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The first photometric analysis and period investigation of the K-type W UMa type binary system V0842 Cep

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Abstract V0842 Cep is a W UMa-type binary star that has been neglected since its discovery. We analysed the VR_cI_c light curves, obtained by the 1 m telescope at Weihai Observatory of Shandong University, using the Wilson-Devinney code. V0842 Cep was found to be a shallow contact binary system (f=8.7%) with a mass ratio of 2.281. Because its orbital inclination is greater than 80°, the photometric results are reliable. A period study is included which reveals a continually decreasing orbital period ($\frac{\mathrm{d}p}{\mathrm{d}t}$=1.50(±0.42)×$10^{-7}$ d yr^{-1}). This trend could be attributed to the angular momentum loss via stellar wind.

Key words: stars: binaries: close — stars: binaries: eclipsing — stars: individual (V0842 Cep)

1 INTRODUCTION

W UMa-type binary systems (contact binaries) usually contain two main sequence stars whose spectral types vary from F to K. There is a common convective envelope that encases both stars. The orbital periods of these systems are generally less than a day. In the past fifty years, many researchers have investigated these types of binaries (e.g., Hilditch 1989; Stepien 2006; Zhang et al. 2011; Qian et al. 2013a, 2014, 2017); however, there are still a few questions regarding their structures and evolution, such as short-period cutoff (e.g., Rucinski 1992; Jiang et al. 2012; Li et al. 2019, 2020), and lower mass-ratio limit (e.g., Webbink 1976; Yang & Qian 2015; Kjurkchieva et al. 2018, 2020). Therefore, W UMa-type binaries should be further investigated.

V0842 Cep is a typical W UMa-type eclipsing binary, which exhibits continuous light variation, and the depths of the two light minima are similar. The orbital period of V0842 Cep (GSC 04586-01412, V=14.7 mag) is 0.288957 d, making it a very short period (VSP) system. The object was discovered by Kuzmin (2007) and confirmed by ASAS-SN[1] (Shappee et al. 2014; Jayasinghe et al. 2019). Jayasinghe et al. (2019) found that this object is an EW-type binary with V magnitude of 14.34 mag, amplitude of 0.67 mag and period of 0.288954 d. Applying the observations of VR_cI_c charge-coupled device (CCD) light curves, we include here a complete synthetic light curve analysis and period study.

2 OBSERVATION

V0842 Cep was observed by relying on the 1 m telescope at Weihai Observatory, Shandong University (Hu et al. 2014) on 2018 October 24. To this end, a PIXIS 2048B CCD camera was also employed; the camera has a format of 2048 × 2048 pixels, revealing a $12' \times 12'$ field of view. The Johnson–Cousins–Bessel VR_cI_c data were derived using the CCD photometric system. The typical exposure times were 100 s for V band, 45 s for R band and 25 s for I band.

The data were reduced utilizing C-Munipack[2] including bias and flat correction. We then applied an aperture photometry method to measure instrumental magnitudes. Figure 1 displays one of the processed images, where the variable star (i.e., V0842 Cep), comparison star and check star are expressed as “V”, “C” and “CH”, respectively. The photometric results of the three bands as well as the difference in the magnitudes of the comparison and check stars are featured in Figure 2. Two light

[1] `http://www.astronomy.ohio-state.edu/asassn/index.shtml.`

[2] C-Munipack a CCD photometry data processing software, developed based on Munipack. The program supports graphical user interfaces and command line models.

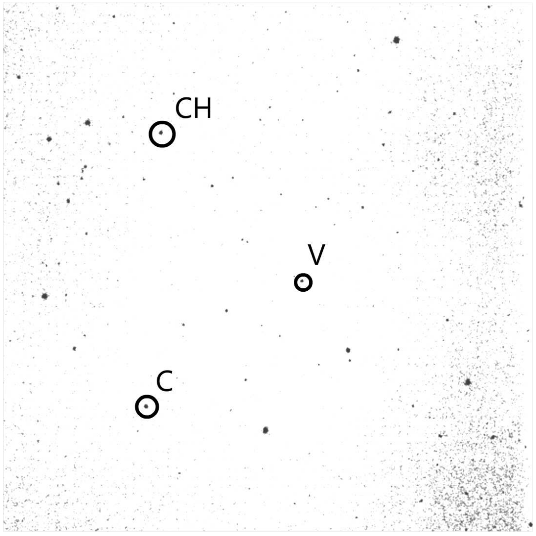

Fig. 1 CCD image around V0842 Cep has been presented. "V" signifies the variable star; "C", comparison star; and "CH", check star.

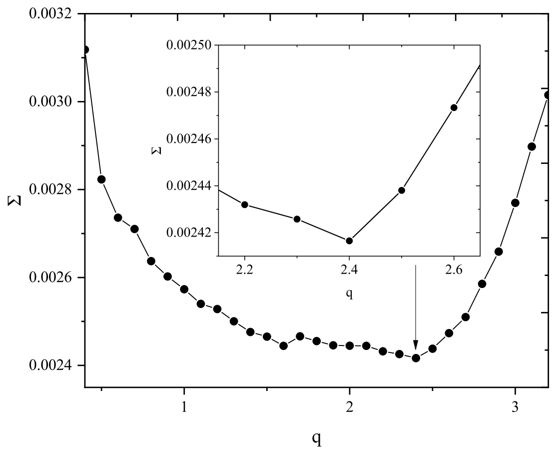

Fig. 3 Relationship between q and Σ, and the inserted figure presents values around the lowest point.

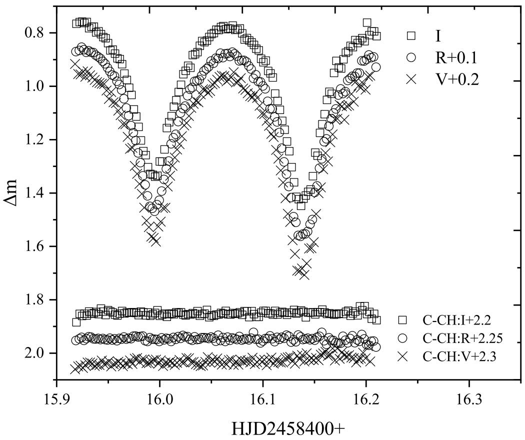

Fig. 2 Light curves of V0842 Cep at three bands. The figure also presents the difference in magnitude between the comparison and check stars.

minima were determined as 2458415.99495($\pm$0.00056) and 2458416.13833($\pm$0.00054).

3 PHOTOMETRIC SOLUTIONS

We analysed the VR_cI_c light curves via the Wilson-Devinney (W-D) code (Wilson & Devinney 1971; Wilson 1990, 1994). First, we determined stellar effective temperature 4920 K from the Gaia Data Release 2 (DR2) database[3] (Gaia Collaboration et al. 2016, 2018), and noticed that its typical accuracy is 324 K (Andrae et al. 2018). Preliminary solutions demonstrate that the luminosity of the secondary star is greater than that of the primary star; therefore, we set the stellar effective temperature as the temperature of the secondary star. V0842 Cep is a late-type binary star; thus, a few parameters can be fixed to match the corresponding convective envelope, such as the gravity-darkening coefficients (g_1 = g_2 = 0.32) (Lucy 1967) and bolometric albedo (A_1 = A_2 = 0.5) (Rucinski 1969). Bolometric and bandpass limb-darkening coefficients can be obtained from Van Hamme (1993).

Evidently, the three-bandpass light curves are EW-type, indicating that V0842 Cep is a contact binary system. Therefore, we selected mode 3 during our modelling. There are a few adjustable parameters, such as the monochromatic luminosity of the primary component (L_{1V}, L_{1R} and L_{1I}), orbital inclination (i), effective temperature of the primary component (T_1) and potentials of two components ($\Omega_1 = \Omega_2$).

We determined the mass ratio of V0842 Cep via a q-search method. We plotted the relation between mass ratio q and the weighted sum of the squared residuals $\Sigma W_i(O-C)_i$ in Figure 3 to obtain the most reliable mass ratio. When q is 2.4, Σ can be employed to derive the minimum value. Therefore, we set q = 2.4 as an initial value and ensured that it could be varied. Then, the results were derived. Photometric solutions are summarised in Table 1 and the corresponding theoretical light curves are illustrated in Figure 4.

[3] `https://gea.esac.esa.int/archive/.`

Table 1 Photometric Solutions of V0842 Cep

Parameters	Values	Errors
$g_1 = g_2$	0.32	Assumed
$A_1 = A_2$	0.5	Assumed
$T_1(K)$	5197	12
$T_2(K)$	4920	Assumed
$q(M_2/M_1)$	2.281	0.034
$\Omega_{\rm in}$	5.6450	Assumed
$\Omega_{\rm out}$	5.0401	Assumed
Ω_1=Ω_2	5.5926	0.0428
i	80.0	0.2
$(L_1/L_1 + L_2)_V$	0.3944	0.0024
$(L_1/L_1 + L_2)_{Rc}$	0.3796	0.0022
$(L_1/L_1 + L_2)_{Ic}$	0.3704	0.0021
r_1(pole)	0.2938	0.0010
r_1(side)	0.3070	0.0011
r_1(back)	0.3425	0.0014
r_2(pole)	0.4295	0.0044
r_2(side)	0.4584	0.0059
r_2(back)	0.4873	0.0082
f	8.7%	7.1%

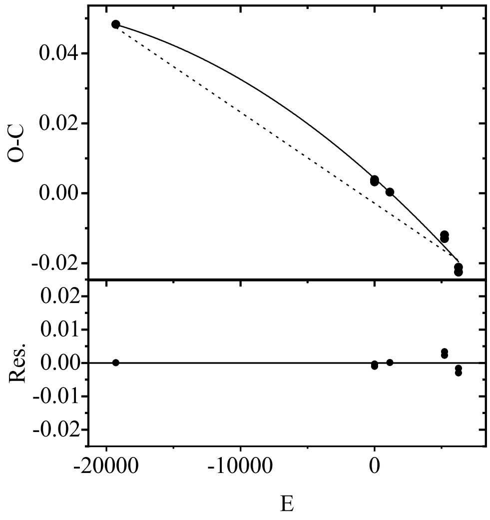

Fig. 5 $O - C$ diagram of V0842 Cep.

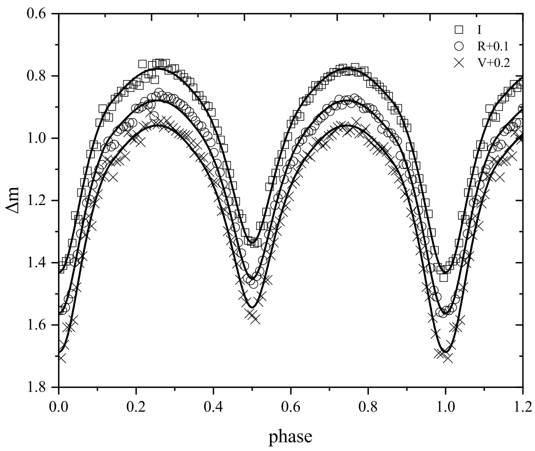

Fig. 4 Fitting result of the theoretical and observational light curves.

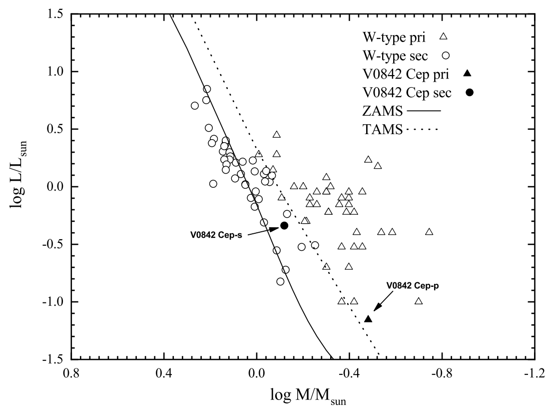

Fig. 6 Log M-Log L diagram: ZAMS and TAMS lines are constructed based on the binary star evolution code provided by Hurley et al. (2002). Simultaneously, the observations of 42 W-subtype binaries, obtained by Yakut & Eggleton (2005), are indicated for comparison. Both components of V0842 Cep are signified using bold arrows.

4 ORBITAL PERIOD INVESTIGATIONS

In addition to the results calculated using our own data and AAVSO[4] , the light minimum times can also be obtained from the O-C Gateway[5] and relevant references.

There are a total of eight times of light minimum, and the corresponding $O-C$ values were calculated by a linear ephemeris

$$Min.I = 2456908.3776 + 0.288957E. \quad (1)$$

The $O - C$ curve can be fitted to represent the dotted line in Figure 5; however, it cannot completely describe the variation trend. Therefore, we applied the least-squares method and found a good fit by adding a quadratic term

$$\begin{aligned} Min.I =& 2456908.37367(\pm0.00295) \\ &+ 0.28895094(\pm0.000000432171) \times E \quad (2) \\ &+ -5.95(\pm1.65) \times 10^{-11} E^2. \end{aligned}$$

Based on the quadratic term, we could calculate the period decrease rate $\frac{dp}{dt}$=1.50(±0.42)×10^{-7} d yr^{-1}. The fitting curve is plotted and illustrated as the solid line in Figure 5, further, the corresponding residuals are presented at the bottom of Figure 5. The details of each data point are listed in Table 2.

[4] https://www.aavso.org/
[5] http://var.astro.cz/ocgate/.

Table 2 Times of Light Minimum

JD (Hel.)	Error	Method	Type	E	$(O-C)_1$	$(O-C)_2$	Residuals	Reference
2451330.6850		ccd	P	–19303	–0.00255	–0.09122	0.0001	O-C gateway
2456908.3776	0.0003	ccd	P	0	0.00393	0.0036	–0.0003	OEJV 0179
2456908.5214	0.0004	ccd	S	0.5	0.00325	0.00292	–0.0010	OEJV 0179
2457238.5074	0.0003	ccd	S	1142.5	0.00337	0.00688	0.0001	OEJV 0179
2458715.7786	0.0008	ccd	P	6255	–0.00404	0.01415	–0.0016	This paper (AAVSO)
2458716.7885	0.0005	ccd	S	6258.5	–0.00605	–0.01274	–0.0030	This paper (AAVSO)
2458415.9950	0.0006	ccd	S	5217.5	0.00188	0.01781	0.0034	This paper (1m)
2458416.1383	0.0005	ccd	P	5218	0.00078	0.1672	0.0023	This paper (1m)

Table 3 Parameters for K-type Binaries

Binary	period(d)	q	f	T_1(K)	T_2(K)	$\frac{dp}{dt}$	Reference
NSVS 4484038	0.2186	2.74	10%	4839	4750	-	Zhang et al. (2014)
CC Com	0.2207	1.90	17%	4300	4200	-1.3×10^{-8}	Kose et al. (2011)
07g-3-00820	0.2270	1.30	5%	5100	4967	-	Gao et al. (2017)
V1104 Her	0.2279	1.61	17.1%	4050	3902	-2.9×10^{-8}	Liu et al. (2015)
1SWASP J161335.80-284722.2	0.2298	1.06	18.7%	4317	4126	-4.3×10^{-7}	Fang et al. (2019)
V523 Cas	0.2337	1.76	21.6%	5082	4763	-	Jeong et al. (2010)
YZ Phe	0.2347	2.64	9.7%	4908	4658	-2.6×10^{-8}	Samec & Terrell (1995)
FY Boo	0.2411	2.55	11%	4750	4555	-	Samec et al. (2011)
NSVS 2706134	0.2448	2.60	15.3%	4660	4204	-	Martignoni et al. (2016)
1SWASP J064501.21+342154.9	0.2486	2.11	15.3%	4450	4367	-	Liu et al. (2014b)
BI Vul	0.2518	1.04	4.4%	4600	4474	-9.5×10^{-8}	Qian et al. (2013b)
FS Cra	0.2636	1.32	14.6%	4700	4567	-	Bradstreet (1985)
IL Cnc	0.2677	1.76	8.9%	5000	4731	7.0×10^{-9}	Liu et al. (2020)
RV CVn	0.2696	1.74	9.8%	4750	4607	-	Liu et al. (2014a)
FG Sct	0.2706	1.35	21.4%	4536	4373	6.4×10^{-8}	Yue et al. (2019)
V0842 Cep	0.2890	2.28	8.7%	5197	4920	-1.5×10^{-7}	This paper
V1799 Ori	0.2903	1.34	3.5%	5000	4781	1.8×10^{-8}	Liu et al. (2014c)

5 DISCUSSION

The VR_cI_c light curves were analysed via the W-D program. This is the first time to determine the photometric solutions of V0842 Cep. The solutions indicate that V0842 Cep is a W-type shallow contact binary with a mass ratio of 2.281 and contact degree of 8.7%. Also, its orbital inclination is more than 80 degrees, which means the photometric solution results are quite reliable (Pribulla et al. 2003; Terrell & Wilson 2005). Since there are no spectroscopic observations of this star, absolute parameters cannot be uniquely determined. If the more massive component is a normal, main sequence star, its estimated mass is 0.76 $M_\odot$ according to the effective temperature 4920 K (Cox 2000). The mass of the less massive component can be calculated as follows: q=M_2/M_1. The result obtained is 0.33 $M_\odot$. Other absolute parameters are a=1.89 $R_\odot$, R_1=0.59 $R_\odot$, R_2=0.87 $R_\odot$, R_1=0.23 $R_\odot$ and L_2=0.40 $L_\odot$.

According to the colour index obtained from APASS-DR9[6] and interstellar reddening coefficient measured by Schlafly & Finkbeiner (2011), the $(B-I)_0$ can be determined as 0.6238. Using the following equation proposed by Rucinski & Duerbeck (1997), the absolute magnitude was calculated to be M_V = 4.40 mag

$$M_V = -4.44\log P + 3.02(B-V)_0 + 0.12. \quad (3)$$

According to Samus et al. (2017), the V band magnitude under maximum light can be determined to be m_V = 14 mag; further, after considering interstellar extinction, the revised value can be calculated as 12.80 mag (Schlafly & Finkbeiner 2011). The distance modulus can then be determined as m_V - M_V =8.40 mag, and the corresponding distance can be estimated to be 478.63 pc, which is similar to the distance derived by Gaia DR2, 485.12 pc.

To estimate the evolutionary status of V0842 Cep, both the components of V0842 Cep are marked on the mass-luminosity diagram in Figure 6. We constructed Zero Age Main Sequence (ZAMS) and Terminal Age Main Sequence (TAMS) lines using the binary star evolution code provided by Hurley et al. (2002). Simultaneously, the parameters of 42 W-type binaries, obtained by Yakut & Eggleton (2005), are indicated for comparison. The primary star of the object is located above the TAMS, implying that the primary star has evolved out of the main sequence and is over-luminous and over-sized. By contrast,

[6] The AAVSO Photometric All Sky Survey (APASS) project is designed to bridge the gap between the shallow Tycho2 two-bandpass photometric catalogue that is complete to V=11 and the deeper Henden et al. (2016) work.

the secondary star of the object lies between the ZAMS and TAMS, indicating that it is an evolved main sequence star. V0842 Cep exhibits an evolutionary status similar to those of other W-type binaries.

According to the eight minimum light times, we did the period analysis for the first time. The downward parabolic trend of $O-C$ means a long-term decrease in $\frac{\mathrm{d}p}{\mathrm{d}t}$=1.50(±0.42)×$10^{-7}$ d yr^{-1}. Assuming this trend is caused by conservative mass transfer between two components, corresponding parameters should satisfy the following equation

$$\frac{\dot{P}}{P}=-3\dot{M_1}(\frac{1}{M_1}-\frac{1}{M_2}). \quad (4)$$

We can then obtain the following: $\frac{\mathrm{d}M_1}{\mathrm{d}t}$ = +1.01(±0.28)×$10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. The positive sign implies that the more massive component is losing mass, and the corresponding timescale should be $\tau\sim\frac{M_2}{\dot{M_2}}\sim7.52\times10^6$ yr, which is approximately 7 times shorter than the thermal timescale of the more massive component ($\frac{GM^2}{RL}\sim5.20\times10^7$ yr). Therefore, the long-term period decreases may be attributed to angular momentum loss via magnetic stellar wind. By the decreasing orbital period, we can estimate that the shallow contact binary system will evolve into a deep contact binary system in the future.

V0842 Cep is a K-type binary. A few K-type contact binaries have been listed and are compared in Table 3. We statistically determined that K-type binaries have a few common features. First, temperature of the more massive component is lower than that of the primary component for all these systems, indicating that most K-type contact binaries are W-subtype systems. Second, most systems are shallow contact binaries ($f\leq25\%$), corresponding to the character of W-subtype contact binaries. Third, the periods of these systems are fairly short (less than 0.3 d), which can be satisfied with the period–colour relation (Rucinski 1998).

V0842 Cep is worthy of further investigation. More spectroscopic and photometric observations are required for determining the precise mass ratio and orbital period variation of binary stars.

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