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On the Period Variation of the W UMa-type Contact Binary V502 Ophiuchi *

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Abstract The variation in the orbital period of the W UMa type contact binary V502 Oph is analyzed. The orbital period exhibits a wavelike variation with a periodicity of 23.0 years and an amplitude of $\Delta P = 1.24 \times 10^{-6}$ days superimposed on secular decrease of $dP/dt = 1.68 \times 10^{-7}$ day per year. The long-term decrease may be accompanied by the contraction of the secondary at a rate of 83 m per year and a mass transfer rate from the primary to the secondary of $4.28 \times 10^{-8} M_{\odot}$ per year. The short-term oscillation may be explained by the presence of a third component. Orbital elements of the third body and its possible mass are presented.

Key words: stars: contact binary – period change – star: individual: V502 Oph

1 INTRODUCTION

V502 Oph (BD$+0^{\circ}$3562, HD150484) was discovered to be an eclipsing binary by Hoffmeister (1935). The first ephemeris based on visual observations was published by Lause (1937). Over the years, this binary has been the subject of numerous investigations. Photometric observations of V502 Oph have been published by Kwee (1958, 1968), Hinderer (1960), Magalashvili & Kumsishvili (1964), Wilson (1967), Binnendijk (1969), Polushina (1975), Zola & Krzesinski (1988), and Rovithis et al. (1988). The light curve of the system is not stable and the orbital period was found to undergo a change in the years 1955–1966 (Binnendijk 1969). The period is continually decreasing, but the rate of the change observed in the years 1989–2003 has not been constant (Kreiner 2003, private communication). The light curves of the system have been analyzed (Kopal & Shapley 1956; Hinderer 1960; Maceroni et al. 1982; Rovithis et al. 1988).

Spectroscopic observations and radial velocity curves of V502 Oph have been published (Struve & Gratton 1948; Struve & Zebergs 1959; King & Hilditch 1984) and more recently presented by Pych et al. (2004). The derived orbital elements based on these older observations are surprisingly close to the values based on the more recent data. The spectra of the components were classified as G1 V for the primary and F9 V for the secondary component (Struve & Zebergs 1959). The spectral type in SIMBAD database is G2 V+.... The spectral type of the system based on the Tycho-2 color index (Hog et al. 2000), $B - V = 0.615$, is G1. Pych et al. (2004) argued for a spectral type of G0 V.

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2 PERIOD CHANGE

The ephemeris elements of V502 Oph were given by Kwee (1958) ($P = 0.453396$), Kwee (1968) ($P = 0.4533963$), Binnendijk (1969) ($P = 0.45339304$), Polushina (1975) ($P = 0.45339345$), Maddox & Bookmyer (1979) ($P = 0.45339293$), Zola & Krzesinski (1988) ($P = 0.453388363$), Rovithis et al. (1988) ($P = 0.45339293$), Hobart et al. (1989) ($P = 0.4533925$), and Derman & Demircan (1992). In the last paper the authors found that the orbital period of the system is decreasing and improved the light elements of the system:

$$\mathrm{Pri.Min.} = \mathrm{HJD}2439639.9562 + 0.45339394E. \tag{1}$$

After that, some new photoelectric times of minimum light have been published by Ogloza & Zakrzewski (2004) and Bakis et al. (2005).

We list all the photoelectric minima collected from the literature in Table 1. The residuals $(O-C)_1$ for the times of minima, calculated using the ephemeris (Eq. (1)), are also given in Table 1 and are shown

Table 1 The times of Minima of V502 Oph

HJD(2400000+)	Min.	$(O-C)_1$	$(O-C)_2$	Ref.	HJD(2400000+)	Min.	$(O-C)_1$	$(O-C)_2$	Ref.
34514.7822	I	–0.0089	–0.0010	[1]	41888.3205	I	–0.0162	–0.0005	[11]
34515.4617	II	–0.0095	–0.0016	[2]	42570.4558	II	–0.0121	0.0071	[14]
34840.5465	II	–0.0081	–0.0011	[2]	43238.5245	I	–0.0194	0.0037	[15]
34897.4501	I	–0.0055	0.0015	[3]	43292.4761	I	–0.0217	0.0018	[15]
34899.4888	II	–0.0071	–0.0071	[4]	43665.8463	II	–0.0214	0.0044	[16]
35257.4459	I	–0.0045	0.0017	[5]	43666.7545	II	–0.0200	0.0059	[16]
35261.526	I	–0.005	0.0013	[5]	43668.7951	I	–0.0197	0.0062	[16]
35262.4322	I	–0.0055	0.0007	[5]	43671.7469	II	–0.0149	0.0109	[16]
35544.6726	II	–0.0028	0.0029	[5]	44370.8684	II	–0.0269	0.0039	[17]
35579.5852	II	–0.0016	0.0041	[5]	46528.5488	II	–0.0482	0.0006	[18]
35582.5274	I	–0.0064	–0.0008	[5]	46529.4572	II	–0.0466	0.0022	[18]
35587.5148	I	–0.0064	–0.0007	[5]	46530.5866	I	–0.0507	–0.0019	[18]
35617.4408	I	–0.0044	0.0012	[5]	46555.5244	I	–0.0496	–0.0005	[18]
35621.5205	I	–0.0052	0.0004	[5]	46582.495	II	–0.056	–0.0066	[19]
37394.974	II	–0.002	0.002	[6]	46584.5358	I	–0.0554	–0.0060	[19]
37404.9460	II	–0.005	–0.0004	[6]	46585.4414	I	–0.0566	–0.0072	[19]
37405.8546	II	–0.0030	0.0014	[6]	46586.3495	I	–0.0553	–0.0059	[19]
37437.3571	I	–0.0113	–0.0069	[7]	46587.4816	II	–0.0566	–0.0073	[19]
37459.3454	II	–0.0126	–0.0082	[7]	46590.4288	I	–0.0565	–0.0071	[19]
39631.7829	I	–0.0122	–0.0047	[8]	46595.4177	I	–0.0549	–0.0055	[19]
39637.9078	II	–0.0081	–0.0006	[8]	46915.5165	I	-0.0523	0.0003	[18]
39639.9436	I	–0.0126	–0.0051	[8]	47707.3612	II	–0.0601	0.0006	[20]
39642.8951	II	–0.0082	–0.0007	[8]	48094.3284	I	–0.0646	0.0003	[20]
40719.4714	I	–0.0158	–0.0050	[9]	48096.3673	II	–0.0660	–0.0010	[20]
40778.411	I	–0.017	–0.006	[9]	48099.3150	I	–0.0653	–0.0004	[20]
41174.2288	I	–0.0125	0.0001	[10]	48114.2770	I	–0.0653	–0.0002	[20]
41184.2031	I	–0.0129	–0.0003	[10]	51266.9174	II	–0.0997	0.0054	[21]
41194.1799	I	–0.0107	0.0019	[10]	51267.1421	I	–0.1017	0.0034	[21]
41214.1326	I	–0.0074	0.0054	[10]	51320.6436	I	–0.1008	0.0052	[21]
41491.3772	II	–0.0132	0.0007	[11]	51320.4155	II	–0.1021	0.0038	[21]
41802.632	I	–0.0133	0.0020	[12]	51388.8781	II	–0.1020	0.0049	[21]
41833.462	I	–0.0141	0.0014	[13]	51389.1042	I	–0.1026	0.0043	[21]
41844.344	I	–0.0135	0.0020	[13]	52772.3815	I	–0.1302	0.0024	[22]

[1]=Fitch (1964); [2]=Kwee (1958); [3]=Szafraniec (1962); [4]=Hinderer (1960); [5]=Kwee (1968); [6]=Wilson (1967); [7]=Magalashvili et al. (1964); [8]=Binnendijk (1969); [9]=Popovici (1971); [10]= Polushina (1975); [11]=Kizihrmak et al. (1974) [12]=Strauss (1976); [13]=Vader et al. (1973); [14]=Pohl et al. (1976); [15]=Ebersberger et al. (1978); [16]=Maddox et al. (1979); [17]=Scarfe et al. (1984); [18]=Zola et al. (1988); [19]=Rovithis et al. (1988); [20]=Derman et al. (1992); [21]=Ogloza et al. (2004); [22]=Bakis et al. (2005).

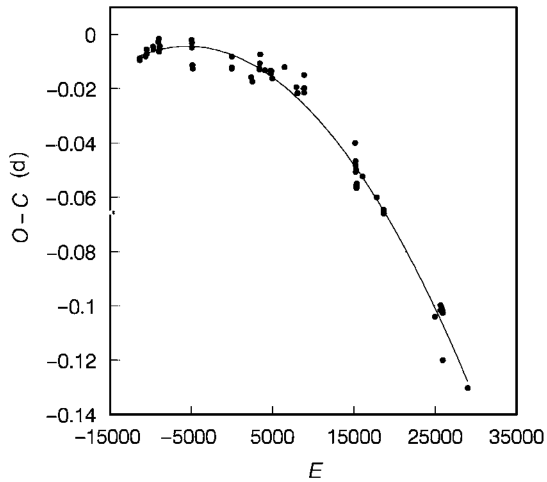

Fig. 1 $O - C$ diagram of the period change for V502 Oph. The $O - C$ values are from the $(O - C)_1$ column in Table 1. The parabola is fitted to the observations.

in Figure 1. In the figure the filled circles indicate the photoelectric data and a parabola is fitted to the observations. Since the $(O-C)_1$ residuals in Figure 1 show a parabolic distribution, we applied a quadratic fitting test. The following quadratic ephemeris was obtained:

$$\mathrm{Pri.Min.} = \mathrm{HJD}2439639.9487(4) + 0.45339280(12)E - 1.04(6) \times 10^{-10}E^2. \quad (2)$$

With the coefficient of the square term, one can determine a period decrease rate, $\Delta P/P = -2.08 \times 10^{-10}$, equivalent to a period decrease of $dP/dt = 1.68 \times 10^{-7}$ d yr^{-1}.

Using the quadratic ephemeris (Eq.(2)), we calculated the residuals $(O-C)_2$ and listed them in Table 1. The $(O-C)_2$ values are shown in Figure 2. The figure shows that the period of V502 Oph may have changed with a small-amplitude oscillation superimposed on the secular decrease. The semi-amplitude of the $O - C$ values is about 0.00365 days and the modulation period is about 23.0 years.

The $O - C$ diagram in Figure 2 was analyzed using the method of Kalimeris et al. (1994). We find that a single seven-order polynomial fits the observed times of minimum light well (the solid curve in Fig. 2). Using the equations given by Kalimeris et al., we calculated the real period $P_{\rm e}$ as a function of the epoch E. The result is shown in Figure 3, where we plotted the difference between $P_{\rm e}$ and the ephemeris period $P_{\rm o}$ in units of 10^{-4} days. As can be seen, the orbital period of V502 Oph exhibits a wavelike variation with a periodicity of 23.0 years and an amplitude of $\Delta P = 1.24 \times 10^{-6}$ days.

3 CONTRACTION OF THE SECONDARY AND MASS TRANSFER

Secular instability of the secondary component of a W UMa type contact binary arises as it obtains the luminosity transferred from the primary component (Lucy & Wilson 1979; Hazlehurst 1985; Wang 1994). Wang (1994) studied the interaction between the secondary and the common convective envelope in contact binaries, and suggested that the two subtypes of W UMa type binaries may be in two different states of thermal relaxation oscillation: in the W-subtypes, the secondary is shrinking; while in the A-subtypes, the secondary is swelling. Therefore, in the W-subtypes the orbital period should be continually decreasing while in the A-subtypes it should be continually increasing. V502 Oph is a W-subtype W UMa type contact binary, so we expect the secular decrease of the orbital period to be accompanied by the contraction of the secondary component. The rate of contraction of the secondary can be calculated from the rate of decrease in the period.

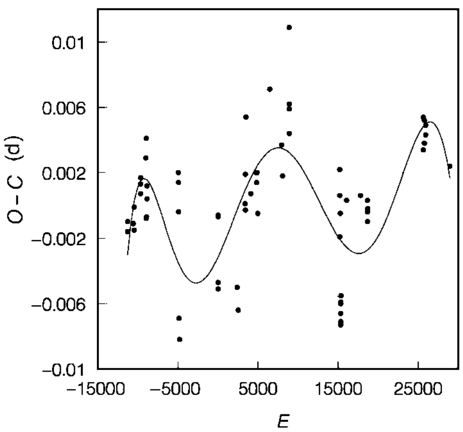

Fig. 2 $O - C$ diagram of the period change for V502 Oph, the numerical values being those shown in Table 1. The curve is fitted to the observations.

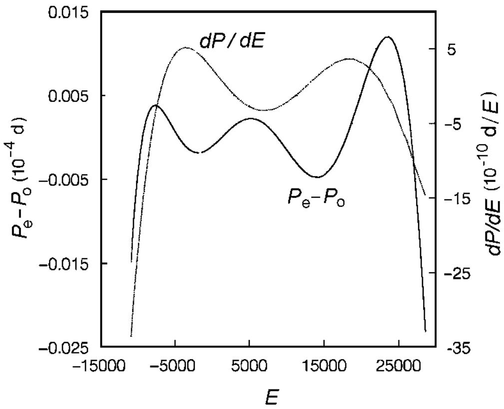

Fig. 3 Differences between the real period $P_{\rm e}$ and the ephemeris period $P_{\rm o}$ for V502 Oph as a function of epochs E (the solid curve) and the period variation rate dP/dE as a function of epochs E.

Kepler's Third Law can be written as

$$A^3 = 74.5P^2M, \tag{3}$$

where A is the separation between the two components in solar radii, P is the orbital period in days and M is the total mass of the two components in solar masses. From the definition of the relative radius of one of the two components, we have

$$A = \frac{R_1 + R_2}{r_1 + r_2}. \tag{4}$$

According to Binnendijk (1970) and Lacy (1977), we have

$$r_1 + r_2 = 0.76 \tag{5}$$

and

$$\frac{R_2}{R_1} = q^{0.92}. \tag{6}$$

Now, we may use the Roche radii as an approximation to the radii of the components of W-subtype systems in shallow contact, thus, inserting Equations (4), (5) and (6) into Equation (3), we have

$$R_2^3\Big(1 + \frac{1}{q^{0.92}}\Big)^3 = 32.7P^2M. \tag{7}$$

Assuming conservation of total mass of the system, we can obtain from Equation (7),

$$\frac{dR_2}{dt} = \frac{21.8PMq^{2.76}}{R_2^2(1+q^{0.92})^3}\frac{dP}{dt} + \frac{0.92R_2}{q(1+q^{0.92})}\frac{dq}{dt}\,. \tag{8}$$

A relation between the mass transfer rate dM/dt and the rate of change of the mass ratio, dq/dt, may be deduced from assuming conservation of the total mass,

$$\frac{dq}{dt} = \frac{(1-q)}{m_1}\frac{dM}{dt}. \tag{9}$$

Table 2 Possible Parameters of the Third Component

i_3	90°	60°	45°	30°	15°
$m_3(M_\odot)$	0.12	0.14	0.17	0.25	0.52
a_3 (AU)	9.9	10.0	10.0	10.2	10.6

According to Pribulla et al. (1999), the mass transfer rate is

$$\frac{dM}{dt} = \frac{qM}{3(1-q^2)}\frac{dP}{dt}. \tag{10}$$

Inserting the Equations (9) and (10) into Equation (8), we obtain

$$\frac{dR_2}{dt} = \Big[\frac{21.8PMq^{2.76}}{R_2^2(1+q^{0.92})^3} + \frac{0.31R_2}{(1+q^{0.92})}\Big]\frac{dP}{dt}. \tag{11}$$

From Equation (11) and adopting the obtained rate of decrease in the orbital period and the parameters given by Maceroni & van't Veer(1996), we find a rate of contraction of the secondary component, dR_2/dt = -2.6×10^{-4} cm s^{-1}, or 83 m yr^{-1}. The mass transfer rate from the primary to the secondary is found to be $dM/dt = 4.28\times10^{-8}\,M_\odot$ yr^{-1}.

4 THE THIRD COMPONENT OF THE SYSTEM

Observations of V502 Oph with the VLA revealed it to be a binary radio source (Hughes & McLean 1984). Since W UMa type systems usually show low radio activity (Rucinski 1995), this may suggest the existence of an optically undetected companion to the eclipsing binary system (Hughes & McLean 1984). The presence of a late-type, third component was in fact noticed in the spectrum of the system by Hendry & Mochnacki (1998). In spite of a large scatter of the $O-C$ values in Figure 2, the short-term wavelike variation in the orbital period of the system is remarkable and could be caused by a light-time effect. A preliminary analysis of the third body orbit gives the following parameters: $P_3(\mathrm{period}) = 8391\pm67$ d, i.e., 23.0 yr; T_0 (time of periastron) = JD2448781±52; A (semiamplitude) $= 0.00365\pm0.00004$ d; e_3 (eccentricity) = 0.12±0.05; and w_3 (length of periastron) = $283.1^\circ\pm3.6^\circ$. These values were obtained together with the new mean linear ephemeris

$$\mathrm{Pri.Min.} = \mathrm{HJD}2439639.9481(3) + 0.45339293(6)E, \tag{12}$$

by the least squares method. The value of the mass function of the third body was found to be $f(m_3) = 4.8\times10^{-4}M_\odot$. Adopting a total mass of the eclipsing pair m_1+m_2 = 1.74 $M_\odot$ (Maceroni & van't Veer 1996) and assuming an inclination of the third body $i_3 = 90^\circ$, we can obtain a lower limit to the mass of the third component, $m_{3,\mathrm{min}} = 0.12\,M_\odot$, with a mean orbital radius $a_{3,\mathrm{min}} = 9.9$ AU. Some parameters of the third component for assuming different values of i_3 are calculated and listed in Table 2. The table shows that the mass of the third component could be from $0.25\,M_\odot$ to $0.50\,M_\odot$ and its orbital radius could be 10.2–10.6 AU.

5 DISCUSSION

The observed long-term decrease in the orbital period of V502 Oph can be explained by a mass transfer rate $\Delta M/dt = 4.28\times10^{-8}M_\odot$. An interesting problem has arisen from the present study, namely, which of the two factors causes the secular decrease in the orbital period of a W-subtype W UMa type system, mass transfer from the primary to secondary, or the contraction of the secondary?

According to Lucy (1976) and Flannery (1976), a zero-age W UMa system should undergo periodic thermal relaxation oscillation (TRO theory) about a state of marginal contact as a result of being unable to achieve thermal equilibrium. Dynamical equilibrium requires the secondary not to be in thermal equilibrium, and then it tries to expand towards equilibrium. This slight expansion causes the secondary to transfer mass to the primary. Conservation of total mass and orbital angular momentum then leads to a slow increase in the orbital period and the separation of the two components, eventually breaking the contact. The mass and energy transfer then ceases and the two components become effectively single, but with radii very different from their equilibrium ones as single stars, the secondary shrinks towards its zero age-main-sequence (ZAMS) radius, while the primary grows, and overflows its Roche lobe before reaching its ZAMS radius. This starts mass transfer from the primary to the secondary, causing the orbital period and the separation of the two stars to decrease again until contact is re-established. Once the contact has been re-established the secondary tries to swell towards its thermal equilibrium radius, and the direction of mass transfer reverses once again and the cycle is repeated. The TRO theory suggests that the mass transfer from the primary to the secondary and the orbital period decreas should occur when the secondary is shrinking towards its ZAMS radius. Long-term decrease of the orbital period of a system is typical for many other W-subtype W UMa contact binaries such as RT LMi (Yang & Liu 2004), FG Hya (Qian & Yang 2005), V781 Tau (Liu & Yang 2000), RW Com (Yang & Liu 2003), V1073 Cyg (Yang & Liu 2000) and CC Com (Yang & Liu 2003). As is well known, the observed continuous orbital period decrease of a W UMa type contact binary can be explained by a mass transfer from the primary to the secondary. According to the TRO theory, the W-subtype W UMa contact binaries are when the secondary component is contracting.

From Equations (10) and (11), we can obtain the following relation between the rate of contraction of the secondary and the mass transfer rate,

$$\frac{dR_2}{dt} = \Big[\frac{65.4Pq^{1.76}(1-q^2)}{R_2^2(1+q^{0.92})^3} + \frac{0.92R_2(1-q^2)}{qM(1+q^{0.92})}\Big]\frac{dM}{dt}. \tag{13}$$

When the secondary is in a state of expansion, the secondary transfers its mass to the primary and the orbital period increases. From an observed period increase rate, one may calculate the rate of expansion of the secondary by Equation (11) and mass transfer rate from the secondary to the primary by Equation (13).

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