by Rucinski (1993) and Eggleton (1996). In this paper, based on the obtained V light curves of J1643+2517, we determine the most important parameters of the system.

2. OBSERVATIONS AND DATA REDUCTION

CCD observations were made during three observing runs, with the 0.84-m f/15 Ritchey-Chrétien telescope at Observatorio Astronómico Nacional at Sierra San Pedro Mártir (OAN-SPM), the Mexman filter-wheel, and the ESOPO CCD detector (e2v CCD42-90), which has a 2048×4608 13.5 μm square pixel array, a gain of 1.7 e^-/ADU, and a readout noise of 3.8 e^-. A 2×2 binning was used during our observations. The combination of the telescope and detector characteristics ensured an unvignetted field of view of $7.4' \times 9.3'$. Since the observations were obtained with AH Her as the primary target, we obtained mainly V photometry. During our last run we made BVR photometry, basically to obtain sufficient information to derive the spectral type of the primary. The log of the observations is shown in Table 1. Sky flats and bias exposures were also taken each night.

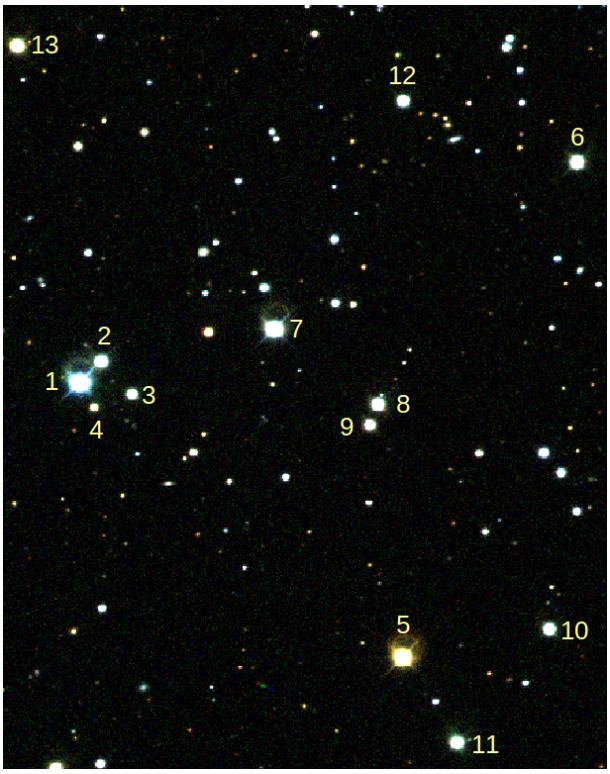


Fig. 1. Observed field. The numbered stars are calibrated photometrically and are shown in Table 2. J1643+2517 is star number 6 while AH Her is star number 1. The comparison star used is number 12.

All CCD images were processed using the IRAF[4] package. Images were bias subtracted and flat field corrected and then cosmic rays were removed with the help of the L.A. Cosmic[5] script. Then, the instrumental magnitudes of the stars were computed using the standard aperture photometry method.

During an observing run of $UBVRI$ photometry of Galactic stellar clusters this field (Figure 1) was included in the list of targets, so that its stars could

[4]IRAF is distributed by the National Optical Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[5]http://www.astro.yale.edu/dokkum/lacosmic

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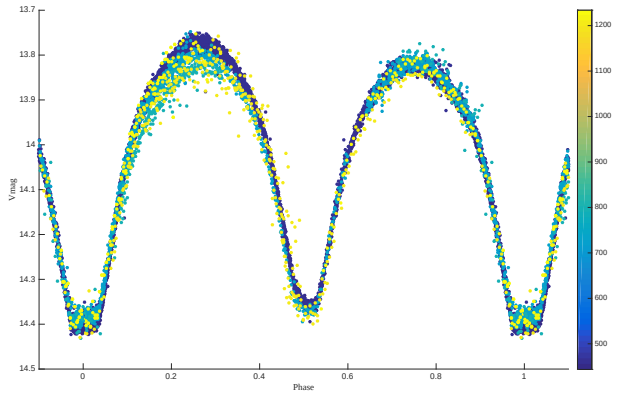


Fig. 2. Phase diagram of the V photometry of J1643+2517 (see text for the colour code). Notice that there is a clear distinction between the primary and secondary eclipses and that the primary's maxima (phase 0.25) show much larger variations than the secondary maxima (phase 0.75). The color figure can be viewed online.

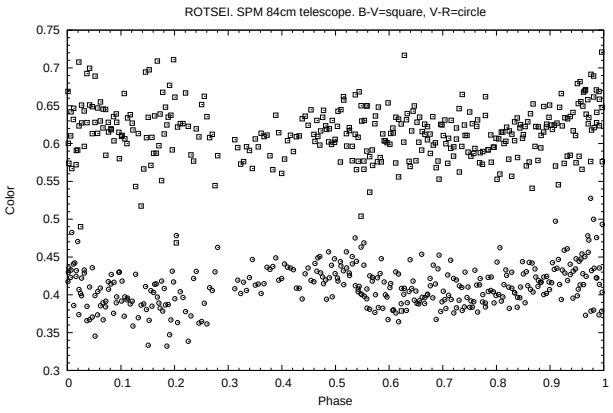


Fig. 3. The color index diagram in 2015 data. The $B-V$ and $V-R$ colour indexes at around 0 phase are smaller than those at 0.5 phase, which indicates a lower temperature for the primary star.

be calibrated in the Johnson-Cousins system. The results are presented in Table 2. Although dimmer than other stars in the field, star number 12 was used as the comparison star to obtain the differential photometry, since it has a similar colour to J1643+2517.

3. PHOTOMETRIC ANALYSIS

The orbital period of the light curve was derived from a frequency search algorithm, using the Peranso program (Vanmuster 2014). The derived period was $P = 0.323456 \pm 0.000024$ days. The following ephemeris has been obtained:

$$HJD_0 = 2456443.5675(9) + 0.3234561(4)\,E, \quad (1)$$

where phase zero is defined by the lower of the two minima, corresponding in this case, to the inferior conjunction of the primary star. This definition follows the convention that the deeper minimum of the light curve is defined as the primary minimum (e.g. Binnedijk 1984). Therefore, the primary maximum occurs at phase 0.25. The parentheses indicate the error in the previous digit. Using this ephemeris, we obtain the phased light curve of J1643+2517 shown in Figure 2. The figure shows our three observing runs. In order to identify the observing time sequence, we have included a colour bar in which the labels of the ticks are HJD days and show the date, starting from 2456443.

4. SPECTRAL TYPE OF THE PRIMARY STAR

From the photometry obtained at phase zero, we found colours $B - V = 0.64$ and $V - R = 0.43$. The $B - V$ index indicates a G2V star, while the $V - R$ index suggests a later spectral type of G9V. Thus the system appears to have a small extinction. We adopted a G0V spectral type to reconcile these indices and an initial temperature of 5900 K. This spectral type and temperature are important, as we said, in the sense that they provide initial values for modeling the binary.

5. MODELING THE BINARY

A preliminary solution of the phased light curve was obtained by Fox Machado et al. (2015a) with the PHOEBE package (Prša & Zwitter 2005), following the strategy explained in Fox Machado et al. (2015b). PHOEBE is an interactive software package for modeling eclipsing binary stars based on the Wilson-Devinney code (WDc) (Wilson & Devinney (1971); Wilson (1990, 1994)). It permits the creation of a synthetic light curve that fits the observational data by adjusting interactively the orbital and stellar parameters through a user friendly graphical interface. The preliminary results from Fox Machado et al. (2015a) were used in the present paper as a starting solution for the latest version of the WDc code (Wilson & Van Hamme 2014) available in 2015 in the electronic link `ftp://ftp.astro.ufl.edu/pub/wilson/lcdc2015/`.

A final solution was then achieved using this new code. Some insights about the morphology of the binary system can be obtained from the shape of the light curve. Since there is a total eclipse of the secondary star by the primary star, a flat bottom at the primary minimum is seen. indicating a high inclination angle of the system. The primary and secondary eclipses occur at 0.5 phase intervals, with no clear beginning and end of the eclipses, suggesting a circular

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TABLE 2

UBVRI PHOTOMETRY OF THE FIELD STARS*

ID	RA	DEC	U	B	V	R	I	eU	eB	eV	eR	eI	Name	$B0$	$V0$
1	251.04172	+25.25060	11.517	12.354	12.297	12.143	11.954	0.001	0.003	0.002	0.004	0.007	V*AHHer		
2	251.03647	+25.25510	14.788	14.747	14.139	13.769	13.408	0.002	0.007	0.001	0.002	0.005	[HH95]AHHer-27	14.800	14.187
3	251.02930	+25.24806	16.202	15.815	15.058	14.621	14.238	0.004	0.005	0.002	0.002	0.009	[HH95]AHHer-26	15.892	15.117
4	251.03827	+25.24531	18.520	17.322	16.164	15.442	14.843	0.012	0.012	0.002	0.007	0.008	[HH95]AHHer-25	17.429	16.205
5	250.96619	+25.19135	15.274	13.851	12.532	11.831	11.194	0.003	0.004	0.002	0.003	0.004	2MASSJ16435186+251128		
6	250.92379	+25.29666	14.573	14.432	13.784	13.380	13.024	0.016	0.004	0.001	0.003	0.010	J1643+2517		
7	250.99569	+25.26163	13.117	13.184	12.670	12.369	12.059	0.002	0.003	0.002	0.004	0.004	2MASSJ16435895+2515418		
8	250.97129	+25.24536	14.762	14.749	14.079	13.654	13.224	0.002	0.007	0.002	0.002	0.007	[HH95]AHHer-21	14.721	14.035
9	250.97337	+25.24101	15.990	15.580	14.720	14.234	13.751	0.001	0.007	0.002	0.003	0.006	[HH95]AHHer-22	15.565	14.688
10	250.93149	+25.19695	15.181	15.029	14.417	14.040	13.696	0.001	0.006	0.002	0.004	0.005	2MASSJ16434356+2511489		
11	250.95348	+25.17302	14.700	14.627	14.022	13.605	13.243	0.005	0.011	0.004	0.003	0.009	[HH95]AHHer-18	14.592	13.938
12	250.96468	+25.31011	15.299	15.243	14.602	14.201	13.836	0.006	0.009	0.003	0.005	0.011	[HH95]AHHer-33	15.226	14.560
13	251.05568	+25.32264	15.771	14.723	13.665	13.079	12.618	0.006	0.011	0.003	0.010	0.001	[HH95]AHHer-2	14.714	13.645

*The values in the last two columns are those found in the literature.

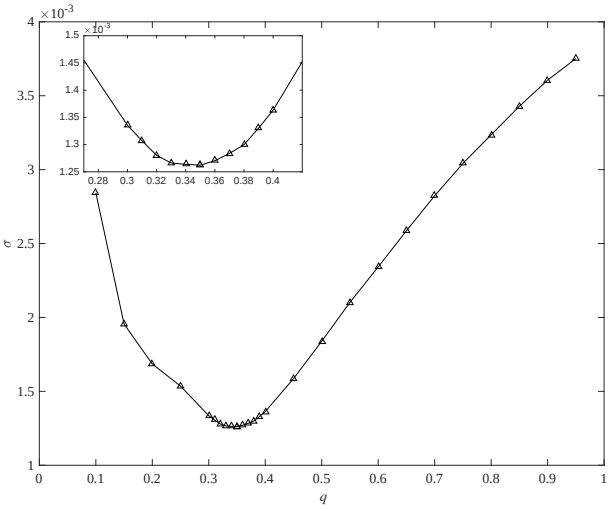


Fig. 4. The q-search strategy for the mass ratio determination. The mass ratio at minimum σ is at around 0.35.

orbit. These properties are consistent with a short period over-contact binary of the W UMa type. The lower minima appear at the primary minimum when the secondary star is covered by the primary star at around phase zero (see § 3). In this case, we obtain a lower effective temperature of the more massive star. The different magnitudes of two maxima in the light curve are known as the *O'Connell effect*, after first being recognized by O'Connell (1951).

During all the observations of J1643+2517 the primary maxima showed strong variations, with the profile of the light curve changing on a time scale larger than a day. The secondary maxima were much more stable, particularly during the third run. To model all of these variations, we found that the best solution was one with two hot spots on the primary star. Since we cannot make a uniform model for the light curves, we separated the data into the three observed epochs in order to perform independent analyses.

TABLE 3

SPOTS PARAMETERS FOR THE DATA OF EACH PART*

Parameter	Spot 1	Spot 2
*Epoch*1		
Colatitude (deg)	68.0 ± 1.3	75.0 ± 1.4
Longitude (deg)	112.00 ± 0.02	16.00 ± 0.02
Radius (deg)	22.0 ± 4.7	30.0 ± 1.4
Temp. factor	1.07 ± 0.012	1.0500 ± 0.002
*Epoch*2		
Colatitude (deg)	55.0 ± 0.52	85.0 ± 1.46
Longitude (deg)	155.00 ± 0.016	22.01 ± 0.02
Radius (deg)	21.0 ± 2.7	19.0 ± 1.1
Temp. factor	1.06 ± 0.022	1.0500 ± 0.015
*Epoch*3		
Colatitude (deg)		60.0 ± 9.4
Longitude (deg)		34.90 ± 0.16
Radius (deg)		28.1 ± 9.48
Temp. factor		1.026 ± 0.002

*The spots are all on the primary star. There is only one significant spot on the system for the third data part.

Some of the parameters of the contact binary model could be fixed or well estimated. The thermal albedo $A1 = A2 = 0.5$ (Lucy 1967) and the gravitational constant $g1 = g2 = 0.32$ (Rucinski 1969) were assumed fixed by the convective envelope of both stars, and the limb darkening was automatically interpolated by the WDc from the van Hamme (1993)

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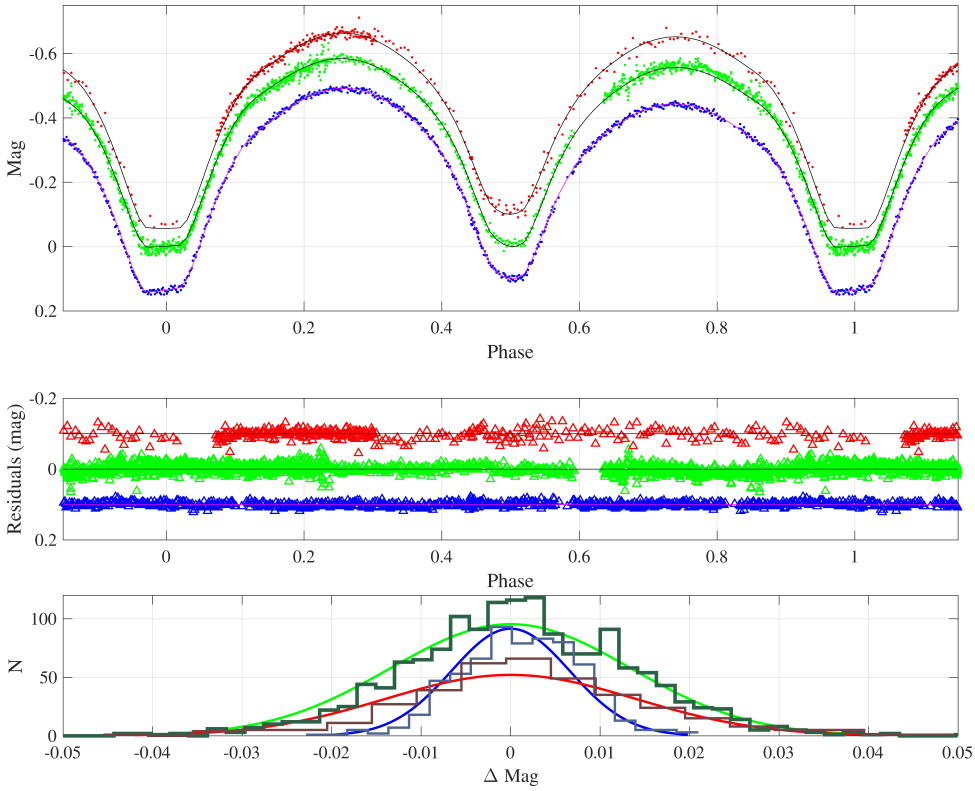


Fig. 5. *Top*. Simulated (solid lines) light curves fitted to the observations. Blue points correspond to the 2013 observations, green points to the 2014 observations and red points to 2015 observations. *Middle*. The residuals of the simulations. *Bottom*. The statistical distribution of residuals and their Gaussian distribution fits. The color figure can be viewed online.

TABLE 4

LIGHT-CURVE PARAMETERS OF J1643+2517 AT 2013.06.01*

Parameter	Primary	Secondary
HJD_0	2456443.5675±0.0009	
P_{orb} (day)	0.3234561±0.0000004	
incl	84.35 ±0.31	
q=m2/m1	0.3425 ±0.0014	
$\Omega=\Omega_1=\Omega_2$	2.520 ±0.005	
T (K)	5648[a]	5873± 7
$g1 = g2$	0.32[a]	
$A1 = A2$	0.5[a]	
$x1(bolo) = x2(bolo)$	0.646[a]	
$y1(bolo) = y2(bolo)$	0.212[a]	
$x1_v = x2_v$	0.749[a]	
$y1_v = y2_v$	0.209[a]	
$L/(L_1 + L_2)_V$	0.6857 ±0.0012	
r=R/a (*pole*)	0.4547 ±0.0005	0.2767 ± 0.0014
r=R/a (*side*)	0.4895 ±0.0007	0.2892 ± 0.0017
r=R/a (*back*)	0.5187 ±0.0008	0.3267 ± 0.0032

*The parameters with superscript *a* are assumed.

table. Based on the BVR observations (see § 4), the spectral class could be estimated as close to G0V, giving an initial temperature of the primary of ≈ 5700 K.

As the standard to build the model for this system, we used the 2013 data, which had the best photometric quality. A q-search strategy was applied to find the mass ratio of the system (Figure 4). The best fitted parameters of the simulation are listed in Table 4, and comparisons between simulations and observations are displayed in Figure 5.

We also provide the residuals and the statistics histogram in the same figure. With the Kolmogorov-Smirnov test, the residuals are seen to follow a Gaussian distribution with $\sigma \approx 0.0064$ at 95% confidence. We also present in Figure 6 the shape of the system provided by the new feature of the WDc.

6. DISCUSSION

Our analysis of this eclipsing binary reveals properties similar in many respects to those of the W UMa systems [Zhu et al. (2010); Dimitrov & Kjurkchieva (2015)], which are characterized by having short orbital periods and an over-contact configuration that is composed of F-K stars sharing a common envelope that thermalizes the stars. This system appears to have a mass ratio of $q \approx 0.323$, an

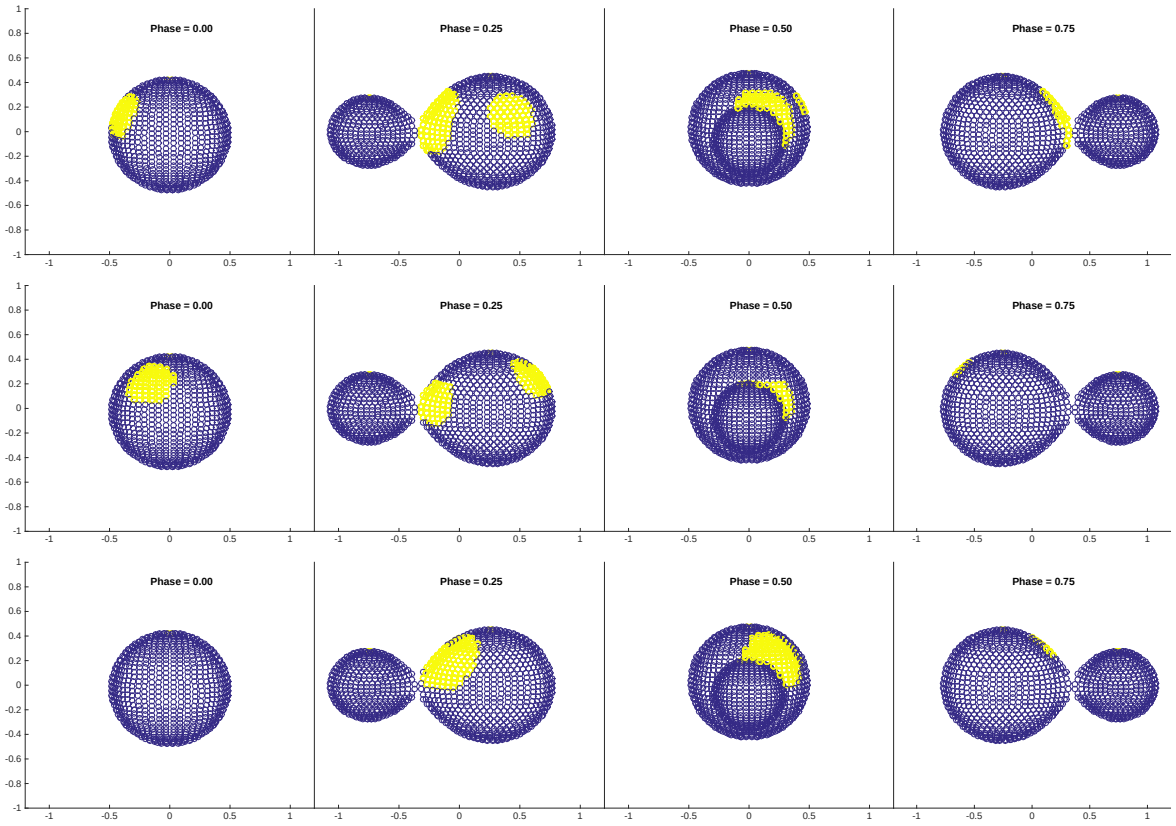


Fig. 6. The shape of system for the three epochs. We present four subfigures of the shape for each epoch. The figures from top left to bottom right are for the first, second, and third year, respectively. The blue part is the shape of the star, and the yellow part represents the hot spots. The color figure can be viewed online.

inclination of $i \approx 84.3°$, and a secondary star temperature of $T_2 \approx 5873$K. It is also interesting to note that, based on our results, the degree of over-contact in the system, defined as

$$f = \frac{\Omega_{in} - \Omega}{\Omega_{in} - \Omega_{out}},$$

where the potentials Ω_{in} and Ω_{out} define the inner and outer critical surfaces in Roche geometry and Ω is the potential corresponding to the surface of the over-contact binary, is calculated to be $f \approx 11.5\%$.

The fact that the primary maximum is variable and sometimes brighter than the secondary maximum can be explained by hot spot activity. The variation of the light curve profile can be well simulated by adjusting the parameters of the spots. For a simplified strategy, we assumed at the beginning that the location and temperature of the spots were fixed. Figure 7 presents the size variation of two hot spots in 19 days of the first epoch. Figure 5 and Table 3 present the spots parameter results of the

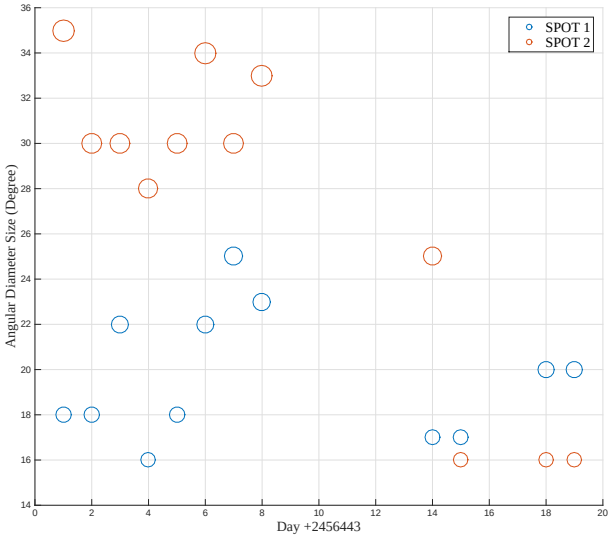


Fig. 7. The variation of spots in the first epoch. Spot 2(red) presents a significant decline over tens of days. The color figure can be viewed online.

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second and third epochs, and Figure 6 presents the star shapes. Two similar spots can be identified in the first and second epochs, but only one spot can be found in the third part of the data. With all the parameters found, the temperature of the massive component is about 230 K cooler than that of the smaller one.

7. CONCLUSIONS

Using the WDc and long term photometric observations of ROTSE-I J1643+25, we were able to determine its basic physical properties and establish that this system belongs to the group of W UMa variables. With a mass ratio of ≈ 0.34, it presents an inclination of ≈ 84.6 degrees and a degree of overcontact of 11%. The analysis of the data shows spots variations on the primary star, which imply strong activity on its surface.

Acknowledgments

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