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A photometric study of the high-mass-ratio contact binary AV Puppis

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Abstract The multi-color photometric light curves for contact binary AV Puppis (AV Pup) in VR_cI_c bandpasses are presented and analyzed by using the 2013 version of the Wilson-Devinney (W-D) code. The solutions suggest that AV Pup is a peculiar A-subtype W UMa contact binary with a high mass ratio ($q = m_2/m_1 = 0.896$) and a low fill-out factor ($f = 10\%$). Combining our newly determined times of minimum with those collected from literatures, the orbital period changes of this system are investigated. The $O - C$ analysis indicates that the orbital period of AV Pup is increasing at a rate of $\mathrm{d}P/\mathrm{d}t = 4.83 \times 10^{-7}\,\mathrm{days\,yr^{-1}}$, which can be explained by mass transfer from the less massive component to the more massive one.

Key words: techniques: photometric — stars: magnetic field — stars: individual: AV Pupis

1 INTRODUCTION

W Ursae Majoris (W UMa) contact binaries are the most common eclipsing systems in the vicinity of the solar system (Shapley 1948). They are short-period binary systems with both components filling their inner Roche lobes and sharing a common envelope. The formation and evolutionary ending of contact binaries are still open questions in astrophysics. The most plausible scenario is that they are formed from detached binaries via angular momentum loss (AML) (Vilhu 1982) or evolutionary expansion of the components (Webbink 1976). Model calculations suggest that this type of system will ultimately evolve into a contact binary with an extreme mass ratio or even into a fast-rotating single star under the influence of AML (Li et al. 2004b).

AV Puppis (AV Pup, GSC 05998–02010, $\alpha_{2000} = 08^{\mathrm{h}}24^{\mathrm{m}}32.30^{\mathrm{s}}$, $\delta_{2000} = -16^\circ 24' \, 11.24''$) was firstly reported by Hoffmeister (1930) as a variable star. Brancewicz & Dworak (1980) classified it as a semi-detached binary star with light curves of W UMa type. Wadhwa (2005) analyzed this system by using the V band photometric data of the All Sky Automated Survey (ASAS). He found this system is a contact binary with a high mass ratio of 0.80 and a low fill-out factor of 10%. This system has since been barely studied.

In this work, we present two years of photometric observations in VR_cI_c bandpasses targeting AV Pup. We also obtain new photometric solutions and perform a period analysis for this system. The rest of this article is organized as follows: in Section 2, the new observations for AV Pup are presented; in Section 3, a period analysis is conducted for AV Pup; in Section 4, the photometric solutions for the system are presented; finally, the summary and some discussions are given in Section 5.

2 OBSERVATIONS

New VR_cI_c photometric observations of AV Pup were obtained in 2014 and 2015 using the 1 m Cassegrain reflector telescope operated by Yunnan Observatories. An Andor DW436 2048×2048 CCD camera with an effective field of view of $7.3\times 7.3\,\mathrm{arcmin}^2$ is mounted on the telescope. The aperture photometry package in IRAF was applied for the data reduction. In our observations, the nearby stars TYC 5998–1820–1 and TYC 5998–2135–1 were employed as the comparison star and the check star, respectively. Their coordinates are listed in Table 1. The new light curves observed in two recent observing seasons are displayed in Figure 1. It is found in Figure 1 that the two sets of light curves are quite similar, and there is only a slight difference between phases 0.25 and 0.75.

Six new times of minimum were determined by using the Kwee-van Woerden (K-W) method (Kwee & van Woerden 1956) based on our observations. We then took

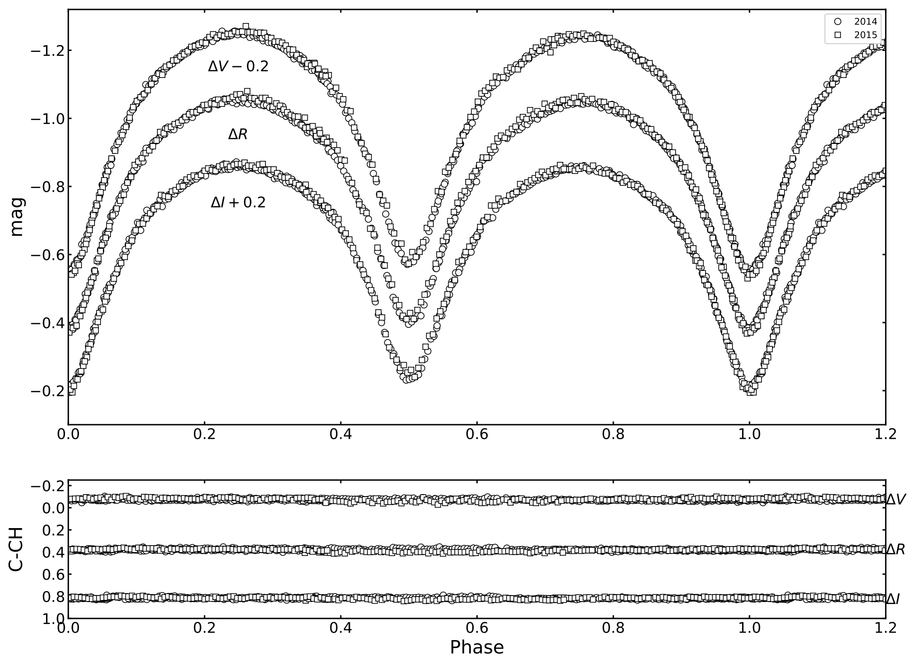

Fig. 1 The observed light curves in VR_cI_c bandpasses for AV Pup. The bottom panel is the magnitude differences between comparison and check stars. *Open circles* and *open squares* represent the data from 2014 and 2015, respectively.

Table 1 Coordinates of AV Pup, the Comparison Star and the Check Star

Target	Name	α_{J2000}	δ_{J2000}	$V_{\rm mag}$
Variable	AV Pup	08 24 32.30	–16 24 11.24	10.68
The comparison	TYC 5998–1820–1	08 24 15.30	–16 23 13.43	11.56
The check	TYC 5998–2135–1	08 24 22.63	–16 25 15.75	11.53

Table 2 New Times of Minimum for AV Pup

HJD	Error	p/s	Filter
2456715.2366	0.0001	p	VR_cI_c
2456716.1067	0.0001	p	VR_cI_c
2456717.1950	0.0001	s	VR_cI_c
2457094.1343	0.0002	p	VR_cI_c
2457096.0923	0.0002	s	VR_cI_c
2457098.0494	0.0001	p	VR_cI_c

the average value of three bandpasses as one minimum, which are listed in Table 2.

3 ORBITAL PERIOD ANALYSIS

Besides the new times of minimum derived by us from our observations, we also collected other times of minimum from the $O-C$ Gateway database[1], AAVSO[2] and literatures. We only used the CCD data (listed in Table 3) with a relatively high accuracy to investigate the changes in orbital period of AV Pup, since the visual observations are too dispersive (in the $O-C$ diagram) to aid the analysis of period changes for this object. Wadhwa (2005) assigned the orbital period of AV Pup as 0.435010 d, which is different from 0.556339 d obtained by Brancewicz & Dworak (1980). We find that the former seems to be more reliable based on our new observations. Utilizing the orbital period 0.435010 d and a primary minimum at HJD 2456715.2366, we can express the following linear ephemeris

$$\text{Min.I} = \text{HJD } 2456715.2366 + 0.435010 \times E\,. \qquad (1)$$

The $O-C$ values are calculated based on Equation (1) and are listed in the fourth column of Table 3. As seen in Table 3, the minimum at HJD 2453109.6840 evidently deviates from the other minima, so we neglected this value. The $O-C$ values are shown in Figure 2. A clear parabolic trend can be seen from this figure. We use a least-squares solution to fit all available times of minima and arrive at the following quadratic ephemeris

$$\begin{aligned}\text{Min.I} =& \text{HJD } 2456715.2369(3) + 0.4350142(1) \times E \\ &+ 2.88(16) \times 10^{-10} \times E^2\,.\end{aligned} \qquad (2)$$

The period of AV Pup exhibits a secular increase. The rate of increase is derived as $\mathrm{d}P/\mathrm{d}t = 4.83 \times 10^{-7}\,\mathrm{d\,yr^{-1}}$ based on Equation (2). Since the CCD times of minimum only last less than 20 yr, there is no clear cyclic variation apparent in the $O-C$ diagram.

4 LIGHT CURVE SOLUTION

We analyzed our new light curves based on the 2013 version of the Wilson-Devinney (W-D) code (Wilson &

[1] `http://var.astro.cz/ocgate/`
[2] `https://www.aavso.org/`

Table 3 All CCD Times of Minimum for AV Pup

HJD (2400000+)	Error	Epoch	$O-C$	Min	Filter	Reference
52002.5424	-	–10833.5	–0.0134	II	CCD	AAVSO
52237.2300	-	–10294.0	–0.0137	I	R_c	Nagai (2001)
52655.0563	-	–9333.5	–0.0145	II	R_c	Nagai (2004)
53020.0299	-	–8494.5	–0.0143	II	R_c	Nagai (2005)
53021.7705	-	–8490.5	–0.0137	II	CCD	AAVSO
53035.6907	-	–8458.5	–0.0138	II	CCD	AAVSO
53043.0860	-	–8441.5	–0.0137	II	R_c	Nagai (2005)
53074.6232	-	–8369.0	–0.0147	I	CCD	AAVSO
53109.6840	-	–8288.5	0.0278	II	CCD	AAVSO
53403.0552	-	–7614.0	–0.0153	I	R_c	Nagai (2006)
53405.0126	-	–7609.5	–0.0154	II	R_c	Nagai (2006)
53426.9828	-	–7559.0	–0.0132	I	V	Nagai (2006)
53743.2333	-	–6832.0	–0.0150	I	V	Nagai (2007)
53761.0689	-	–6791.0	–0.0148	I	V	Nagai (2007)
54119.0815	-	–5968.0	–0.0154	I	V	Nagai (2008)
54126.0425	-	–5952.0	–0.0146	I	V	Nagai (2008)
54127.7825	0.0003	–5948.0	–0.0146	I	CCD	Samolyk (2008)
54526.6873	0.0001	–5031.0	–0.0140	I	CCD	Samolyk (2008)
54526.6874	0.0002	–5031.0	–0.0139	I	CCD	Samolyk (2008)
54545.6101	0.0002	–4987.5	–0.0141	II	CCD	Samolyk (2008)
54548.0023	-	–4982.0	–0.0145	I	V	Nagai (2009)
54877.7380	0.0004	–4224.0	–0.0164	I	CCD	Samolyk (2009)
54901.6674	0.0002	–4169.0	–0.0125	I	CCD	Samolyk (2010b)
55175.9443	0.0005	–3538.5	–0.0094	II	CCD	Samolyk (2010a)
55232.7119	0.0003	–3408.0	–0.0106	I	CCD	Samolyk (2010a)
55271.6457	0.0001	–3318.5	–0.0102	II	CCD	Samolyk (2011a)
55612.6958	0.0002	–2534.5	–0.0080	II	V	Samolyk (2011b)
55622.7003	0.0002	–2511.5	–0.0087	II	V	Samolyk (2011b)
55630.7481	0.0002	–2493.0	–0.0086	I	V	Diethelm (2011)
56290.8767	0.0015	–975.5	–0.0076	II	V	Diethelm (2013)
56737.6404	0.0001	51.5	0.0008	II	V	Samolyk (2014)
56715.2366	0.0001	0.0	0.0000	I	VR_cI_c	This paper
56716.1067	0.0001	2.0	0.0001	I	VR_cI_c	This paper
56717.1950	0.0001	4.5	0.0009	II	VR_cI_c	This paper
57034.5430	0.0040	734.0	0.0091	I	CCD	Paschke (2015)
57094.1343	0.0002	871.0	0.0040	I	VR_cI_c	This paper
57096.0923	0.0002	875.5	0.0044	II	VR_cI_c	This paper
57098.0494	0.0001	880.0	0.0040	I	VR_cI_c	This paper
58133.1690	-	3259.5	0.0044	II	BVI_c	Nagai (2019)
58135.7783	0.0001	3265.5	0.0040	II	V	AAVSO
58203.6405	0.0001	3421.5	0.0040	II	V	AAVSO

Devinney 1971; Wilson 1979, 1990). Wadhwa (2005) assigned the surface temperature of AV Pup as 6255 K, which corresponds to a spectral type of F8 in the General Catalog of Variable Stars. We took this value as the effective temperature of star 1 (eclipsed at phase 0.0) in our calculation. This effective temperature means that AV Pup should have a common convective envelope, so the bolometric albedos and gravity-darkening coefficients were set as $A_1 = A_2 = 0.5$ (Ruciński 1969) and $g_1 = g_2 = 0.32$ (Lucy 1967), respectively. We applied the logarithmic law format of limb-darkening coefficients (van Hamme 1993), which were computed internally by the DC program of the W-D code.

Due to the lack of spectroscopic mass ratio, a q-search procedure was performed to determine the initial mass ratio of AV Pup. A series of fixed mass ratios, ranging from 0.1 to 5.0 with a step of 0.05, was applied. In the q-search procedure, the adjustable parameters in our calculation were: the orbital inclination (i), the effective temperature of star 2 (T_2), the surface potential (Ω_1 and Ω_2) and the bandpass luminosity of star 1 (L_1). Due to the confusion between the semi-detached configuration and contact configuration for AV Pup, we ran the DC subroutine of the W-D code beginning with Mode 2 (a detached configuration) for each fixed q. However, the program quickly converged to Mode 3 (a contact configuration) at last, which means AV Pup should be a contact binary, as derived by Wadhwa (2005). For a clear view, Figure 3 only shows the relation between Σ (the mean residuals for input data) and q in the range of $q = 0.3$ to 3.5. As ascertained from Figure 3, the results of two q-search procedures based on the light curves observed in 2014 and 2015 are quite similar. They have a flat pattern from $q = 0.5$ to $q = 2.0$ and a minimum at $q = 0.85$. We took $q = 0.85$ as an initial mass ratio and assigned q to be an adjustable parameter for the later calculation.

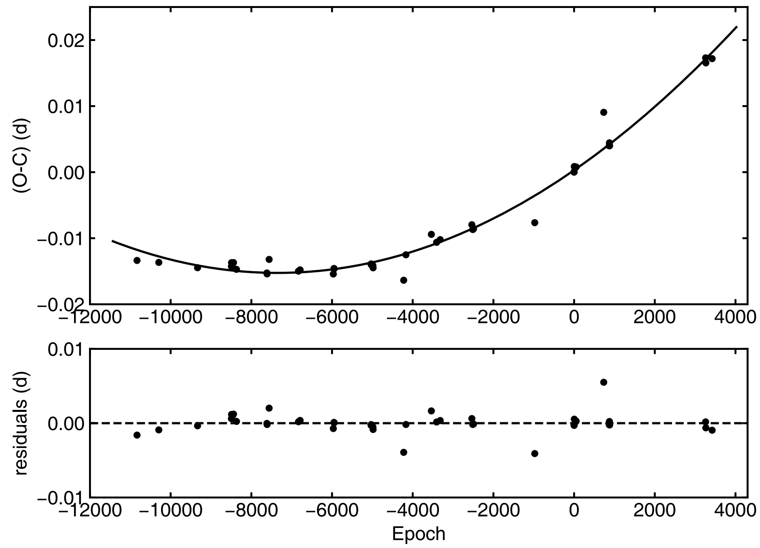

Fig. 2 $O - C$ diagram of AV Pup. The *points* are the $O - C$ values calculated with Eq. (1). The *solid line* represents the least-squares solution. The lower panel displays the corresponding residuals.

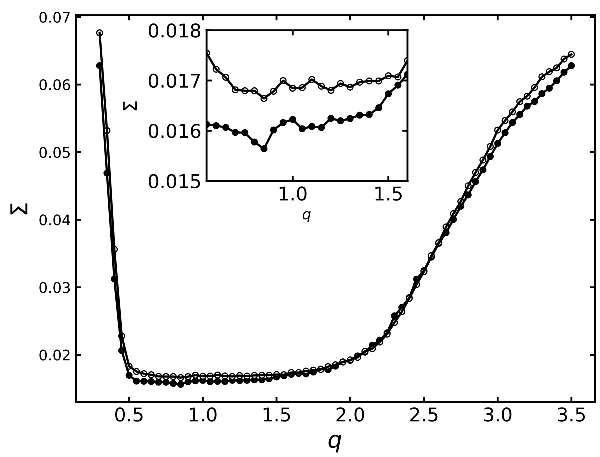

Fig. 3 The relation between Σ (the mean residuals for input data) and the mass ratio q of AV Pup. The *filled circles* and *open circles* represent for data from 2014 and 2015, respectively.

As seen from Figure 1, a slight O'Connell effect is manifested in the light curves of AV Pup, so we attempted to model the light curves with spots. During the calculation, a third light was also taken into account. After some attempts, we finally got the best convergent solutions with a cool spot located on star 1 for the data spanning two years. The results are given in Table 4 and the comparison between observed and computed light curves is highlighted in Figure 4.

Our solutions suggest that AV Pup is an A-subtype contact binary. It has a high mass ratio of 0.896 and an inclination around 81°. The system is a shallow contact system with a fill-out factor around 10%, which coincides with the result of Wadhwa (2005). The slight difference between light curves from the two years that we analyzed can be explained by spot activity. Because there are no radial velocity curves observed for this system, we cannot obtain the precise absolute parameters for the components of AV Pup. Therefore, we utilized the mass-temperature relation (Harmanec 1988) to derive the mass of the primary star. The primary's mass can be estimated as $M_1 = 1.27\,M_\odot$, then the mass of the secondary star is determined to be $M_2 = 1.14 \pm 0.01\,M_\odot$ based on our photometric solution. The radii and luminosities for the two components can also be obtained as: $R_1 = 1.29 \pm 0.01\,R_\odot$, $L_1 = 2.29 \pm 0.02\,L_\odot$, $R_2 = 1.23 \pm 0.02\,R_\odot$ and $L_2 = 1.94 \pm 0.10\,L_\odot$.

5 SUMMARY AND DISCUSSION

In this paper, we presented two years of CCD photometric observations targeting AV Pup. We derived the photomet-

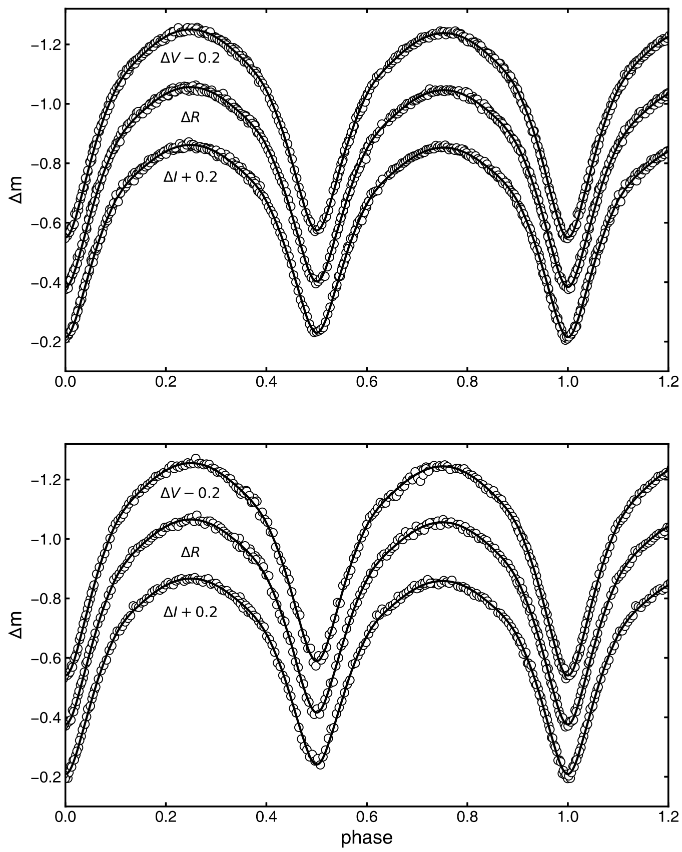

Fig. 4 Comparison of observed (*open circles*) and computed (*black lines*) light curves for AV Pup. The upper and lower panels highlight the comparison of data from 2014 and 2015, respectively.

Table 4 Photometric Solutions of AV Pup

Parameter	2014	2015
$g_1 = g_2$	0.32 (fixed)	0.32 (fixed)
$A_1 = A_2$	0.5 (fixed)	0.5 (fixed)
T_1 (K)	6255 (fixed)	6255 (fixed)
T_2 (K)	6145 ± 7	6150 ± 9
$q(M_2/M_1)$	0.896 ± 0.005	0.896 ± 0.003
$\Omega_1 = \Omega_2$	3.525 ± 0.008	3.529 ± 0.005
i (deg)	81.222 ± 0.101	80.845 ± 0.109
$L_1/(L_1 + L_2 + L_3)_V$	0.516 ± 0.003	0.530 ± 0.008
$L_1/(L_1 + L_2 + L_3)_{R_c}$	0.509 ± 0.003	0.524 ± 0.007
$L_1/(L_1 + L_2 + L_3)_{I_c}$	0.500 ± 0.003	0.512 ± 0.006
$L_3/(L_1 + L_2 + L_3)_V$	0.052 ± 0.003	0.025 ± 0.010
$L_3/(L_1 + L_2 + L_3)_{R_c}$	0.060 ± 0.003	0.031 ± 0.009
$L_3/(L_1 + L_2 + L_3)_{I_c}$	0.071 ± 0.003	0.048 ± 0.008
r_1(pole)	0.3726 ± 0.0005	0.3720 ± 0.0004
r_1(side)	0.3932 ± 0.0005	0.3924 ± 0.0005
r_1(back)	0.4273 ± 0.0005	0.4263 ± 0.0006
r_2(pole)	0.3536 ± 0.0018	0.3538 ± 0.0011
r_2(side)	0.3721 ± 0.0023	0.3723 ± 0.0014
r_2(back)	0.4070 ± 0.0036	0.4072 ± 0.0022
$f(\%)$	10.9 ± 1.6	10.2 ± 1.1
Spot parameters:		
Latitude (deg)	24.4	29.6
Longitude (deg)	144.0	97.4
Radius (deg)	31.0	16.9
T/T_1	0.92	0.89

ric solutions for this system. Two solutions indicate that AV Pup is an A-subtype contact binary with a high mass

Table 5 A-subtype Contact Binaries with a High Mass Ratio

Name	T_1 (K)	T_2 (K)	q	f (%)	Reference
OO Aql	5700	5472	0.844	21.4	İçli et al. (2013)
V2150 Cyg	8000	7920	0.802	19.0	Kreiner et al. (2003)
V1101 Her	5920	5690	0.800	14.2	Pi et al. (2017)
AU Ser	5495	5153	0.710	19.8	Gürol (2005)

ratio of $q = m_2/m_1 = 0.896$. The system is a shallow contact binary with a low fill-out factor of around 10%. The two years of observations manifest a slight difference, which can be explained by spot variation. Contact binaries tend to have a low mass ratio (Rucinski 2001), consequently only a few contact binaries with high mass ratio have been discovered, such as WZ And ($q = 1.0$, Zhang & Zhang 2006), HT Vir ($q = 0.9$, Bensch et al. 2014) and so on. Meanwhile, A-subtype contact binaries have a relatively low mass ratio and a relatively high contact degree in general (Hilditch et al. 1988; Jiang et al. 2009). However, a few A-subtype contact binaries were found to have a high mass ratio and a shallow common envelope (listed in Table 5). AV Pup seems to exhibit the same characteristics as these peculiar contact binaries.

We also conducted the first period change analysis for AV Pup. A least-squares fitting indicates that the orbital period of AV Pup is experiencing a secular increase at a rate of $\mathrm{d}P/\mathrm{d}t = 4.83\times10^{-7}\,\mathrm{d\,yr^{-1}}$, which may be caused by mass transfer from the less massive component to the more massive one. Assuming the mass transfer is conservative, we can calculate the mass transfer rate from the formula derived from Kepler's third law

$$\frac{\mathrm{d}M_2}{\mathrm{d}t} = \dot{M_2} = \frac{\dot{P}M_1M_2}{3P(M_2 - M_1)}\,. \tag{3}$$

The estimated mass transfer rate is $\mathrm{d}M_2/\mathrm{d}t = -4.12 \times 10^{-6}\,M_\odot\,\mathrm{yr^{-1}}$. This mass transfer rate seems quite high for contact binaries, but it coincides with the mass transfer properties of contact binaries in the Kepler Eclipsing Binary Catalog (Kouzuma 2018). The time scale of mass transfer for the donor star can be estimated as $\tau_{\rm MT} = 2.77 \times 10^5$ yr, which is much shorter than the thermal time scale $\tau_{\rm th} \sim (GM^2)/(RL) \sim 1.70 \times 10^7$ yr (Paczyński 1971). This suggests that the donor star cannot maintain its thermal equilibrium. This system might be evolving from a contact configuration to a semi-detached configuration of the thermal relaxation oscillation (Lucy 1976; Flannery 1976; Li et al. 2004a, 2005, 2008). In the same way, the period increase may be part of a long-period cyclic variation caused by a third body, which is reflected by the third light appearing in the photometric solutions. We should also notice that these results were achieved according to the absolute parameters only derived from the photometric observations and, therefore, spectroscopic observations are urgently needed.

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References

Bensch, K., Dimitrov, W., Zywucka, N., et al. 2014, Information Bulletin on Variable Stars, 6121
Brancewicz, H. K., & Dworak, T. Z. 1980, Acta Astronomica, 30, 501
Diethelm, R. 2011, Information Bulletin on Variable Stars, 5992
Diethelm, R. 2013, Information Bulletin on Variable Stars, 6042
Flannery, B. P. 1976, ApJ, 205, 217
Gürol, B. 2005, New Astron., 10, 653
Harmanec, P. 1988, Bulletin of the Astronomical Institutes of Czechoslovakia, 39, 329
Hilditch, R. W., King, D. J., & McFarlane, T. M. 1988, MNRAS, 231, 341
Hoffmeister, C. 1930, Astronomische Nachrichten, 240, 193
İçli, T., Koçak, D., Boz, G. Ç., & Yakut, K. 2013, AJ, 145, 127
Jiang, D., Han, Z., Jiang, T., & Li, L. 2009, MNRAS, 396, 2176
Kouzuma, S. 2018, PASJ, 70, 90
Kreiner, J. M., Rucinski, S. M., Zola, S., et al. 2003, A&A, 412, 465
Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Netherlands, 12, 327
Li, L., Han, Z., & Zhang, F. 2004a, MNRAS, 351, 137
Li, L., Han, Z., & Zhang, F. 2004b, MNRAS, 355, 1383
Li, L., Han, Z., & Zhang, F. 2005, MNRAS, 360, 272
Li, L., Zhang, F., Han, Z., Jiang, D., & Jiang, T. 2008, MNRAS, 387, 97
Lucy, L. B. 1967, ZAp, 65, 89
Lucy, L. B. 1976, ApJ, 205, 208
Nagai, K. 2001, Variable Star Bulletin, 39, 5
Nagai, K. 2004, Variable Star Bulletin, 42, 1
Nagai, K. 2005, Variable Star Bulletin, 43, 1
Nagai, K. 2006, Variable Star Bulletin, 44, 1
Nagai, K. 2007, Variable Star Bulletin, 45, 1
Nagai, K. 2008, Variable Star Bulletin, 42, 1
Nagai, K. 2009, Variable Star Bulletin, 48, 1
Nagai, K. 2019, Variable Star Bulletin, 66, 1
Paczyński, B. 1971, ARA&A, 9, 183
Paschke, A. 2015, Open European Journal on Variable Stars, 172, 1
Pi, Q.-f., Zhang, L.-y., Bi, S.-l., et al. 2017, AJ, 154, 260
Ruciński, S. M. 1969, Acta Astronomica, 19, 245
Rucinski, S. M. 2001, AJ, 122, 1007
Samolyk, G. 2008, Journal of the American Association of Variable Star Observers (JAAVSO), 36, 186
Samolyk, G. 2009, Journal of the American Association of Variable Star Observers (JAAVSO), 37, 44
Samolyk, G. 2010a, Journal of the American Association of Variable Star Observers (JAAVSO), 38, 183
Samolyk, G. 2010b, Journal of the American Association of Variable Star Observers (JAAVSO), 38, 85
Samolyk, G. 2011a, Journal of the American Association of Variable Star Observers (JAAVSO), 39, 94
Samolyk, G. 2011b, Journal of the American Association of Variable Star Observers (JAAVSO), 39, 177
Samolyk, G. 2014, Journal of the American Association of Variable Star Observers (JAAVSO), 42, 426
Shapley, H. 1948, Harvard Observatory Monographs, 7, 249
van Hamme, W. 1993, AJ, 106, 2096
Vilhu, O. 1982, A&A, 109, 17
Wadhwa, S. S. 2005, Ap&SS, 300, 289
Webbink, R. F. 1976, ApJS, 32, 583
Wilson, R. E. 1979, ApJ, 234, 1054
Wilson, R. E. 1990, ApJ, 356, 613
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Zhang, X. B., & Zhang, R. X. 2006, New Astron., 11, 339