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Velocity Curve Studies of Spectroscopic Binary Stars V380 Cygni, V401 Cyg, V523 Cas, V373 Cas and V2388 Oph

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Abstract. Using measured radial velocity data of five double lined spectroscopic binary systems V380 Cygni, V401 Cyg, V523 Cas, V373 Cas and V2388 Oph, we find corresponding orbital and spectroscopic elements via the method introduced by Karami & Mohebi (2007) and Karami & Teimoorinia (2007). Our numerical results are in good agreement with those obtained by others using more traditional methods.

Key words. Stars: binaries: eclipsing—stars: binaries: spectroscopic.

Determining the orbital elements of binary stars helps us to obtain the necessary information such as the mass and the radius of stars which play important roles in the evolution of the stellar structures. Analyzing both the light and the radial velocity curves deducing from the photometric and the spectroscopic observations, respectively, leads to derivation of the orbital parameters. One of the usual methods to analyze the velocity curve is the method of Lehmann-Filhés, see Smart (1990). Here we use the method introduced by Karami & Mohebi (2007) and Karami & Teimoorinia (2007) (hereafter KM2007 and KT2007) for obtaining the orbits of five double-lined spectroscopic binary systems V380 Cygni, V401 Cyg, V523 Cas, V373 Cas and V2388 Oph.

V380 Cygni is a close detached binary with $P = 12.425612$ days. The spectral type is $B1.5II - III$, $B2V$ for the primary and secondary components, respectively. The polar temperature of primary is 24,500 K and for secondary is 23,600 K. The angle of inclination is $80.1 \pm 0.7^\circ$ (Hill & Batten 1984). The V401 Cyg appears to be a rather typical contact system and is a double-lined spectroscopic binary. The orbital period is 0.582714 days (Rucinski *et al.* 2002a, b). V523 Cas is one of the faintest known contact binaries. The spectral type is $K4V$ and the period is $P = 0.233693$ days (Rucinski *et al.* 2003a, b). V373 Cas is known to be a double-lined spectroscopic binary. The primary component is highly evolved and should be close to the Roche limiting surface of periastron. The spectral type of the primary and secondary components is $B0.5II$ and $B4III$, respectively. The mean effective temperature is $T_e = 22{,}000$ and 18,000 for the primary and secondary components. The angle of inclination is $\sim 60^\circ$ with a period of 13.4 days. See Hill & Fisher (1987). V2388 Oph is very close visual binary and has been the subject of many speckle interferometry investigations. The spectral type is W UMa-type with a relatively long period of 0.802 days. The system appears to be one of the most luminous among currently known contact binaries. Orbital inclination angle is 90° (Rucinski *et al.* 2002a, b).

This paper is organized as follows. In section 2, we give a brief review of the method of KM2007 and KT2007. In section 3, the numerical results implemented for the five different binary systems are reported. Section 4 is devoted to conclusions.

1. A brief review of the method of KM2007 and KT2007

The radial velocity of star in a binary system is defined as follows:

$$\mathrm{RV} = V_{cm} + \dot{Z}, \tag{1}$$

where V_{cm} is the radial velocity of the center of mass of system with respect to the sun and

$$\dot{Z} = K[\cos(\theta + \omega) + e\cos\omega], \tag{2}$$

is the radial velocity of star with reference to the center of mass of the binary, see Smart (1990). In equation (2), the dot denotes the time derivative and θ, ω and e are the angular polar coordinate (true anomaly), the longitude of periastron and the eccentricity, respectively. Note that the quantities θ and ω are measured from the periastron point and the spectroscopic reference line (plane of sky), respectively. Also,

$$K = \frac{2\pi}{P}\frac{a\sin i}{\sqrt{1-e^2}}, \tag{3}$$

where P is the period of motion and inclination i is the angle between the line of sight and the normal of the orbital plane.

Following KM2007 and KT2007, one may show that the radial acceleration scaled by the period is obtained as:

$$P\ddot{Z} = \frac{-2\pi K}{(1-e^2)^{3/2}}\sin\left(\cos^{-1}\left(\frac{\dot{Z}}{K} - e\cos\omega\right)\right) \times \left\{1 + e\cos\left(-\omega + \cos^{-1}\left(\frac{\dot{Z}}{K} - e\cos\omega\right)\right)\right\}^2. \tag{4}$$

Equation (4) describes a nonlinear relation, $P\ddot{Z} = P\ddot{Z}(\dot{Z}, K, e, \omega)$, in terms of the orbital elements K, e and ω. Using the nonlinear regression of equation (4), one can estimate the parameters K, e and ω, simultaneously. Also one may show that the adopted spectroscopic elements, i.e., m_p/m_s, $m_p\sin^3 i$ and $m_s\sin^3 i$, are related to the orbital parameters. See KM2007 and KT2007.

2. Numerical results

Here we use the method of KM2007 and KT2007 to derive both the orbital and combined elements for the five different double lined spectroscopic systems V380 Cygni,

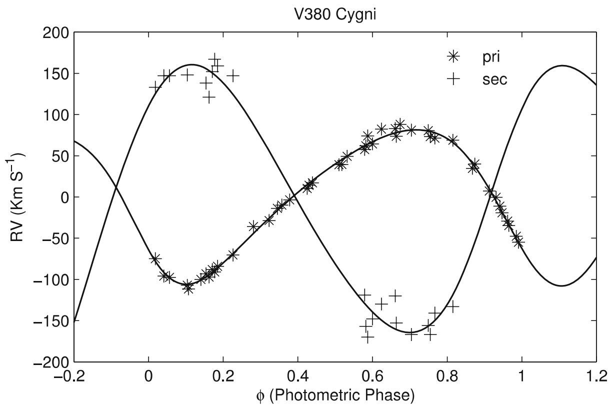

Figure 1. Radial velocities of the primary and secondary components of V380 Cygni plotted against the photometric phase. The observational data belong to Hill & Batten (1984).

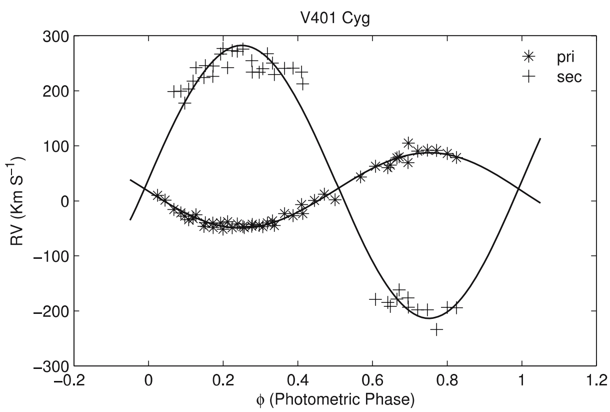

Figure 2. Same as Fig. 1, but for V401 Cyg. The observational data have been derived from Rucinski *et al.* (2002a, b).

V401 Cyg, V523 Cas, V373 Cas and V2388 Oph. Using the measured experimental data for radial velocities of the two components of these systems obtained by Hill & Batten (1984) for V380 Cygni, Rucinski *et al.* (2002a, b) for V401 Cyg and V2388 Oph, Hill & Fisher (1987) for V373 Cas and Rucinski *et al.* (2003a, b) for V523 Cas, the fitted velocity curves are plotted in terms of the photometric phase in Figs. 1–5.

Figures 6–15 show the radial acceleration scaled by the period versus the radial velocity for the primary and secondary components of V380 Cygni, V401 Cyg, V523 Cas, V373 Cas and V2388 Oph, respectively. The solid closed curves are the results of the nonlinear regression of equation (4), which their good coincidence with the measured data yields to derive the optimized parameters K, e and ω. Figures show that also for V401 Cyg, V523 Cas, and V2388 Oph due to having small eccentricities, their radial velocity-acceleration curves display an elliptical shape, while, in contrast for the eccentric systems V380 Cygni and V373 Cas, the acceleration-velocity curve shows some deviation from an ellipse (see Karami & Mohebi 2007).

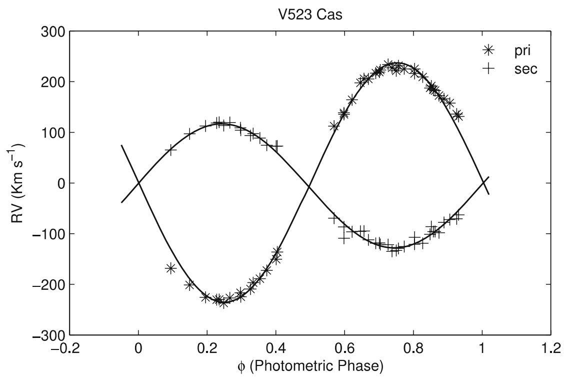

Figure 3. Same as Fig. 1, but for V523 Cas. The observational data belong to Rucinski *et al.* (2003a, b).

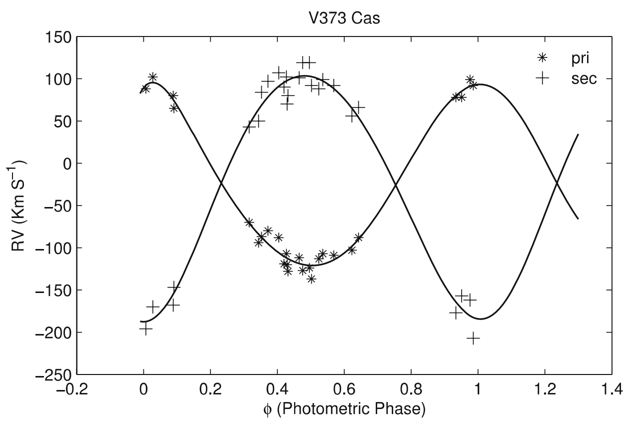

Figure 4. Same as Fig. 1, but for V373 Cas. The observational data belong to Hill & Fisher (1987).

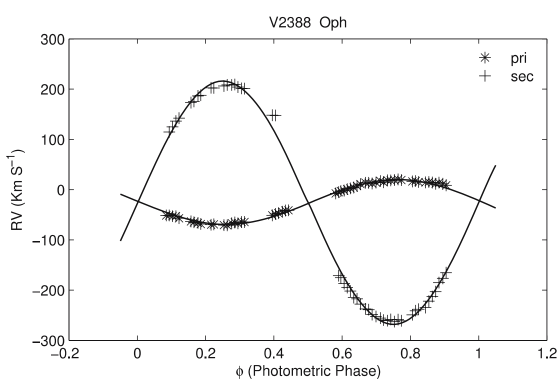

Figure 5. Same as Fig. 1, but for V2388 Oph. The observational data belong to Rucinski *et al.* (2002a, b).

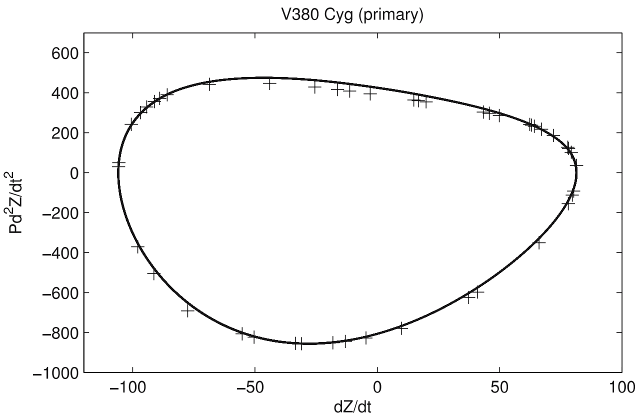

Figure 6. The radial acceleration scaled by the period *versus* the radial velocity of the primary component of V380 Cyg. The solid curve is obtained from the nonlinear regression of equation (14). The plus points are the experimental data.

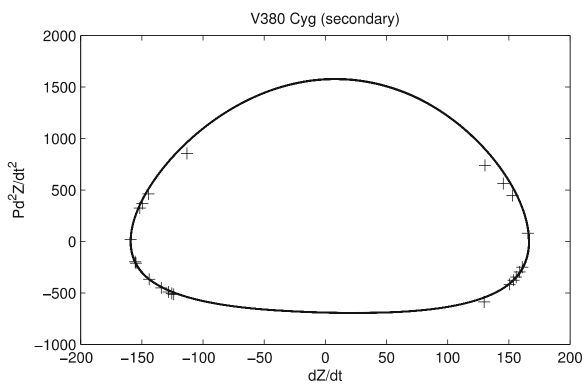

Figure 7. Same as Fig. 6, but for the secondary component of V380 Cyg.

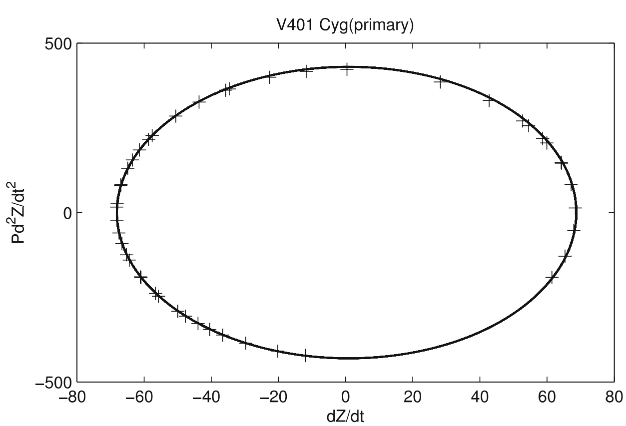

Figure 8. Same as Fig. 6, but for the primary component of V401 Cyg.

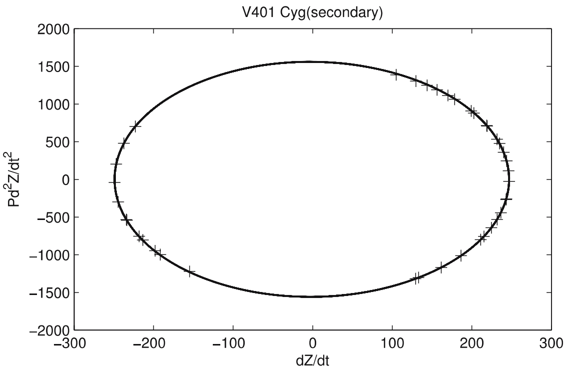

Figure 9. Same as Fig. 6, but for the secondary component of V401 Cyg.

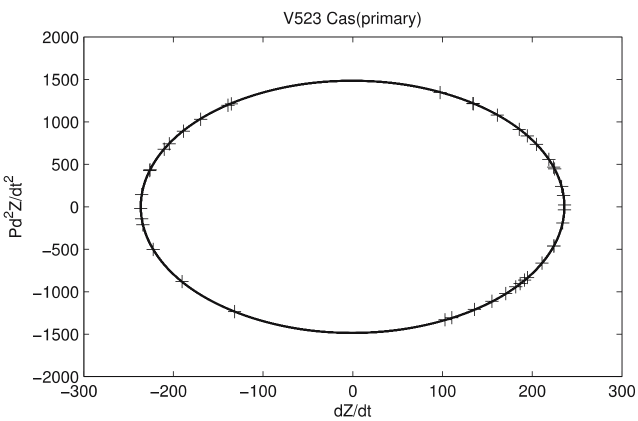

Figure 10. Same as Fig. 6, but for the primary component of V523 Cas.

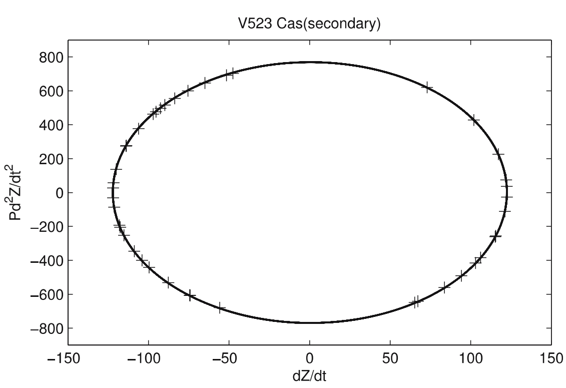

Figure 11. Same as Fig. 6, but for the secondary component of V523 Cas.

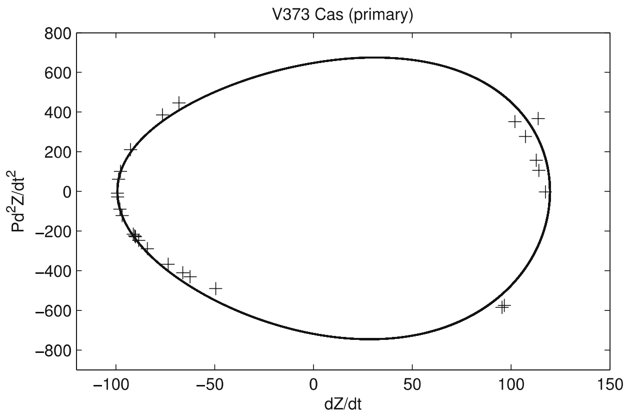

Figure 12. Same as Fig. 6, but for the primary component of V373 Cas.

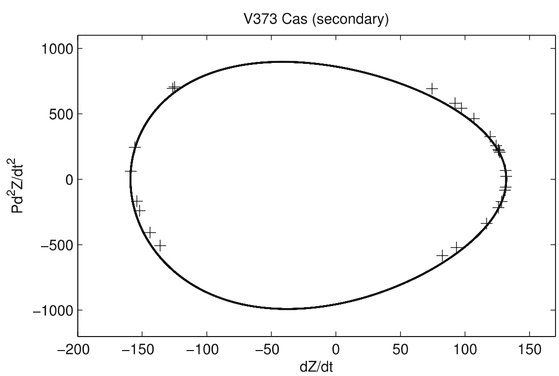

Figure 13. Same as Fig. 6, but for the secondary component of V373 Cas.

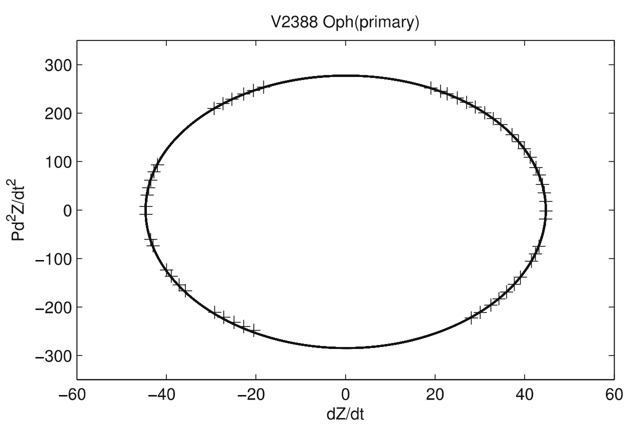

Figure 14. Same as Fig. 6, but for the primary component of V2388 Oph.

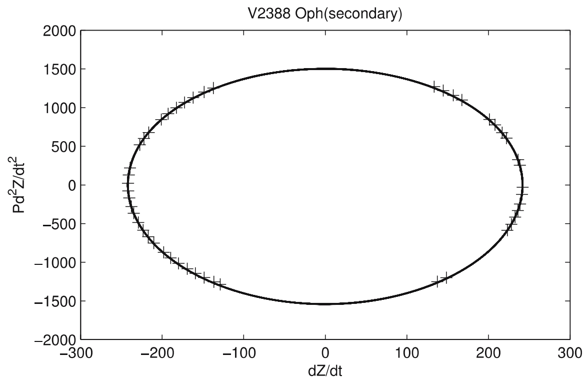

Figure 15. Same as Fig. 6, but for the secondary component of V2388 Oph.

Table 1. Spectroscopic and combined orbit of V380 Cygni.

	This paper	Batten (1960)	Hill & Batten (1984)
Primary			
V_{cm} (km s^{-1})	-2.85 ± 0.23	-2.9 ± 0.8	-0.7 ± 0.7
K_p (km s^{-1})	93.68 ± 0.12	93.4 ± 1.2	92.3 ± 1.1
e	0.204 ± 0.002	0.229 ± 0.013	0.22 ± 0.01
$\omega(^\circ)$	129.7 ± 0.7	128 ± 3.1	127.6 ± 2.8
Secondary			
V_{cm} (km s^{-1})	-2.85 ± 0.23	2.5 ± 6.1	-18 ± 4.7
K_s (km s^{-1})	162.82 ± 0.28	161.6 ± 7	168 ± 5.3
e	$e_s = e_p$	0.23	0.22
$\omega(^\circ)$	276.37 ± 0.33	128.0 (fixed)	127.6 (fixed)
$m_p \sin^3 i / M_\odot$	12.94 ± 0.08	12.4 ± 0.3	12.4 ± 0.3
$m_s \sin^3 i / M_\odot$	7.44 ± 0.04	7.2 ± 0.2	7.1 ± 0.2
$(a_p + a_s) \sin i / R_\odot$	61.64 ± 0.12	60.9 ± 1.7	60.7 ± 2
m_p / m_s	1.74 ± 0.01	1.72 ± 0.05	1.73 ± 0.06

The orbital parameters, K, e and ω, resulting from the nonlinear least squares of equation (4) for V380 Cygni, V401 Cyg, V523 Cas, V373 Cas and V2388 Oph, are tabulated in Tables 1, 2, 3, 4 and 5, respectively. The velocity of the center of mass, $V_{\rm cm}$, is obtained by calculating the areas above and below the radial velocity curve. Where these areas become equal to each other, then the velocity of center of mass is obtained. Tables 1–5 show that the results are in good agreement with those obtained by Hill & Batten (1984) for V380 Cygni, Rucinski *et al.* (2002a, b) for V401 Cyg and V2388 Oph, Rucinski *et al.* (2003a, b) for V523 Cas and Hill & Fisher (1987) for V373 Cas. Note that in Table 1, the absolute value of $V_{\rm cm}$ of V380 Cygni in this paper is not in concord with the result obtained by Hill & Batten (1984) but it is in good agreement with the result of Batten (1960). In a binary

Table 2. Same as Table 1, but for V401 Cyg.

	This paper	Rucinski *et al.* (2002a, b)
Primary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	27.24 ± 0.15	25.53(2.14)
$K_p\,(\mathrm{km\,s^{-1}})$	68.46 ± 0.02	72.23(2.43)
e	$e_p = e_s$	–
$\omega\,(^\circ)$	$w_p = w_s + 180^\circ$	–
Secondary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	27.24 ± 0.15	25.53(2.14)
$K_s\,(\mathrm{km\,s^{-1}})$	247.99 ± 0.02	249.13(4.53)
e	0.0046 ± 0.0001	–
$\omega\,(^\circ)$	180.65 ± 5.21	–
$m_p \sin^3 i/M_\odot$	1.4993 ± 0.0005	–
$m_s \sin^3 i/M_\odot$	0.4139 ± 0.0002	–
$(a_p + a_s) \sin i/R_\odot$	3.643 ± 0.001	–
m_p/m_s	0.276 ± 0.001	0.290(11)
$(m_p + m_s) \sin^3 i/M_\odot$	1.9132 ± 0.0008	2.008(130)

Table 3. Same as Table 1, but for V523 Cas.

	This paper	Rucinski *et al.* (2003a, b)
Primary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	-2.31 ± 0.71	−2.54(0.90)
$K_p\,(\mathrm{km\,s^{-1}})$	236.22 ± 0.04	235.95(1.41)
e	0.0012 ± 0.0002	–
$\omega\,(^\circ)$	189.65 ± 10.61	–
Secondary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	-2.31 ± 0.71	−2.54(0.90)
$K_s\,(\mathrm{km\,s^{-1}})$	122.38 ± 0.02	121.64(1.14)
e	$e_s = e_p$	–
$\omega\,(^\circ)$	$w_s = w_p - 180^\circ$	–
$m_p \sin^3 i/M_\odot$	0.381 ± 0.002	–
$m_s \sin^3 i/M_\odot$	0.7355 ± 0.0004	–
$(a_p + a_s) \sin i/R_\odot$	1.6557 ± 0.0003	–
m_p/m_s	0.5181 ± 0.0002	0.516(7)
$(m_p + m_s) \sin^3 i/M_\odot$	1.117 ± 0.001	1.11(24)

system, the V_{cm} of the two components should be the same. In Table 1, there is another difference which is related to ω_s. Since we did not fix it, the method derives it freely.

Table 4. Same as Table 1, but for V373 Cas.

	This paper	Hill & Fisher (1987)
Primary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	-25.14 ± 0.76	-24.5 ± 2
$K_p\,(\mathrm{km\,s^{-1}})$	109.52 ± 0.22	106.7 ± 2.7
e	$e_p = e_s$	–
$\omega\,(^\circ)$	$w_p = w_s + 180^\circ$	–
Secondary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	-25.14 ± 0.76	–
$K_s\,(\mathrm{km\,s^{-1}})$	145.53 ± 0.02	–
e	0.0972 ± 0.0002	–
$\omega\,(^\circ)$	164.54 ± 0.27	–
$m_p \sin^3 i / M_\odot$	12.98 ± 0.03	12.6 ± 0.2
$m_s \sin^3 i / M_\odot$	9.77 ± 0.04	9.3 ± 0.2
$(a_p + a_s) \sin i / R_\odot$	67.305 ± 0.064	66.1 ± 0.9
m_p / m_s	1.33 ± 0.03	1.35 ± 0.04

Table 5. Same as Table 1, but for V2388 Oph.

	This paper	Rucinski *et al.* (2002a, b)
Primary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	-25.35 ± 0.88	$-25.88(0.52)$
$K_p\,(\mathrm{km\,s^{-1}})$	44.71 ± 0.01	$44.62(0.48)$
e	0.006 ± 0.001	–
$\omega\,(^\circ)$	275.62 ± 2.09	–
Secondary		
$V_{cm}\,(\mathrm{km\,s^{-1}})$	-25.35 ± 0.88	$-25.88(0.52)$
$K_s\,(\mathrm{km\,s^{-1}})$	241.99 ± 0.03	$240.22(0.98)$
e	$e_s = e_p$	–
$\omega\,(^\circ)$	$w_s = w_p - 180^\circ$	–
$m_p \sin^3 i / M_\odot$	1.653 ± 0.001	–
$m_s \sin^3 i / M_\odot$	0.3055 ± 0.0001	–
$(a_p + a_s) \sin i / R_\odot$	4.545 ± 0.001	–
m_p / m_s	0.184 ± 0.001	$0.186(2)$
$(m_p + m_s) \sin^3 i / M_\odot$	1.959 ± 0.001	$1.926(30)$

The combined spectroscopic elements including $m_p \sin^3 i$, $m_s \sin^3 i$, $(a_p + a_s) \sin i$ and m_p/m_s obtaining from the estimated parameters K, e and ω for the five systems are tabulated in Tables 1, 2, 3, 4 and 5 and show that our results are in good agreement with the those obtained by Hill & Batten (1984) for V380 Cygni, Rucinski *et al.* (2002a, b) for V401 Cyg and V2388 Oph, Rucinski *et al.* (2003a, b) for V523 Cas and Hill & Fisher (1987) for V373 Cas, respectively.

3. Conclusions

Using the measured experimental data for radial velocities of V380 Cygni, V401 Cyg, V523 Cas, V373 Cas and V2388 Oph obtained by Hill & Batten (1984), Rucinski *et al.* (2002a, b), Rucinski *et al.* (2003a, b) and Hill & Fisher (1987) respectively, we find the orbital elements of these systems by the method of KM2007 and KT2007. Our numerical calculations show that the results obtained for both the orbital elements and the combined spectroscopic parameters are in good agreement with the those obtained by others using more traditional methods. In a subsequent paper we intend to study the other different systems.

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