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Reanalysis of the orbital period variations of two DLMR overcontact binaries: FG Hya and GR Vir

Xu-Dong Zhang, Yun-Xia Yu, Fu-Yuan Xiang and Ke Hu

Department of Physics, Xiangtan University, 411105 Xiangtan, China; *fyxiang@xtu.edu.cn*

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Abstract We investigate orbital period changes of two deep, low mass ratio (DLMR) overcontact W UMa-type binaries, FG Hya and GR Vir. It is found that the orbital period of FG Hya shows a cyclic change with a period of $P_{\rm mod} = 54.44$ yr. The cyclic oscillation may be due to a third body in an eccentric orbit, while the orbital period of GR Vir shows a periodic variation with a period of $P_{\rm mod} = 28.56$ yr and an amplitude of $A = 0.0352$ d. The periodic variation of GR Vir can be interpreted as a result of either the light-time effect of an unseen third body or the magnetic activity cycle.

Key words: binaries: close — binaries: eclipsing — stars: individual (FG Hya, GR Vir)

1 INTRODUCTION

FG Hya (AN 1934.0334, BD $+03°1979$, GSC 0201.01844, Hip 041437) is a W UMa-type binary with a very low mass ratio and very high degree of overcontact (Qian & Yang 2005). It was discovered by Hoffmeister (1934). After its discovery, this system has been observed by many authors. Firstly, Tsesevich (1949) made visual observations and classified it as a cluster type. Photoelectric and spectroscopic observations were subsequently performed by Smith (Smith 1955, 1963), who suggested that FG Hya is a W UMa-type system with the spectral type of G0. Binnendijk (1963) published complete light curves in the B and V bands, from which Lafta & Grainger (1986) determined the mass ratio to be $q = M_2/M_1 = 0.19$. Yang et al. (1991) performed a photometric study in which FG Hya was further identified as an A-type contact system with a fill-out factor of 90%. Lu & Rucinski (1999) presented spectroscopic observations. They derived a spectroscopic mass ratio of $q_{\rm sp} = 0.112$ and the absolute parameters $a = 2.32\,R_\odot$, $M_1 = 1.41\,M_\odot$ and $M_2 = 0.16\,M_\odot$. Yang & Liu (2000) acquired CCD photometric observations. By comparing their observations with the previous photometric data obtained by Smith (1955); Binnendijk (1963); Mahdy et al. (1985); Yang et al. (1991), they found that the shape of the light curves of FG Hya shows long-term changes in the light level changes. Qian & Yang (2005) reported that the light curves showed asymmetries. They interpreted such variations in the light curves as a dark spot on the primary component. Combining their own CCD photometric observations with the spectroscopic elements of Lu & Rucinski (1999), Qian & Yang (2005) improved the absolute parameters (in solar units) which are summarized in Table 1.

The orbital period changes of FG Hya were first noted and investigated by Qian et al. (1999). They revealed that its orbital period had undergone five sudden changes from 1950 to 1999, and suggested that these sudden changes are related to asymmetries in the light curves. However, subsequent analysis of its orbital period performed by Yang & Liu (2000) revealed a secular decrease at a rate of $\Delta P/P = -2.8 \times 10^{-10}$. Qian & Yang (2005) studied the orbital period changes again. They found that the orbital period of FG Hya shows a sinusoidal variation with a period of $P_{\rm mod} = 36.4$ yr superimposed on a secular period decrease at a rate of $dP/dt = -1.96 \times 10^{-7}\,{\rm d\,yr^{-1}}$.

GR Vir (BD $-06°4068$, GSC 4998.00885, HD 129903, Hip 072138, SAO 140120) is another W UMa-type binary with very low mass ratio and very high degree of overcontact. It was discovered by Strohmeier et al. (1965). Its eclipsing nature was identified by Harris (1979). The complete photoelectric light curves of GR Vir were reported almost at the same time by Cereda et al. (1988) and Halbedel (1988). The radial velocity curves of the system were obtained by

Table 1 Summary of Absolute Parameters for FG Hya and GR Vir

Star	M_1	M_2	R_1	R_2	a	L_1	L_2	T_1	T_2	Reference
FG Hya	1.44	0.16	1.41	0.59	2.34	2.16	0.41	5900	6012	Qian & Yang (2005)
GR Vir	1.37	0.17	1.42	0.61	2.40	2.87	0.48	6300	6163	Qian & Yang (2004)

Rucinski & Lu (1999), who suggested a spectral type of F7/F8. Qian & Yang (2004) made the CCD photometric observations, from which they revealed that GR Vir is an A-type overcontact system with a degree of overcontact of $f = 78.6\%$. Combining their own CCD photometric solutions with the spectroscopic elements of Rucinski & Lu (1999), Qian & Yang (2004) determined the absolute parameters of GR Vir which are compiled in Table 1. Also, Qian & Yang (2004) analyzed the orbital period changes of GR Vir, where a secular decrease in its orbital period has revealed the orbital period of GR Vir varies with a cyclic period of $P_{\rm mod} = 19.3\,{\rm yr}$ superimposed on a secular period decrease at a rate of $dP/dt = -4.32 \times 10^{-7}\,{\rm d\,yr^{-1}}$.

In the most recent decade, a large number of times of light minimum for FG Hya and GR Vir have been published. Unfortunately, these new times cannot be predicted well and even significantly deviate from the non-linear ephemeris obtained in previous studies. Therefore, it is necessary to revisit the orbital period changes for these two systems, aiming to uncover the underlying physical processes and provide a useful clue for understanding their evolutionary status.

2 ORBITAL PERIOD ANALYSES

2.1 FG Hya

In order to reveal the orbital period changes of FG Hya, we have performed a careful search for all available photoelectric and CCD times of light minimum. Some of them have been compiled by Qian & Yang (2005). Others are listed in Table 2. With the linear ephemeris given by Kreiner (2004),

$$\mathrm{Min.I} = 2452500.1360 + 0.3278322 \times E, \quad (1)$$

the $(O-C)$ values are calculated and displayed in Figure 1, where solid dots represent the photoelectric and CCD observations. From Figure 1, we can see that the orbital period change of FG Hya is continuous, and the $(O-C)$ trend shows obvious cyclic variation, which may be caused by the light-time effect of a third body. As shown in the figure, the shape of the the oscillation is not strictly sinusoidal, meaning that the third body is moving in an elliptical orbit. By using the least-squares method, the following equation is obtained,

$$(O-C) = a_1 + a_2E + \sum_{i=1}^{3}\Big[b_i\cos(i\omega E) + c_i\sin(i\omega E)\Big], \quad (2)$$

where b_i, c_i and ω are well-known Fourier constants. The values of the fitted parameters are listed in Table 3. The residuals that have no other variations are displayed in the lower panel of Figure 1, which means our fitting is sufficient. With $\omega = 360^\circ P_e/P_{\rm mod}$, the orbital period of the third body rotating around the eclipsing pair was determined to be $P_{\rm mod} = 54.44\,{\rm yr}$. The orbital parameters of the tertiary component were computed with the formulae given by Vinko (1989),

$$e = \frac{4}{3}\sqrt{\frac{b_3^2 + c_3^2}{b_2^2 + c_2^2}}, \quad (3)$$

$$\omega' = \arctan\frac{(c_1^2 - b_1^2)c_2 + 2b_1b_2c_1}{(b_1^2 - c_1^2)b_2 + 2b_1c_1c_2}\left(1 - \frac{e^2}{3}\right), \quad (4)$$

$$\tau = T_0 - \frac{P_{\rm mod}}{2\pi}\arctan\frac{1 - \frac{b_1}{c_1}\frac{h_1}{g_1}\tan\omega'}{\frac{b_1}{c_1} + \frac{h_1}{g_1}\tan\omega'}, \quad (5)$$

$$a_{12}\sin i = c\frac{\sqrt{b_1^2 + c_1^2}}{h_1^2 + \left(g_1^2 - h_1^2\right)\cos\omega'^2}, \quad (6)$$

where $g_1 = 1 - \frac{5e^2}{8}$ and $h_1 = 1 - \frac{3e^2}{8}$. The results are listed in Table 4.

2.2 GR Vir

To study the orbital period change of GR Vir in detail, we have collected all available photoelectric and CCD times of light minimum from the literature. Since some of the data have been tabulated by Qian & Yang (2004), here we only list the others in Table 5. The $(O-C)$ values computed with the linear ephemeris given by Kreiner (2004),

$$\mathrm{Min.I} = 2452500.0891 + 0.34697014 \times E, \quad (7)$$

Table 2 Times of Light Minimum for FG Hya

HJD.2400000+	Method	E	Type	$O-C$	Ref.	HJD.2400000+	Method	E	Type	$O-C$	Ref.
48271.4960	CCD	–12899	I	0.0675	[1]	53402.0060	CCD	2751	I	0.00362	[1]
48290.5064	CCD	–12841	I	0.06368	[1]	53402.1700	CCD	2751.5	II	0.0037	[1]
48358.3682	CCD	–12634	I	0.06416	[1]	53404.6285	CCD	2759	I	0.00346	[1]
48500.3210	CCD	–12201	I	0.06567	[1]	53404.7926	CCD	2759.5	II	0.00364	[1]
48625.5493	CCD	–11819	I	0.06207	[1]	53405.6126	CCD	2762	I	0.00406	[1]
48683.4109	CCD	–11642.5	II	0.06129	[1]	53405.7800	CCD	2762.5	II	0.00755	[1]
49004.5203	CCD	–10663	I	0.0591	[1]	53406.7616	CCD	2765.5	II	0.00565	[1]
49004.6796	CCD	–10662.5	II	0.05443	[1]	53409.7104	CCD	2774.5	II	0.00396	[1]
49393.3247	CCD	37899	I	0.02473	[1]	53410.3672	CCD	2776.5	II	0.0051	[1]
49416.4349	CCD	–9406.5	II	0.05249	[1]	53410.5292	CCD	2777	I	0.00318	[1]
49772.4535	CCD	–8320.5	II	0.04532	[2]	53445.4428	CCD	2883.5	II	0.00265	[1]
51192.1180	CCD	–3990	I	0.03248	[1]	53764.0943	CCD	3855.5	II	0.00125	[1]
51216.0490	CCD	–3917	I	0.03173	[1]	53774.0928	CCD	3886	I	0.00087	[1]
51485.8480	CCD	–3094	I	0.02483	[1]	53775.0773	CCD	3889	I	0.00187	[1]
51908.2566	CCD	–1805.5	II	0.02164	[1]	53799.0056	CCD	3962	I	–0.00158	[1]
51950.0564	CCD	–1678	I	0.02283	[1]	53829.0034	CCD	4053.5	II	–0.00042	[1]
51958.0953	CCD	–1653.5	II	0.02984	[1]	54499.7477	CCD	6099.5	II	–0.0008	[1]
52297.0621	CCD	–619.5	II	0.01815	[1]	54529.5808	CCD	6190.5	II	–0.00043	[1]
52299.0260	CCD	–613.5	II	0.01505	[1]	54554.9858	CCD	6268	I	–0.00243	[1]
52300.0136	CCD	–610.5	II	0.01916	[1]	54829.8831	CCD	7106.5	II	0.00757	[1]
52341.9745	CCD	–482.5	II	0.01754	[1]	54889.7014	CCD	7289	I	–0.00351	[1]
52343.1236	CCD	–479	I	0.01922	[1]	55593.0691	CCD	9434.5	II	0.00021	[1]
52347.5530	CCD	–465.5	II	0.02289	[3]	55623.3952	CCD	9527	I	0.00183	[1]
52629.8087	CCD	395.5	II	0.01506	[3]	55632.7353	CCD	9555.5	II	–0.00129	[1]
52657.1851	CCD	479	I	0.01748	[1]	55979.5835	CCD	10613.5	II	0.00045	[1]
52660.7860	CCD	490	I	0.01222	[1]	56000.7286	CCD	10678	I	0.00037	[1]
52696.0303	CCD	597.5	II	0.01456	[1]	56003.3548	CCD	10686	I	0.00391	[1]
53018.1229	CCD	1580	I	0.01202	[1]	56298.8936	CCD	11587.5	II	0.00198	[1]
53025.8222	CCD	1603.5	II	0.00727	[3]	56743.4426	CCD	12943.5	II	0.01052	[1]
53055.0030	CCD	1692.5	II	0.011	[1]	56745.4071	CCD	12949.5	II	0.00803	[1]
53088.6048	CCD	1795	I	0.01	[3]	57010.1411	CCD	13757	I	0.01752	[1]
53094.3444	CCD	1812.5	II	0.01254	[1]	57048.3330	CCD	13873.5	II	0.01697	[1]
53105.1573	CCD	1845.5	II	0.00697	[1]	57048.4950	CCD	13874	I	0.01506	[1]
53387.4199	CCD	2706.5	II	0.00605	[1]	57097.3480	CCD	14023	I	0.02106	[1]
53387.5812	CCD	2707	I	0.00343	[1]	57415.0261	CCD	14992	I	0.02976	[1]
53387.7496	CCD	2707.5	II	0.00792	[1]	57415.0262	CCD	14992	I	0.02986	[1]
53388.7329	CCD	2710.5	II	0.00772	[1]	57415.0278	CCD	14992	I	0.03146	[1]
53389.7165	CCD	2713.5	II	0.00783	[1]	57415.0281	CCD	14992	I	0.03176	[1]
53400.6934	CCD	2747	I	0.00235	[1]	57498.4590	CCD	15246.5	II	0.02936	[1]

Notes: References [1] *http://var2.astro.cz/ocgate/*; [2] Agerer & Hubscher (1996); [3] Samolyk (2012).

are displayed in Figure 2. By using the least-squares method, the following equation is obtained,

$$
\begin{aligned}
(O-C) \; = \; & +0.0181^{\rm d}(\pm 0.0007) \\
& +0.1804^{\rm d}(\pm 0.0056) \times 10^{-5} \times E \\
& +0.0352^{\rm d}(\pm 0.0007) \\
& \times \sin\Big[0.0120^\circ(\pm 0.0000^\circ) \times E \\
& -89.8^\circ(\pm 1.8^\circ)\Big]. \qquad (8)
\end{aligned}
$$

The sinusoidal term in Equation (8) suggests a cyclic oscillation with a period of $P_{\rm mod} = 28.56$ yr and an amplitude of $A = 0.0352$ d. The orbital parameter of the third body was computed to be $a_{12} \sin i = 6.10$ AU with the well-know equation

$$a_{12} \sin i = A \times c, \qquad (9)$$

where a_{12} is the orbital radius of the binary rotating around the common center of mass, i is the inclination of the orbit of the third component and c is the speed of light.

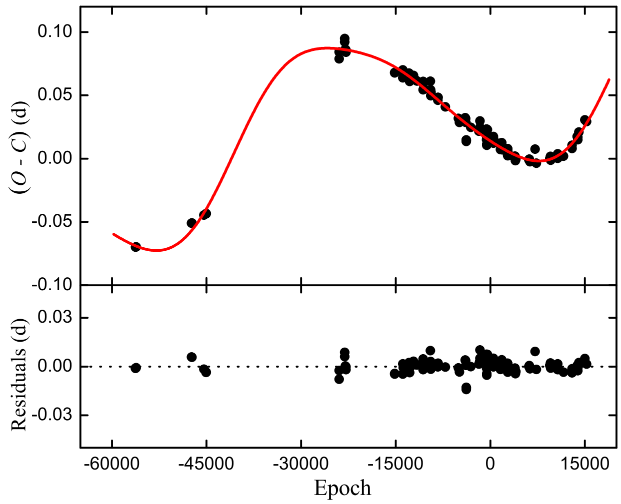

Fig. 1 $(O-C)$ curve of FG Hya. The *dots* refer to photoelectric and CCD data. The *solid line* in the *upper panel* represents our fitting curve (Eq. (2)). Residuals of FG Hya with respect to Equation (2) are displayed in the *lower panel*.

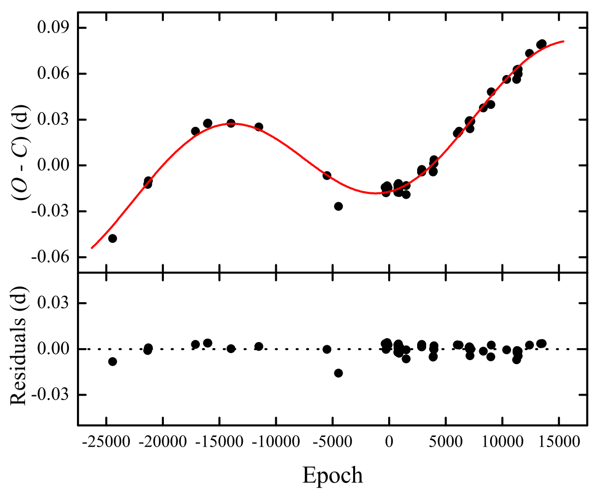

Fig. 2 Same as Fig. 1 but for GR Vir. In the *upper panel*, the *dots* refer to photoelectric and CCD data computed by the linear ephemeris (i.e., Equation (7)). The *solid line* represents our fitting curve. Residuals coming from Equation (8) are displayed in the *lower panel*.

In Figure 2, one can clearly see that our fitting is reasonable, and the sum of squares of the residuals $\sum_i(O-C)_i^2 = 0.00076\,\mathrm{d}^2$ is very acceptable. The residuals from Equation (8) are displayed in the lower panel of Figure 2.

3 MECHANISMS OF THE ORBITAL PERIOD VARIATIONS

3.1 Light-Time Effect of a Third Companion

The orbital period oscillation of FG Hya and GR Vir may be caused by the light-time effect of a third companion. If this is true, the orbital period of the third body rotating around the eclipsing pair is about 54.44 yr and 28.56 yr for FG Hya and GR Vir, respectively. For GR Vir, considering the third body is moving in a circular orbit and inserting the absolute parameters compiled in Table 1 into the well-known equations

$$f(m) = \frac{(M_3 \sin i)^3}{(M_1+M_2+M_3)^2} = \frac{4\pi^2}{GP_{\rm mod}^2} a_{12}^3 \sin^3 i, \quad (10)$$

$$a_3 = \frac{M_1+M_2}{M_3} a_{12}, \quad (11)$$

Table 3 Parameters in the Period Changes of FG Hya

Parameter	Value	Error
a_1	0.0577	±0.0031
a_2	0.1166×10^{-5}	$\pm0.0030 \times 10^{-5}$
b_1	–0.0520	±0.0053
b_2	0.0079	±0.0013
b_3	0.0015	±0.0004
c_1	–0.0374	±0.0027
c_2	–0.0069	±0.0014
c_3	0.0028	±0.0002
ω	0.1036×10^{-3} (rad)	$\pm0.1119 \times 10^{-6}$ (rad)

Table 4 Orbital Parameters of the Tertiary Component Star in FG Hya

Parameter	Value	Unit
T_0	2452500.1937	(d)
$P_{\rm mod}$	54.44	(yr)
e	0.40	–
ω'	113.7	(°)
$a_{12}\sin i$	13.00	(AU)
τ	2444804	(d)
$f(m)$	0.7023	$(M_\odot)$

we can compute the lower limit on the third body's mass and the upper limit on orbital radius to be $M_3 = 1.31\,M_\odot$ and $a_3 = 7.17$ AU respectively.

For FG Hya, the third body is moving in an elliptical orbit. By inserting the absolute parameters of FG Hya (Table 1) and the orbital parameters of the tertiary component star (Table 4) into Equation (10), the minimum mass of the third body can be computed to be $M_3 = 2.14\,M_\odot$.

3.2 Magnetic Activity Mechanism

Since the spectral type of GR Vir is G0, it is a late-type binary, and its $(O - C)$ curve shows normal sinusoidal variation. This means that the magnetic activity mechanism is also a possibility for explaining cyclic variations of the period in this system. Using the following formula (Lanza et al. 1998)

$$\frac{\Delta P}{P} = -9\left(\frac{R}{a}\right)^2 \frac{\Delta Q}{MR^2}, \tag{12}$$

where

$$\frac{\Delta P}{P} = \frac{2\pi A}{P_{\rm mod}}, \tag{13}$$

we can calculate variation of the quadruple moment $\Delta Q_1 = 1.7942 \times 10^{50}\,{\rm g\,cm^2}$ for the primary star and $\Delta Q_2 = 2.2264 \times 10^{49}\,{\rm g\,cm^2}$ for the secondary star.

4 DISCUSSION AND CONCLUSIONS

We have analyzed the orbital period of FG Hya and GR Vir. It is found that both FG Hya and GR Vir show period oscillations. We can compare our results with the works of Qian & Yang (2004, 2005). They found that orbital periods of both FG Hya and GR Vir show sinusoidal variations superimposed on secular period decreases (see Sect. 1). In our results, we found that each of the orbital periods of these two systems only shows a periodic oscillation. No secular period changes were discovered in either overcontact binary, meaning that FG Hya and GR Vir may be in the transition between thermal relaxation oscillation (TRO)-controlled and variable angular momentum loss (AML)-controlled stages (Qian et al. 2005).

In Section 3, we interpreted the orbital period oscillations of FG Hya and GR Vir by the light-time effect of third bodies, and obtained the mass of the third body $M_3 \geq 2.14\,M_\odot$ for FG Hya and $M_3 \geq 1.31\,M_\odot$ for GR Vir. If such large third bodies really exist, they should be found photometrically. So far, no third lights have been observed in either system, suggesting that the third bodies may be unseen components, e.g., a small black hole or a white dwarf.

Since the spectral type of GR Vir is G0, the orbital period oscillation can also be explained by magnetic activity on both components of the system. This mechanism is based on the hypothesis that a hydromagnetic dynamo can produce changes in the gravitational quadrupole moment of an active star through a redistribution of the internal angular momentum and/or action of the Lorentz force in the stellar convective zone (Applegate 1992; Lanza et al. 1998). If energy for transferring angular momentum is provided by luminosity variation of the active star, there must be $\Delta L \leq 0.1L$. Based on the equation given by Yu et al. (2015),

$$\frac{\Delta L}{L} = \frac{5G^2}{24\pi^2\sigma}\frac{M^3}{R^6}\left(\frac{a}{RT}\right)^4\frac{(\Delta P)^2}{P_{\rm mod}}, \tag{14}$$

we can obtain $\Delta L_1/L_1 = 0.083$ and $\Delta L_2/L_2 = 0.028$, implying that the mechanism of magnetic activity can be used to explain cyclic variations of GR Vir. In this equation, G, σ and T are the gravitational constant, Stefan-Boltzman constant and surface temperature of the active star, respectively. All these physical elements are in the international system of units.

In summary, the orbital periods of FG Hya and GR Vir show periodic oscillations with periods of $P_{\rm mod} = 54.44$ yr and $P_{\rm mod} = 28.56$ yr, respectively. Our study demonstrates that periodic variations in FG Hya and GR Vir can be explained by the light-time effect of

Table 5 Times of Light Minimum for GR Vir

HJD.2400000+	Method	E	Type	$O-C$	Ref.	HJD.2400000+	Method	E	Type	$O-C$	Ref.
48500.069	CCD	–11528.5	II	0.02516	[1]	54961.0042	CCD	7092.5	II	0.02938	[1]
50594.002	CCD	–5493.5	II	–0.00664	[1]	54966.0339	CCD	7107	I	0.02802	[1]
52782.511	CCD	814	I	–0.01179	[1]	54976.9647	CCD	7138.5	II	0.02926	[1]
53489.1241	CCD	2850.5	II	–0.00338	[1]	54978.0003	CCD	7141.5	II	0.02395	[1]
53490.6846	CCD	2855	I	–0.00425	[2]	55004.375	CCD	7217.5	II	0.02891	[1]
53492.594	CCD	2860.5	II	–0.00319	[2]	55384.316	CCD	8312.5	II	0.03761	[1]
53492.7665	CCD	2861	I	–0.00417	[2]	55616.6148	CCD	8982	I	0.0399	[1]
53496.7582	CCD	2872.5	II	–0.00263	[2]	55632.5836	CCD	9028	I	0.04808	[4]
53497.624	CCD	2875	I	–0.00425	[2]	56100.481	CCD	10376.5	II	0.05624	[1]
53497.7983	CCD	2875.5	II	–0.00344	[2]	56404.4268	CCD	11252.5	II	0.05622	[1]
53846.1555	CCD	3879.5	II	–0.00426	[1]	56419.0047	CCD	11294.5	II	0.06135	[1]
53854.1363	CCD	3902.5	II	–0.00377	[1]	56421.0878	CCD	11300.5	II	0.06251	[1]
53861.0808	CCD	3922.5	II	0.00133	[1]	56426.9863	CCD	11317.5	II	0.06267	[1]
53877.0415	CCD	3968.5	II	0.0014	[1]	56455.435	CCD	11399.5	II	0.05979	[1]
53877.2173	CCD	3969	I	0.00371	[1]	56456.479	CCD	11402.5	II	0.06288	[1]
54587.1354	CCD	6015	I	0.02091	[1]	56805.5413	CCD	12408.5	II	0.07324	[1]
54647.3362	CCD	6188.5	II	0.02239	[3]	57140.0262	CCD	13372.5	II	0.0789	[1]
54951.1149	CCD	7064	I	0.02873	[1]	57187.7353	CCD	13510	I	0.07961	[1]
54954.0645	CCD	7072.5	II	0.02908	[1]						

Notes: References [1] *http://var2.astro.cz/ocgate/*; [2] Ogloza et al. (2008); [3] Yilmaz et al. (2009); [4] Hubscher et al. (2012).

third bodies. For GR Vir, the orbital period oscillation can be also explained by magnetic activity on both components of the system. In order to check these conclusions, more observations are needed.

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