RAA 2015 Vol. **15** No. **12**, 2237–2243 doi: 10.1088/1674–4527/15/12/011
http://www.raa-journal.org *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

SDSS J012119.10–001949.9: a very short period M dwarf contact binary from SDSS stripe 82

Lin-Qiao Jiang[1,2,3], Sheng-Bang Qian[1,2,3] and Jia Zhang[1,2]

[1] Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China; *linqiao@ynao.ac.cn*
[2] Key Laboratory of the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China
[3] University of Chinese Academy of Sciences, Beijing 100049, China

Received 2015 February 26; accepted 2015 May 9

Abstract We present the first multicolor photometric observations of the short period low-mass eclipsing binary SDSS J012119.10–001949.9. By using the 2013 version of the Wilson-Devinney code, the photometric solutions are derived. It is found that the system is in a contact configuration ($f = 18.9 \pm 6.0\%$) with a moderate mass ratio of 0.5 ± 0.01. A third light contributing about $6.1 \pm 1.3\%$ of the total luminosity in the V band was found, which may come from a cool tertiary component. The derived high orbital inclination ($i = 83.9^\circ \pm 0.5^\circ$) and the almost symmetric three light curves suggest that the determined parameters are reliable. Both the color class and spectral class of the system correspond to a spectral type of M0, which may indicate that SDSS J012119.10–001949.9 belongs to a very rare class of M dwarf contact binaries that are below the theoretical short period limit.

Key words: binaries: eclipsing — stars: individual (SDSS J012119.10–001949.9) — techniques: photometric

1 INTRODUCTION

The orbital period distribution of W UMa type contact binaries shows a sharp and well defined cut-off around 0.22 d (Rucinski 1992, 2007). According to the period-color relation diagram of contact binaries, systems with a period below 0.22 d should contain two very low mass and late-type (late K or M type) components. Observations and investigations of these kinds of systems can provide valuable information on the origin and evolution of low mass contact binaries (Qian et al. 2014).

Observationally, only a handful of contact systems with periods below 0.22 d have been confirmed and well studied. Among them, only one M-type binary, SDSS J001641.03–000925.2 ($P = 0.1985615$ d), has been confirmed as a contact system by Davenport et al. (2013). According to the study of Koen (2014), 1SWASP J23440181–212229 ($P = 0.2137$ d) may be another contact binary comprised of two M dwarfs on the basis of analysis of multicolor photometry. It must be mentioned here that both binaries are potentially triple systems. Recently, Qian et al. (2015) did not find the rapid decrease in the orbital period described by Davenport et al. (2013). Rather, the $O - C$ diagram of SDSS J001641.03–000925.2 showed a cyclic change, which can be plausibly explained by the light-travel time effect via the presence of a tertiary component. Not coincidentally, a rapid decrease in orbital period of 1SWASP J23440181–212229 was also initially reported by Lohr et al. (2012), but further observations subsequently indicated this to be part of a long term sinusoidal variation (Lohr et al. 2013a), which was argued in Lohr et al. (2013b) to be probably caused by a third body.

It is believed that W UMa type contact binaries are formed from detached binaries with short periods that are losing angular momentum (AM) via magnetic breaking (Guinan & Bradstreet 1988). According to the study of Stepien (2006), the time needed to reach Roche lobe overflow (RLOF) by an initial primary mass of 0.7 $M_\odot$ is more than 13 Gyr, and the AM loss time scale increases substantially with decreasing stellar mass. Thus, the time needed for binaries with less massive primaries is too long to reach RLOF within the age of the Universe. Therefore, the third companion should play an important role in the origin and evolution of the contact system by removing AM from the central pair (Qian et al. 2013). As Qian et al. (2015) proposed, it may be that all short period contact binaries are actually triple systems.

The system SDSS J012119.10–001949.9 (hereafter J012119) was identified as a periodic variable with low-mass stars in Sloan Digital Sky Survey Stripe 82 (Becker et al. 2011). It is unusual in that the system is composed of two M dwarfs, and the light-curve shapes suggest that the system may be in a contact configuration. Furthermore, the orbital period of the system is only 0.2072812 d, which is under the short period limit. All those features indicate that this star is an interesting target. Thus, this source was put into our observation plan.

2 NEW PHOTOMETRIC OBSERVATIONS

According to the result of Becker et al. (2011), the mean r-band magnitude of J012119 is $15^{\rm m}.50$. Due to its intrinsic faintness, the source was monitored on 2014 December 23 by using the 2.4 m telescope at Lijiang Gaomeigu observing station that is administered by Yunnan Observatories, which is equipped with a PI VersArray 1300B CCD. The effective field of view was about $10' \times 10'$. The filter system was a standard Johnson-Cousins $UBVR_{\rm c}I_{\rm c}$ system. During the observations, the integration times for each image in the V, $R_{\rm c}$ and $I_{\rm c}$ bands were 40 s, 20 s and 15 s, respectively. The comparison star (2MASS 01212700–0020427) and the check star (2MASS 01213167–0019175) were chosen near the target. In the image preprocessing step, bias subtractions and flat-field corrections were applied with the CCDPROC package in IRAF. Then, image reductions were done using the task PHOT that is part of the aperture photometry package in IRAF which generates magnitude measurements for a list of stars. The photometry aperture was set to 1.2 times the full width at half maximum in the reductions. Complete high precision $VR_{\rm c}I_{\rm c}$ light curves were obtained during one night. The typical errors associated with these measurements are 0.007$-$0.010 mag in the V band, and 0.006$-$0.009 mag in the $R_{\rm c}$ and $I_{\rm c}$ bands.

By using a least-squares parabolic fitting method, two eclipse timings were determined (MinI$=$ 2457014.9863 ± 0.0004, MinII$=$ 2457015.0889 ± 0.0002). At first, the phases of the observations were calculated with a period of 0.2072812 d provided by Becker et al. (2011). The phased light curve shows an evident shift at 0.5 phase, which may be due to an inaccurate value for period. Thus, a new period of 0.2052(8) d was derived based on our two eclipse timings. By using this newly derived period, the phases of the observations were computed again, which are plotted in Figure 1. It is shown that the light curves in all bands are symmetric and no O'Connell effects (different heights of the two maximum times) are visible.

3 THE ANALYSIS OF LIGHT CURVES

As a newly discovered W UMa-type binary, so far, there are no published photometric solutions for the system J012119. Therefore, the multicolor light curves were analyzed simultaneously using the 2013 version of the Wilson-Devinney code (Wilson & Devinney 1971; Wilson 1979, 1990; Van

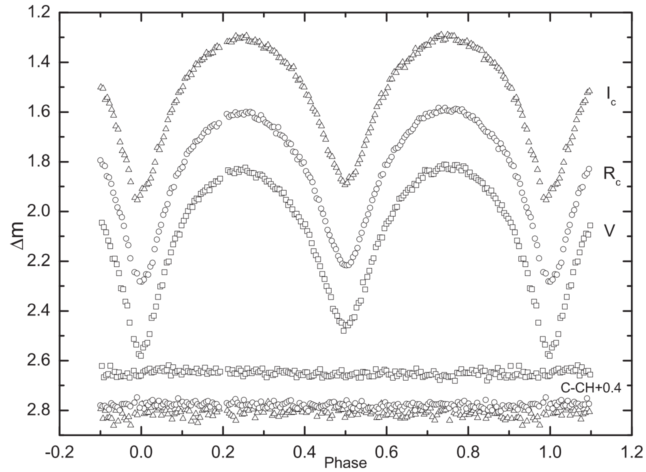

Fig. 1 Light curves of J012119 obtained on 2014 December 23. Open squares, open circles and open triangles represent V, $R_{\rm c}$ and $I_{\rm c}$ band observations respectively. Also shown with the same symbols are the magnitude differences between the comparison and check stars.

Hamme & Wilson 2007; Wilson 2008; Wilson et al. 2010; Wilson 2012). According to the result of Becker et al. (2011), both the color class and spectral class of the system correspond to a spectral type of M0. Therefore, the temperature for star 1 (star eclipsed at primary minimum) was fixed at $T_1 = 3840$ K (Cox 2000) during the analysis. The gravity-darkening coefficients $g_1 = g_2 = 0.32$ and the bolometric albedo $A_1 = A_2 = 0.5$ were chosen because of the convective envelopes for both component stars. For the bolometric and bandpass limb-darkening coefficients, an internal computation based on the result of van Hamme (1993) with the logarithmic law was used. Different modes (Modes 2, 3, 4 and 5 correspond to detached, contact, semi-detached with star 1 completely filling its Roche lobe, and semi-detached with star 2 completely filling its Roche lobe, respectively.) were tried, and the solutions only converged at mode 3.

Based on the previous discussions in the third paragraph of Section 1, i.e., all short period contact binaries may actually be triple systems, two models (with and without a third light) were used during the analysis. The mass-ratio is not known due to the lack of spectroscopy, therefore a q-search method was used to determine it. The relation between the resulting sum of weighted squared deviations Σ and the mass ratio q is plotted in Figure 2. The best solutions are found near $q = 0.45$ without a third light (we call this solution A) and $q = 0.52$ with a third light (we call this solution B). Then, we expanded the range of adjustable parameters with the mass ratio and started the iterations with the initial values of $q = 0.45$ and $q = 0.52$. Differential corrections were performed until it converged. The final solutions were derived, which are listed in Table 1. The corresponding theoretical light curves of those photometric elements are plotted in Figure 3.

After careful comparison between the two sets of solutions listed in Table 1, it is found that the results for basic parameters (i.e. inclination, mass ratio, temperature ratio, luminosity ratio and radius ratio) are close to each other. The agreements add credence to photometric parameters of the binary. However, one can see that solution B is much better than solution A, which is also exhibited in Figure 3, i.e., the theoretical light curve fittings derived by solution B (the green line) at the primary minimum in the V and $R_{\rm c}$ bands are better than those of solution A (the red line). Therefore solution B was accepted for J012119. The geometrical structure at phase 0.25 is displayed in Figure 4.

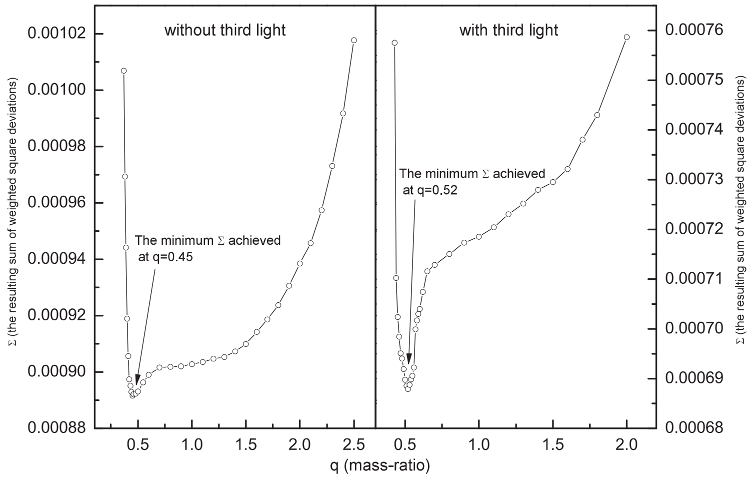

Fig. 2 Relation between the resulting sum of weighted squared deviations Σ and the mass ratio q. *Left panel*: the curve of Σ and q determined without a third light. *Right panel*: same as the left panel but with a third light.

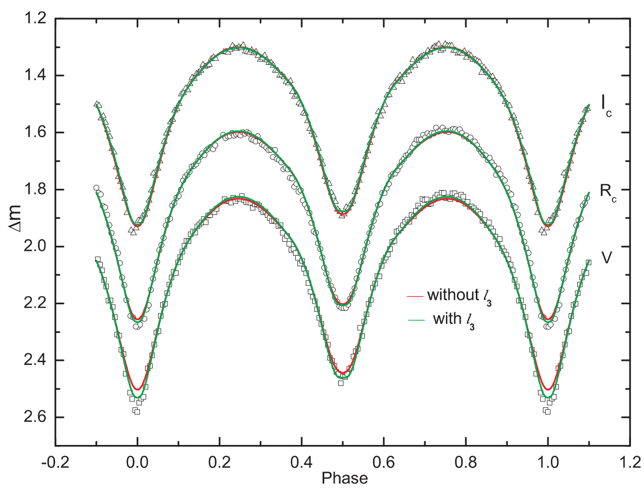

Fig. 3 The observed and theoretical light curves (*solid lines*) of J012119. Open squares, open circles and open triangles represent V, R_c and I_c band observations, respectively. The red line is calculated without a third light while the green line is calculated with a third light.

4 CONCLUSIONS AND DISCUSSION

Photometric solutions of J012119 have been obtained by analyzing the three symmetric light curves. The solutions suggest that the system is a shallow contact binary with a degree of contact $f = 18.9 \pm 6.0\%$. The mass ratio was determined to be $q = 0.5 \pm 0.01$. The more massive component is about 28 ± 5 K hotter than the less massive one, which indicates that J012119 may be a W UMa system which can be further classified as A-subtype. The solutions also reveal the existence of a third light in the system. As shown in Table 1, the luminosity contribution of the additional component is

Table 1 Photometric Solutions of J012119

Parameter	Solution A $l_3 = 0$	Solution B $l_3 \neq 0$
Mode	3	3
i [°]	81.2 (±0.4)	83.9 (±0.5)
q $[m_2/m_1]$	0.43 (±0.01)	0.50 (±0.01)
T_1 [K]	3840	3840
T_2 [K]	3801 (±4)	3812 (±5)
$\Omega_1 = \Omega_2$	2.7092 (±0.0175)	2.8111 (±0.0178)
$L_1/(L_{\rm total}$ (V)	0.6987 (±0.0015)	0.6248 (±0.0105)
$L_1/(L_{\rm total}$ $(R_{\rm c})$	0.6979 (±0.0014)	0.6092 (±0.0099)
$L_1/(L_{\rm total}$ $(I_{\rm c})$	0.6946 (±0.0014)	0.5927 (±0.0093)
$L_3/(L_{\rm total}$ (V) (%)	–	6.1 (±1.3)
$L_3/(L_{\rm total}$ $(R_{\rm c})$ (%)	–	8.4 (±1.2)
$L_3/(L_{\rm total}$ $(I_{\rm c})$ (%)	–	10.5 (±1.2)
r_1 (pole)	0.4323 (±0.0017)	0.4247 (±0.0015)
r_1 (side)	0.4619 (±0.0021)	0.4533 (±0.0017)
r_1 (back)	0.4914 (±0.0020)	0.4852 (±0.0016)
r_2 (pole)	0.2944 (±0.0071)	0.3088 (±0.0071)
r_2 (side)	0.3079 (±0.0087)	0.3238 (±0.0088)
r_2 (back)	0.3448 (±0.0153)	0.3631 (±0.0156)
Degree of contact (f)	12.4 (±6.7)%	18.9 (±6.0)%
Σ	0.00084	0.00065

Notes: $L_{\rm total} = L_1 + L_2$ in solutions without a third light and $L_{\rm total} = L_1 + L_2 + L_3$ in solutions with a third light.

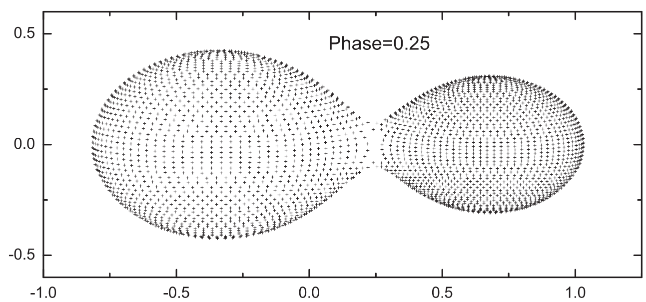

Fig. 4 Geometrical structure of J012119 at phase 0.25.

about $6.1 \pm 1.3\%$ in the V band, $8.4 \pm 1.2\%$ in the $R_{\rm c}$ band and $10.5 \pm 1.2\%$ in the $I_{\rm c}$ band, which suggests that the third body could be cooler and fainter than the primary and secondary components. Since our solutions are based on the light curves of three different bands and the fact that all the light curves are almost symmetric, as well as the high orbital inclination of $83.9° \pm 0.5°$, all these factors greatly improve credibility of the derived photometric solutions.

According to the result of Becker et al. (2011), both the color class and spectral class of J012119 correspond to a spectral type of M0. By assuming that the primary component is a normal main sequence star, the mass of the more massive component of $M_1 = 0.51\ M_\odot$ can be estimated (Cox 2000). Then, the absolute physical parameters of the components can be determined as follows: $M_1 = 0.51\ M_\odot$, $M_2 = 0.26\ M_\odot$, $R_1 = 0.61\ R_\odot$, $R_2 = 0.45\ R_\odot$, $L_1 = 0.0725\ L_\odot$ and $L_2 = 0.0395\ L_\odot$, according to the same method used by Zhang et al. (2014).

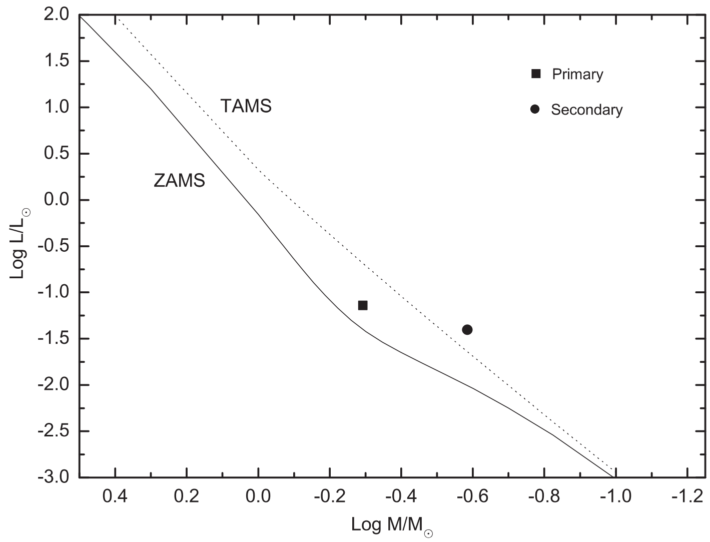

Fig. 5 Components of J012119 on a mass-luminosity diagram. The square and circle represent the primary (more massive) component and secondary (less massive) one respectively. The solid and dotted lines refer to the ZAMS and TAMS, which were constructed by the Binary Star Evolution (BSE) Code (Hurley et al. 2002).

The positions of the two components of J012119 on the mass-luminosity diagram are shown in Figure 5. It is found that the more massive component of J012119 is close to the zero age main sequence (ZAMS) line, and the less massive component lies above the terminal age main sequence (TAMS) line, indicating that the primary component could be a main-sequence star, as assumed, where the secondary component seems to be overluminous and oversized. These properties are similar to most W UMa stars. The oversized secondary component may be the result of energy transfer from the primary to the secondary in the contact phase (Webbink 2003), or it may be a consequence of strong magnetic activity on the surface of the components. It is well-known that, although M-type stars are the most common stars in the Galaxy, their physical properties are poorly understood. A serious problem in this field is that the observed radius is systematically larger than theoretical calculations by about 10%. One of the widely accepted explanations is that the fast rotation and/or strong magnetic activities of the components in short period late-type binaries result in a reduced heat flux and thus larger radii (Chabrier et al. 2007; Morales et al. 2008, 2010; Qian et al. 2012). J012119 is an extremely short period contact binary which consists of two M-type components. Fast rotation along with a deep convective envelope could produce strong photospheric activity, which may cause one of the components to be oversized. To support those hypotheses and results, further observations including photometric and spectroscopic observations are urgently needed.

Acknowledgements This work is supported by the National Natural Science Foundation of China (Grant Nos. 11133007 and 11325315), the Strategic Priority Research Program "The Emergence of Cosmological Structure" of the Chinese Academy of Sciences (Grant No. XDB09010202) and the Science Foundation of Yunnan Province (Grant No. 2012HC011). The new CCD photometric observations of the system were obtained by the 2.4 m telescope at the Lijiang Gaomeigu Observing Station administered by Yunnan Observatories.

References

Becker, A. C., Bochanski, J. J., Hawley, S. L., et al. 2011, ApJ, 731, 17
Chabrier, G., Gallardo, J., & Baraffe, I. 2007, A&A, 472, L17
Cox, A. N. 2000, Allen's Astrophysical Quantities, ed. A. N. Cox (4th ed. New York: AIP Press; Springer), 1
Davenport, J. R. A., Becker, A. C., West, A. A., et al. 2013, ApJ, 764, 62
Guinan, E. F., & Bradstreet, D. H. 1988, in NATO Advanced Science Institutes (ASI) Series C, 241, NATO Advanced Science Institutes (ASI) Series C, eds. A. K. Dupree, & M. T. V. T. Lago, 345
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
Koen, C. 2014, MNRAS, 441, 3075
Lohr, M. E., Norton, A. J., Kolb, U. C., et al. 2012, A&A, 542, A124
Lohr, M. E., Norton, A. J., Kolb, U. C., et al. 2013a, A&A, 549, A86
Lohr, M. E., Norton, A. J., Kolb, U. C., & Boyd, D. R. S. 2013b, A&A, 558, A71
Morales, J. C., Ribas, I., & Jordi, C. 2008, A&A, 478, 507
Morales, J. C., Gallardo, J., Ribas, I., et al. 2010, ApJ, 718, 502
Qian, S.-B., Zhang, J., Zhu, L.-Y., et al. 2012, MNRAS, 423, 3646
Qian, S.-B., Liu, N.-P., Li, K., et al. 2013, ApJS, 209, 13
Qian, S.-B., Jiang, L.-Q., Zhu, L.-Y., et al. 2014, Contributions of the Astronomical Observatory Skalnate Pleso, 43, 290
Qian, S.-B., Jiang, L.-Q., Fernández Lajús, E., et al. 2015, ApJ, 798, L42
Rucinski, S. M. 1992, AJ, 103, 960
Rucinski, S. M. 2007, MNRAS, 382, 393
Stepien, K. 2006, Acta Astronomica, 56, 347
van Hamme, W. 1993, AJ, 106, 2096
Van Hamme, W., & Wilson, R. E. 2007, ApJ, 661, 1129
Webbink, R. F. 2003, in Astronomical Society of the Pacific Conference Series, 293, 3D Stellar Evolution, eds. S. Turcotte, S. C. Keller, & R. M. Cavallo, 76
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Wilson, R. E. 1979, ApJ, 234, 1054
Wilson, R. E. 1990, ApJ, 356, 613
Wilson, R. E. 2008, ApJ, 672, 575
Wilson, R. E., Van Hamme, W., & Terrell, D. 2010, ApJ, 723, 1469
Wilson, R. E. 2012, AJ, 144, 73
Zhang, X. B., Deng, L. C., Wang, K., et al. 2014, AJ, 148, 40