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The new RS CVn binary V1034 Her revisited and the orbital period — activity relation of short-period RS CVn binaries using photometric distortion amplitude [*]

Li-Yun Zhang

College of Science / Department of Physics & NAOC-GZU-Sponsored Center for Astronomy Research, Guizhou University, Guiyang 550025, China; *Liy_zhang@hotmail.com*

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Abstract This paper presents new CCD $BVRI$ light curves of the newly discovered RS CVn eclipsing binary V1034 Her in 2009 and 2010, the shapes of which are different from previously published results. They show an asymmetric outside eclipse, and we try to use a spot model to explain the phenomenon. Using the Wilson-Devinney program with a one-spot or two-spot model, photometric solutions of the system and starspot parameters were derived. Comparing the two results shows that the case of two spots is more successful in reproducing light-curve distortions. Looking at all the spot longitudes, the trend is towards active longitude belts and each active longitude belt may switch. Comparing the light curves from 2009 and 2010, we can see that the light curve changes over the long time scale of a year, especially in phase 0.25. In addition, we also collected the values of the maximum amplitudes of photometric distortion of the short-period RS CVn binary. We found for the first time that there is a trend of increasing activity with decreasing orbital period. Finally, fitting all available light minimum times including our newly obtained ones with a polynomial function confirmed that the orbital period of V1034 Her increased.

Key words: stars: binaries: late-type — stars: binaries: eclipsing — stars: individuals (V1034 Her) — stars: spots

1 INTRODUCTION

V1034 Her (GSC 0983.1044, ROTSE 1 J165241.80+124905.2) is a newly identified RS CVn-type eclipsing binary, which is also characterized by light-curve asymmetries (Kaiser et al. 2002; Doğru et al. 2009; Ordway & Van Hamme 2004). It is an intriguing object in which to study stellar magnetic activity and test the effect of magnetic braking. However, it has been poorly studied by astronomers, so we re-observed it in two different seasons to discuss starspot activity.

V1034 Her was discovered by Akerlof et al. (2000) as a 13th mag eclipsing binary with a period of 0.40763 d and an amplitude of 1.022 mag from the ROTSE 1 sky survey. Later, Kaiser et al. (2002) revised the standard magnitude $V = 12.90$ and color indices $B - V = 0.78$. They also derived the linear ephemeris of the system with a period of 0.8153 d and suggested that V1034 Her

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is an RS CVn type eclipsing detached binary due to the light-curve variations, which were explained using a two-spot model on the secondary component. Later, Ordway & Van Hamme (2004) also obtained the $BVRI$ light curves (LCs) of the system and analyzed them using a Wilson-Devinney program with the spot model. Recently, Doğru et al. (2009) revised the ephemeris and considered first the possibility of orbital period variation. The $O-C$ diagram shows an upward parabola, which indicates a secular increase in the orbital period of the system. They also confirmed that it contained the characteristics of an RS CVn type binary and explained them in terms of two large dark starspots on the primary component.

As part of our on-going program of study of the RS CVn binary with multi-color photometry and high-resolution spectra (Gu et al. 2002; Zhang & Gu 2007, 2008; Zhang et al. 2010a and related references), we present new $B, V, R,$ and I CCD LCs of V1034 Her in two different seasons and analyze them to study the properties of active regions using the 2003 version of the Wilson-Devinney code. In addition, we accumulated the maximum amplitudes of photometric distortions of a short-period RS CVn binary from the literature to discuss the relationship between the photospheric starspot activity and the orbital period.

2 OBSERVATIONS

The new photometric observations were made on seven consecutive nights (2009 March 22, 24, 25, 26, 30, and 31, and April 1) and two later consecutive nights (2010 March 26 and 27) with an 85-cm telescope at the Xinglong station of the National Astronomical Observatories of China. The camera was equipped with a 1024×1024 pixel CCD and the standard Johnson-Cousin-Bessell $BVRI$ filters (Zhou et al. 2009). Our observations of V1034 Her were made in the B, V, R, and I bands. All observed CCD images were reduced using the Apphot sub-package of IRAF in the standard fashion (including image trimming, bias subtraction, flat-field division, cosmic ray removal, and aperture photometry). The comparison star GSC 0983–566 and the check star GSC $0983-556$ (α_{2000}=16$^{\rm h}$52$^{\rm m}$19$^{\rm s}$.07; δ_{2000}=$12°50'43''$.9) were chosen near the target. The LCs of V1034 Her are plotted in Figure 1, where circles (○) indicate the observations from 2009 Mar. 26 – Apr. 1, and squares (□) those from 2010 Mar. 26–27. The errors of individual points are better than 0.01 mag in all bands.

From our observations, two primary minimum times (2454916.3181±0.0044; 2454921.2101± 0.0010) and one secondary minimum (2454923.2477± 0.0003) were obtained using the method of Kwee & van Woerden (1956). To calculate an updated ephemeris and period variation, all published minimum times were collected from the literature (Table 1). Using the CCD minimum times, an updated linear ephemeris formula was obtained as follows

$$\mathrm{Min.I(HJD)} = 2451767.6630(\pm0.0003) + 0.8152912^{\rm d}(\pm0.0000001) \times E. \qquad (1)$$

For our new observations, the phases of data points are calculated using the above Equation (1).

Doğru et al. (2009) found the ($O-C$) (observed times of light minimum minus calculated times of light minimum) diagram shows an upward parabola. To revise the period change, we reanalyzed them with our new minimum. During the analysis, the weights 0, 1 and 5 were given to visual, photographic and CCD observations respectively. The two CCD minimum times (deviating too much) whose $O-C$ values are higher than 0.0070 were omitted because they might be influenced by spots and shifted. They are listed under the line at the end of Table 1. Then, with the least-squares method, the following quadratic ephemeris was obtained.

$$\begin{aligned}\mathrm{Min.I(HJD)} = 2451767.6632(\pm0.00008) + 0.81529075^{\rm d}(\pm0.00000004) \times E \\ +1.38^{\rm d}(\pm0.08) \times 10^{-10} \times E^2. \qquad (2)\end{aligned}$$

It indicates that the orbital period shows a continuous secular increase of the period at a rate of $dp/dt = 1.24(\pm0.07) \times 10^{-7}\,\mathrm{d\ yr}^{-1}$ (or $0.0107\ (\pm0.0006)$ s per year). The $O-C$ values are listed in the third column of Table 1 and plotted in Figure 2.

Table 1 Minimum Times of V1034 Her

JD (Hel.)	Cycle	$(O-C)$	Method	Reference
2445901.652	−7195.0	−0.0043	pg	Kaiser et al. (2002)
2446116.891	−6931.0	−0.0066	pg	Kaiser et al. (2002)
2451738.7197	−35.5	−0.0016	CCD	Kaiser et al. (2002)
2451740.7594	−33.0	−0.0001	CCD	Kaiser et al. (2002)
2451747.6883	24.5	−0.0012	CCD	Kaiser et al. (2002)
2451753.8028	−17.0	−0.0014	CCD	Kaiser et al. (2002)
2451767.6641	0.0	0.0002	CCD	Kaiser et al. (2002)
2452084.8118	389.0	0.0004	CCD	Kaiser et al. (2002)
2452873.1962	1356.0	−0.0021	CCD	Krajci (2005)
2453130.4213	1671.5	0.0012	CCD	Krajci (2005)
2453518.5010	2147.5	0.0001	CCD	Hübscher et al. (2006)
2453596.3613	2243.0	0.0002	CCD	Bakis et al. (2005)
2453872.3376	2581.5	0.0006	CCD	Doğru et al. (2009)
2453874.3761	2584.0	0.0008	CCD	Doğru et al. (2009)
2453922.4776	2643.0	0.0002	CCD	Doğru et al. (2009)
2454200.4918	2984.0	0.0003	CCD	Hübscher (2007)
2454916.3181	3862.0	0.0013	CCD	present paper
2454921.2101	3868.0	0.0016	CCD	present paper
2454923.2477	3870.5	0.0010	CCD	present paper
2451265.8420	−615.5000	−0.0112	CCD	Diethelm (2001)
2451311.9100	−559.0000	−0.0071	CCD	Diethelm (2001)
2452792.489	1257.0	−0.0043	vis	Diethelm (2003)
2453149.585	1695.0	−0.0031	vis	Diethelm (2004)
2453440.647	2052.0	0.0064	vis	Locher (2005)

Notes: pg represents the photographic observations, while vis represents the visual observations.

3 PHOTOMETRIC ANALYSIS OF V1034 HER

Because our data from 2009 have high time-resolution and full phase coverage, we can re-obtain the photometric solution of V1034 Her using the 2003 version of the Wilson-Devinney program

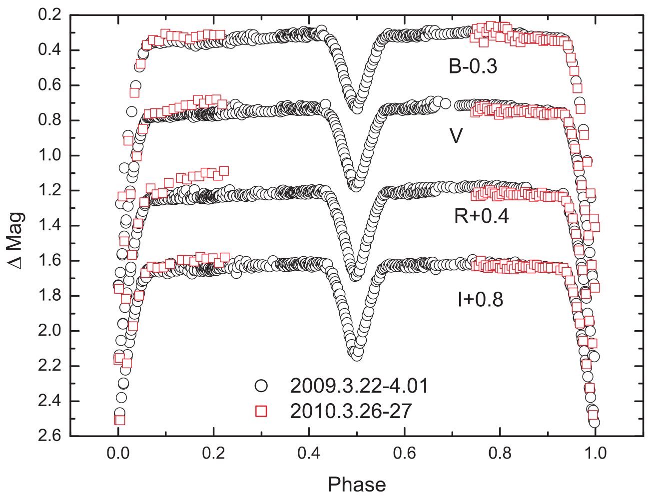

Fig. 1 B, V, R, and I observations of V1034 Her in 2009 and 2010 at the Xinglong station. Circles (○) indicate values from 2009 Mar. 22 – Apr. 1 and squares (□) those from 2010 Mar. 26 – 27.

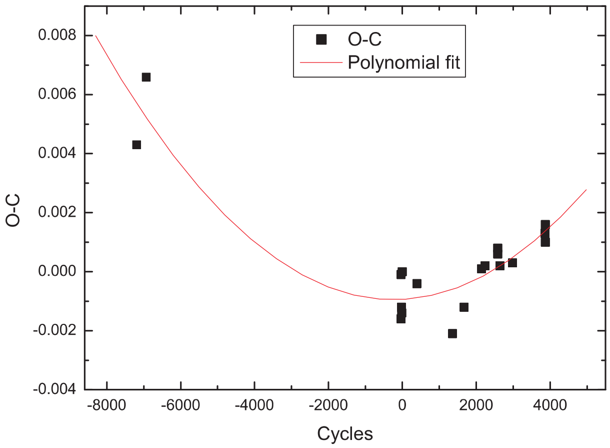

Fig. 2 $(O-C)$ diagram for the minimum times of V1034 Her. The solid line represents the quadratic fitting and shows a period increase.

(Wilson & Devinney 1971; Wilson 1979, 1990, 1994; Wilson & Van Hamme 2004, privately circulated monograph, and related references).

Due to the asymmetric LCs outside the primary eclipse, there is at least a large distortion in the phase range 0.1–0.3 (Spot 1). From a comparison between the observed LCs and the clean theoretical ones (the system parameters with less distortional effects are taken from the papers of Kaiser et al. 2002 and Doğru et al. 2009), it indicates that there might be a depression around 0.9 (Spot 2). Hence, we are not able to tell whether there is one spot or two. Moreover, because of having no spectroscopic observation, it is very difficult to tell whether the spots are located on the primary or secondary components, especially spots on the quadratures. Therefore, we calculated two solutions (one is the one-spot model on the primary, and the other is the two-spot model on the primary) to obtain the final result. The details of the procedure for finding the photometric solution are similar to those in our previous work of RT And (Zhang & Gu 2007), DV Psc (Zhang et al. 2010a), GSC 3576–0170 (Zhang et al. 2010b) and KQ Gem (Zhang 2010).

All $BVRI$ LCs are analyzed simultaneously. In computing the photometric solutions, mode 2 of the Wilson-Devinney code (appropriate for detached binaries) is employed with synchronous rotation and zero eccentricity. Simple treatment is used to compute the reflection effect, and the linear limb-darkening law is used to compute the limb-darkening effect. The bolometric albedo A_1=A_2=0.5 (Ruciński 1973), the limb-darkening coefficients x_{1B} = 0.819, x_{2B} = 0.906, x_{1V} = 0.686, x_{2V} = 0.763, x_{1R} = 0.568, x_{2R} = 0.629, x_{1I} = 0.467, x_{2I} = 0.512 are from van Hamme (1993) and the gravity-darkening coefficients g_1 = g_2 = 0.32 for convective envelopes (Lucy 1967) are set for the primary and the secondary, as usual. According to the color index of $B-V$=0.78 obtained by Kaiser et al. (2002), the effective temperature of the primary is T_1=5360 K from Budding & Demircan (2007) (see Doğru et al. 2009).

We have obtained two solutions: the one-spot model and the two-spot model on the primary. The preliminary values of the orbital parameters are taken from the prior photometric solutions derived by Kaiser et al. (2002) and Doğru et al. (2009). Separately, we adjusted the orbital parameters and the spot parameters until the theoretical curves fitted the observed ones well. For the two-spot model, we fixed the spot latitude and temperature to avoid correlation among the spot latitude, temperature and radius. According to the temperature relation of the starspot and its modeled photosphere for active stars (Berdyugina 2005), we could determine that the starspot temperature is about 1500 K

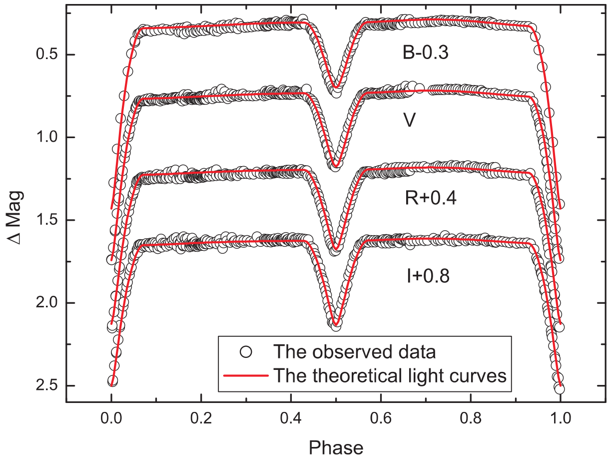

Fig. 3 Observational and theoretical LCs of V1034 Her in 2009. The circles and solid lines represent the observational and theoretical LCs, respectively.

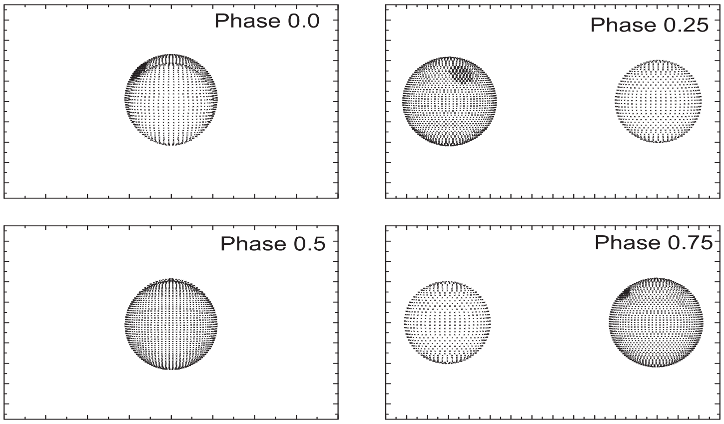

Fig. 4 Configurations of V1034 Her in phases 0.0, 0.25, 0.5 and 0.75.

below the photosphere of the primary for V1034 Her. Therefore, the temperature factor is assumed to be 0.75. The preliminary latitude was set at the intermediate latitude of 50° based on the prior result for the RS CVn binary. After a lot of runs, two photometric solutions for V1034 Her were derived and listed in Table 2. The weighted sum of squares of residuals of the two-spot model is smaller than that of the one-spot model, so we concluded that the two-spot model on the primary is more successful at describing the LCs of V1034 Her. The theoretical LCs for the spotted solutions and the observed LCs are shown in Figure 3. Corresponding configurations for V1034 Her in phases 0.0, 0.25, 0.5 and 0.75 are shown in Figure 4.

As can be seen from Figure 1, the LCs do not have full phase coverage in 2010 due to the weather conditions. Comparison of the LCs from 2009 and 2010 indicates small variations around 0.2 and 0.8 over a long time scale of one year (see Fig. 1). The variations might be explained by spot variations. However, we could not derive the spot parameters because one small spot could affect more than half of the LC, and our LCs have very large data gaps in 2010.

Table 2 Photometric Solutions for V1034 Her

Parameters	Values (one spot)	Values (two spots)
T_1(K)	5360^a	5360^a
T_2(K)	4823±5	4857±4
$i(^\circ)$	87.57±0.08	88.50±0.09
q	1.006±0.007	0.98±0.01
Ω_1	5.825±0.040	5.560±0.024
Ω_2	5.681±0.042	5.583±0.047
$L_1/(L_1+L_2)$ (B)	0.6688±0.0017	0.7063±0.0009
$L_1/(L_1+L_2)$ (V)	0.6291±0.0020	0.6716±0.0011
$L_1/(L_1+L_2)$ (R)	0.6005±0.0022	0.6462±0.0012
$L_1/(L_1+L_2)$ (I)	0.5795±0.0023	0.6275±0.0013
r_1(pole)	0.2066±0.0017	0.2174±0.0012
r_1(point)	0.2120±0.0019	0.2240±0.0014
r_1(side)	0.2085±0.0018	0.2197±0.0013
r_1(back)	0.2111±0.0019	0.2228±0.0014
r_2(pole)	0.2138±0.0019	0.2015±0.0020
r_2(point)	0.2200±0.0022	0.2064±0.0022
r_2(side)	0.2159±0.0020	0.2031±0.0020
r_2(back)	0.2189±0.0021	0.2055±0.0021
$\mathrm{latitude}_{\mathrm{spot1}}(^\circ)$	50.0±12.0	50^a
$\mathrm{longitude}_{\mathrm{spot1}}(^\circ)$	68.1±5.1	70.2±5.1
$\mathrm{radius}_{\mathrm{spot1}}(^\circ)$	14.6±5.1	15.3±0.4
temperature f_{spot1}	0.82±0.09	0.75^a
$\mathrm{latitude}_{\mathrm{spot2}}(^\circ)$	-	50^a
$\mathrm{longitude}_{\mathrm{spot2}}(^\circ)$	-	333.9±2.6
$\mathrm{radius}_{\mathrm{spot2}}(^\circ)$	-	10.9±1.6
temperature f_{spot2}	-	0.75^a
$\sum_i (O-C)_i^2$	0.2862	0.2238

Notes: Parameters not adjusted in the solution are denoted by a mark "^{a}."

4 DISCUSSION AND CONCLUSIONS

In this paper, our new LCs in the $BVRI$ bands were analyzed using the 2003 version of the Wilson-Devinney code with a spot model. New absolute physical parameters and starspot parameters were obtained. Second, we discussed the relationship between photospheric starspot activity and the orbital period for the short-period RS CVn binary. Finally, the variations in the orbital period of V1034 Her were reanalyzed.

4.1 Photometric Solution and Starspot Activity of V1034 Her

The marked asymmetry of the LCs of V1034 Her might suggest high-level surface activity, which was explained by a starspot. From our results, we derived that the two-spot model on the primary star is more successful in representing the distortions of the LCs. For the orbital parameters, the contribution of the primary component of V1034 Her to the total light is 0.71 in B, 0.67 in V, 0.65 in R and 0.63 in the I band. Our new orbital parameters of luminosity ratios, the temperature of the secondary, and the orbital inclination are similar to those derived by Kaiser et al. (2002) and Doğru et al. (2009). However, the dimensionless potentials of the primary and secondary components Ω_1 and Ω_2 are a bit smaller than the results derived by Kaiser et al. (2002) and Doğru et al. (2009). These may be affected by the starspot.

It is well known that active-region longitude is the most reliable spot parameter determined by the traditional light-curve method. For the result derived by Kaiser et al. (2002), the longitudes of two spots in 2001 were about 118° and 335°, respectively. The spot longitude was transformed to the binary orbital motion system. Later, Doğru et al. (2009) derived that the longitudes of the two cool

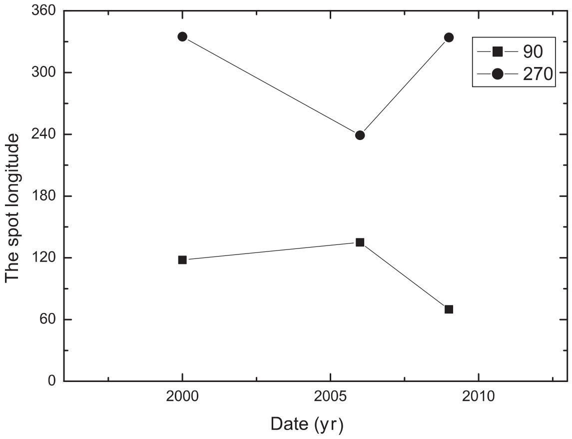

Fig. 5 Spot longitudes from 2000 to 2009.

spots were $135°$ and $239°$ in 2006, respectively. For our starspot parameters, the longitude of Spot 1 is $70°$ and that of Spot 2 is about $334°$. Therefore, it could be suggested that the active regions tend to appear in two active longitude belts near $90°$ and $270°$, and each active longitude might migrate in the orbital reference frame (see Fig. 5). An active longitude phenomenon has also been found using photometry of many other active RS CVn binary systems, such as EI Eri (Berdyugina & Tuominen 1998), σ Gem (Henry et al. 1995), HK Lac (Olah et al. 1991), DV Psc (Zhang et al. 2010a), SV Cam (Zeilik et al. 1988) and RT And (Pribulla et al. 2000; Zeilik et al. 1989; Zhang & Gu 2007).

Comparison of the LCs of 2009 and 2010 indicates that Spot 1 becomes weaker at phase 0.2 and Spot 2 becomes a bit stronger at phase 0.8 in 2010. Therefore, the spot activity changed over a long time scale of one year. Indeed, Kaiser et al. (2002) also found that the LCs differ on the order of 0.04 magnitude at phase 0.9 during their observations in 2000 and 2001. This indicates starspot variation on a time scale of one year.

4.2 The Orbital Period - Activity Relation for the Short Period RS CVn Binary

For our observational LCs of V1034 Her, Max.II is around 0.04 mag in B, 0.07 mag in V, 0.06 mag in R and 0.04 mag in the I band brighter than Max.I. As is well known, LC distortions are caused by dark photospheric spots for RS CVn stars. In order to detect the relation of the orbital period and the photospheric activity, we have also collected the values of the maximum amplitude of photometric distortions of other short-period RS CVn binaries (Strassmeier et al. 1993; Eker et al. 2008). The values are listed in Table 3, which includes the object name, spectral type, the orbital period, and the maximum distortion amplitudes in $BVRI$ bands. For these values, the number of BV band values is greater than that for the RI bands. To detect the amplitude variation with the orbital period, they are plotted in Figure 6. As can be seen from Figure 6, there is a trend of increasing activity as the orbital period decreases, and the trend is basically consistent with the B and V bands (see Fig. 6). To clarify the change, we also used the linear least-squares method to make the fit, and the linear formulas were obtained for the B and V bands as follows

$$\text{The } B \text{ amplitude(mag)} = 0.257(\pm 0.067) - 0.223(\pm 0.106) \times P\,.$$
$$\text{The } V \text{ amplitude(mag)} = 0.151(\pm 0.052) - 0.068(\pm 0.083) \times P\,.$$

These fits are also plotted in Figure 6 with solid lines. They are consistent with the rotation-activity correlation of RS CVn binaries by using chromospheric activity indicators (Montes et al. 1995, 1996), radio luminosity (Gunn 1998) and extreme ultraviolet emission (Mitrou et al. 1997).

Table 3 Maximum Distortion Amplitudes of a Short-Period RS CVn Binary in the B, V, R and I Bands

Object	Spectral type	Period	Distortion amplitude (mag)				Reference
		(d)	B	V	R	I	
RT And	F8-G0V+K1-3V	0.629	0.095	0.075		0.05	Pribulla et al. (2000); Zhang & Gu (2007)
V1034 Her	G5-9V+K1-4V	0.815	0.040	0.070	0.06	0.04	Kaiser et al. (2002); Doğru et al. (2009); this paper
DV Psc	K4V+	0.309	0.122	0.109	0.09	0.06	Zhang & Zhang (2007); Zhang et al. (2010a)
XY Uma	G2-5V+K5V	0.479	0.292	0.251	0.12	0.10	Pribulla et al. (2001); Yuan (2010)
CG Cyg	G0V+K3V	0.631	0.170	0.140	0.05	0.05	Heckert (1996); Afşar et al. (2004); Kozhevnikova et al. (2007b)
BH Vir	F8V+G5V-M2V	0.817	0.030	0.100			Xiang et al. (2000); Kozhevnikova et al. (2007a)
WY Cnc	G5V+K7V	0.830		0.110			Kozhevnikova et al. (2007a)
GSC03377-0296	K3+	0.422	0.140	0.120	0.10		Lloyd et al. (2007)
DK CVn	K7V+M	0.495	0.159a	0.117a	0.10a	0.08a	Koff et al. (2005); Terrell et al. (2005)
SV Cam	G0-G5V+K4V	0.593	0.150a	0.150			Pribulla et al. (2003)
UCAC3 295-68871		0.461			0.10a		Solovyov et al. (2011)
GSC 2038.0293	G6-9+K1-3	0.495	0.090	0.070	0.06		Bernhard & Frank (2006)
UV Psc	G5V-8+K2-3V	0.861	0.094	0.100			Akan (1988); Kjurkchieva et al. (2005)
ER Vul	G0V+G5V	0.698	0.080a	0.050			Heckert & Zeilik (1991); Qian (2001); Pribulla et al. (2003)
BB Scl	K3-5V+K4V	0.477		0.070			Bromage et al. (1996); Watson et al. (2001)
UV Leo	G0V+G2V	0.600		0.050			Kjurkchieva & Marchev (2007)
BC Phe	G5-8V+K3-5V	0.649		0.170			Cutispoto (1995)

Notes: The values are denoted by a letter "a," which are approximately calculated by the LCs from literature.

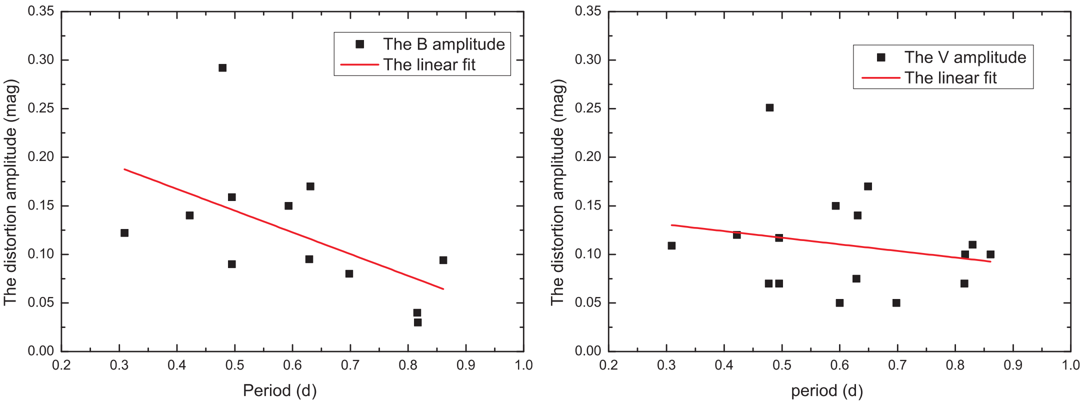

Fig. 6 Relations between the orbital period and photometric distortion amplitudes in the B and V bands.

4.3 The Period Variation of V1034 Her

The variation of the orbital period of V1034 was reanalyzed on the basis of our new minimum times and those collected from the literature. The quadratic term indicates that the orbital period of V1034 Her shows a continuous increase at a rate of $0.0107(\pm 0.0006)\,\mathrm{s\,yr^{-1}}$. The rate is similar to the result derived by Doğru et al. (2009). Since V1034 Her is a detached system, it is impossible that mass transfers directly from the less massive component to the larger massive primary. So it is probable that the coronal mass flows from the less massive component to the large massive component by stellar wind (Gálvez et al. 2007). Because the photometric mass ratio is about one, it is difficult to tell if the massive component is the primary star or the secondary component. Because the time range of $(O-C)$ information is rather short, about 25 yr, it is too early to decide about the character of the period variation. The upward parabola may be part of a long periodic oscillation caused by a presumed third component or by a magnetic activity cycle (Applegate 1992; Lanza et al. 1998). More new observations are needed to confirm it in the next 20–30 yr.

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