First photometric study of ultrashort-period contact binary 1SWASP J140533.33+114639.1

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Abstract In this paper, CCD photometric light curves for the short-period eclipsing binary 1SWASP J140533.33+114639.1 (hereafter J1405) in the BV R bands are presented and analyzed using the 2013 version of the Wilson-Devinney (W-D) code. It is discovered that J1405 is a W-subtype shallow contact binary with a contact degree of \( f = 7.9 \pm 0.5\% \) and a mass ratio of \( q = 1.55 \pm 0.02 \). In order to explain the asymmetric light curves of the system, a cool starspot on the more massive component is employed. This shallow contact eclipsing binary may have been formed from a short-period detached system through orbital shrinkage due to angular momentum loss. Based on the \((O-C)\) method, the variation of orbital period is studied using all the available times of minimum light. The \((O-C)\) diagram reveals that the period is increasing continuously at a rate of \( \frac{dP}{dt} = +2.09 \times 10^{-7} \text{ yr}^{-1} \), which can be explained by mass transfer from the less massive component to the more massive one.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual (1SWASP J140533.33+114639.1)

1 INTRODUCTION

W UMa type contact binaries exhibit a sharp period cutoff phenomenon around 0.22 days (Rucinski 1992). A recent study using data released by the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) found that the updated value is around 0.2 days (Qian et al. 2017). Ultrashort-period (less than 0.23 days) contact eclipsing binaries (EBs) are important for modern astrophysics: (1) they can be utilized to detect the distance of stars by relying on their empirical period-luminosity relation (Rucinski 2004); (2) these binaries offer significant information about origin and evolution of late-type stars including mass and angular momentum loss (AML), and even the merging (Qian et al. 2014; Kjurkchieva et al. 2016). With the development of technology, more and more contact EBs with short-periods have been discovered by some sky surveys around the world (e.g., SDSS, SuperWASP and NSVS). Till now, some of them have been studied in detail, such as CC Com (Köse et al. 2011; Yang & Liu 2003), GSC 1387–475 (Rucinski & Pribulla 2008), 1SWASP J015100.23-100524.2 (Qian et al. 2015b), NSVS 4484038 (Zhang et al. 2014) and the stable red-dwarf contact binary SDSS J001641-000925 (Davenport et al. 2013; Qian et al. 2015a).

1SWASP J140533.33+114639.1 (hereafter J1405), as a short-period contact EB candidate with an orbital period of about 0.225123 days, was first detected in 2013 (Lohr et al. 2013). Its light curves (LCs) present characteristics of a typical EW-type (nearly equal light minima). The Two Micron All Sky Survey (2MASS, Cutri et al. 2003) provides its magnitude of \( V=15.51, J=14.019, H=13.487 \) and \( K=13.328 \), and the corresponding color indexes are \( V−K=2.182, J−H=0.532 \).
and \( H - K = 0.159 \) for the system, which imply an average spectral type of about K4. However, there is no spectroscopic element, photometric solution or period research published until now. In the present paper, the LCs are analyzed using the Wilson-Devinney (W-D) program and its photometric solutions are obtained. All times of minimum light are collected and the period variations are analyzed. The evolutionary scenario and magnetic activity are also discussed.

### 2 MULTI-COLOR CCD PHOTOMETRIC OBSERVATIONS

Photometric observations of J1405 were carried out on 2016 March 17 and 22 utilizing the 84 cm telescope at the Observatorio Astronómico Nacional (OAN) in Sierra San Pedro Mártir, Mexico. This relatively small telescope is mainly employed for photometric observations, because more than 60% of the nights at this site have photometric quality (Tapia 2003). The integration times for each image in \( BVR \) bands were 70 s, 40 s and 25 s, respectively. All the observed images were reduced using the aperture photometric package PHOT of IRAF by Mr. Michel. Another two stars near the target were chosen as the comparison star and check star. The coordinates of the variable star, comparison star and check star are listed in Table 1. Two sets of LCs obtained are plotted in Figure 1. The LCs are asymmetric and show a weak O’Connell effect (O’Connell 1951), where the maxima following the primary minima are higher than the other maxima. The average observational errors and the amplitudes of light variation in different bands are listed in Table 2.

Meanwhile, some new times of light minimum for J1405 were also observed and determined using the least-squares parabolic fitting method. By applying the following linear ephemeris

\[
\text{Min.(HJD)} = 2457466.00294(\pm 0.00019) + 0.225123^d \times E,
\]

the \((O-C)\) values and observational LCs’ phase were calculated. The zeropoint displayed in this linear ephemeris was one of the primary eclipse times, which was determined with observed data from the 84 cm telescope, and the orbital period we adopted came from the SuperWASP EB catalog (Lohr et al. 2013). All the minima times and their corresponding \((O-C)\) values are listed in Table 3.

### 3 ORBITAL PERIOD INVESTIGATION

The \((O-C)\) method is the traditional way to reveal variations in orbital period. Before the present work, only one minimum time of J1405 had been published. For analyzing the period changes of the system, we collected all the CCD times of light minima. Mr. Marcus Lohr sent us 121 minima times from SuperWASP, and the LCs obtained from OAN offered another 4. Minima times with the same epoch have been averaged, and only the mean values are listed in Table 3. In our fitting process, according to determined errors listed in Table 3, the weight of the SuperWASP data is 1 and that of our data is 5.

The \((O-C)\) diagram shows a upward parabolic variation and the fitting curve is plotted in Figure 2. Based on the least-squares method, the new ephemeris

\[
\text{Min. I} = 2457470.95618(\pm 0.0003) + 0.22512639^d(\pm 0.00000003) \times E + 1.29(\pm 0.02) \times 10^{-10} \times E^2,
\]

was obtained. With the quadratic term included in this equation, a secular period increase rate is determined to be \(dP/dt = 2.09 \times 10^{-7} \text{ d yr}^{-1}\).

### 4 PHOTOMETRIC SOLUTIONS

To derive its physical parameters, the 2013 version of the W-D program (Wilson & Devinney 1971; Wilson & Van Hamme 2003; Wilson et al. 2010) is utilized. The numbers of observational data applied in the program are 81 in the \(B\) band, 78 in the \(V\) band and 72 in the \(R\) band.

Before analyzing the LCs, the values of some input parameters were set. The temperature for star 1 (star eclipsed at the primary light minimum), \(T_1 = 4680 \text{ K}\), was fixed according to mean color index (Cox 2000). We took the same values of gravity-darkening coefficients and bolometric albedo for both components, i.e., \(g_1 = g_2 = 0.32\) according to the stellar temperatures given by Claret (2000) and \(A_1 = A_2 = 0.5\) (Lu & Rucinski 1993) were set for late-type stars with a convective envelope. The bolometric and bandpass limb-darkening coefficients were chosen from van Hamme
Fig. 1 The observational LCs of J1405 in BVR bands. The differential LCs of the comparison star relative to the check star are also plotted.

Fig. 2 The \((O - C)\) diagram of J1405 formed by all available measurements. The \((O - C)\) values were computed by using a newly determined linear ephemeris (Eq. (1)). The solid line represents the quadratic fit (Eq. (2)). The bottom panel plots residuals for Eq. (2).

Table 2 Average Observational Errors and Amplitudes of Light Variation in March 2016

| Band | Date | Error (mag) | \(\Delta m\) (mag) | Date | Error (mag) | \(\Delta m\) (mag) |
|------|------|-------------|-------------------|------|-------------|-------------------|
| B    | 17   | 0.0071      | 0.5852            | 22   | 0.0102      | 0.6646            |
| V    | 17   | 0.0071      | 0.5231            | 22   | 0.0087      | 0.5592            |
| R    | 17   | 0.0067      | 0.5480            | 22   | 0.0081      | 0.5303            |

(1993). To account for the limb-darkening in detail, logarithmic functions were used. These fixed parameters are listed in Table 4. The adjustable parameters were: mass ratio, \(q\); orbital inclination, \(i\); mean temperature of star 2, \(T_2\); dimensionless potentials of the two components \(\Omega_1\) and \(\Omega_2\); monochromatic light of star 1, \(L_{1B}\), \(L_{1V}\) and \(L_{1R}\).

Two sets of LCs were obtained, but the data from March 17 have better quality. So, we started the analysis with this set of LCs. Mode 3 for a contact binary system is adopted \((\Omega_1 = \Omega_2\) in this case). Because there are no spectroscopic observations for J1405 published, we apply a \(q\)-search method (with fixed \(q\)) to obtain initial input parameters. The solutions are carried out with mass ratios ranging from less than 0.25 to larger than 3.0. The relation between the sum of weighted square deviations \(\Sigma\omega(O - C)^2\) and \(q\) is plotted in Figure 3. Values of \(\Sigma - q\) exhibit their lowest value at \(q = 1.55\). We then set the
initial value of $q$ to be 1.55 and treat it as an adjustable parameter. After all the free parameters converge, one set of solutions is derived. Because our LCs are asymmetric, and the main reason for this result is the variation of spot location and size (Kang et al. 2002). Considering this case, the cool starspot model was used to obtain better solutions. As is well known, four parameters can be used to describe a spot, namely the temperature, $T_s$; latitude, $Lat$; longitude $Lon$ and angular radius $Rad$. During our analysis, only $T_s$ was fixed in a series of trial values until we identified the best solution. Finally, we found that one cool star spot on the secondary component could yield the best fit, and the fitting residual of our solution with a spot is much smaller than that without a spot. Therefore, we adopted the cool star spot model as the final solution. The derived photometric solutions are listed in Table 5 and the theoretical LCs computed with the cool starspot model are plotted in Figure 4. Furthermore, we also derive the geometrical structure of the system, which is shown in Figure 5. Because the LCs obtained on March 22 have worse quality, we did not analyze them.

5 DISCUSSIONS AND CONCLUSIONS

The asymmetry displayed by the observed LCs suggests there is spot activity in the system. Therefore, we analyzed the LCs and obtained the photometric solutions with a cool star spot on the more massive component using the 2013 version of the W-D code. The results suggest that J1405 is a W-type contact EB near the short-
The $\Sigma - q$ curve for J1405. The minimum for residuals is at $q = 1.55$.

Observed (open circles, triangles and squares) and theoretical LCs (solid lines) calculated with the cool starspot parameters listed in Table 5. Residuals from the solutions are shown in the bottom panel.

Geometric structure of J1405 at phase 0.25.

Table 4 Fixed Parameters During Photometric Analysis

| Parameter | Value |
|-----------|-------|
| $g_1 = g_2$ | 0.32 |
| $A_1 = A_2$ | 0.50 |
| $x_{1\,\text{bolo}} - x_{2\,\text{bolo}}$ | 0.641, 0.638 |
| $y_{1\,\text{bolo}} - y_{2\,\text{bolo}}$ | 0.172, 0.163 |
| $x_{1\,\text{B}} - x_{2\,\text{B}}$ | 0.848, 0.844 |
| $y_{1\,\text{B}} - y_{2\,\text{B}}$ | 0.096, 0.129 |
| $x_{1\,\text{V}} - x_{2\,\text{V}}$ | 0.802, 0.801 |
| $y_{1\,\text{V}} - y_{2\,\text{V}}$ | 0.045, 0.022 |
| $x_{1\,\text{R}} - x_{2\,\text{R}}$ | 0.749, 0.755 |
| $y_{1\,\text{R}} - y_{2\,\text{R}}$ | 0.123, 0.108 |

Table 5 Photometric Solutions for J1405

| Parameter | March 17th | March 17th |
|-----------|------------|------------|
| $T_1$ (K) | 4680 Assumed | 4680 Assumed |
| $q$ | 1.5501 ± 0.0199 | 1.5488 ± 0.0163 |
| $T_2$ (K) | 4563 ± 16 | 4523 ± 21 |
| $i$ (°) | 68.996 ± 0.257 | 68.616 ± 0.321 |
| $L_1/(L_1 + L_2)(B)$ | 0.4545 ± 0.0074 | 0.4742 ± 0.0135 |
| $L_1/(L_1 + L_2)(V)$ | 0.4434 ± 0.0058 | 0.4590 ± 0.0121 |
| $L_1/(L_1 + L_2)(R)$ | 0.4342 ± 0.0045 | 0.4466 ± 0.0112 |
| $\Omega_1 = \Omega_2$ | 4.5612 ± 0.0092 | 4.5528 ± 0.0026 |
| $r_1$ (pole) | 0.3237 ± 0.0009 | 0.3247 ± 0.0011 |
| $r_1$ (side) | 0.3391 ± 0.0011 | 0.3402 ± 0.0015 |
| $r_1$ (back) | 0.3733 ± 0.0016 | 0.3751 ± 0.0022 |
| $r_2$ (pole) | 0.3967 ± 0.0009 | 0.3976 ± 0.0014 |
| $r_2$ (side) | 0.4201 ± 0.0011 | 0.4213 ± 0.0018 |
| $r_2$ (back) | 0.4510 ± 0.0015 | 0.4526 ± 0.0025 |
| $f$ (%) | 6.7 ± 1.6 | 7.9 ± 0.5 |
| Latitude (°) | 334.392 ± 4.242 |
| Longitude (°) | 253.902 ± 6.187 |
| Radius (radian) | 0.356 ± 0.089 |
| $T_s$ | 0.85 Assumed |

Another feature of J1405 is its spot activity. Generally, for late-type contact binary stars, their deep period cutoff with a mass ratio of $q = 1.55 \pm 0.02$. The mean contact degree ($f = 7.3\%$) reveals that it is a shallow contact system with similar surface temperature of the components ($\Delta T = 140$ K). Similar contact binaries include AH Vir (Lu & Rucinski 1993; Kjurkchieva et al. 2015), RZ Com (He & Qian 2008; Xiang & Zhou 2004), AM Leo (Hiller et al. 2004), U Peg (Mohajerani & Percy 2011; Djurašević et al. 2001) and SW Lac (Šenavcı 2012). W UMa-type binaries are formed from initially detached binaries by AML via magnetic braking (Qian et al. 2013). Like other late K-type contact binaries with short periods, J1405 is also in marginal contact and presents remarkably asymmetric LCs, representing probable surface activities (Zhang et al. 2014; Jiang et al. 2015a). Just as Qian et al. (2015b) discussed, the orbital shrinkage due to AML may result in the formation of a contact system similar to J1405. The progenitor of J1405 may be a short-period detached EB system similar to DV Psc (Pi et al. 2014), and J1405 may be at the same evolutionary phase as 1SWASP J015100.23-100524.2 (Qian et al. 2015b).
convective envelope along with fast rotation can help to produce a strong magnetic dynamo, thus they will display some solar-like activity such as photospheric cool starspots (Li et al. 2015). A cool starspot is known to be a strong magnetic area which can change the shape of LCs. We adopted the cool starspot model in the W-D program with one spot on the secondary component to explain it. Just as Figure 4 shows, the fitted LCs with a cool starspot coincides very well with the observational data at all phases. Therefore, using the cool starspot model to explain the asymmetry of LCs is reasonable.

Based on analysis of the \((O-C)\) diagram, we found that the orbital period of J1405 shows an upward parabolic variation, which represents an increase of the period. According to the obtained parameters, the rate of \(\frac{dP}{dt} = 2.09 \times 10^{-7} \text{ d yr}^{-1}\) is derived. The secular increase of the orbital period may be interpreted as mass transfer from the less massive component to the more massive one, such as EP And (Liao et al. 2013), 1SWASP J074658.6+224448.5 (Jiang et al. 2015a) and 1SWASP J075102.1+342405.3 (Jiang et al. 2015b). However, the time span of our data is only 10 years, and the increase of period might be only a part of long-term changes. Further observations are required to confirm this result.

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