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A photometric study of a weak-contact binary: V873 Per

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HIGHLIGHTS

- V873 Per, a weak-contact binary with a contact degree of $f = 18.10\%$ is presented.
- The cyclic period variation with a period of about 4 yr was found.
- The long-term orbital period of V873 Per tends to be stable rather than decreasing.

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ABSTRACT

We present a photometric study of a weak-contact binary V873 Per. New observations in *BVR* filter bands showed asymmetric light curves to be a negative type of the O'Connell effect, which can be described by magnetic activity of a cool spot on the more massive component. Our photometric solutions showed that V873 Per is a W-type with a mass ratio of $q = 2.504(\pm 0.0029)$, confirming the results of Samec et al. (2009). The derived contact degree was found to be $f = 18.10\%(\pm 1.36\%)$. Moreover, our analysis found the cyclic variation with the period of about 4 yr that could be due to existence of the third companion in the system or the mechanism of magnetic activity cycle in the binary. While available data indicated that the long-term orbital period tends to be stable rather than decreasing.

1. Introduction

Contact binary systems are typically believed to have been formed from detached close binaries, which are losing angular momentum and had a decreasing orbital period, by a process called angular momentum loss (AML) (e.g. Vilhu, 1981; Rahunen, 1981; Rucinski, 1982). These systems are transformed into two categories according to the relative depth of minimum light. The systems with the more massive component, eclipsed by the other one at primary minimum, are called A-type. Whereas the systems with the opposite phenomena are called W-type (Binnendijk, 1970).

Many contact binaries have been systematically observed and studied using both photometric and spectroscopic methods. Period variations were found to be helpful to understand geometric structures and evolutionary stages of those systems. The systems with long-term period decrease, were predicted to be undergoing a process of mass transfer from more massive component to the less massive one (Samus and Chaubey, 1986; Pribulla, 1998). The orbital period decrease was usually referred to the AML via magnetic breaking. The separation between the components will shrink, leading to the deeper contact configuration (Yang et al., 2010; Li and Qian, 2013). On the other hand, the systems with period increase, were explained the opposite direction of mass transfer, and cause the separation between the components to spread out. The contact configuration was predicted by using thermal relaxation oscillation (TRO) theory (e.g. Lucy, 1976; Robertson and Eggleton, 1977), to evolve into the TRO cycle (e.g. Qian, 2002; Li and Qian, 2013).

V873 Per (RA(2000) = $02^h47^m08^s.21$, Dec. (2000) = $41^\circ22'31''.9$), is a recently discovered contact binary system, that was first identified by Nicholson and Varley (2006). The orbital period was reported as 0.2949 d. Samec et al. (2009) revised the orbital period and found to be 0.2949039 d. V873 Per was denoted as W-type system. Moreover, spectral type of this system was classified to be K0V by using spectroscopic data, observed with the Dominion Astrophysical Observatory 1.8 m telescope (Samec et al., 2009), same as that recorded in the General Catalog of Variable Stars database (Samec, 2009).

This study aims to investigate the orbital period change, cyclic period variation and photometric solution of V873 Per. New CCD photometric observations are described in Section 2. Section 3

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explains calculations of the orbital period change. Light curve fit and photometric solutions of V873 Per are mentioned in Section 4. Finally, Section 5 contains our discussion and conclusions.

2. Observations

BVR photometric observations of V873 Per were carried out on the 0.5-m telescope at Sirindhorn Observatory, Chiang Mai University. The photometric data were taken during four nights (November 27–30, 2011), by using SBIG CCD (Model of ST10-XME), with exposure time of 90 s. A total of 855 individual observations were obtained in three filter bands (285 observations per filter band). The IRAF package was used for data reduction and the *BVR* magnitude measurements.

In order to determine the *BVR* differential magnitudes, GSC 2853-294 (RA(2000) = $02^h47^m18^s.01$, Dec. (2000) = $41°23'07''.4$) and GSC 2853-312 (RA(2000) = $02^h47^m08^s.42$, Dec. (2000) = $41°20'49''.7$) were used as comparison and check stars, respectively. HJD and the differential magnitudes are listed in Table 4, which is available in only the electronic version of the paper, and the *BVR* observed light curves for four nights are shown in Fig. 1. The amplitudes of the variable light are about 0.72, 0.65 and 0.62 mag, for *B*-, *V*- and *R*-bands, respectively. The O'Connell effect was found to be a negative type, i.e., Max.I at phase 0.25 is slightly fainter than Max.II at phase 0.75 (Liu and Yang, 2000).

3. Orbital period change

The new photometric data of V873 Per covered six times of minimum light for all *BVR* filter bands. Three primary and three secondary minima were determined by using a least-squares method. The minimum light times in this study, combining with minimum light data from literature, were used to estimate the revised orbital period. Using all available minimum light times listed in Table 1, a linear least-squares solution was fitted and the result contributed the orbital period of 0.2949025(±0.0000002) d as shown in the following equation:

$$\mathrm{Min.I} = \mathrm{HJD}2455892.9201(\pm0.0007) + 0.2949025(\pm0.0000002) \times E \tag{1}$$

The orbital period of V873 Per was significantly shorter than the value obtained by Samec et al. (2009). The $(O{-}C)_1$ residuals of those minimum light times were calculated as listed in Table 1 and the quadratic least-squares fitting solution yielded the Eq. (2). It was found that the orbital period of this system decreased at a rate of $dP/dt = -3.31 \times 10^{-7}$ d yr^{-1}.

$$(O{-}C)_1 = 0.0003(\pm0.0003) - 1.39(\pm0.14)\times10^{-6}E - 1.34(\pm0.11)\times10^{-10}E^2 \tag{2}$$

The $(O{-}C)$ diagram in Fig. 2 shows the corresponding $(O{-}C)_1$ curve as a downward parabolic line in the upper panel and the residuals after the parabolic trend line was subtracted in the lower panel. However, for this scenario, there was a large gap of minimum light times between the first epoch and the others, and that first point seemed to be out of data group. Considering the data without that first point of minimum light, the orbital period was fitted for the second scenario as shown in the Eq. (3).

$$\mathrm{Min.I} = \mathrm{HJD}2455892.9198(\pm0.0003) + 0.2949015(\pm0.0000001) \times E \tag{3}$$

The $(O{-}C)_2$ listed in the Table 1, was fitted by using a linear least-squares. The fitting solution exhibited a flat trend line as shown in Eq. (4), and the corresponding $(O{-}C)_2$ curve is shown in Fig. 3. There was no significant change for the long-term period in the second scenario. The *rms* of the model-subtracted residuals for both scenarios were found to be 0.00125 and 0.00119, respectively. This indicated that the period decrease found in the first scenario was due to only the first minimum light. Thus, the possibility for explanation of the

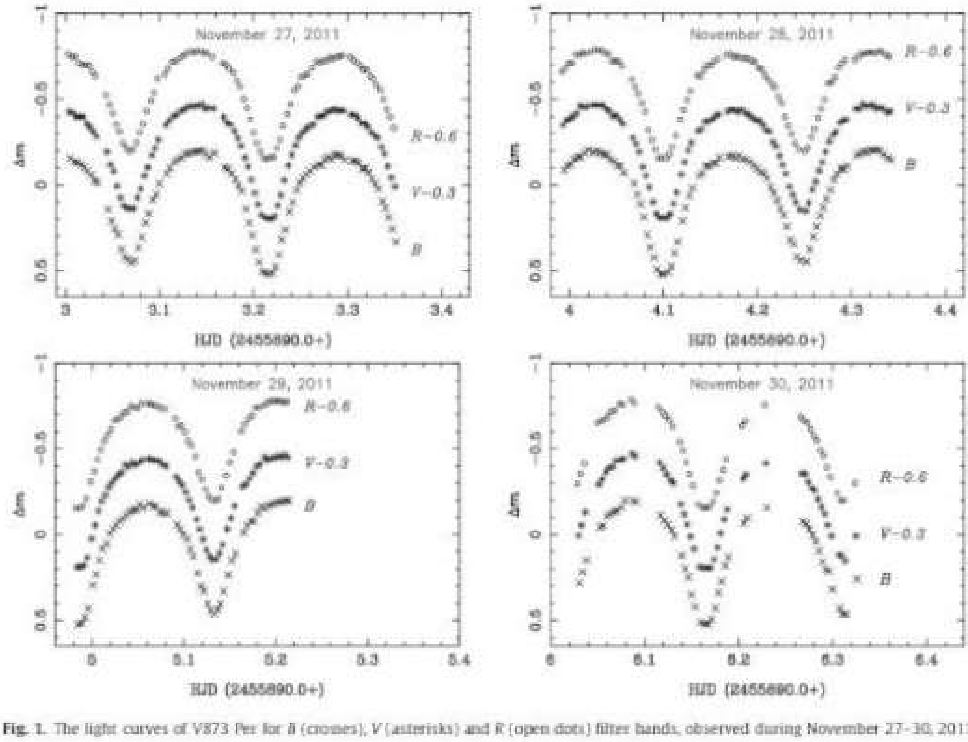


Fig. 1. The light curves of V873 Per for *B* (crosses), *V* (asterisks) and *R* (open dots) filter bands, observed during November 27–30, 2011.

Table 1
All times of light minimum for V873 Per.

HJD 1	Min 2	Ref. 3	Epoch 4	$(O-C)_1$ 5	$(O-C)_2$ 6
2451370.8753	I	[1]	−15334.0	−0.0102	
2454438.7605	I	[2]	−4931.0	0.0046	0.0002
2454440.5298	I	[2]	−4925.0	0.0045	0.0001
2454455.7199	II	[2]	−4873.5	0.0071	0.0027
2454462.6464	I	[2]	−4850.0	0.0034	−0.0010
2454462.7943	II	[2]	−4849.5	0.0038	−0.0005
2454516.6131	I	[2]	−4667.0	0.0029	−0.0012
2455197.6874	II	[3]	−2357.5	−0.0001	−0.0020
2455484.9228	II	[4]	−1383.5	0.0003	−0.0007
2455845.8839	II	[5]	−159.5	0.0008	0.0009
2455893.0680	II	[6]	0.5	0.0005	0.0007
2455893.2152	I	[6]	1.0	0.0002	0.0005
2455894.1001	I	[6]	4.0	0.0005	0.0007
2455894.2475	II	[6]	4.5	0.0004	0.0007
2455895.1321	II	[6]	7.5	0.0003	0.0006
2455896.1646	I	[6]	11.0	0.0006	0.0009
2456190.3242	II	[7]	1008.5	−0.0050	−0.0038
2456190.4764	I	[7]	1009.0	−0.0003	0.0010
2456215.8368	I	[8]	1095.0	−0.0015	−0.0002
2456215.9849	II	[8]	1095.5	−0.0008	0.0005
2456241.0505	II	[9]	1180.5	−0.0019	−0.0006
2456241.1985	I	[9]	1181.0	−0.0004	0.0010
2456241.9360	II	[9]	1183.5	−0.0012	0.0002
2456242.0841	I	[9]	1184.0	−0.0005	0.0009
2456242.2304	II	[9]	1184.5	−0.0017	−0.0003
2456554.0883	I	[10]	2242.0	−0.0031	−0.0007
2456554.2359	II	[10]	2242.5	−0.0030	−0.0006

Notes: Column 1: HJD at light minimum. Column 2: types of minimum. Column 3: references for sources are as follow: [1] Nicholson and Varley (2006); [2] Samec et al. (2009); [3] Diethelm (2010); [4] Diethelm (2011); [5] Diethelm (2012); [6] This study; [7] Hasanzadeh (2013); [8] Diethelm (2013); [9] Nagai (2013); [10] Nagai (2014). Column 4: epoch. Column 5: $(O-C)_1$ for the first scenario, corresponding to the Eq. (2). Column 6: $(O-C)_2$ for the second scenario, corresponding to the Eq. (4).

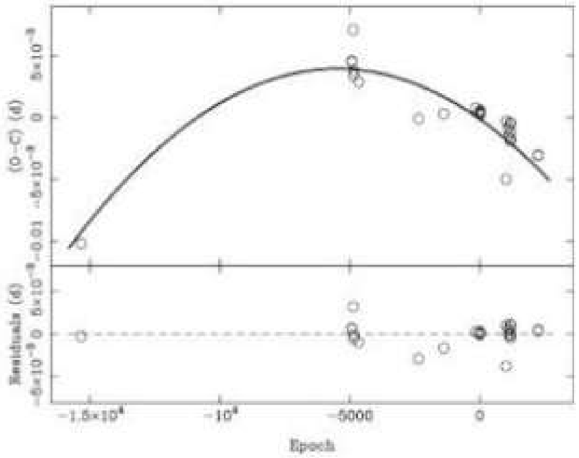


Fig. 2. The $(O-C)_1$ curve (upper panel), calculated by using the least-squares fit in the Eq. (2) and the residuals (lower panel) for V873 Per.

long-term period change of the quadratic trend line seemed to be weaker than the linear fit, as it depended only on one point.

$$(O-C)_2 = 0.00000259(\pm 2.54) \times 10^{-4} - 0.00000132(\pm 9.92) \times 10^{-8} E \tag{4}$$

The model-subtracted residuals for both scenarios seemed to exhibit a cyclic variation, which could be explained by two mechanisms: the light time effect (LITE) due to a third body in the system (Irwin, 1952; Pribulla and Rucinski, 2006) or magnetic activity cycle (Applegate, 1992). The cyclic period change will then be discussed in the Section 5.

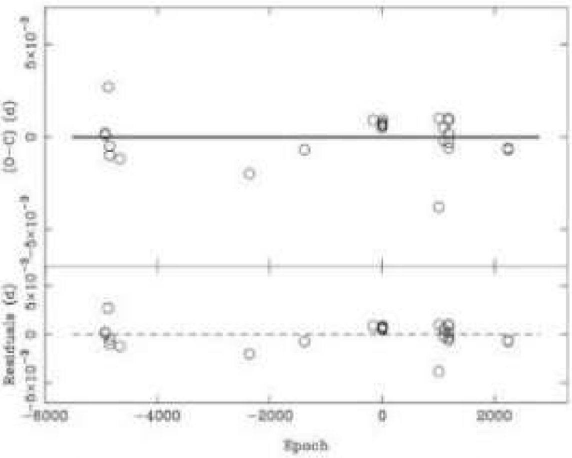


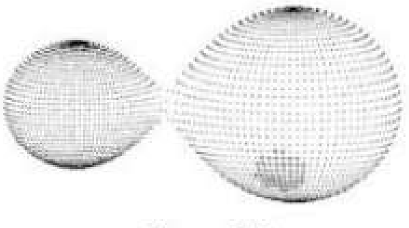
Fig. 3. The $(O-C)_2$ curve (upper panel), calculated by using the linear least-squares fit in the Eq. (4) for the data since HJD 2454438 and the residuals (lower panel).

4. Photometric solutions

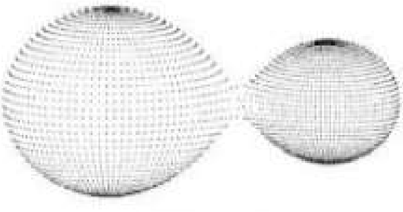
A well-known method to derive photometric solutions of binary systems is the Wilson–Devinney (W–D) method (Wilson and Devinney, 1971; Wilson, 1979; Wilson, 1990; Wilson and van Hamme, 2003). In this study, the W–D code was used to deduce the physical properties of V873 Per. Fixed parameters were adopted, as follows: the gravity darkening exponents of $g_1 = g_2 = 0.32$ (Lucy, 1967), the bolometric albedo coefficients of $A_1 = A_2 = 0.50$ (Rucinski, 1973), the effective temperature of the star 1, T_1, estimated from the spectral class, using the calibration table of Cox (2000) and the limb darkening coefficients of x_1 and x_2 for *BVR* bands, corresponding to the temperature T_1 (van Hamme, 1993). The adjustable parameters, i.e., the mass ratio, q, the surface potential of the components, $\Omega_1 = \Omega_2$, the temperature of the star 2, T_2, the orbital inclination, i, and the monochromatic luminosities of the star 1, L_1, were adopted to deduce the photometric solutions. The relative luminosities of the star 2, L_2, were automatically determined by the W–D code, following the model of stellar atmospheres (Kurucz, 1993).

According to the report of Samec et al. (2009), the spectral type of V873 Per was recorded as K0V. Thus, the effective temperature of the star 1, T_1 was assumed as 5150 K (Cox 2000). The limb darkening coefficients were fixed as $x_{1B} = x_{2B} = 0.859$, $x_{1V} = x_{2V} = 0.688$ and $x_{1R} = x_{2R} = 0.552$ (van Hamme, 1993).

The derived photometric solutions of this W-type contact system agreed with the *BVR* observed light curves fairly well. The sum of squared residuals for input values, $\Sigma(O-C)^2 = 0.0158$, was achieved at a mass ratio of $q = 2.504(\pm 0.0029)$. The geometry of this system was shown as a total eclipse, with the inclination of $i = 82.89°$, and the corresponding graphic is shown in Fig. 4. Thus, the mass ratio could be reliable, although it was determined by using only light curve analysis (Singh and Chaubey, 2005). The temperature of the more massive component was found to be about 200 K cooler than the less massive one. The main parameters obtained in this study were similar to the results of Samec et al. (2009). But our fit applied a cool spot on the more massive component, corresponding to the characteristic of the asymmetric light curves. The contact degree in this study confirmed that V873 Per



Phase = 0.25



Phase = 0.75

Fig. 4. Geometric structure of the weak-contact binary V873 Per at the orbital phases 0.25 (upper panel) and 0.75 (lower panel).

is a weak-contact system with $f = 18.10\%(\pm1.36\%)$, which was slightly larger than the value, reported by Samec et al. (2009). All parameters are listed in Table 2, and the corresponding theoretical light curves are shown in Fig. 5.

5. Discussion and conclusions

New photometric data were obtained in the *BVR* filter bands during November 27–30, 2011. Six minimum light times were determined and used to estimate the revised orbital period and the period change. The *BVR* observed light curves were fitted to obtain the photometric parameters by using the W–D method. Our results confirmed that V873 Per is a W-type contact binary, with a weak-contact degree of $f = 18.10\%(\pm1.36\%)$. The photometric solutions showed a good fit with the sum of squared residuals, $\Sigma(O-C)^2 = 0.0158$, at a mass ratio of $q = 2.504(\pm0.0029)$.

Table 2
Photometric parameters for the light curve fit for V873 Per.

Parameters	Values	
	Samec et al. (2009)	This study
q	2.62(±0.02)	2.504(±0.0029)
T_1 (K)	5150	5150
T_2 (K)	5023(±5)	4965(±19)
i (°)	81.63(±0.09)	82.89(±0.22)
$\Omega_1 = \Omega_2$	6.057(±0.025)	5.8890(±0.0034)
$g_1 = g_2$	0.32	0.32
$A_1 = A_2$	0.50	0.50
$x_{1B} = x_{2B}$	0.851	0.859
$x_{1V} = x_{2V}$	0.790	0.688
$x_{1R} = x_{2R}$	0.724	0.552
$L_{1B}/(L_{1B} + L_{2B})$	0.32(±0.04)	0.3600(±0.0259)
$L_{1V}/(L_{1V} + L_{2V})$	0.32(±0.02)	0.3474(±0.0386)
$L_{1R}/(L_{1R} + L_{2R})$	0.32(±0.04)	0.3373(±0.0187)
r_1 (pole)	0.282(±0.001)	0.2872(±0.0035)
r_1 (side)	0.295(±0.002)	0.3000(±0.0040)
r_1 (back)	0.326(±0.007)	0.3361(±0.0042)
r_2 (pole)	0.440(±0.001)	0.4374(±0.0027)
r_2 (side)	0.471(±0.001)	0.4679(±0.0035)
r_2 (back)	0.499(±0.005)	0.4964(±0.0023)
Spot colatitude (°)*	–	126.05(±4.83)
Spot longitude (°)*	–	80.21(±3.46)
Spot radius (°)*	–	16.04(±1.62)
Temperature factor*	–	0.80(±0.04)
$\Sigma(O-C)^2$	0.0376	0.0158
f (%)	5.5(±4)	18.10(±1.36)

Notes: * Parameters of a starspot on the more massive star.

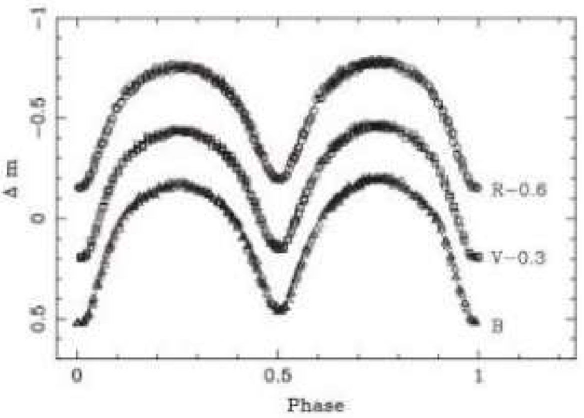


Fig. 5. The observed light curves in *B* (triangles), *V* (squares) and *R* (open dots) filter bands and the theoretical light curves (solid lines) versus orbital phase for V873 Per.

Two scenarios of the $O-C$ fit for the data of minimum light times were analyzed. The first scenario, the quadratic $(O-C)_1$ curve fit showed a long-term period decrease, whereas the second one, the $(O-C)_2$ solution for the data since HJD 2454438 contributed no long-term period change with better residuals than the former. However, the residuals for both scenarios show a cyclic variation, which could be explained by the LITE due to the third companion (Irwin, 1952; Pribulla and Rucinski, 2006). Thus, the formulae of Irwin (1952) were adapted to the second scenario as the following equation (e.g. Pribulla and Rucinski, 2006; Li et al., 2014):

$$
\begin{aligned}
(O-C)_2 &= \Delta T + \Delta P \times E + A\left[\frac{1-e^2}{1+e\cos v}\sin(v+\omega) + \sin\omega\right] \\
&= \Delta T + \Delta P \times E + A\left[\sqrt{1-e^2}\sin E^{*}\cos\omega + \cos E^{*}\sin\omega\right] \quad (5)
\end{aligned}
$$

where $\Delta T + \Delta P \times E$ is the part of the linear fit. $A = a_{12}\sin i_3/c$ is the amplitude of the cyclic period change. The parameters a_{12}, i_3, e and ω are the orbital parameters, and v is the true anomaly of the binary on orbit around the mass center of the triple system. E^{*} is the eccentric anomaly, used with the relation (e.g. Irwin, 1952; Yang et al., 2013; Li et al., 2014):

$$2\pi\frac{t-T}{P_3} = M = E^{*} - e\sin E^{*} \quad (6)$$

where M is the mean anomaly, t is the time of minimum light, T is the time of periastron passage and P_3 is the period of the $(O-C)_2$ variation due to the LITE. The fitted parameters were obtained as listed in Table 3 with the rms of the residuals of 0.00106 d. The LITE predicted that the amplitude the cyclic period change is 0.0010 d, interpreting the value of $a_{12}\sin i_3 = 0.17$ AU. The period of the orbit of the third companion was found to be $P_3 = 4.04$ yr, with a small eccentricity of $e = 0.19$. The diagram of the $(O-C)_2$ added the LITE and the corresponding residuals are shown in Fig. 6.

Another way to explain the cyclic period variation is a magnetic activity cycle (Applegate, 1992). Applegate (1992) proposed that the magnetic activity in an active star can change its gravitational quadrupole moment. For a binary containing at least one active component, the variation of the quadrupole moment can produce the period modulation. Thus, the Eq. (37) of Applegate (1992)

Table 3
Parameters for the $(O-C)_2$ fit, added the models for cyclic period change.

Parameters	Values	
	LITE	MAC*
ΔT (d)	−0.00028(±0.00007)	−0.00026(±0.00005)
ΔP ($\times 10^{-7}$ d)	1.44(±0.21)	1.41(±0.23)
A (d)	0.0010(±0.0002)	–
$a_{12}\sin i_3$ (AU)	0.17(±0.03)	–
e	0.19(±0.09)	–
ω (°)	58.2(±4.3)	–
P_3 (yr)	4.04(±0.31)	–
T (d)	2455730.6(±107.3)	–
A_{mod} ($\times 10^{-9}$ d^{-1})	–	9.01(±0.21)
P_{mod} (yr)	–	4.08(±0.36)
ϕ (°)	–	9.3(±2.4)

Notes: * MAC stands for the magnetic activity cycle.

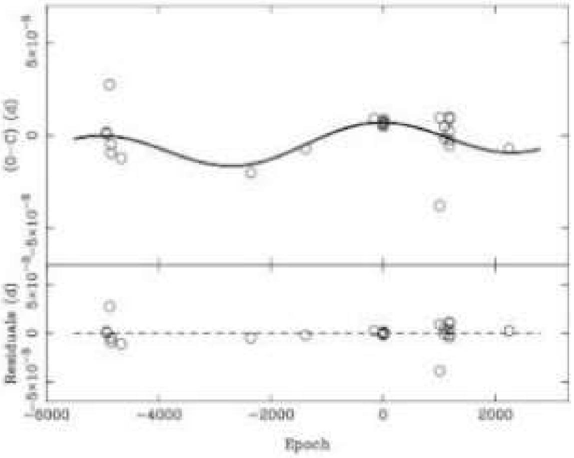


Fig. 6. The $(O-C)_2$ curve (upper panel), calculated by using the linear least-squares fit, added the LITE for cyclic variation due to the third companion and the residuals (lower panel).

was adapted to the $(O-C)_2$ fitting model by adding the term of $(A_{mod}P/2\pi v)\cos(PvE+\phi)$, where $(A_{mod}P/2\pi v)$ and ϕ are the amplitude and the phase shift of the cycle, $v = 2\pi/P_{mod}$ and P_{mod} is the modulation period. We obtained the following equation:

$$(O-C)_2 = \Delta T + \Delta P \times E + \frac{A_{mod}PP_{mod}}{(2\pi)^2}\cos\left[\frac{2\pi PE}{P_{mod}} + \phi\right] \tag{7}$$

The fitting solution was obtained with the rms of residuals of 0.00106 d. The derived modulation period was found to be 4.08 yr, whereas the parameter A_{mod} was obtained as $9.01\times10^{-9} d^{-1}$, corresponding to the amplitude of the modulation cycle of 0.0010 d.

Both mechanisms gave similar values of cyclic period and amplitude with the equivalent significant level of the predictions. Therefore, cyclic period variation of V873 Per may be an evidence of the LITE or magnetic activity cycle similar to CK Boo (Yang et al., 2012) and AB And (Li et al., 2014).

Since we now have only about 1.5 cycles of the period variation within 6 year data plus the early isolated minimum light, it is difficult to have a precise conclusion for the long-term period change. Although the second scenario seems to be a better explanation for the long-term change than the first one, there may be a possibility for the $(O-C)_1$ fit. Until more observations would be extended over a long time period in the future, there cannot be a more precise conclusion. If the first light minimum was not neglected, the $(O-C)_1$ fit showed the possible long-term period decrease of $dP/dt = -3.31\times10^{-7}$ d yr^{-1}. This means that the binary may be undergoing a process of mass transfer between the components, leading to the orbital period change. A relative mass transfer rate $\dot{m}_2/m_2$ can be calculated, using an assumption of conservative mass transfer (Samus and Chaubey, 1986; Pribulla, 1998) as the following equation:

$$\frac{\dot{P}}{P} = 3\left(\frac{m_2}{m_1} - 1\right)\frac{\dot{m}_2}{m_2} \tag{8}$$

Assuming that the period change is due to mass transfer alone, the result exhibited that the more massive component, m_2 is losing mass, transferred to its less massive companion with a relative rate of $\dot{m}_2/m_2 = -2.49\times10^{-7}$ yr^{-1}. With the mass transfer and/or angular momentum loss via magnetic breaking, the inner and outer critical Roche lobes would shrink, and cause the contact degree to increase (e.g. Yang et al., 2007; Christopoulou et al., 2011). Therefore, if the period decrease exists, the weak-contact binary, V873 Per may evolve into a deep-contact system, similar to EI CVn (Yang, 2011) and GV Leo (Kriwattanawong and Poojon, 2013).

According to the available data of V873 Per, there exists cyclic variation with the period of about 4 yr, which may be caused by the third body in the triple system or magnetic activity cycle in the binary. While, the stable long-term orbital period scenario was found to have higher significance than the decreasing period one. Whether the long-term period would be stable or not, further photometric and spectroscopic observations are still required to verify our results and the nature of long-term changes of this system.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.newast.2014.10.004.

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