Radial Velocity Studies of Close Binary Stars. XIV[1]

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ABSTRACT

Radial-velocity measurements and sine-curve fits to the orbital radial velocity variations are presented for ten close binary systems: TZ Boo, VW Boo, EL Boo, VZ CVn, GK Cep, RW Com, V2610 Oph, V1387 Ori, AU Ser, and FT UMa. Our spectroscopy revealed two quadruple systems, TZ Boo and V2610 Oph, while three stars showing small photometric amplitudes, EL Boo, V1387 Ori, and FT UMa, were found to be triple systems. GK Cep is close binary with a faint third component.

While most of the studied eclipsing systems are contact binaries, VZ CVn and GK Cep are detached or semi-detached double-lined binaries, and EL Boo, V1387 Ori and FT UMa are close binaries of uncertain binary type. The large fraction of triple

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and quadruple systems found in this sample supports the hypothesis of formation of close binaries in multiple stellar systems; it also demonstrates that low photometric amplitude binaries are a fertile ground for further discoveries of multiple systems.

Subject headings: stars: close binaries - stars: eclipsing binaries – stars: variable stars

1. INTRODUCTION

This paper is a continuation of a series of papers (Papers I – XIII) of radial-velocity studies of close binary stars and presents data for the thirteenth group of ten close binary stars observed at the David Dunlap Observatory (DDO). Because of the closure of the observatory, it is most likely the last paper which retains the usual format of 10 new orbits per paper; the last Paper XV will conclude the series with results for partly covered systems and for variable stars which were found not to be binaries. For full references to the previous papers, see the last paper by Rucinski et al. (2008, Paper XIII); for technical details and conventions, for preliminary estimates of uncertainties, and for a description of the broadening functions (BFs) technique, see the interim summary paper Rucinski (2002, Paper VII). The DDO studies have used the efficient program of Pych (2004) for removal of cosmic rays from 2-D images.

All data used in the present paper were obtained using the broadening functions extracted from the region of the Mg I triplet at 5184 Å, as in most of the previous papers, using the new 2160 lines/mm grating acquired at DDO in August 2005. The radial-velocity (hereafter RV) observations reported in this paper have been collected between May 2006 and the memorable day of July 2, 2008 when the David Dunlap Observatory ceased to operate. The ranges of dates for individual systems can be found in Table 1; for TZ Boo, where we used the smoothed BFs, the dates are in Table 3 giving RVs for the companion of the short-period binary.

Throughout our program, selection of the targets was quasi-random: At a given time, we observed a few dozen close binary systems with periods usually shorter than one day, brighter than $10-11$ magnitude and with declinations $> -20°$; we published the results in groups of ten systems as soon as reasonable orbital elements were obtained from measurements evenly distributed in orbital phases.

Among the present targets, three targets, AU Ser, VW Boo and VZ CVn, have had reliable radial velocity orbits previously published. In addition, EL Boo and FT UMa were originally classified as pulsating variables while V1387 Ori does not have any ground-based photometry, but only Hipparcos data. More details are given in Section 2 in the descriptions of the individual stars.

The RVs for the short period binaries reported in this paper were determined by fitting the

[1]Based on the data obtained at the David Dunlap Observatory, University of Toronto.

double rotational profiles to the extracted BFs, as explained in Pribulla et al. (2006). Similarly as in our previous papers dealing with multiple systems (here the six cases of TZ Boo, EL Boo, GK Cep, V2610 Oph, V1387 Ori, and FT UMa), the RVs for the eclipsing pair were obtained after removal of the slowly rotating components, as was described most recently in Rucinski et al. (2008). In the case of GK Cep, where the third component is faint and not well visible in all spectra, its average profile was subtracted before the binary star analysis.

As in other papers of this series, whenever possible, we estimated spectral types of the program stars using new classification spectra centered at 4200 or 4400 Å. Good quality, multiple classification spectra were obtained before the closure of the observatory only for EL Boo, VZ CVn, GK Cep, V1387 Ori, and FT UMa; for the remaining targets the classification spectra were obtained only once and generally poorer so that the spectral types are less reliable. The spectral types were compared with the mean $(B-V)$ color indices usually taken from the Tycho-2 catalog (Høg et al. 2000) and the photometric estimates of the spectral types using the relations of Bessell (1979). In this paper we also made use of infrared colors determined from the 2μ All Sky Survey (2MASS, Skrut et al. (2006)). Especially useful is the $J-K$ color index, which is monotonically rising from the early spectral types to about M0V (Cox 2000). This infrared color is less affected by the interstellar absorption than the $B-V$ index. Parallaxes cited throughout the paper were adopted from the new reduction of the Hipparcos raw data (van Leeuwen 2007) which supersedes the original reductions (ESA 1997).

This paper is structured in a way similar to that of previous papers, in that most of the data for the observed binaries are in two tables consisting of the RV measurements in Table 1 and of their preliminary sine-curve solutions in Table 2. Radial velocities and the corresponding spectroscopic orbits for all ten systems are shown in phase diagrams in Figures 1 – 3. The measured RV's are listed in Table 1. Table 2 contains also our new spectral classifications of the program objects. Section 2 of the paper contains summaries of previous studies for individual systems and comments on the new data. Examples of BFs of individual systems extracted from spectra observed close to quadratures are shown in Fig. 4.

The data in Table 2 are organized in the same manner as in the previous papers of this series. In addition to the parameters of spectroscopic orbits, the table provides information about the relation between the spectroscopically observed upper conjunction of the more massive component, T_0 (not necessarily the primary eclipse) and the recent photometric determinations of the primary minimum in the form of the $O-C$ deviations for the number of elapsed periods E. The reference ephemerides were taken from various sources: for EL Boo, and FT UMa, we doubled the Hipparcos period and shifted the instant of the maximum by $0.25P$; for V1387 Ori we used the Hipparcos ephemeris; and for V2610 Oph, it has been adopted from Wils & Dworak (2003). For the rest of the systems, the ephemerides given in the on-line version of "An Atlas of O-C diagrams of eclipsing binary stars"[2] (Kreiner 2004) were adopted. Because the on-line ephemerides are frequently updated, we give

[2]http://www.as.wsp.krakow.pl/ephem/

those used for the computation of the $O - C$ residuals below Table 2 (the status as of July 2008). The deeper eclipse in W-type contact binary systems corresponds to the lower conjunction of the more massive component; in such cases the epoch in Table 2 is a half-integer number.

2. RESULTS FOR INDIVIDUAL SYSTEMS

2.1. TZ Boo

TZ Boo (HIP 74061, BD+40°2857) is a well known contact binary discovered by Guthnick & Prager (1926). The system is unusual: It depths of the minima change, switching between the A and W-type light curve (LC) types and the LC shows very large variations of its shape (Hoffmann 1978a). In spite of total eclipses, the large variability of the LC made a reliable photometric solution of the system impossible; thus, there exists no modern LC synthesis solution assuming the Roche model. The orbital period of the system is also variable. The continuous orbital period decrease of TZ Boo, accompanied by wave-like variations was interpreted by Pribulla & Rucinski (2006) in terms of light-time effect caused by a third component on a 34 years orbit. But an adaptive optics search for close visual companions to contact binaries (Rucinski et al. 2007) did not show any close companion to TZ Boo.

TZ Boo is a very difficult system for spectroscopic studies. Chang (1948) found that spectral lines do not double in quadratures, but noticed that the measured RV of the system varies in the range of about 60 km s^{-1}. The author did not find any correlation between the RV and the predicted photometric orbital phase. Later Hoffmann (1978b) tried to interpret the results of Chang (1948) by fast systemic velocity changes induced by a third body on a 10.31 day orbit. Hoffmann (1978b) added a new set of spectroscopic observations to the older observations, but could not solve the problem. The author estimated mass ratio as $q = 0.2$ (which in fact is identical to our current result) and interpreted the inexplicable behavior of the profiles by the enhanced activity in the system. Finally, McLean & Hilditch (1983) obtained the first, seemingly fully satisfactory spectroscopic orbit of the system: $V_0 = -36.7$ km s^{-1}, $K_1 = 33 \pm 7$ km s^{-1}, and $K_2 = 249 \pm 38$ km s^{-1} resulting in $q = 0.13 \pm 0.03$. The authors did not notice any third component in the profile which – as we suspect now – was probably blended with the primary component; this makes this spectroscopic orbit solution to be of a limited use.

Our spectroscopy shows that TZ Boo is either a triple system with a third body on a 9.48 day orbit or – more likely – a quadruple system consisting of a contact eclipsing binary and a second, non-eclipsing, single-line binary with the period of 9.48 days. The system was found to be fairly difficult for the DDO telescope due to the short orbital period of the contact binary, $P_{12} = 0.297$ days, its relatively low brightness, $V_{max} = 10.4$, and the obviously composite spectra. To determine reliable parameters, we took as many as 215 spectra spanning more than two years. First, we fitted a three-Gaussian model to each BF and subtracted the third component contribution. The BFs of the contact binary were rather noisy so we decided to smooth and rebin them with the 0.01 step in the orbital phase. The resulting mass ratio, $q = 0.207 \pm 0.005$, is rather small and inconsistent with the large photometric amplitude of the system (0.59 mag in the General Catalogue of Variable Stars, 0.39 mag in Hipparcos photometry, and 0.35 mag according to Fig. 1 of Schaub (1990)). It is possible that the pronounced LC changes and the W/A-type switching are caused by the activity and/or by relatively slow (and of unexplained nature) pulsations of the third component. Also, a possibility of eclipses in the second binary cannot be ruled out. The changes of the LC amplitude (very well seen in Fig. 2 of Awadalla et al. (2006)) could also be caused by significant long-term brightness changes of the third/fourth component. Another explanation is the precession of the eclipsing-pair orbit, but this is less likely because all LCs have shown total eclipses. The system deserves a dedicated study of the light curve changes in a standardized photometric system to relate the relative LC shape changes to its overall brightness.

The orbit of the second (or outer) binary is circular – which is rather surprising for the long orbital period – and is very well defined with $K_3 = 43.15 \pm 0.14$ km s^{-1} (see Fig. 4 and Table 4). The center-of-mass velocities of the contact binary, $V_0^{12} = -46.57 \pm 0.90$ km s^{-1}, and the non-eclipsing binary, $V_0^{34} = -54.64 \pm 0.12$ km s^{-1} are different, indicating a slow orbital motion. The light contribution of the third component around the quadratures of the contact binary is $L_3/(L_1 + L_2) = 0.28 \pm 0.05$. Because of the well recognized problems with a proper continuum rectification of the spectra of combined broad and sharp line components (Rucinski & Pribulla 2008), we regard this estimate of the third light as an upper limit.

The RVs of the contact pair show a rather large point-to-point scatter of about 10 km s^{-1}. The scatter does not decrease under an assumption that TZ Boo is a tight triple system and that the contact binary revolves around the common center of mass with the third component. Although with the present data we cannot fully exclude this possibility, it is much more probable that TZ Boo is a hierarchic quadruple consisting of two binaries revolving in 34-year orbit, as indicated by the cyclic period changes.

2MASS infrared color, $J - K = 0.454$ corresponds to G7V spectral type. Our single spectral classification spectrum indicates a range of admissible spectral types between late F and G5. The Hipparcos parallax, $\pi = 6.63 \pm 1.54$ mas is of a limited value.

2.2. VW Boo

VW Boo (HIP 69826, GSC 908 1170) is a short-period ($P = 0.3422$ days) close binary which was discovered by Hoffmeister (1935). Binnendijk (1973) obtained and analysed BV photoelectric photometry of the system, which shows that components have rather different temperatures for such a close binary. Therefore, VW Boo belongs to a small group of short-period contact binaries having poor thermal contact (others are e.g., CN And, FT Lup, V432 Per or AU Ser).

Rainger et al. (1990) re-analyzed LCs of Binnendijk (1973) and obtained the first spectroscopic data for the system. The authors interpreted the LCs by a contact configuration with a hot spot on the secondary component, about 640 K hotter than the surrounding photosphere. The CCF analysis of the spectra yielded the following spectroscopic elements for VW Boo: $K_1 = 99.2 \pm 2.1$ km s^{-1}, $K_2 = 230.1 \pm 5.4$ km s^{-1} (resulting in $q = 0.428 \pm 0.030$), $V_{01} = 21.5 \pm 1.5$ km s^{-1} and $V_{02} = 26.3 \pm 4.2$ km s^{-1} (determined separately for the two components). Independent observations of Hrivnak (1993) resulted in $q = 0.45$ and the total projected mass of $(M_1 + M_2)\sin^3 i = 1.34$ M$_\odot$.

Our spectroscopic elements (Table 2) are in a good accord with the results of Rainger et al. (1990). However, the extracted BFs do not show any irregularities which could indicate the presence of either hot or cool spots on the surface. The rotational profiles of the components in BFs taken at the orbital quadratures suggest that system is either in marginal physical contact or is a detached one.

Although the system was observed by Hipparcos, its trigonometric parallax, $\pi = 2.12 \pm 2.52$ mas is too poor to be of any use. The 2MASS infrared color of the system, $J - K = 0.467$ corresponds to the G8V spectral type which agrees with our classification G5V.

2.3. EL Boo

Variability of EL Boo (HIP 72391, SAO 101223) was detected during the Hipparcos mission, where it was classified as a δ Sct variable with $P = 0.2068860$ days. Later, it was identified as an X-ray source (Mickaelian et al. 2006). Only two moments of minima are available in the literature (Senavci et al. 2007; Hubscher & Walter 2007). In the ASAS database[3] it is classified as an eclipsing binary. The ASAS light-curve indicates a W UMa-type classification and total eclipses. No other photometry or spectroscopy of the target has been published yet.

The BFs (see Fig. 4) clearly show that EL Boo is a triple system containing a a very close (possibly contact) binary and a slowly-rotating third star. The system was not previously known to be a visual binary. The orbital period of the eclipsing pair, $P = 0.413772$, is two times longer than the previous Hipparcos (pulsation) period. The third component contributes about a half of light to the total brightness of the system, $L_3/(L_1 + L_2) = 1.00 \pm 0.08$. The RV of the third component was found to be constant, $RV_3 = -22.6 \pm 1.1$ km s^{-1}, rather close to the systemic velocity of the close eclipsing binary, $V_0 = -24.6 \pm 1.1$ km s^{-1} indicating a physical bond. The projected rotation velocity of the third component is low but detectable even at our rather moderate spectral resolution, $v \sin i \approx 23$ km s^{-1}. The outer orbital period of this triple must be at least several years long.

The relatively small photometric amplitude of the system, 0.19 mag, results from the significant light contribution of the third component and from the rather low mass ratio of the binary, $q = 0.248 \pm 0.007$. On the other hand, the projected mass of the close binary, $(M_1 + M_2)\sin^3 i =$

[3]http://www.astrouw.edu.pl/asas/

1.448 ± 0.028 $M_\odot$ is high for the F5V spectral type indicating a high inclination angle and the implied possibility of total eclipses. The photometric amplitude of the close binary, without the diluting effect of the third light, is expected to be about 0.42 mag, which is unexpectedely large, even if eclipses of the close binary were total; this discrepancy, which is similar to that in TZ Boo, indicates that the amount of the third light may have been overestimated by us. The system definitely deserves a new, high-precision photometric observations.

The published F8 spectral type is fairly late for a contact binary with the 0.414 day orbital period, but it mainly reflects the contribution of the third component because spectral lines of the contact binary are highly broadened by the fast rotation and are practically invisible in classification dispersion spectra. The 2MASS infrared color, $J - K = 0.282$, corresponds to the F5V spectral type and our own classification spectra also indicate the F5V type. The Hipparcos parallax of the system, 5.16 ± 1.69 mas is too small and uncertain to draw any conclusions.

2.4. VZ CVn

VZ CVn (HD 117777, HIP 66017) is a rather bright ($V_{max} = 9.35$), detached eclipsing binary. It was discovered to be variable by Strohmeier & Knigge (1960). The system is known to show a slow intrinsic variability in the LC (see Popper (1988)). Recently, Ibanoğlu et al. (2007) – after removing the eclipse variability – detected γ Dor-type oscillations of the primary component and determined the first set of photometric elements. With the orbital period of 0.842 days it is difficult to cover all orbital phases from one site and intrinsic night-to-night variations of few hundreds of magnitude make a consistent LC solution almost impossible using the ground-based photometry. The system is therefore a prime candidate for satellite, continuous photometric observations.

VZ CVn was observed spectroscopically by Popper (1988), who determined the first radial velocity orbit from photographic spectra: $K_1 = 144.1 \pm 1.2$ km s^{-1}, $K_2 = 185.4 \pm 3.0$ km s^{-1} and the separate systemic velocities of the two components as $V_{01} = -20.7 \pm 0.7$ km s^{-1}, and $V_{02} = -21.7 \pm 2.0$ km s^{-1}.

Our observations provide the very well defined BFs leading to spectroscopic elements fairly consistent with those of Popper (1988). The largest discrepancy is the smaller value of the semi-amplitude K_2. The spectroscopic orbit is, however, of an excellent quality leading to the total projected mass of $(M_1+M_2)\sin^3 i = 2.676 \pm 0.007 M_\odot$, which corresponds to the relative precision as good as 0.26 %. The broadening functions are well separated in the orbital quadratures supporting the photometric classification of the system as a detached binary.

The 2MASS infrared color of the system, $J - K = 0.216$ indicates the F2V spectral type. Our classification spectra correspond to F0V. The Hipparcos parallax is small, 2.23 ± 1.22 mas.

2.5. GK Cep

The bright variable star GK Cep (HD 205372, HIP 106226; $V_{max} = 6.99$), originally classified as an RR Lyr pulsator, was later found to be an eclipsing binary with the 0.483 days period (see Strohmeier (1963)). Bartollini et al. (1965) observed the system photometrically and spectroscopically and determined the correct orbital period, $P = 0.936171$ days, and the first set of spectroscopic elements: $V_0 = -22$ km s^{-1}, $K_1 = 172$ km s^{-1}, $K_2 = 187$ km s^{-1}. The authors classified GK Cep as a β Lyrae variable and, with the photometrically determined inclination angle, $i = 71°$, they determined the masses of the components, $M_1 = 2.7\ M_\odot$ and $M_1 = 2.5\ M_\odot$. Later, Hutchings & Hill (1973) analyzed the LCs of the system assuming Roche model and found that the system is a close, but detached binary with the more massive component being the cooler one.

The orbital period analysis of Kreiner et al. (1990) suggests the presence of an invisible third body in the system on the 18.8 years orbit. Assuming the co-planarity of the orbits, the authors estimated mass of the third component as 1.34 $M_\odot$.

Our spectroscopy confirms the existence of the third component. It is, however, rather faint with its light contribution as small as $L_3/(L_1 + L_2) \approx 0.025$. The profile of the third component is not well visible in all BFs because it blends with the more massive component, especially around the second quadrature. This circumstance complicated our usual approach, i.e. the fitting a triple Gaussian model to the observed BFs. Hence we averaged all BFs (in the heliocentric RV system) and the mean BF was used to define the third component contribution which was subsequently subtracted from all individual BFs. The RV of the third component, $RV_3 = -19.3$ km s^{-1} is rather different from the systemic velocity of the system, $V_0 = -31.06 \pm 0.45$ km s^{-1}.

Our spectroscopic elements (Table 2), agree fairly well with those of Bartollini et al. (1965). The RV semi-amplitudes are, however, smaller resulting in the total mass of the system by about 15% smaller. The very large mass ratio, $q = 0.913 \pm 0.005$, which would be unusual if it were a contact binary, supports the result of Hutchings & Hill (1973) that the system is detached.

The Hipparcos parallax $\pi = 5.17 \pm 0.32$ mas (the distance $d = 193 \pm 11$ pc) has a high precision thanks to the high ecliptical latitude on the Hipparcos sky. The 2MASS infrared color, $J - K = 0.007$ corresponds to the A1V spectral type, which is in good accord with the previous spectral classification, A2V (Hill et al., 1975). Our classification spectra give a slightly earlier spectral type, A0V. If the components of GK Cep are normal main-sequence stars, the best accord with the Hipparcos parallax is achieved for the A2V spectral type.

2.6. RW Com

RW Com (HIP61243, $V_{max} \approx 11.0$ mag, sp. type G5 – G8) is one of the shortest-period ($P = 0.237346$ day) W UMa systems. It was discovered in 1923 (Jordan 1923). This late-type contact binary is known to show an enhanced surface activity resulting in an asymmetric LC (see Milone et al. (1987)). The orbital period of the system shows a continuous decrease with $dP/dt = -6.06 \times 10^{-8}$ day/year (Qian 2002) accompanied by a sinusoidal variation with a 16-year periodicity.

The first spectroscopy of RW Com was carried out by Struve (1950) who found the H & K Ca II lines in emission. Later, Milone et al. (1985) presented the first RV orbit of the system: $K_1 + K_2 = 304 \pm 5$ km s^{-1}, $(M_1 + M_2) \sin^3 i = 0.69 \pm 0.04 M_\odot$, $M_1/M_2 = 2.9 \pm 0.2$ (this corresponds to $q = 0.349 \pm 0.022$) and $V_0 = -53 \pm 4$ km s^{-1}. Unfortunately, the spectra were of a poor quality, with relatively long exposure times typically lasting 20 minutes, which resulted in a heavy blending of the cross-correlation functions used for radial velocity determinations.

Because of the short orbital period of the system, we kept all our exposures equal to 500 sec (2.43% of the orbital period). Our data, however, by far supersede those presented by Milone et al. (1985). The broadening functions do not show any trace of the third component which was indicated by the cyclic period change. This sets the upper limit on its luminosity at about $L_3/(L_1+L_2) < 0.03$. The resulting parameters given in Table 2 are inconsistent with those given by Milone et al. (1985); the most striking difference is our much higher mass ratio, $q = 0.471 \pm 0.006$, and the substantially larger total projected mass, $(M_1 + M_2) \sin^3 i = 1.052 \pm 0.013 M_\odot$. It is interesting to note, that very similar mass ratios, all close to 0.5, have been found for two other contact, very late-type binaries with extremely short orbital periods, CC Com ($q = 0.527$, Pribulla et al. (2007)) and GSC 1387 475 ($q = 0.474$, Rucinski & Pribulla (2008)).

Using the Hipparcos parallax, $\pi = 14.33 \pm 3.36$ mas and $V_{max} = 11.0$, one obtains $M_V = 6.8 \pm 0.8$. With the calibration of Rucinski & Duerbeck (1997) and using $B - V = 1.07$ from the TYCHO2 catalogue, $M_V^{cal} = 6.12$. The 2MASS infrared color of RW Com, $J - K = 0.618$ corresponds to K2V spectral type which is inconsistent with G5–G8 spectral type estimated by Milone et al. (1985) but is in a better accord with the very short orbital period of the binary and our rather rough estimate of K2/5V.

2.7. V2610 Oph

V2610 Oph (HD162905, SAO141948) was found to be variable by Wils & Dworak (2003) on the Stardial images. The authors classified it as a W UMa-type binary with an amplitude of about 0.16 mag and noted that its spectral type, K0, is too late for the period. Later Tas & Evren (2006) obtained precise BVR light curves and determined preliminary geometric parameters of the system as $q = 0.55$, $i = 54.22°$ and found that the system is detached but close to contact. The authors assumed no third light in the system. No spectroscopic observations of the systems have been published yet.

Our spectroscopy immediately revealed a rather different picture: V2610 Oph is a quadruple system. It is somewhat similar to VW LMi (Pribulla et al. 2006) as it consists of an eclipsing contact binary and a detached non-eclipsing pair. The orbit of the second binary with $P = 8.47$

days is slightly eccentric (see Table 4 and Fig. 4).

The multiplicity of V2610 Oph makes the photometric solution of Tas & Evren (2006) completely inapplicable. The spectroscopic mass ratio, $q = 0.289$ and the large projected masses of the components, $(M_1 + M_2)\sin^3 i = 1.408 M_\odot$ indicate a much higher inclination angle than that found before. The light contribution of the second binary in V2610 Oph around the maxima of the eclipsing pair, as found by modeling of the BFs, is $(L_3 + L_4)/(L_1 + L_2) = 1.28 \pm 0.11$, i.e., non-eclipsing pair is brighter than the contact binary. When we correct the observed photometric amplitude, $\Delta V = 0.163$ mag (Tas & Evren 2006) for this contribution, we obtain the full amplitude of the binary 0.41 ± 0.02 mag indicating a high orbital inclination angle.

The center-of-mass RV of the second pair, $V_0 = 60.76 \pm 0.11$ km s^{-1} is fairly close to the systemic velocity of the eclipsing binary, 71.70 ± 1.27 km s^{-1}. The RV difference indicates a mutual orbital motion of the binaries. No systemic-velocity changes in either of the binaries were noted during our observing run which extended for almost one year. Hence, the outer orbital period is at least several years long. The angular separation between the binaries must be smaller than about 1 arcsec, because V2610 Oph appeared to be single on our spectrograph slit even during the nights of excellent seeing; besides, the system is not known to be a visual binary (Mason et al. 2001).

A new LC analysis using the new spectroscopic mass ratio and including the third light is necessary to determine the inclination angle. Then, having the masses of the close binary, masses of all four components could be determined using the "linked mass-ratio" technique as used in Pribulla et al. (2006) for VW LMi.

The infrared color of the system, $J - K = 0.393$, corresponds to G4V spectral type, while the TYCHO color, $B - V = 0.587$ corresponds to G0V spectral type. The direct spectral classification is hard to do; it indicates a range of admissible types within F8/G2V but is consistent with the projected mass of the dominant primary component in the contact binary, $M_1 = 1.09 M_\odot$. V2610 Oph was not observed by the Hipparcos satellite and its trigonometric parallax is unknown.

2.8. V1387 Ori

V1387 Ori (HD 42969, HIP 29186) is a member of a trapezoidal, visual, multiple system; the other members are GSC 1318 59 and GSC 1318 317; the latter star forms the close visual binary HDS 838. Neither of these visual companions was entering our spectrograph slit. Establishing the physical bond between the members of this mini-cluster would require precise proper motions and RVs.

The variability of V1387 Ori was discovered during the Hipparcos mission (ESA 1997). In the Hipparcos catalogue it was classified as a β Lyrae system, but later Duerbeck (1997) suggested it to be a contact, W UMa-type system. The Hipparcos light curve shows maximum following the primary minimum substantially brighter than the other maximum (similar to contact binaries

AG Vir and DU Boo). No ground-based photometric nor spectroscopic observations of the system have been published yet.

Our spectroscopy revealed that V1387 Ori is a triple system. The radial velocity of the third component appears to vary as indicated by the the first of our spectra at HJD 2454073.7873, giving $RV_3 = 34.43$ km s^{-1}. This observation was well separated in time from the remaining observations which give a constant velocity of $RV_3 = 24.4 \pm 0.4$ km s^{-1}. The contribution of third component is affected by the large O'Connell effect observed in the system: At Max I, $L_3/(L_1+L_2) = 0.128 \pm 0.012$ while at Max II, $L_3/(L_1 + L_2) = 0.186 \pm 0.023$. When the third-body signatures are removed from the BFs, the orbit of the eclipsing pair is well defined with a low mass ratio, $q = 0.165 \pm 0.005$, which would be rather typical for a A-type contact binary. No surface inhomogeneities on either of components were noticed in the BFs in spite of the large O'Connell effect.

The Hipparcos parallax for this system is negative, $\pi = -7.86 \pm 1.96$ mas, which most probably results from V1387 Ori being located in the visual multiple system. The 2MASS color, $J - K = 0.155$, corresponding to A2V is consistent with our spectral classification, A4V.

2.9. AU Ser

AU Ser (GSC 1502 1762) is a rather faint ($V_{max} = 10.9$) contact binary discovered by Hoffmeister (1935). The first photoelectric photometry presented by Binnendijk (1972) showed a significant asymmetry of the LC ($MaxI - MaxII = -0.05$ mag) and a 0.2 mag difference in the depth of the eclipses. The light curves obtained by Binnendijk (1972) were later analyzed by Kaluzny (1986) who interpreted the large asymmetry by a hot spot located close to the "neck" connecting the components. The best solution assuming the A-type of the light curve was obtained for a rather large mass ratio $q = 0.80$. The authors, however, admitted that the acceptable range of mass ratio is rather wide, between 0.70 and 1.15. Later Gurol (2005) analyzed photometric data covering period from 1969 till 2003. Their analysis of the observed times of minima indicates the presence of a third body on a 94.15 years orbit with the estimated minimum mass of about $M_3 = 0.53 M_\odot$. According to the authors the differences in the LC maxima levels appear to be cyclic on a time scale of about 30 years.

The spectroscopic observation of the system were performed by Hrivnak (1993), who gave $q = 0.71$ and projected total mass of the system $(M_1 + M_2) \sin^3 i = 1.51 M_\odot$. The systemic velocity of the system was not given. Our new spectroscopy leads to the projected mass and the mass ratio within the errors of those found by Hrivnak (1993). We do not see any third component in the BFs. The phased BFs, however, show a large cool spot on the secondary component which is visible after the second quadrature (see Fig. 4). This dark, localized spot significantly deforms the BFs and affects the determined RVs. A reliable determination of the spectroscopic elements would require modeling of simultaneous spectroscopic and photometric observations.

The system appears to have a realtively late spectral type, G4V, for its orbital period of 0.386

d. AU Ser was too faint for the Hipparcos mission, hence its parallax is unknown.

2.10. FT UMa

Variability of FT UMa (HD 75840, HIP 43738) was discovered by the Hipparcos satellite. In the special General Catalogue of Variable Stars namelist (Kazarovets et al. 1999), the RRc classification was suggested with the pulsational period of 0.3273519 days. The high precision BVR photometric observations of FT UMa were published by Selam et al. (2007). The authors correctly classified system as a close binary, obtained a rather low mass ratio of $q = 0.25 \pm 0.01$, the low orbital inclination $i = 54.48 \pm 0.80^\circ$, and suggested a contact configuration for the system. In spite of its relatively high brightness, $V_{max} = 9.25$, and the photometric amplitude as large as 0.17 mag, no other observations of FT UMa have been published yet.

Our spectroscopy clearly shows that FT UMa is a triple system containing the close eclipsing binary with the period of $P = 0.6547038$ days. FT UMa is not listed in the WDS catalogue as a visual binary. During our spectroscopic observations the star always appeared as a single object, which sets an upper limit to the angular separation of the components at about 1 arcsec. The center-of-mass velocity of the close binary, $V_0 = -33.66 \pm 1.30$ km s^{-1}, is significantly different from the third-component velocity which slowly changed from -22 km s^{-1} to about -10 km s^{-1} during our run. Unfortunately, the RVs of the close pair are rather imprecise to resolve the hierarchy and multiplicity of the system: It can either be a hierarchical triple or a quadruple system consisting of two binaries (with the non-eclipsing pair being the SB1). The light contribution of the third component around the maxima of the eclipsing pair is $L_3/(L_1 + L_2) = 1.01 \pm 0.03$. The full, undiluted, photometric amplitude of the eclipsing binary would be then about 0.37 mag. The presence of such a strong third light made photometric solution of (Selam et al. 2007) of limited use.

The profiles of all three components are well separated in the extracted BFs, indicating that the close eclipsing binary is very probably detached, which is consistent with the large mass ratio, $q = M_2/M_1 = 0.984 \pm 0.019$, but rather atypical for contact binaries. On the other hand, Hipparcos photometry phased with the adopted period of 0.6547038 days results in the LC which appears to be rather typical for contact binaries.

The TYCHO2 color of the system, $B - V = 0.404$ reflects the combined contributions of the eclipsing pair and of the third component. Our spectral classification spectra suggest the F0V spectral type, which is consistent with the 2MASS $J - K = 0.207$. The Hipparcos parallax is fairly small, 6.90 ± 1.28 mas.

3. SUMMARY

With the new ten short-period binaries, this paper brings the number of the systems studied at the David Dunlap Observatory to one hundred thirty. With the closure of the observatory, this series is coming to an end. However, the number of known, bright close binaries which remained unobserved at DDO is not large; only a dozen or so known W UMa-type eclipsing binaries brighter than about $V = 10$ and accessible from DDO remained. We plan to publish the data for the unfinished cases in the last, fifteenth installment of this series.

The highlights of the current series are: (1) the discoveries of two quadruple systems TZ Boo and V2610 Oph, (2) the discoveries of four triple systems: EL Boo, GK Cep, V1387 Ori, and FT UMa, (3) the spotted contact binary AU Ser, with a large spot on the secondary component. None of the detected spectroscopic multiple systems was previously noted to be a visual binary (see Mason et al. (2001)).

While for four systems, EL Boo, V2610 Oph, V1387 Ori and FT UMa, we are presenting the first spectroscopic observations, the quality of the data for the remaining six systems is much improved relative to the previously published investigations.

Numerous discoveries and reliable solutions of triple and quadruple systems show that the BF deconvolution approach utilizing the SVD method is really a powerful technique. In this series, good examples are the three triple systems with the dominant third component, EL Boo, V2610 Oph and FT UMa. The BF technique enabled also to determine the first reliable set of spectroscopic elements for TZ Boo and to reveal the true nature of the system. The third component of this system, moving in 9.48 day orbit, blends with the components of the close binary, a condition which made all previous spectroscopic studies of TZ Boo so unsuccessful. The second binary may be the cause of the large perturbations observed in the light curve of the eclipsing pair. However, with several multiple systems analyzed in the DDO papers, we also see the weakness of the BF technique which should be addressed in the future: As described in Rucinski & Pribulla (2008), the contribution of the third component to the total light of the system is always overestimated. There are two reasons for this discrepancy: (i) The continuum spectrum rectification differently affects spectra of (usually) sharp-lined companions and of heavily broadened short-period binaries; (ii) The technique must use a single template spectrum, but this affects the luminosity ratio when the spectral types of the third component and the contact binary are significantly different.

We express our thanks to Wojtek Pych for providing his cosmic-ray removal code. Support from the Natural Sciences and Engineering Council of Canada to SMR from the Polish Science Committee (KBN grants PO3D 006 22 and P03D 003 24) to WO is acknowledged with gratitude. The travel of TP to Canada has been supported by a Slovak Academy of Sciences VEGA grant 2/7010/7. In 2008, TP has been a recipient of the Post-Doctoral Fellowship of the Canadian Space Agency; he appreciates the hospitality and support of the local staff during his stay at DDO.

The research made use of the SIMBAD database, operated at the CDS, Strasbourg, France and accessible through the Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada. This research made also use of the Washington Double Star (WDS) Catalog maintained at the U.S. Naval Observatory.

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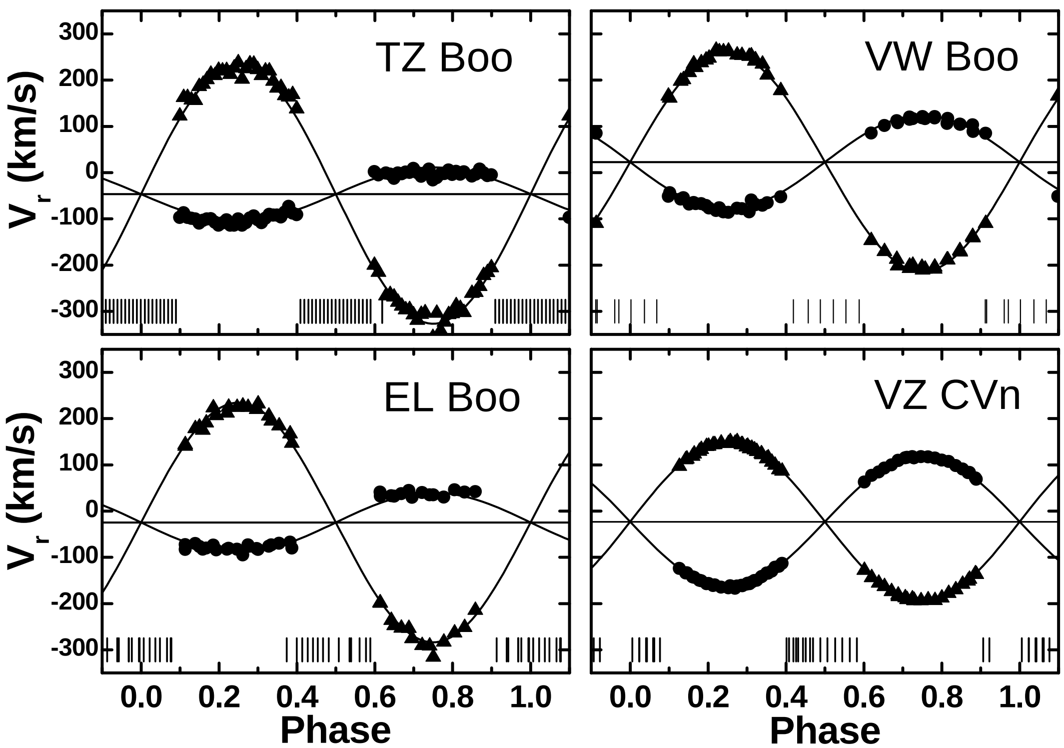
Captions to figures:

Fig. 1.— Radial velocities of the systems TZ Boo, VW Boo, EL Boo, and VZ CVn are plotted in individual panels versus the orbital phases. The lines give the respective circular-orbit (sine-curve) fits to the RVs. TZ Boo is a quadruple system consisting of contact and detached single-line binary while VW Boo is a contact binary. EL Boo is a triple system harboring a close binary and VZ CVn is a detached or a semi-detached binary. The circles and triangles in this and the next two figures correspond to components with velocities V_1 and V_2, as listed in Table 1, respectively. The component eclipsed at the minimum corresponding to T_0 (as given in Table 2) is the one which shows negative velocities for the phase interval $0.0 - 0.5$ and which is the more massive one. Short marks in the lower parts of the panels show phases of available observations which were not used in the solutions because of the spectral line blending.

Fig. 2.— The same as for Figure 1, but for GK Cep, RW Com, V2610 Oph, and V1387 Ori. GK Cep is a close binary with a faint third component; RW Com is a contact binary; V2610 Oph is a quadruple system consisting of contact eclipsing binary and a wide non-eclipsing pair; V1387 Ori is a triple system containing a close eclipsing binary. V1387 Ori forms a part of a trapezoidal visual multiple.

Fig. 3.— The same as for Figures 1 and 2, for the two remaining systems AU Ser, and FT UMa. AU Ser is a contact binary, FT UMa is a triple system containing close eclipsing binary.

Fig. 4.— The broadening functions (BFs) for all ten systems of this group, selected for orbital phases close to 0.25 or 0.75. The phases are marked by numbers in the individual panels. Additional components to the close binaries, TZ Boo, EL Boo, V2610 Oph, V1387 Ori, and FT UMa, are strong and clearly visible. The third component in GK Cep is a small peak close to the systemic velocity. All panels have the same horizontal range, -500 to $+500$ km s^{-1}.



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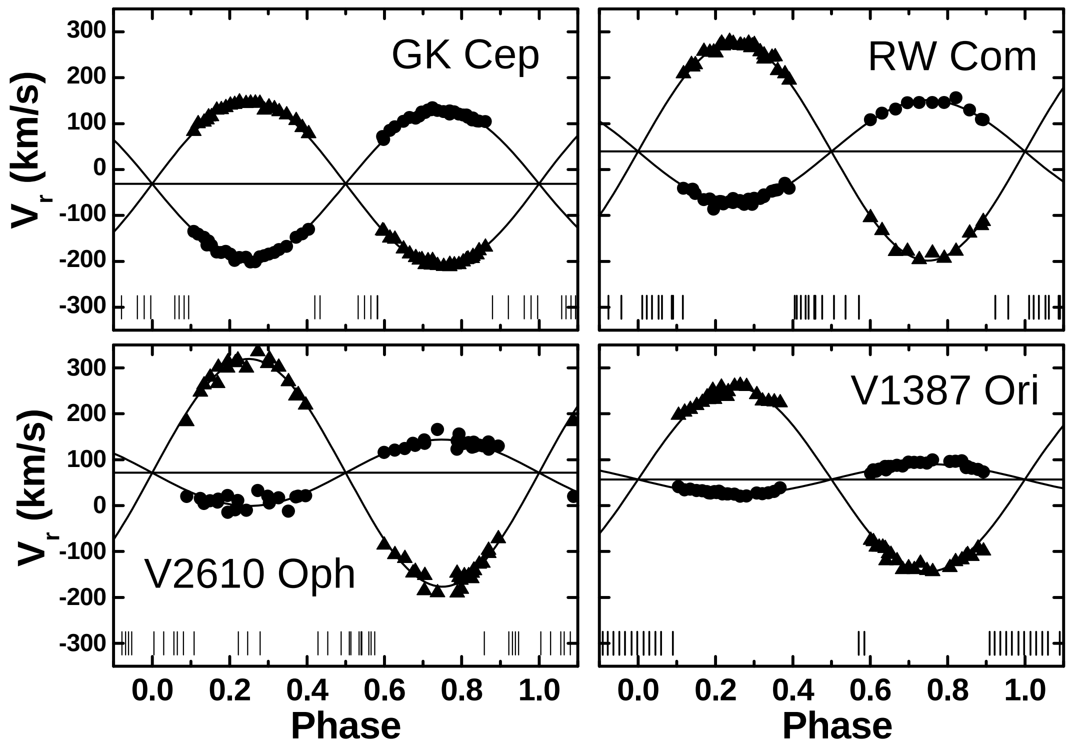

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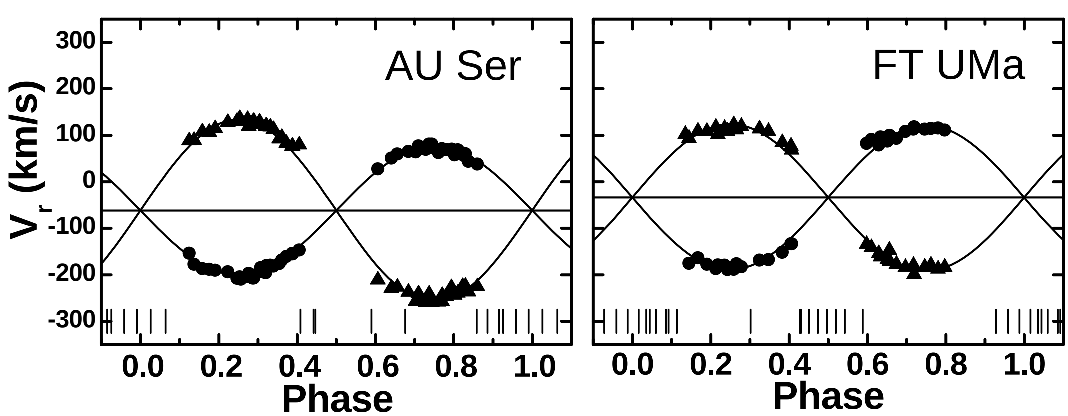

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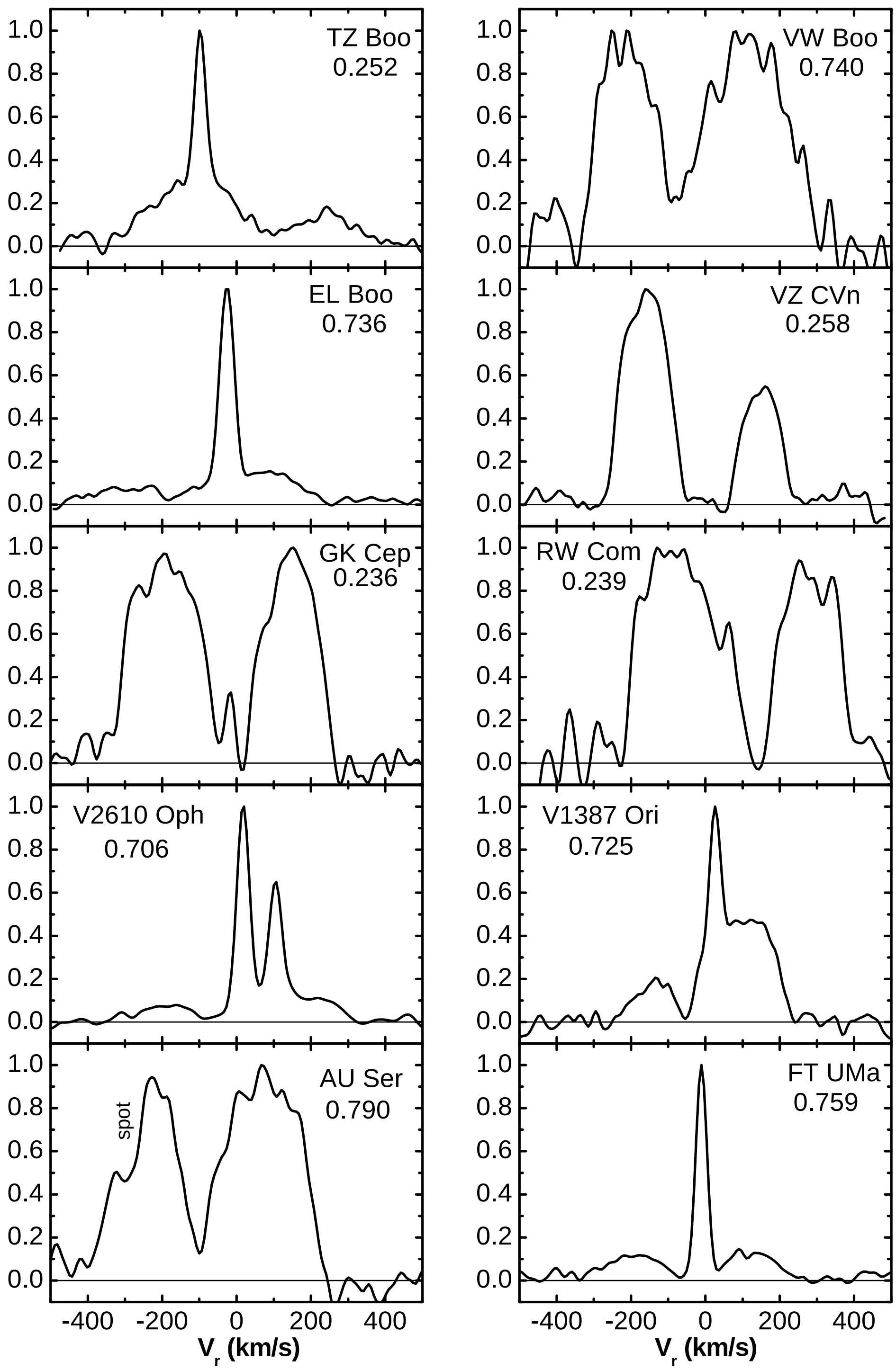

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Table 1. DDO radial velocity observations (the full table is available only in the electronic form)

Target	HJD–2,400,000	V_1 [km s^{-1}]	W_1	V_2 [km s^{-1}]	W_2	Phase
VW Boo	54558.8318	0.00	0.00	0.00	0.00	0.9153
VW Boo	54558.8472	0.00	0.00	0.00	0.00	0.9602
VW Boo	54558.9127	−68.22	0.50	216.48	0.50	0.1516
VW Boo	54558.9233	−67.24	1.00	237.55	1.00	0.1826
VW Boo	54559.7940	116.90	1.00	−200.04	1.00	0.7261
VW Boo	54559.8047	116.91	1.00	−208.79	1.00	0.7574
VW Boo	54563.6869	−51.23	1.00	165.41	1.00	0.0984
VW Boo	54563.6977	−57.31	1.00	197.76	1.00	0.1299
VW Boo	54563.7091	−64.92	1.00	235.53	1.00	0.1632
VW Boo	54563.7200	−71.21	1.00	243.67	1.00	0.1951

Note. — The table gives the RVs V_i for observations described in the paper. The first 10 rows of the table for typical program star, VW Boo, are shown. For first program star, TZ Boo, where phase smoothed BFs were used, the heliocentric Julian dates are not given. Observations leading to entirely inseparable broadening function peaks are given zero weight; these observations may be eventually used in more extensive modelling of broadening functions. Zero weights were assigned to observations of marginally visible peaks of the secondary (sometimes even primary) component. The RVs designated as V_1 correspond to the more massive component; it was always the component eclipsed during the minimum at the epoch T_0 (this does not always correspond to the deeper minimum and photometric phase 0.0). The phases correspond to spectroscopic T_0 and periods given in Table 2, but not necesarily to the photometric ephemerides given below the table).

Table 2. Spectroscopic orbital elements

Name	Type Sp. type	Other names	V_0	K_1 K_2	ϵ_1 ϵ_2	T$_0$ – 2,400,000 $(O-C)$(d) [E]	P (days) $(M_1+M_2)\sin^3 i$	q
TZ Boo	EW(A/W)	BD+40 2857	−46.57(0.90)	57.8(1.45)	8.70	54042.7482(4)	0.2971597	0.207(5)
	F/G5	HIP74061		280.02(1.50)	10.49	+0.0002 [+5.191.0]	1.188(18)	
VW Boo	EW		22.79(0.66)	101.39(1.07)	6.65	54573.9227(4)	0.3423157	0.428(5)
	G5V	HIP69826		236.74(1.03)	5.99	−0.0032 [+6,058.5]	1.371(14)	
EL Boo	EW	BD+14 2788	−24.58(1.12)	64.19(1.70)	9.58	54584.1779(9)	0.413772	0.248(7)
	F5V	HIP72391		259.07(1.89)	9.31	−0.0850 [+14,704]	1.448(28)	
VZ CVn	EB	HD117777	−22.99(0.16)	141.51(0.26)	1.64	54573.9540(3)	0.84246123	0.8252(19)
	F0V	HIP66017		171.48(0.25)	1.72	+0.0009 [+2,461]	2.676(7)	
GK Cep	EB	HD205372	−31.06(0.45)	163.44(0.73)	5.05	54464.4014(8)	0.936169	0.913(5)
	A0V	HIP106226		178.95(0.73)	4.20	−0.0062 [+2,098]	3.893(26)	
RW Com	EW(W)		39.35(0.86)	112.04(1.28)	6.33	54272.7645(3)	0.2373464(7)	0.471(6)
	K2/5V	HIP61243		237.70(1.29)	7.39	+0.0005 [+7,465.5]	1.052(13)	
V2610 Oph	EW(A)	HD162905	71.70(1.27)	72.06(2.06)	11.87	54461.5659(10)	0.426512(3)	0.291(9)
	F8/G2V			247.42(2.08)	12.11	+0.0109 [+4,904]	1.441(31)	
V1387 Ori	EW?	HD42069	56.92(0.65)	33.21(0.98)	4.37	54204.0187(13)	0.730166	0.165(5)
	A4V	HIP29186		200.72(1.18)	8.50	+0.0082 [+7,811]	0.969(16)	
AU Ser	EW(A)		−61.59(0.84)	138.77(1.33)	6.36	54597.4761(7)	0.386499	0.709(8)
	G4V			195.64(1.34)	10.43	+0.0042 [+5,426]	1.498(19)	
FT UMa	EB	HD75840	−33.66(1.30)	155.15(2.14)	10.78	54561.9614(19)	0.654704	0.984(19)
	F0V	HIP43738		157.73(2.13)	10.88	−0.0136 [+9,258.5]	2.077(45)	

Note. — The spectral types given in column 2 relate to the combined spectral type of all components in a system; they are given in parentheses if taken from the literature, otherwise they are new. The convention of naming the binary components in the table is that the more massive star is marked by the subscript "1", so that the mass ratio is defined to be always $q \leq 1$. The standard errors of the circular solutions in the table are expressed in units of last decimal Places quoted; they are given in parentheses after each value. The center-of-mass velocities (V_0), the velocity amplitudes (K_i) and the standard unit-weight errors of the solutions (ϵ) are all expressed in km s^{-1}. The spectroscopically determined moments of primary or secondary minima are given by T_0 (correspond approximately to the average Julian date of the run); the corresponding $(O-C)$ deviations (in days) have been calculated from the available prediction on primary minimum, as given in the text, using the assumed periods and the number of epochs given by [E]. The values of $(M_1+M_2)\sin^3 i$ are in the solar mass units.
Ephemerides (HJD_{min} – 2,400,000 + period in days) used for the computation of the $(O-C)$ residuals:
TZ Boo: 52500.1920 + 0.2971597
VW Boo: 52500.0062 + 0.3423157
EL Boo: 48500.1594 + 0.413772
VZ CVn: 52500.6560 + 0.84246123
GK Cep: 52500.325 + 0.936169
RW Com: 52500.1432 + 0.2373463
V2610 Oph: 52369.95 + 0.42651
V1387 Ori: 48500.6839 + 0.730166
AU Ser: 52500.3392 + 0.386497
FT UMa: 48500.3999 + 0.6547038

Table 3. Radial velocity observations (the full table is available only in electronic form) of third and fourth components of multiple systems

Target	HJD–2,400,000	V_3 [km s^{-1}]	V_4 [km s^{-1}]
V2610 Oph	54302.7053	91.91	27.54
V2610 Oph	54302.7160	91.99	28.35
V2610 Oph	54306.6868	17.32	107.57
V2610 Oph	54306.6976	16.85	106.22
V2610 Oph	54306.7090	20.25	108.84
V2610 Oph	54306.7197	17.23	106.02
V2610 Oph	54307.5974	48.53	76.07
V2610 Oph	54307.6080	48.49	75.25
V2610 Oph	54307.6193	49.66	75.37
V2610 Oph	54307.6299	49.44	73.04

Note. — The table gives the RVs V_i for the third and fourth components. The typical 10 rows of the table for quadruple system, V2610 Oph, are shown. Observations of quadruple system V2610 Oph leading to entirely inseparable broadening function peaks of components of the second binary have been omitted from the table and not used in computation of the orbit.

Table 4. Spectroscopic orbital elements of the second non-eclipsing binaries in the quadruple systems TZ Boo and V2610 Oph . Orbit of the second binary in TZ Boo is circular, thus $e_{34} = 0.00$ and $\omega_{34} = \pi/2$

Parameter		error
TZ Boo		
P_{34} [days]	9.47765	0.00034
T_0 [HJD]	2 454 042.818	0.007
V_0 [km s^{-1}]	−54.64	0.12
K_3 [km s^{-1}]	43.15	0.14
$a_3 \sin i$ [R$_\odot$]	8.08	0.03
$f(m)$ [M$_\odot$]	0.0793	0.0008
V2610 Oph		
P_{34} [days]	8.47093	0.00025
e_{34}	0.073	0.003
ω [rad]	5.88	0.04
T_0 [HJD]	2 454 461.85	0.06
V_0 [km s^{-1}]	60.76	0.11
K_3 [km s^{-1}]	57.77	0.23
K_4 [km s^{-1}]	62.15	0.24
$q = K_4/K_3$	0.929	0.005
$(a_3 + a_4)\sin i$ [R$_\odot$]	20.01	0.06
$(M_3 + M_4)\sin^3 i$ [M$_\odot$]	1.502	0.013

Note. — The table gives spectroscopic elements of the second binaries in TZ Boo and V2610 Oph: orbital period (P_{34}), eccentricity (e_{34}), longitude of the periastron passage (ω), time of the periastron passage (T_0), systemic velocity (V_0), semi-amplitudes of the RV changes (K_3, K_4). Corresponding mass ratio q, and projected relative semi-major ($(a_3 + a_4)\sin i$) and total mass ($(M_3 + M_4)\sin^3 i$) is given for V2610 Oph where both lines of the second binary could be measured. For single-lined non-eclipsing binary in TZ Boo only $a_3 \sin i$ and $f(m)$ is given.