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Velocity curve analysis of spectroscopic binary stars EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni by nonlinear regression

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Abstract

Using measured radial velocity data of five double-lined spectroscopic binary systems EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni, we find corresponding orbital and spectroscopic elements via the method introduced by Karami & Teimoorinia and Karami & Mohebi. Our numerical results are in good agreement with those obtained by others using more traditional methods.

Keywords: stars, binaries, eclipsing – stars, binaries, spectroscopic

1. Introduction

Determining the orbital elements of binary stars helps us to obtain fundamental information, such as the masses and radii of individual stars, that has an important role in understanding the present state and evolution of many interesting stellar objects. Analysis of both light and radial velocity (hereafter RV) curves, derived from photometric and spectroscopic observations, respectively, yields a complete set of basic absolute parameters. One historically well-known method to analyze the RV curve is that of Lehmann-Filhés [3]. In the present paper we use the method introduced by Karami & Teimoorinia (=KT) [1] and Karami & Mohebi (=KM) [2], to obtain orbital parameters of the five double-lined spectroscopic binary systems: EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni. Our aim is to show the validity of our new method to a wide range of different types of binary.

The EQ Tau is a close binary system. The spectral type is G2 with a period of P=0.341348 days [4]. V376 And is a contact binary of W UMa-type. The spectral type of the binary is A4V.

The relatively long period, 0.799 days, is consistent with the spectral type [4]. V776 Cas is a contact, A-type system of a very small mass ratio due to a low orbital inclination. The spectral type is F2V and the orbital period is 0.440413 days [4]. V2377 Oph is a fairly uncomplicated W-type contact binary. The spectral type is G0/1V and the orbital period is 0.425401 days [5]. 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 24500K and for secondary is 23600K. The angle of inclination is $80.1 \pm 0.7^{\circ}$ [6].

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

2. A brief review on the method of KT and KM

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

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

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

$$\dot{Z}=K\left(cos\left(\theta+\omega\right)+ecos\omega\right), \tag{2}$$

is the radial velocity of the star with respect to the center of mass of the binary [3]. In eq. (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

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

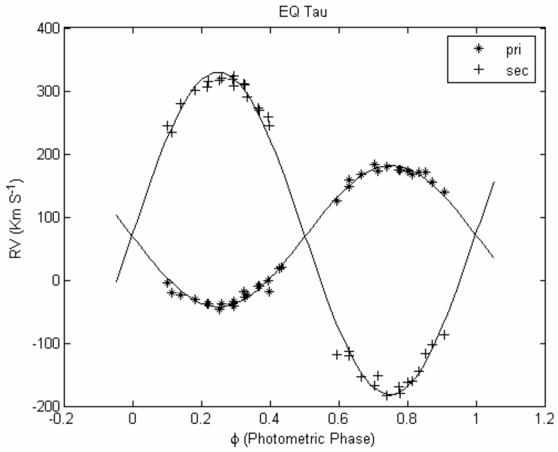

Figure 1. Radial velocities of the primary and secondary components of EQ Tau plotted against the photometric phase. The observational data have been derived from Rucinski et al. [4].

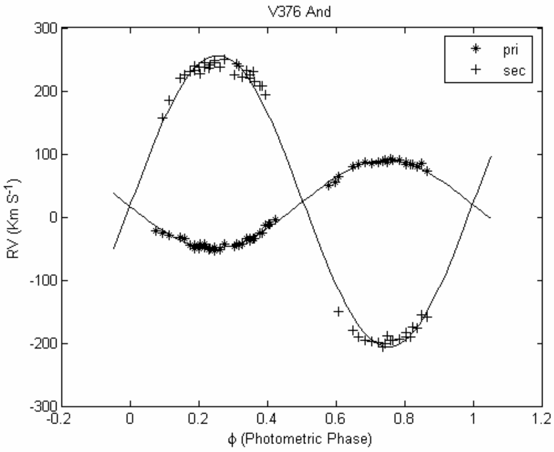

Figure 2. Same as figure 1, for V376 And. The observational data have been derived from Rucinski et al. [4].

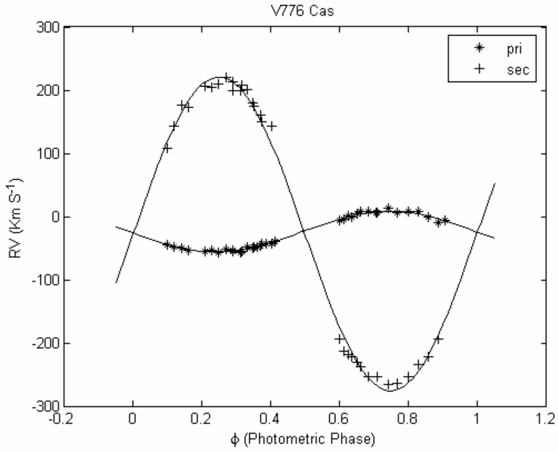

Figure 3. Same as figure 1, for V776 Cas. The observational data have been derived from Rucinski et al. [4].

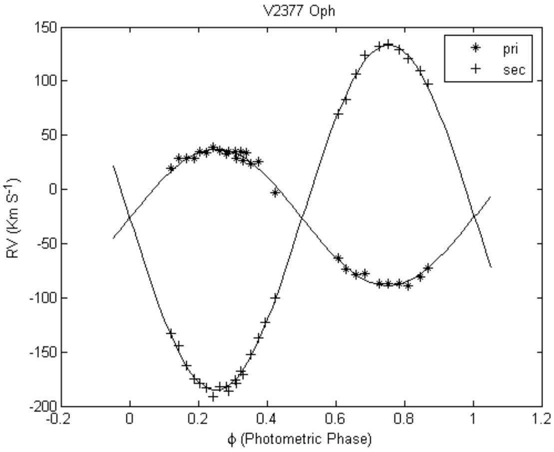

Figure 4. Same as figure 1, for V2377 Oph. The observational data have been derived from Lu et al. [5].

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 KT and KM, one may show that the radial acceleration scaled by the period is obtained as

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

Eq. (4) describes a nonlinear relation, $P\ddot{Z} = P\ddot{Z}$ ($\dot{Z}$, K, e, ω), in terms of the orbital elements K, e and ω. Using the nonlinear regression of eq. (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 [1].

3. Numerical results

Here we use the method of KT and KM to derive both the orbital and combined elements for the five different double-lined spectroscopic systems EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni. Using measured radial velocity data of the two components of these systems obtained by Rucinski et al. [4] for EQ Tau, V376 And, V776 Cas, Lu et al. [5] for V2377 Oph and Hill & Batten [6] for V380 Cygni, the fitted velocity curves are plotted in terms of the photometric phase in figures. 1, 2, 3, 4 and 5.

Figures 6 to 15 show the radial acceleration scaled by the period versus the radial velocity for the primary and secondary components of EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni, respectively. The solid closed curves are results obtained from the non-linear regression of eq. (4), which their good coincidence

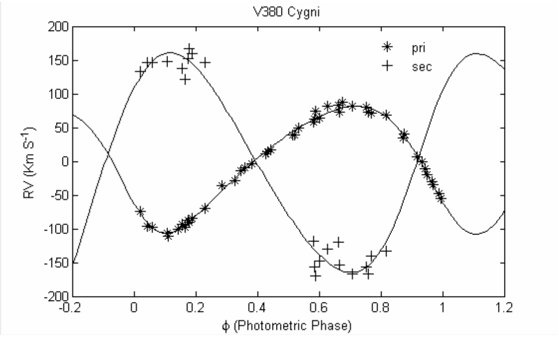

Figure 5. Same as figure 1, for V380 Cygni. The observational data have been derived from Hill & Batten [6].

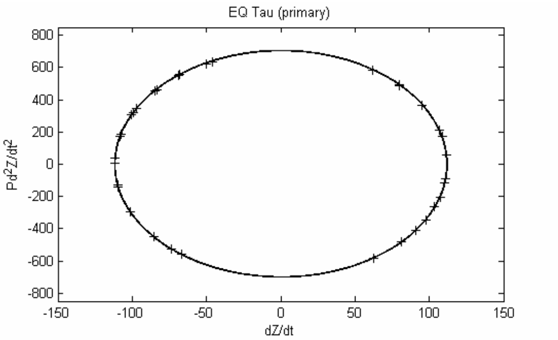

Figure 6. The radial acceleration scaled by the period *versus* the radial velocity of the primary component of EQ Tau. The solid curve is obtained from the nonlinear regression of equation (4). The plus points are the experimental data.

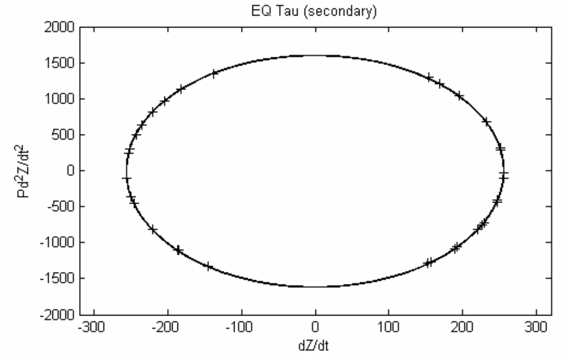

Figure 7. Same as figure 6, for the secondary component of EQ Tau.

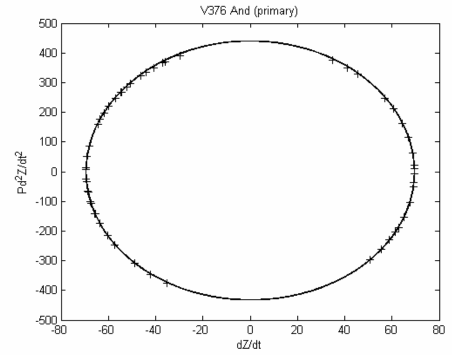

Figure 8. Same as figure 6, for the primary component of V376 And.

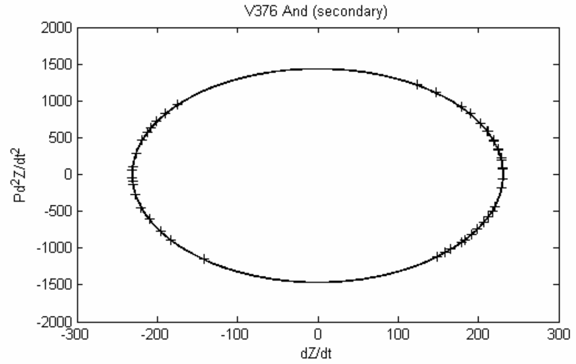

Figure 9. Same as figure 6, for the secondary component of V376 And.

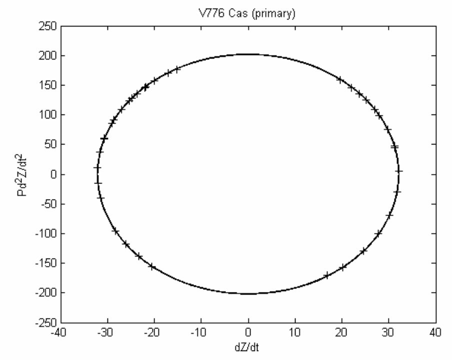

Figure 10. Same as figure 6, for the primary component of V776 Cas.

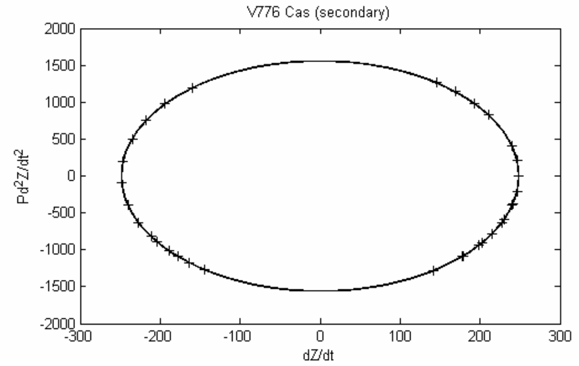

Figure 11. Same as figure 6, for the secondary component of V776 Cas.

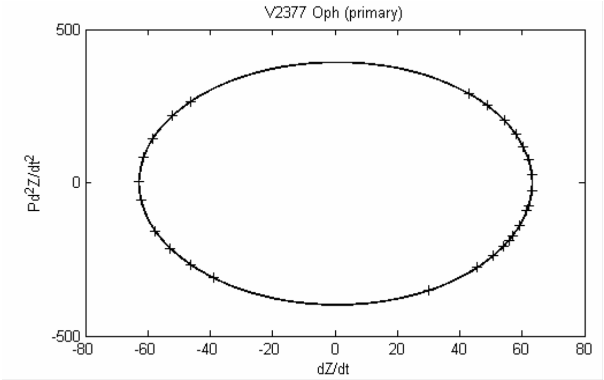

Figure 12. Same as figure 6, for the primary component of V2377 Oph.

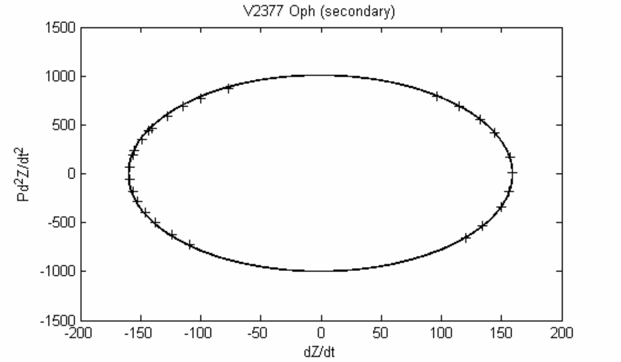

Figure 13. Same as figure 6, for the secondary component of V2377 Oph.

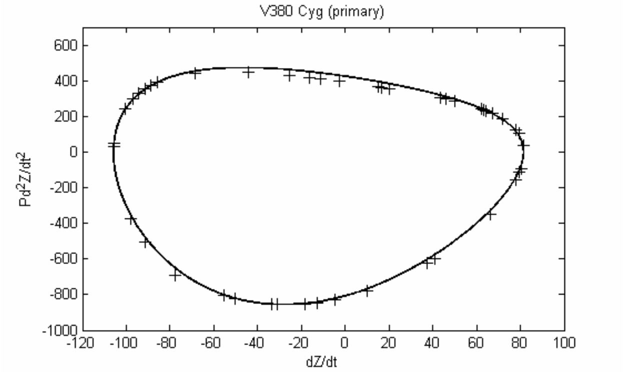

Figure 14. Same as figure 6, for the primary component of V380 Cygni.

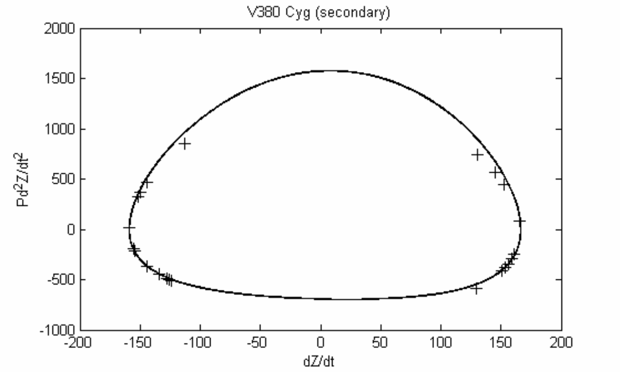

Figure 15. Same as figure 6, for the secondary component of V380 Cygni.

Table 1. Spectroscopic and combined orbit of EQ Tau.

EQ Tau	This paper	Rucinski et al. [4]
Primary		
$V_{cm}\left(\text{kms}^{-\backslash}\right)$	71.44 ± 0.34	71.95 (1.22)
$K_p\left(\text{kms}^{-\backslash}\right)$	111.871 ± 0.002	112.41 (1.43)
e	0.0027 ± 0.0001	-
$\omega(^\circ)$	292.397 ± 0.685	-
Secondary		
$V_{cm}\left(\text{kms}^{-1}\right)$	71.44 ± 0.34	71.95 (1.22)
$K_s\left(\text{kms}^{-\backslash}\right)$	256.21 ± 0.03	254.38 (2.42)
e	$e_s = e_p$	-
$\omega(^\circ)$	$\omega_s = \omega_p - 180^\circ$	-
$m_p sin^3 i / M_\otimes$	1.2276 ± 0.0004	-
$m_s sin^3 i / M_\otimes$	0.5360 ± 0.0001	-
$\left(m_p + m_s\right) sin^3 i / M_\otimes$	1.7636 ± 0.0005	1.749 (55)
m_s / m_p	0.437 ± 0.001	0.442 (7)

with the measured data yields to derive the optimized parameters K, e and ω. Figures show that also for the selected systems due to having small eccentricities, their radial velocity-acceleration curves are elliptical. But in contrast for an eccentric system, the acceleration-velocity curve shows some deviation from an ellipse [7,8].

The orbital parameters, K, e and ω, obtained from the non-linear least squares of eq. (4) for EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni are tabulated in Tables 1, 2, 3, 4 and 5, respectively. The velocity of the center of mass, V_{cm}, is obtained by calculating the areas above and below of the radial velocity curve. Where these areas become equal to each other, the velocity of center of mass is obtained. Tables 1, 2, 3, 4 and 5 show that the results are in good accordance with the those obtained by Rucinski et al. [4] for EQ Tau, V376 And, V776 Cas, Lu et al. [5] for V2377 Oph and Hill & Batten [6] for V380 Cygni.

The combined spectroscopic elements including $m_p sin^3 i / M_\otimes$, $m_s sin^3 i / M_\otimes$, $\left(a_p + a_s\right) sin i / R_\otimes$ and m_s / m_p obtained from the estimated parameters K, e and ω for the five systems are tabulated in Tables 1, 2, 3, 4 and 5 show that our results are in good agreement with those obtained by Rucinski et al. [4] for EQ Tau, V376 And, V776 Cas, Lu et al. [5] for V2377 Oph and Hill & Batten [6] for V380

Table 2. Same as Table 1, for V376 And.

V376 And	This paper	Rucinski et al. [4]
Primary		
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	22.77 ± 0.52	22.83 (0.89)
$K_p\left(\mathrm{kms}^{-1}\right)$	69.482 ± 0.001	70.00 (0.67)
e	0.0049 ± 0.0001	-
$\omega(^\circ)$	274.797 ± 0.194	-
Secondary		
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	22.77 ± 0.52	22.83 (0.89)
$K_s\left(\mathrm{kms}^{-1}\right)$	231.03 ± 0.02	229.67 (1.78)
e	$e_s = e_p$	-
$\omega(^\circ)$	$\omega_s = \omega_p - 180^\circ$	-
$m_p sin^3 i / M_{\otimes}$	1.7264 ± 0.0003	-
$m_s sin^3 i / M_{\otimes}$	0.5192 ± 0.0001	-
$\left(m_p + m_s\right) sin^3 i / M_{\otimes}$	2.2456 ± 0.0004	2.232 (55)
m_s / m_p	0.3007 ± 0.0001	0.305 (5)

Table 3. Same as Table 1, for V776 Cas.

V776 Cas	This paper	Rucinski et al. [4]
Primary		
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	-25.79 ± 0.89	-24.71 (1.11)
$K_p\left(\mathrm{kms}^{-1}\right)$	32.13 ± 0.02	31.97 (0.64)
e	0.0003 ± 0.0001	-
$\omega(^\circ)$	287.197 ± 3.444	-
Secondary		
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	-25.79 ± 0.89	-24.71 (1.11)
$K_s\left(\mathrm{kms}^{-1}\right)$	248.34 ± 0.02	245.31 (1.83)
e	$e_s = e_p$	-
$\omega(^\circ)$	$\omega_s = \omega_p - 180^\circ$	-
$m_p sin^3 i / M_{\otimes}$	0.8913 ± 0.0003	-
$m_s sin^3 i / M_{\otimes}$	0.1153 ± 0.0001	-
$\left(m_p + m_s\right) sin^3 i / M_{\otimes}$	1.006 ± 0.004	0.975 (26)
m_s / m_p	0.1294 ± 0.0001	0.130 (4)

Table 4. Same as Table 1, for V2377 Oph.

V2377 Oph	This paper	Lu et al. [5]
Primary		
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	-25.91 ±0.26	-25.79 (03.8)
$K_p\left(\mathrm{kms}^{-1}\right)$	63.003 ± 0.003	62.99 (0.62)
e	0.0044 ± 0.0001	-
$\omega(^\circ)$	44.57 ± 0.94	-
Secondary		
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	-25.91 ±0.26	-25.79 (03.8)
$K_s\left(\mathrm{kms}^{-1}\right)$	159.78 ± 0.02	159.64 (0.70)
e	$e_s = e_p$	-
$\omega(^\circ)$	$\omega_s = \omega_p + 180^\circ$	-
$m_p sin^3 i / M_{\otimes}$	0.3496 ± 0.0001	-
$m_s sin^3 i / M_{\otimes}$	0.13782 ± 0.00003	-
$\left(m_p + m_s\right) sin^3 i / M_{\otimes}$	0.4874 ± 0.0001	0.487 (9)
m_s / m_p	0.3942 ± 0.0001	0.395 (12)

Table 5. Same as Table 1 for V380 Cygni.

V380 Cygni	This paper	Batten [9]	Hill & Batten [6]
Primary			
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	-2.85 ±0.23	-2.9 ±0.8	-0.7 ±0.7
$K_p\left(\mathrm{kms}^{-1}\right)$	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			
$V_{cm}\left(\mathrm{kms}^{-1}\right)$	-2.85 ±0.23	2.5 ± 6.1	-18 ±4.7
$K_s\left(\mathrm{kms}^{-1}\right)$	162.82 ± 0.28	161.6 ± 7	168 ± 5.3
e	$e_s = e_p$	0.23 (fixed)	0.22 (fixed)
$\omega(^\circ)$	276.37 ± 0.33	128.0 (fixed)	127.6 (fixed)
$m_p sin^3 i / M_{\otimes}$	12.94 ± 0.08	12.4 ± 0.3	12.4 ± 0.3
$m_s sin^3 i / M_{\otimes}$	7.44 ± 0.04	7.2 ± 0.2	7.1 ± 0.2
$\left(a_p + a_s\right) sin i / R_{\otimes}$	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

4. Conclusions

Using the measured experimental data for radial velocities of EQ Tau, V376 And, V776 Cas, V2377 Oph and V380 Cygni obtained by Rucinski et al. [4], Lu et al. [5] and Hill & Batten [6], respectively, we find the orbital elements of these systems by the method of KT and KM. Our numerical calculations show that the results obtained for both the orbital elements and the combined spectroscopic parameters are in good agreement with those obtained by others using more traditional methods. In a subsequent paper we intend to study the other different systems.

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