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1SWASP J034439.97+030425.5: a short-period eclipsing binary system with a close-in stellar companion

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Abstract First multi-wavelength photometric light curves (LCs) of the short-period eclipsing binary (EB) 1SWASP J034439.97+030425.5 (hereafter J0344) are presented and analyzed by using the 2013 version of the Wilson-Devinney (W-D) code. To explain the asymmetric LCs of J0344, a cool star-spot on the less massive component was employed. The photometric solutions suggest that J0344 is a W-subtype shallow contact EB with a contact degree of $f = 4.9\% \pm 3.0\%$ and a mass ratio of $q = 2.456 \pm 0.013$. Moreover, an obvious third light was detected in our analysis. We calculated the average luminosity contribution of the third light to the total light, and that value reaches up to 49.78%. Based on the $O - C$ method, the variations of the orbital period were studied for the first time. Our $O - C$ diagram reveals a secular decrease superimposed on a cyclic oscillation. The orbital period decreases at a rate of $dP/dt = -6.07 \times 10^{-7}$ d yr^{-1}, which can be explained by the mass transfer from the more massive component to the less massive one. Besides, its $O - C$ diagram also shows a cyclic oscillation with an amplitude of 0.0030 d and a period about 7.08 yr, which can be explained by the presence of a third body with a minimum mass of $M_{3\min} = 0.15 \pm 0.02\, M_\odot$. The third component may play an important role in the formation and evolution of J0344 by drawing angular momentum from the central system.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual (1SWASP J034439.97+030425.5)

1 INTRODUCTION

The formation and evolution of short-period contact eclipsing binaries (CEBs) are still unsolved issues in the modern astrophysics (Fabrycky & Tremaine 2007; Zhou et al. 2016a; Zhang et al. 2017a). One of these issues is why the period distribution of the CEBs exhibits a sharp short-period limit around 0.22 d (Lohr et al. 2014). With the development of the several sky surveys in the world, such as SuperWASP (Lohr et al. 2013, 2015), NSVS (Woźniak et al. 2004) and CSS (Drake et al. 2013, 2014), many eclipsing binaries (EBs) with orbital period near or below 0.22 d have been reported without detailed study since 1992 (Rucinski 1992, 2007). Recently, using the data released by the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, Cui et al. 2012; Luo et al. 2012; Zhao et al. 2012; Tian et al. 2018), a statistical study reveals that the new value of the period cut-off of CEBs reduces to 0.20 d (Qian et al. 2017). Besides, by using the data from LAMOST, many EBs have been studied right now (Lee & Lin 2017; Lu et al. 2017; Qian et al. 2018, 2019). After original research, several researchers have pointed out that the presence of the third body may be a possible reason (Jiang et al. 2015; Qian et al. 2015a; Zhang et al. 2018a; Zhang et al. 2019). Besides, some reports indicate that these CEBs are usually shallow contact with small temperature difference between two components ($<$400 K) and strong activity (Kjurkchieva et al. 2018; Liu et al. 2018; Zhang et al. 2018b; Li et al. 2019).

A lot of EBs are formed with an unseen third body (Zhou et al. 2016a; Li et al. 2018). For these triple systems, if the third body is a close-in stellar component, then it will primarily affect the color indices and the spectral identification of the central EBs (Jiang et al. 2015). The reason is that these close-in additional stellar components can contribute many of light for the central system, which can be detected by using the Wilson-Devinney (W-D) code. Based on this method, many EBs with a third light have been discovered, for instance, AS Ser (Zhu et al. 2008), AO Ser (Yang et al. 2010), KIC 9532219 (Lee et al. 2016), KIC 5621294 and KIC 9007918 (Zasche et al. 2015), MQ UMa (Zhou et al. 2015), V548 Cyg (Zhu et al. 2016), EP And (Liao et al. 2013) and VZ Psc (Ma et al. 2018). Besides, the presence of the third body can make the eclipse times of the EBs change periodically (LTTE, Liao & Qian 2010; Wang et al. 2014, 2018). Using the traditional $O-C$ method, we can obtain the orbital parameters of the third body after analyzing the times of light minimum of EBs with a given ephemeris (Liao & Sarotsakulchai 2019; Zhang et al. 2018b; Zhang et al. 2019). For example, V753 Mon (Qian et al. 2013a), BI Vul (Qian et al. 2013b), CSTAR 038663 (Qian et al. 2014), V776 Cas (Zhou et al. 2016b), V2284 Cyg (Wang et al. 2017) and VZ Lib (Liao et al. 2019).

J0344 is first identified as a short-period EB candidate together with another 142 companions discovered by the Super Wide Angle Search for Planets (SuperWASP) in 2013 (Lohr et al. 2013), whose primary aim is to search for transiting extrasolar planets (Pollacco et al. 2006, Norton et al. 2011). Its orbital periods are then determined with a high accuracy (0.22988 d). Later on, J0344 is observed by LAMOST and its spectral type confirmed as K3 with an effective temperature of 5166 K. In order to understand the physical properties, the origin and evolution of this target, the detailed photometric analysis and orbital period study are presented in present work.

2 MULTI-COLOR CCD PHOTOMETRIC OBSERVATIONS

New photometric observations of J0344 in $BVRI$-bands were carried out on 2016 December 22, using the 2k×4k PI1024 camera attached to the 2.4-m telescope at Gaomeigu observational station of Yunnan Observatories (YNOs, Fan et al. 2015; Qian et al. 2015b; Pi et al. 2016). Its filter system is a standard Johnson's multicolor CCD photometric system. The integration time was 55 s for B-band, 50 s for V-band, 40 s for R-band, and 25 s for I-band, respectively. Another two stars near the target were chosen as the comparison star and the check star, respectively. The coordinates of the variable star, the comparison and check stars are listed in Table 1. The light curves (LCs) observed by using the 2.4-m telescope are displayed in Figure 1.

Table 1 Coordinates of the J0344, the Comparison Star, and the Check Star

Star	α_{j2000}	δ_{j2000}	$V_{\rm mag}$
J0344(V)	$03^{\rm h}44^{\rm m}39.97^{\rm s}$	$+03^\circ04^{'}25.5^{''}$	14.26
Comparison(C)	$03^{\rm h}44^{\rm m}48.28^{\rm s}$	$+03^\circ03^{'}13.5^{''}$	14.67
Check(Ch)	$03^{\rm h}44^{\rm m}44.96^{\rm s}$	$+03^\circ01^{'}43.6^{''}$	15.43

PHOT (measure magnitudes for a list of stars) of the aperture photometry package of IRAF[1] was used to reduce the observed images from 2.4-m telescope, including a flat-fielding and bias-fielding correction process. Meanwhile, new determined minimum times of J0344 by using the least-squares method are listed in Table 2.

3 ORBITAL PERIOD INVESTIGATION

Depending on the SuperWASP eclipses offered by Mr. Lohr, the ASAS-SN eclipses (Shappee et al. 2014; Kochanek et al. 2017) and our new observed times of light minima, the orbital period variations of J0344 were reanalyzed by using a least-square fitting method. Their $O-C$ values were calculated with the following linear ephemeris, and the fitting curves are plotted in Figure 2.

$$\begin{aligned}{\rm Min.(HJD)} = &\,2454721.573501\\ &+0^{d}.22987720(6)\times E\,.\end{aligned}\tag{1}$$

It should be noted that the data with larger errors (more than 0.008 d) were removed in our analysis, and the average values were adopted for the eclipses with the same epoches. The new ephemeris were then obtained as follows:

$$\begin{aligned}{\rm Min.\ I} = &\,2454721.57541(\pm0.00019)\\ &+0.^{d}229878801(\pm0.000000062)\times E\\ &-1.91\times10^{-10}(\pm0.38)\times E^{2}\\ &+0.003006(\pm0.000188)\\ &\times\sin(0.03200^\circ(\pm0.00015)\times E\\ &+157.998^\circ(\pm2.930))\,.\end{aligned}\tag{2}$$

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[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of the Universities for Research in Astronomy, inc. (AURA) under cooperative agreement with the National Science Foundation.

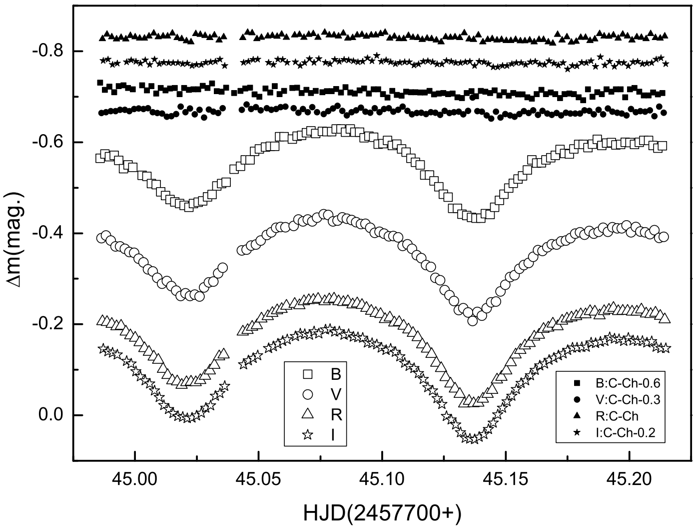

Fig. 1 The light curves of J0344 observed by using the 2.4-m telescope in Yunnan Observatories at Gaomeigu observational station. The ($C - Ch$) curves are plotted at the top, which represent the light curves of the comparison star relative to the check star.

Table 2 New CCD Times of Light Minima for J0344

Star	JD(Hel.)	Error(d)	Method	Filter	Telescope
J0344	2456683.80927		CCD	V	ASAS-SN telescope
J0344	2457007.93426		CCD	V	ASAS-SN telescope
J0344	2457365.84641		CCD	V	ASAS-SN telescope
J0344	2457374.69623		CCD	V	ASAS-SN telescope
J0344	2457421.81968		CCD	V	ASAS-SN telescope
J0344	2457745.02125	±0.00018	CCD	B	Lijiang 2.4 m
J0344	2457745.13732	±0.00019	CCD	B	Lijiang 2.4 m
J0344	2457745.02107	±0.00036	CCD	V	Lijiang 2.4 m
J0344	2457745.13701	±0.00031	CCD	V	Lijiang 2.4 m
J0344	2457745.02092	±0.00021	CCD	R	Lijiang 2.4 m
J0344	2457745.13680	±0.00019	CCD	R	Lijiang 2.4 m
J0344	2457745.02098	±0.00009	CCD	I	Lijiang 2.4 m
J0344	2457745.13687	±0.00011	CCD	I	Lijiang 2.4 m
J0344	2457745.021055	±0.00021	CCD	$BVRI$	Lijiang 2.4 m
J0344	2457745.137000	±0.00020	CCD	$BVRI$	Lijiang 2.4 m
J0344	2458473.143400	±0.00027	CCD	R_c	Kunming 1.0 m
J0344	2458473.143920	±0.00044	CCD	I_c	Kunming 1.0 m
J0344	2458762.330970	±0.00008	CCD	I	Xinglong 0.8 m

Based on the quadratic term included in these new ephemeris, the continuous period change at a rate of $dP/dt = -6.07 \pm 0.27 \times 10^{-7}$ d yr^{-1} is determined. The sinusoidal term in Equation (2) suggests a cyclic oscillation with an amplitude of 0.0030±0.0002 d and a period of 7.08±0.15 yr. The residuals are displayed at the bottom of Figure 2.

4 PHOTOMETRIC SOLUTIONS

To obtain photometric elements of J0344, and understand its evolutionary state, we analyzed the present LCs in the $BVRI$-bands with the 2013 version W-D code (Wilson & Devinney 1971; Wilson 1979, 2012).

The temperature for star 1 (star eclipsed at the primary light minimum), $T_1 = 5165$ K was fixed, with the K3 spectral type according to LAMOST survey. We took the same values of gravity-darkening coefficients and the bolometric albedo for both components, i.e., $g_1 = g_2 = 0.32$ according to the stellar temperatures given by Claret (2000) and $A_1 = A_2 = 0.5$ (Ruciński 1969) were set for late-type stars with a convective envelope. To account for the limb-darkening, logarithmic functions were used during our analysis. The adjustable parameters were: the mean temperature of star 2, T_2; the orbital inclination, i; the monochromatic light of star 1, L_{1B}, L_{1V}, L_{1R} and L_{1I}; the dimensionless potentials of the two components Ω_1 and Ω_2.

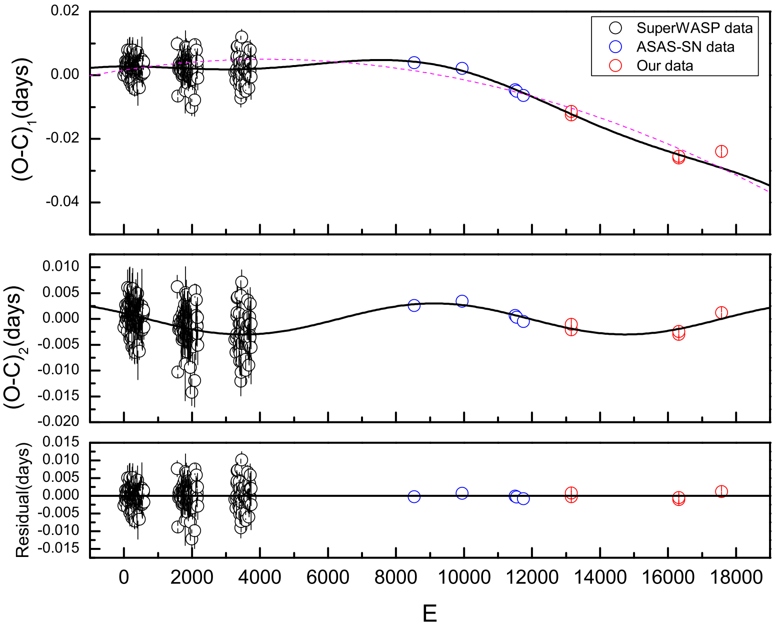

Fig. 2 The $O-C$ diagram for J0344 formed by all available measurements. The $(O-C)_1$ values were computed using the linear ephemeris (Eq. (1)). The *solid line* represents the combination of new linear ephemeris and cycle oscillation, and the *dashed line* represents the quadratic term in the new ephemeris. The $(O-C)_2$ values were computed with a new linear ephemeris in Eq. (2). The bottom panel plots the residuals for the whole effect.

To obtain the input parameters, a q-search method was used beginning our calculation (Zhang et al. 2017b). A wide range was adopted from 0.2 to 3.8 with a step of 0.1. During our analysis, we found that the photometric solutions of the target converged at mode 3 (for contact binaries), and when the mass ratio less than 0.6 we cannot get any convergence solutions. The q-search curve was carried out and plotted in Figure 3 with a lowest point at $q = 2.4$. Then, we set q as an adjustable parameter and put its initial value at $q = 2.4$. Because of the O'Connell effect displayed in its LCs, a cool star-spot was added. Besides, the third light and the changes of the orbital period were also considered during our analysis. Finally, the best photometric solutions were obtained with cool star-spot and the third light, which were listed in Table 3. Because of the short time span of the $(O-C)$ data and the small difference of the photometric solutions with and without dp/dt considered, we adopted the photometric solutions without dp/dt added as our final results. The fitting curves using these photometric elements were plotted in Figure 4. At the same time, the geometrical structure of the system at four different phases are shown in Figure 5. The phases LCs shown in Figure 5 are calculated with the following linear ephemeris:

$$\mathrm{Min.(HJD)} = 2457745.13700(2) + 0^d.22987720(6) \times E\,. \tag{3}$$

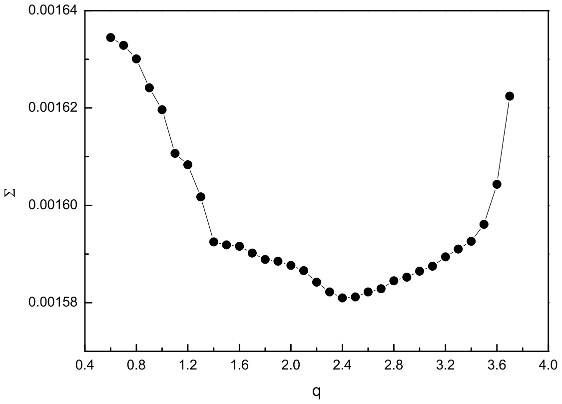

Fig. 3 Q-search curve of J0344.

5 DISCUSSION AND CONCLUSIONS

First photometric solutions for J0344 was obtained by using the 2013 version of the (W-D) code. We found that J0344 is a W-subtype CEB with a low contact degree of $f = 4.9\% \pm 3.0\%$ and a mass ratio of $q = 2.456 \pm 0.013$. The temperature difference between two components is about 250 K. To explain the asymmetric LCs, a cool star-spot on the primary component was employed, which means that it is active at present like other late-type EBs (Zhang et al. 2014). During our analysis, we found the presence of the third light. According to the results listed in

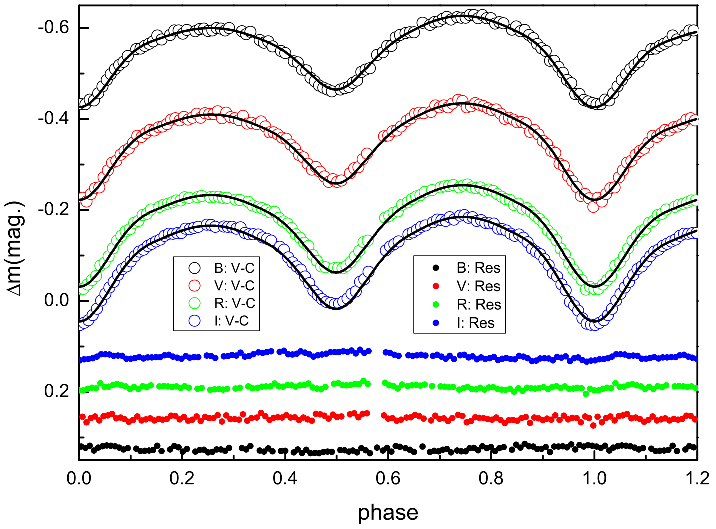

Fig. 4 The observational and theoretical light curves of J0344 in $BVRI$-bands. The *circles* and *solid lines* represent the observational and theoretical light curves, respectively. The fitting residuals are plotted in the bottom panel.

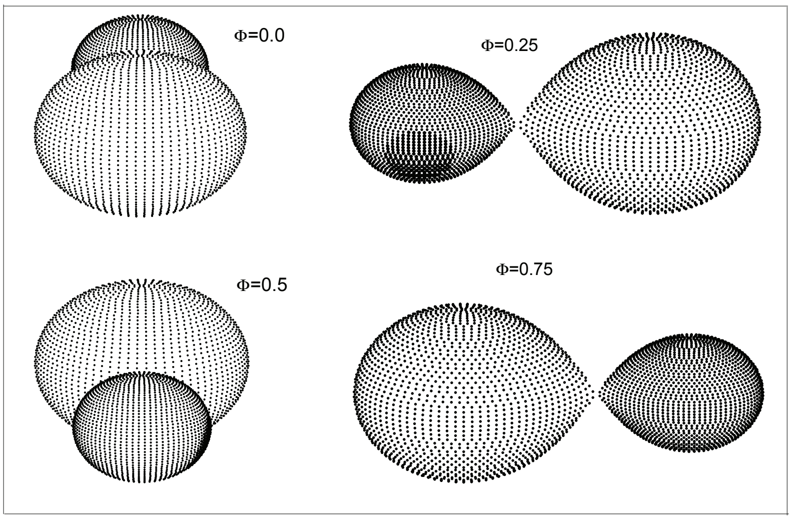

Fig. 5 Geometric configurations for J0344 at different phases (0, 0.25, 0.5, 0.75).

Table 3, the luminosity contribution of the tertiary component to the total light is 57.57%, 52.17%, 46.68%, 42.70% in the B, V, R and I-bands, respectively. One of the mainly features of the W-subtype CEB is that the primary minima of these systems are produced due to the occultation of the more massive and cooler components (Li et al. 2019). If we assume that the mass of the more massive star of J0344 is $M_2 = 0.70 \pm 0.03\,M_{\odot}$ (K3, Cox 2000), then, the mass of the less one is estimated to be $M_1 = 0.29(\pm 0.01)\,M_{\odot}$ through the mass ratio q.

The LCs observed by SuperWASP and ASAS-SN (V-band) surveys also show an obvious LC variation (the O'Connell effect, Li et al. 2015, 2016, 2017). Although the data from these two surveys are very scattered, their LCs also exhibit a negative O'Connell effect (Qian et al. 2015a), which is in agreement with our result. The V-band LCs from 2.4-m telescope shows that the Max. II is brighter than Max. I about 0.015 magnitude. The variation of the LCs can be interpreted by changing positions and parameters of star-spots (Zhou et al. 2018; Zhou & Soonthornthum 2019). At present, we have not found the cycle to cycle variation of the LCs, and more observations are needed in the future.

Using the $O-C$ method, we analyzed the orbital period changes of J0344. The $O-C$ diagram of J0344 shows a downward parabolic variation with a rate of $dP/dt = -6.07 \times 10^{-7}\,\mathrm{d\,yr^{-1}}$, which can be explained by the mass transfer from more massive component to the less massive

Table 3 Photometric Solutions for J0344

	Without dp/dt		With dp/dt	
Parameters	Values	Errors	Values	Errors
$g_1 = g_2$	0.32	Assumed	0.32	Assumed
$A_1 = A_2$	0.5	Assumed	0.5	Assumed
T_1(K)	5166	Assumed	5166	Assumed
q	2.456	±0.013	2.456	±0.013
T_2(K)	4915	±10	4921	±10
$i(^\circ)$	70.703	±0.409	70.677	±0.153
$L_1/(L_1 + L_2)(B)$	0.3875	±0.0077	0.3850	±0.0042
$L_1/(L_1 + L_2)(V)$	0.3697	±0.0076	0.3677	±0.0036
$L_1/(L_1 + L_2)(R)$	0.3546	±0.0073	0.3546	±0.0073
$L_1/(L_1 + L_2)(I)$	0.3451	±0.0071	0.3530	±0.0030
$L_3/(L_1 + L_2 + L_3)(B)$	0.5757	±0.0094	0.5754	±0.0085
$L_3/(L_1 + L_2 + L_3)(V)$	0.5217	±0.0106	0.5216	±0.0096
$L_3/(L_1 + L_2 + L_3)(R)$	0.4668	±0.0117	0.4664	±0.0087
$L_3/(L_1 + L_2 + L_3)(I)$	0.4270	±0.0124	0.4264	±0.0095
Ω_1=Ω_2	5.855	±0.018	5.887	±0.0036
$r_1(pole)$	0.2832	±0.0007	0.2828	±0.0006
$r_1(side)$	0.2952	±0.0008	0.2948	±0.0007
$r_1(back)$	0.3275	±0.0012	0.3271	±0.0008
$r_2(pole)$	0.4312	±0.0016	0.4333	±0.0034
$r_2(side)$	0.4599	±0.0022	0.4627	±0.0046
$r_2(back)$	0.4868	±0.0029	0.4901	±0.0063
Latitude(°)	107.427	±1.318	106.535	±1.207
Longitude(°)	265.873	±1.433	270.000	±2.293
Radius(°)	28.075	±2.253	28.032	±0.459
T_f	0.84	Assumed	0.84	Assumed
$\sum (O - C)_i^2$	0.00166		0.00031	

Table 4 Parameters of the Tertiary Component in J0344

Parameters	Values	Units
P_3	7.08(±0.12)	yr
A_3	0.00301(±0.00027)	d
$a_{12}^{'}$sin(i_3)	0.52±0.13	AU
$f(m)$	2.80(±0.27)× 10^{-3}	$M_\odot$
M_3sin(i_3)	0.15(±0.02)	$M_\odot$
$a_3(i_3 = 90^\circ)$	3.43 (±0.36)	AU

one. In addition, its $O - C$ diagram shows a cyclic variation. Considering the presence of the third light, we think that this cyclic oscillation may be caused due to the presence of the tertiary stellar component. Based on the fitting parameters that we obtained, the projected radius of the orbit that J0344 rotates around at the barycenter of the triple system is calculated with the equation:

$$a_{12} \sin i_3 = A_3 \times c\,, \tag{4}$$

where A_3 is the amplitude of the $O - C$ oscillation, and i_3 is the orbital inclination of the third body and c is the speed of light. Then, the mass function of the tertiary companion is computed with

$$\begin{aligned} f(m) &= \frac{4\pi^2}{GP_3^2} \times (a_{12}^{'} \sin i_3)^3 \\ &= \frac{(M_3 \sin i_3)^3}{(M_1 + M_2 + M_3)^2}\,, \end{aligned} \tag{5}$$

where P_3 is the period of $O - C_2$ oscillation, G is the gravitational constant, and M_3 is the mass of the third body. These parameters of the third body are listed in Table 4. The minima mass ($i_3 = 90^\circ$) of the third body is estimated as $M_{3\min} = 0.15\,M_\odot$. In addition, as shown in Table 3, we noted that the luminosity contribution of the third light decreases from the shorter wavelength to the longer wavelength. The reason for this is that the third body may be a late-type star whose radiation is concentrated in the short wavelengthes. At the same time, it is very close to the central system with a low orbital inclination, which is consistent with our photometric solutions and the period investigation (Zhu et al. 2008). What all these means, J0344 perhaps is a rarely triple system consisting of three late-type stars.

As mentioned earlier, the third light is a usual way offered by the W-D code to search for possible multi-systems. The earlier statistic study from the Kepler photometric database confirmed that at least 20% of close binaries have tertiary companions (Rappaport et al. 2013). We counted all of the published CEBs with a period near the 0.22 d and found that only NSVS 7179685 and CRTS J232100.1+410736 (see Table 5) are W-subtype CEBs with an obvious third light that has been detected. It should be

Table 5 The Well Studied W-subtype CEBs Near the Period Limit With a Third Light

Star	Period (d)	f (%)	$L_3/L_{\rm all}$(%)	log $J_{\rm rel}$	Ref.
NSVS 7179685	0.209740	19	45	–0.9286	[1]
CRTS J232100.1+410736	0.211984	16	20	–0.9170	[2]
J0344	0.2298772	5	50	–0.9039	[3]

Notes: [1] Dimitrov & Kjurkchieva 2015; [2] Li et al. 2019; [3] The present work.

noted that the orbital angular momentum listed in Table 5 was calculated by using the expression (Popper & Ulrich 1977),

$$J_{\rm rel} = M_1M_2(\frac{P}{M_1+M_2})^{\frac{1}{3}}\,. \qquad (6)$$

The origin of these short-period CEBs is still an open question. The progenitor of J0344 may be a system similar to DV Psc (Robb et al. 1999; Zhang & Zhang 2007; Zhang et al. 2010; Pi et al. 2014, 2019), which is an RS CVn-type binary with a spectral type of K4-5 (Stephenson 1986; Lu et al. 2001). Qian et al. (2013a,b, 2014) thought that the existence of an additional stellar component may play an important role for helping to produce these systems. Specifically, the third body may remove the angular momentum from the central binary system during the early dynamical interaction or late evolution, which will accelerate the orbital evolution of these binaries (Zhou et al. 2016b).

In summary, our results support the previously published conclusion , for example, many of these short-period CEBs are W-subtype shallow contact EBs with stellar spot activity and small temperature differences (Kjurkchieva et al. 2018; Liu et al. 2018; Zhang et al. 2015, 2018a; Li et al. 2019). Besides, J0344 is a rare short-period CEB system with a strong third light. As Qian et al. (2015b) discussed, the circumbinary companions play a vital role in the origin and evolution of the short period contact binaries. With the development of worldwide surveys, a great number of contact binaries around the short period cut-off have been identified. One of them, J0344 is an important and rare target for testing theories of short-period W UMa-type binaries' formation and evolution. Consequently, we expect to find more such candidates, which will provide more valuable information on the formation of contact binaries at the short period limit as well as their origin and evolution. However, because the time span of our $(O-C)$ data is relative short (less than 10 yr), long-time and high precision observations are required to confirm our results in the future.

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