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RADIAL VELOCITY STUDIES OF CLOSE BINARY STARS. XV*

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ABSTRACT

Radial velocity (RV) measurements and sine curve fits to the orbital RV variations are presented for the last eight close binary systems analyzed in the same way as in the previous papers of this series: QX And, DY Cet, MR Del, HI Dra, DD Mon, V868 Mon, ER Ori, and Y Sex. For another seven systems (TT Cet, AA Cet, CW Lyn, V563 Lyr, CW Sge, LV Vir, and MW Vir), phase coverage is insufficient to provide reliable orbits but RVs of individual components were measured. Observations of a few complicated systems observed throughout the David Dunlap Observatory (DDO) close binary program are also presented; among them is an especially interesting multiple system V857 Her which—in addition to the contact binary—very probably contains one or more subdwarf components of much earlier spectral type. All suspected binaries which were found to be most probably pulsating stars are briefly discussed in terms of mean RVs and projected rotation velocities ($v \sin i$) as well as spectral-type estimates. In two of them, CU CVn and V752 Mon, the broadening functions show a clear presence of nonradial pulsations. The previously missing spectral types for Paper I are given here in addition to such estimates for most of the program stars of this paper.

Key words: binaries: close – binaries: eclipsing – binaries: spectroscopic – δ Scuti

Online-only material: machine-readable and VO tables

1. INTRODUCTION

This is the last in a series of papers presenting results of spectroscopic observations taken within the program of radial velocity (RV) orbits of close binary stars at the David Dunlap Observatory (DDO); it contains a discussion of all the remaining targets of this program. For full references to the previous papers, see the last paper by Pribulla et al. (2009, Paper XIV (DDO14)); 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 by Rucinski (2002, Paper VII).

Most of the data used in the present paper were obtained—as in most of the previous 14 papers—using the BF approach applied to the spectral region of the Mg I triplet (always centered at 5184 Å). Up to 2005 August, we used a diffraction grating with 1800 lines mm^{-1}, after which a new one with 2160 lines mm^{-1} was used. A small number of observations were taken in the red region centered at 6290 Å which includes a telluric band to resolve our concerns on the stability of the RV system (see Pribulla et al. 2006, Paper XI). The RV observations reported in this paper have been collected between 1996 October and 2008 July 2, the day when the DDO ceased to operate. The ranges of dates for individual systems can be found in Table 1. We note that this program utilized the efficient code of Pych (2004) for the removal of cosmic rays from two-dimensional images.

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 1 day, brighter than 10–11 mag and with declinations $>-20°$; we published the results in groups of 10 systems as soon as reasonable orbital elements were obtained from measurements evenly distributed in orbital phases. This paper is an exception as we have not been able to collect 10 orbits before the observatory closure and we were left with material for a few stars already started. For that reason, in this last paper of the series, we present all remaining spectroscopic observations. Thus, they include: (1) RV orbits for eight close binaries observed and fully analyzed in the same way as in previous publications of this series (QX And, DY Cet, MR Del, HI Dra, DD Mon, V868 Mon, ER Ori, and Y Sex); (2) close binaries with just one quadrature covered or with a few spectra available but not sufficient in number to define a reasonable orbit (TT Cet, AA Cet, CW Lyn, V563 Lyr, CW Sge, LV Vir, and MW Vir); (3) complicated or faint binaries/triples not providing reliable RVs (GO Cyg, V857 Her, V752 Mon, V353 Peg, and MS Vir), (4) additional data and improved orbits for a few multiple systems already presented within this series (ET Boo, XY Leo, and TV UMi); (5) RVs and projected rotational velocities, $v \sin i$, for several stars found to be pulsating rather than being close binaries, and (6) the previously missing spectral-type estimates for close binaries in Lu & Rucinski (1999, Paper I). All the RVs are given in Table 1. Among the present targets, only QX And, ER Ori, and Y Sex have had spectroscopic orbits previously published while preliminary orbits of AA Cet and TT Cet, based on limited data, were given by Duerbeck & Rucinski (2007).

The RVs for the eight short-period binaries reported in this paper were determined by fitting the double rotational profiles to

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Table 1
RV Observations of Close Binary Stars

Target	HJD–2,400,000	V_1 (km s^{-1})	W_1	V_2 (km s^{-1})	W_2	Phase
QX And	51433.6619	−49.23	1.00	225.82	1.00	0.2814
QX And	51433.6788	−54.06	1.00	202.40	1.00	0.3224
QX And	51433.7116	0.00	0.00	0.00	0.00	0.4020
QX And	51433.7274	0.00	0.00	0.00	0.00	0.4403
QX And	51433.7453	0.00	0.00	0.00	0.00	0.4837
QX And	51433.7620	0.00	0.00	0.00	0.00	0.5242
QX And	51433.7788	0.00	0.00	0.00	0.00	0.5650
QX And	51433.7958	45.05	1.00	−135.18	1.00	0.6062
QX And	51433.8121	66.23	1.00	−168.90	1.00	0.6458
QX And	51433.8294	70.40	1.00	−187.34	1.00	0.6878

Notes. The table gives the RVs V_i for observations of close binary stars described in Sections 2 and 3, in the order of constellation. The first 10 rows of the table for a typical program star, QX And, are shown. Observations leading to entirely inseparable BF peaks are given zero weight; these observations may be eventually used in more extensive modeling of BFs. 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 given in Table 2 with the Exception of the following cases taken either from the *Hipparcos* Catalogue or (Kreiner 2004) databases: TT Cet: 52500.1309 + 0.4859541, AA Cet: 52500.3652 + 0.5361685, CW Lyn: 48500.457 + 0.812389, V563 Lyr: 52500.273 + 0.5776407, CW Sge: 52500.567 + 0.6603633, LV Vir: 52500.0315+0.4094453, MW Vir: 48500.3032+0.493078 (*Hipparcos* $T_0 + P/2$ and $2 \times P$).
(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

extracted BFs, as explained in Pribulla et al. (2006). Similarly, as in our previous papers dealing with multiple systems (here the cases of MR Del, V563 Lyr, DD Mon, ER Ori, Y Sex, and LV Vir), the RVs for the eclipsing pair were obtained after the removal of the slowly rotating component, as was described most recently in Pribulla et al. (2009).

As in other papers of this series, whenever possible, we estimated spectral types of the program stars using new classification spectra centered at 4200 Å or 4400 Å. Additional classification spectra were obtained for part of the systems published in Lu & Rucinski (1999, Paper I) where no classifications were given. The estimated 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 Two Micron All Sky Survey (2MASS; Skrutskie 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 index is relatively less affected by the interstellar absorption than $B-V$. Parallaxes cited throughout the paper were adopted from the new reduction of the *Hipparcos* raw data (van Leeuwen 2007) which supersedes the original reductions (European Space Agency 1997).

The RV data for the binaries are given in Table 1. The preliminary sine curve solutions for the eight binaries are in Table 2 while the phase diagrams are shown in Figures 1 and 2. Section 2 contains summaries of previous studies for individual systems with reliable orbits and comments on the new data. Systems with insufficient orbital coverage are discussed in

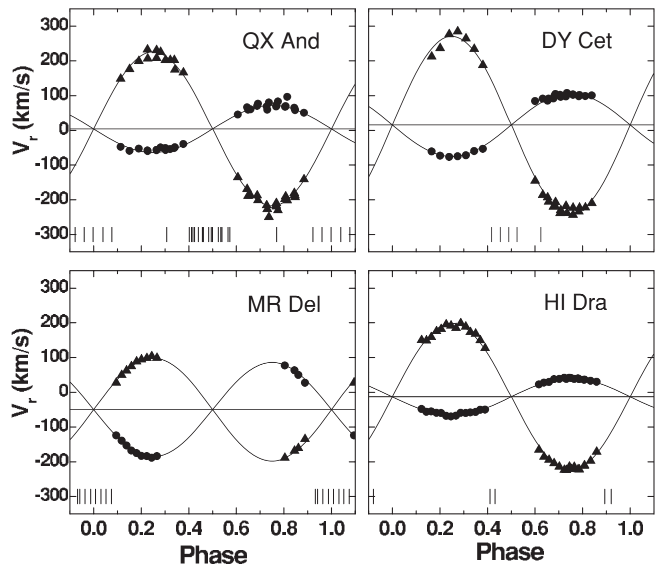

Figure 1. RVs of four systems with spectroscopic orbits, QX And, DY Cet, MR Del, HI Dra, are plotted in individual panels vs. the orbital phases. The lines give the respective circular orbit (sine curve) fits to the RVs. MR Del is a triple system consisting of a close binary and a slowly rotating single star. All systems, except MR Del, are contact binaries. The circles and triangles 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 or poor quality of data.

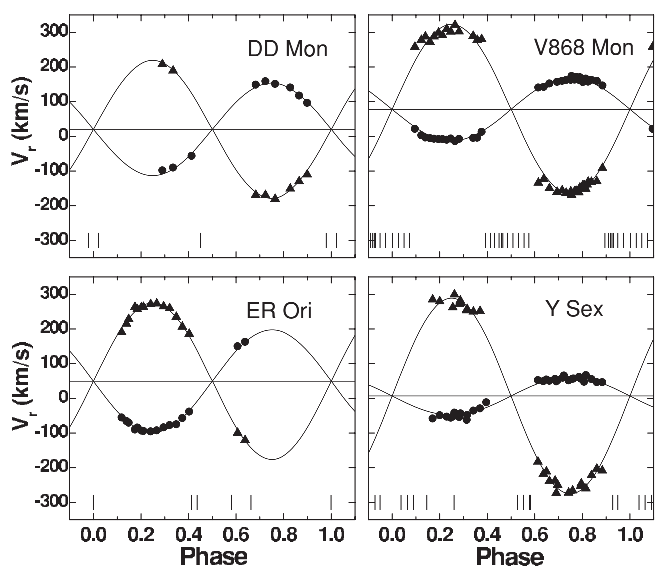

Figure 2. RVs for the second group of systems with spectroscopic orbits, DD Mon, V868 Mon, ER Ori, and Y Sex. While V868 Mon is a contact binary, the remaining systems are triple ones containing a contact or a close binary.

Section 3, while problematic systems for which RVs could not be determined are discussed in Section 4. Targets which were found to be pulsating are presented in Section 5. Examples of BFs of individual systems are shown in Figures 3–5.

Data for the eight close binaries 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

Table 2
Spectroscopic Orbital Elements for Eight Binaries Described in Section 2

Name	Type Sp. Type	Other Names	V_0	K_1 K_2	ϵ_1 ϵ_2	T_0–2,400,000 $(O-C)$ (days) [E]	P (days) $(M_1+M_2)\sin^3 i$	q
QX And	EW(W?)		+4.07(1.17)	67.92(1.82)	8.18	51442.2015(11)	0.4121701	0.306(9)
	(F8)			221.73(1.84)	11.39	+0.0045 [−2,566.5]	1.038(22)	
DY Cet	EW(A)	HD16515	+15.55(1.49)	90.84(2.11)	6.04	52594.3317(12)	0.440790(6)	0.356(9)
	(F5V)	BD−14 495		255.40(2.28)	12.06	−0.0005 [+214.0]	1.896(40)	
MR Del	EB	HD195434	−49.76(0.79)	135.74(1.27)	3.74	54469.1682(8)	0.5216899	0.915(12)
	(K2V+K6V?)	BD+04 4470		148.32(1.27)	4.35	+0.0015 [+3,774.0]	1.239(18)	
HI Dra	EW(A)	HD171848	−12.73(0.69)	52.83(1.08)	2.30	54622.3721(10)	0.597418	0.250(5)
	(F0-2)	BD+58 1824		211.49(1.08)	7.43	+0.0228 [+10,247.5]	1.143(16)	
DD Mon	EB	HD292319	+20.21(1.87)	133.32(3.06)	7.97	52642.7453(21)	0.568020	0.670(19)
	(G0)			198.85(3.18)	8.87	−0.0022 [+251.0]	2.157(65)	
V868 Mon	EW	BD−02 2221	+78.08(1.30)	91.21(1.83)	6.46	54157.0662(18)	0.637705	0.373(8)
	(A5)			244.67(2.22)	14.81	−0.0012 [+1,724.0]	2.504(52)	
ER Ori	EW(W)	BD−08 1050	+49.45(1.65)	147.98(2.30)	5.50	54393.4271(7)	0.4234034	0.656(12)
	F7/8	HIP24156		225.48(2.35)	6.93	+0.0099 [+4,471.5]	2.285(45)	
Y Sex	EW(A)	HD87079	+6.78(1.64)	54.96(2.30)	7.69	54315.4217(13)	0.4198199	0.195(8)
	F5/6	BD+01 2394		281.94(2.86)	18.63	+0.0013 [+4,324.0]	1.663(45)	

Notes. 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 $q < 1$. 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$_{\rm min}$–2,400,000 + period in days) used for the computation of the $(O-C)$ residuals: QX And: 52500.0316 + 0.4121701, DY Cet: 52500.0031 + 0.4407903, MR Del: 52500.309 + 0.5216899, HI Dra: 48500.3186 + 0.597417, DD Mon: 52500.1745 + 0.568020, V868 Mon: 53057.664 + 0.637705, ER Ori: 52500.1689 + 0.4234034, Y Sex: 52500.1192 + 0.4198199.

determinations of the primary minimum in the form of the $O-C$ deviations for the number of elapsed periods E. The reference ephemeris of HI Dra was taken from Gomez-Forrellad & Garcia-Melendo (1996) and for V868 Mon from Otero et al. (2004). For the rest of the systems, the ephemerides were adopted from the online version of "An Atlas of $O-C$ diagrams of eclipsing binary stars"[8] (Kreiner 2004). Because the online ephemerides are frequently updated, we give those used for the computation of the $O-C$ residuals below Table 2 (the status as of 2008 October). 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 an half-integer number.

2. EIGHT STARS WITH RELIABLE ORBITS

2.1. QX And

QX And (GSC 2816 1950, H235 in NGC 752) is a contact binary star in the intermediate-age open cluster NGC 752. Its variability was first noted by Johnson (1953) on the basis of two discordant photometric observations. Platais (1991) gave 99% probability of the cluster membership for QX And based on the proper motion. The first thorough photometric and spectroscopic observations of QX And were presented by Milone et al. (1995). The authors found that QX And is a contact binary, estimated its spectral type as F3-5, determined absolute parameters of the components (masses $M_1 = 1.18\,M_\odot$ and $M_2 = 0.24\,M_\odot$) by simultaneous fits to the observed light and RV variations and found the distance to the binary and the cluster as 381 ± 17 pc. The center-of-mass velocity $V_0 = +11.7 \pm 2.7$ km s^{-1} (given in their Table 16) was larger than the cluster mean velocity, RV $= +5.5$ km s^{-1} (Daniel et al. 1994). Unfortunately, the RV observations of Milone et al. (1995) were of a rather poor quality (see their Figure 5) resulting in only marginally useful orbital parameters.

Preliminary results of the DDO spectroscopy of QX And were published as a part of the PhD thesis of Blake (2002). Here we present an independent determination using the rotational-profile fitting to the extracted BFs. Our spectroscopic orbit (Table 2) is not fully consistent with the previous result of Milone et al. (1995). In particular, the systemic velocity, $V_0 = +4.1 \pm 1.2$ km s^{-1} is now close to that of the cluster, while both, the mass ratio $q = 0.306 \pm 0.009$ and the projected total mass $(M_1 + M_2)\sin^3 i = 1.038 \pm 0.022\,M_\odot$, are larger.

Although QX And was not observed by the *Hipparcos* satellite due to its low brightness, an independent estimate of its distance can be obtained using the absolute magnitude calibration of Rucinski & Duerbeck (1997). Using the photometry of Milone et al. (1995) giving $V_{\rm max} = 11.49$ and the dereddened color $(B-V)_0 = 0.43$ (corresponding to the F5 spectral type), we obtain $M_V = 3.13$ and the distance modulus, $(V - M_V) = 8.36$ (470 pc), which is close to the range considered for NGC 752 by Schiller & Milone (1988): $(V - M_V) = 8.17 \pm 0.15$ from a full binary solution for DS And and 7.9 ± 0.2 from isochrone fitting to unevolved main-sequence stars.

2.2. DY Cet

Variability of DY Cet (HIP 12311, HD 16515) was detected during the *Hipparcos* mission where it was classified as a W UMa binary. The system has been neglected by observers in spite of its large photometric amplitude, $\Delta H_p = 0.56$, possibly because of the negative declination ($-14°18'$). A preliminary analysis of the *Hipparcos* light curve (LC) was performed by Selam (2004), who—using the Fourier-coefficient method—

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

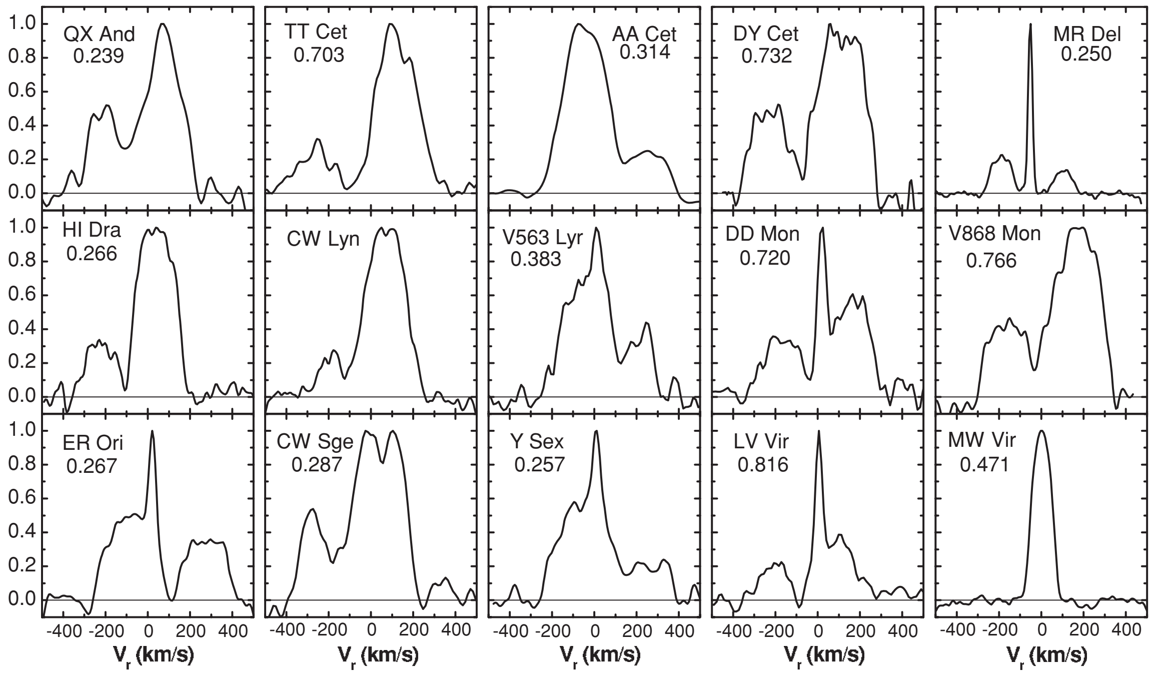

Figure 3. BFs for all systems where RV could be measured, as discussed in Sections 2 and 3, in the constellation order. The BFs were selected for orbital phases close to 0.25 or 0.75. The phases are marked by numbers in the individual panels. Additional components to the close binaries, MR Del, V563 Lyr, DD Mon, ER Ori, Y Sex, and LV Vir are strong and clearly visible. All panels have the same horizontal range, -500 to $+500$ km s^{-1}.

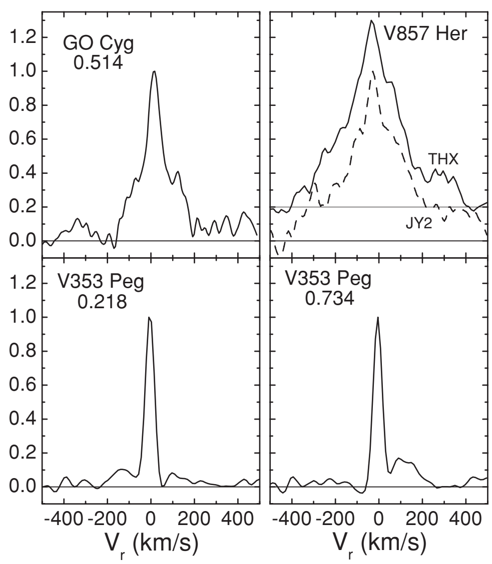

Figure 4. BFs for problematic systems GO Cyg, V857 Her, and V353 Peg. For V857 Her, BFs determined from average spectrum obtained either using the 2160 lines mm^{-1} grating and the JY2 chip or the 1800 lines mm^{-1} grating and the THX chip are shown. In the case of V353 Peg, the presence of the binary is demonstrated by the phase changes of its faint signature between the two orbital quadratures.

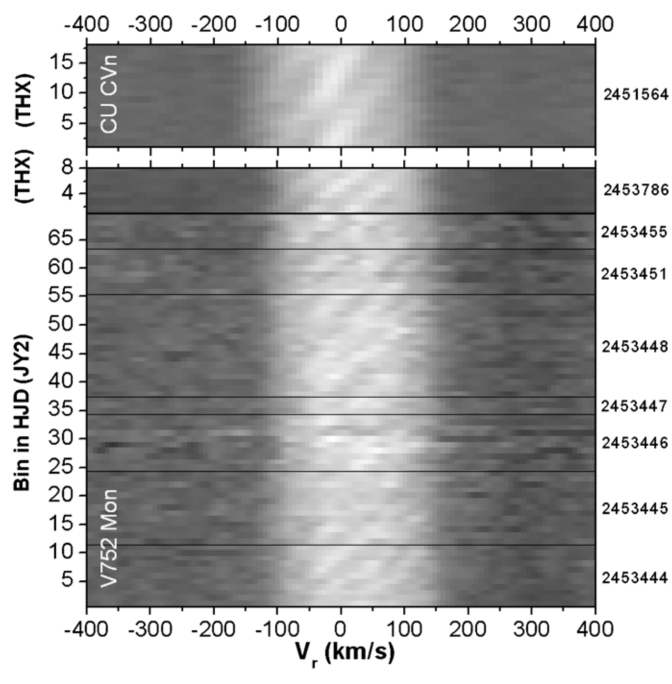

Figure 5. Gray-scale plots for two stars, CU CVn and V752 Mon, very apparently containing pulsating components. The diagonally oriented "ripples" in both cases move in the direction of the rotational motion. The BFs are sorted in time; for V752 Mon, this applies to individual nights which are separated by thin horizontal lines. One bin in the case of CU CVn corresponds to about 7 minutes, while for V752 Mon we used longer exposures and one bin corresponds to 17–18 minutes.

determined the following geometric elements: mass ratio $q_{\rm ph} = 0.45$, fill-out $f = 0.2$, and inclination angle $i = 77\overset{\circ}{.}5$. Except for a few times of minima (Krajci 2006, 2007; Dworak 2006), no systematic, ground-based observations of the system have been performed.

Because of the low sky elevation as seen from DDO, our spectroscopic observations of DY Cet were obtained over a long period of time. The orbital solution (Table 2 and Figure 1) is based on two combined data sets, one using the 1800 lines mm^{-1} grating and a THX chip and the second, more recent, obtained with the 2160 lines mm^{-1} grating and a JY2 chip. Because of the long time interval over which the spectra were taken, it was necessary to optimize the period length, in addition to the initial phase. The RVs show that the deeper minimum is an upper conjunction of the less massive component so that the system is of the A subtype.

The *Hipparcos* parallax of DY Cet, $\pi = 5.11 \pm 1.99$ mas, is of limited value for a luminosity estimate. The *Tycho-2* color index, $(B - V) = 0.39$, corresponds to an F3/4V spectral type, which would be expected for a contact binary with an orbital period of 0.44 days. The 2MASS infrared color, $(J - K) = 0.258$, is also consistent with a spectral type of F4/5V. Unfortunately, we have not obtained any classification spectra for the star.

2.3. MR Del

MR Del (HIP 101236, HD195434) is a part of a visual binary composed of $V = 9.49$ and $V = 9.77$ components, currently separated by 1$''$.8 at a position angle of 71° (Mason et al. 2001b). Cutispoto et al. (1997) found that the brighter visual component is an active eclipsing binary with $P = 0.52175(22)$ days and inferred spectral type of K for all three components. The out-of-eclipse photometric wave with an amplitude of about 0.04 mag was interpreted by the authors as due to photospheric spots. The large proper motion of the whole triple system, 0$''$.416/year, when combined with its low metallicity, $\log[m/H] = -0.99$ (relative to the Sun) indicates that it is a halo or old disk object. Photometric observations of MR Del were later obtained by Clausen et al. (2001; in the *uvby* system) and by Soydugan et al. (2001). No spectroscopy of the system has yet been available.

Our spectra included all components of the visual pair. The third component with $L_3/(L_1 + L_2) = 0.51 \pm 0.06$ (at the maximum light of the eclipsing binary) showed a stable RV, $V_3 = -51.95 \pm 0.35$ km s^{-1}, close to the systemic velocity of the close binary $V_0 = -49.8 \pm 0.8$ km s^{-1}. The BFs suggest that the eclipsing binary is a close, detached system, but without any indications of photospheric spots previously implied by the LC asymmetry and related to the strong X-ray emission (Cutispoto et al. 1997). With the new, reliably determined mass ratio and the projected total mass $(M_1 + M_2)\sin^3 i$, the system requires a new photometric analysis to determine the inclination angle and thus its absolute parameters.

The *Hipparcos* parallax, 20.72 ± 2.49 mas, although of low accuracy, can be combined with the proper motion to give the space velocity of the system, $V = 107 \pm 10$ km s^{-1}. Unfortunately, we have no classification spectra for the components of the system.

2.4. HI Dra

The variability of HI Dra (HIP 90972, HD 171848) was detected during the *Hipparcos* mission where it was classified as an RR Lyr pulsating star. HI Dra was later photometrically observed by Gomez-Forrellad et al. (1999), who suggested that it is a β Lyrae or an ellipsoidal binary system. When folding their new data and the *Hipparcos* photometric observations with the period of 0.597417 days, the authors noticed an O'Connell effect of 0.02 mag which supported the binary interpretation. The *Hipparcos* photometry was re-analyzed by Selam (2004) using the Fourier-coefficient method. The author found that the system is very probably a contact binary and obtained the first set of parameters: the mass ratio $q = 0.15$, inclination angle $i = 52^\circ.5$, and fill-out $f = 0.7$.

Our spectroscopy and the appearance of the BFs (Figure 3) confirm that HI Dra is a contact binary star. The resulting mass ratio, $q = 0.25$, is substantially larger than that found by Selam (2004) documenting the unreliability of photometric mass ratios for partially eclipsing binaries and especially systems with low photometric amplitudes. It is rather surprising, however, that the time of the lower conjunction of the more massive component occurs in photometric phase zero which indicates a W-subtype; for a low mass ratio, one would expect the A-subtype. But it is possible that the orbital period is changing or that the initial epoch was not reliably determined from the *Hipparcos* photometry.

The catalog spectral type of HI Dra, F8, does not correspond to the observed $J - K = 0.123$ (Skrutskie et al. 2006) nor to $B - V = 0.272$ (Høg et al. 2000). The relatively long orbital period of HI Dra also suggests an earlier spectral type. Although we do not have any classification spectra, we found that the best BF template for the observations around the 5184 Å triplet was for the spectral type F0-F2V. The *Hipparcos* parallax of the system is rather small, 3.93 ± 0.68 mas.

2.5. DD Mon

The variability of DD Mon (HD 292319, GSC 4800 372) was first noticed by Hoffmeister (1934). The system was studied thoroughly by Yamasaki et al. (1990), who obtained BV photometric data and medium dispersion (37 Å mm^{-1}) photographic spectra. Analysis of their LCs showed that DD Mon is a near-contact or a semidetached binary with its primary component almost filling its Roche lobe. Due to the low brightness of the system, only the primary component was identified in the spectra resulting in: $V_0 = 8.1 \pm 1.5$ km s^{-1}, $K_1 = 89.1 \pm 2.2$ km s^{-1}. The spectral type was estimated as F5IV/V. A LC analysis led to the mass ratio $q = 0.70 \pm 0.15$ and the inclination $i = 80^\circ \pm 0^\circ.4$. Later, Qian et al. (1997) obtained new *BV* photometry of the system and contrary to Yamasaki et al. (1990) found that the secondary component fills its Roche lobe.

The system is rather faint, $m_{pg} = 11.10$ at the light maximum, and we were able to take only a few spectra of it. They show three components: In addition to the rapidly rotating components of the eclipsing pair, the BFs clearly show a slowly rotating third component at $V_3 = 19.5 \pm 2.6$ km s^{-1}, with $L_3/(L_1 + L_2) \simeq 0.22$. Our orbit is based on only nine RV measurements for the primary and eight RVs of the secondary component. Therefore, we regard the resulting parameters as very preliminary. The binary system mean velocity, $V_0 = 20.2 \pm 1.9$ km s^{-1}, is equal within its error to that of the third component indicating a physical bond. DD Mon was not known to be a multiple system before and it is not listed in the Washington Double Star (WDS) Catalog (Mason et al. 2001b). The profiles of the close binary components have the same projected rotation velocity $v \sin i \simeq 130$ km s^{-1}, with the secondary significantly fainter (Figure 3), indicating detached or semidetached configuration.

We have no spectral classification spectra for DD Mon. The spectral type of the system is probably rather late in spite of the original classification in the HD Catalog of B5. The *Tycho-2* color $B - V = 0.510$ indicates the spectral type F8, while the 2MASS infrared color $J - K = 0.388$ suggests a spectral type as late as G4. The best fitting template for the DD Mon spectra was HD 187691, which has a spectral type F8V.

2.6. V868 Mon

V868 Mon (BD−2 2221, GSC 4835 1947) is a relatively bright ($V = 8.9$) W UMa-type eclipsing binary with photometric amplitude of about 0.50 mag. It was discovered on Stardial images by Wils & Dworak (2003). The authors noted that the eclipses are probably total and determined the following ephemeris for the primary minimum HJD

2452681.731 + 0.63772 × E. Later, Otero et al. (2004) identified this variable star in the NSVS photometry[9] and improved its orbital period to $P = 0.637705$ days. The authors classified this binary as EB. No further observations or investigation of the system have been published since then.

Our spectroscopy shows that V868 Mon is indeed a very close or contact binary; the profiles of the components are never completely separated. The RVs of the secondary component are rather uncertain especially around the second orbital quadrature, where the profiles usually appear to be deformed or asymmetric, indicating an intrinsic variability. An orbital period of Otero et al. (2004) was adopted in our RV orbit solution; our attempts to adjust the period did not lead to any significant improvement of the solution.

V868 Mon has a rather high systemic velocity, $V_0 = 78.1$ km s^{-1}. Unfortunately, the system was not included in the *Hipparcos* mission so that its distance is not known and the proper motion components are not precise enough to determine its space velocity. The 2MASS infrared color index of V868 Mon, $(J - K) = 0.16$, corresponds to an F0 spectral type, while the *Tycho-2* $(B - V) = 0.20$ to about A8V. The best template to the spectra, HD 128167, has a spectral type of F2V, suggesting a slightly later spectral type.

2.7. ER Ori

The variability of ER Ori (HIP 24156, WDS 05112−0833) was first noticed by Hoffmeister (1929), while the variability type was properly assigned by Florja (1931). Later, Struve (1944) obtained a preliminary spectroscopic orbit of the system which is, however, of marginal use because of the inadequate spectral resolution and a small number of observations. Because of its large photometric amplitude ($\Delta V \sim 0.6$) and short period (0.4234 days), the system was subject to many photometric studies. The photometric analyses lead to a rather inconsistent set of geometric parameters; for references and discussion, see Kim et al. (2003). A wavelike pattern in the time-of-minima $(O - C)$ diagram was interpreted in terms of an invisible body on a 35 years orbit by Abhyankar & Panchatsaram (1982).

The breakthrough investigation in the study of ER Ori was that of Goecking et al. (1994). The authors found that (1) the system is totally eclipsing with a totality lasting 12.6 minutes, (2) a third component appears in the cross-correlation functions of the spectra at a place established using speckle interferometry data (separation $\rho = 0\farcs187(7)$, position angle $\theta = 354\fdg1(15)$, intensity ratio $L_3/(L_1 + L_2) = 0.16(3)$ in the H_α filter, as of 1993 March), (3) the orbital period of the third body, as estimated from the binary period variations, is about 63 years and the orbit is seen almost pole-on, (4) the first, reliable spectroscopic orbit based on photographic spectra with parameters: $K_1 = 130.1 \pm 6.8$ km s^{-1}, $K_2 = 235.5 \pm 6.9$ km s^{-1}, $V_0 = 37.9 \pm 3.3$ km s^{-1}; with the photometrically determined inclination angle $i = 87\fdg5$, the masses are $M_1 = 1.39 \pm 0.10\,M_\odot$ and $M_2 = 0.76 \pm 0.08\,M_\odot$; (5) the third component RV is constant, $V_3 = 41 \pm 1.5$ km s^{-1}, and within the error of the systemic velocity of the close binary.

Adaptive optics and infrared observations of Rucinski et al. (2007) confirmed the presence of the third component. In 1998 January, it was practically at the same position ($\rho = 0\farcs183$, $\theta = 354\fdg4$, $\Delta K = 2.14$) as found by Goecking et al. (1994), while in 2005 October it was not detectable, indicating it was closer than the detection limit of about $0\farcs09$ (for the observed ΔK). The disappearance of the companion almost coincides with its predicted periastron passage (2004 July/August; Kim et al. 2003), as based on the observed light-time effect (LITE). The periastron passage in 2004, however, is not fully supported by the large acceleration terms observed during the *Hipparcos* program,[10] $g_\alpha = -19.26 \pm 6.57$ mas yr^{-2} and $g_\delta = -17.34 \pm 4.71$ mas yr^{-2}.

Our spectroscopic elements are different from those of Goecking et al. (1994): $K_1 = 148.0 \pm 2.3$ km s^{-1}, $K_2 = 225.5 \pm 2.3$ km s^{-1}, $V_0 = 49.4 \pm 1.7$ km s^{-1}; the mass ratio is slightly larger, $q = 0.656(12)$. The velocity of the third component was found to vary significantly between +38 km s^{-1} (HJD 2,454,180) and +20 km s^{-1} (HJD 2,454,530). This means that the third component itself is very probably also a binary. Another possibility, that the third component is a single star and revolves around the contact pair, cannot be ruled out completely as our present, good quality data still do not permit to detect the motion of the third component reflected in the contact-binary RVs. The light contribution of the third component, as found from the integrated BFs, is $\beta = L_3/(L_1 + L_2) = 0.16 \pm 0.02$, which is fairly consistent with the result of Goecking et al. (1994).

Although ER Ori was observed by the *Hipparcos* satellite, its parallax, $\pi = 4.47 \pm 3.50$ mas (van Leeuwen 2007), is basically useless (we note that it was strongly negative in the original *Hipparcos* results). The parallax problems are, very probably, due to the presence of the visual companion $13\farcs6$ to the north and to the orbital motion in the tight visual pair. The *Hipparcos* astrometry could possibly be re-analyzed utilizing observed LITE and a distance estimate from the absolute-magnitude calibration of Rucinski & Duerbeck (1997). Our own spectral-type estimate is F7/8. Assuming F8 on the basis of $(B - V)_0 = 0.54$, we obtain $M_V = 3.41$. Taking $V_{max} = 9.325$ (Goecking et al. 1994) and $\beta = 0.16$, we have $V_{max}^{12} = 9.49$ and then $d \simeq 164$ pc or $\pi \simeq 6$ mas.

2.8. Y Sex

Y Sex (HIP 49217) is a contact binary within a tight visual double (WDS 10028+0106, HDS 1451, $\rho = 0\farcs49$, $\theta = 154°$, $V = 10.08 + 12.70$). The variability of Y Sex was first noted by Hoffmeister (1934) and the first photoelectric photometry of the system was obtained by Tanabe & Nakamura (1957). Later, Hill (1979) analyzed its LC assuming the Roche model. He found it to be of the W-subtype and showing total eclipses; his determination of the geometric elements gave: $1/q = 5.72 \pm 0.07$, $i = 76\fdg8$, and a marginal contact $f = 0$. McLean & Hilditch (1983) obtained the first spectroscopic observations of the system. By measuring the metal line centroids those authors obtained the following orbital elements: $V_0 = 9.8 \pm 6$ km s^{-1}, $K_1 = 40.0 \pm 8$ km s^{-1}, and $K_2 = 218 \pm 31$ km s^{-1} resulting in the mass ratio, $q = 0.18 \pm 0.03$, i.e. compatible with the photometric determination of Hill (1979), which is not surprising since the system is totally eclipsing.

Later studies of Y Sex (Herczeg 1993; Qian & Liu 2000; Wolf et al. 2000; He & Qian 2007) concentrated on the variable orbital period of the system. Wolf et al. (2000) found that the sinusoidal variation of the orbital period can be interpreted by the presence of an invisible third body on a 58 years orbit and estimated its spectral type as M4/5 and $M_3 \simeq 0.3\,M_\odot$. Finally, Yang & Liu (2003) detected a tiny third light $L_3 = 0.0064 \pm 0.0008$ in

9 http://www.skydot.lanl.gov/nsvs/nsvs.php

10 In the new reductions of van Leeuwen (2007), the astrometric solution did not require any acceleration terms.

their LC solution. It is surprising that all investigators somehow overlooked the fact that Y Sex is part of a tight visual binary detected by the *Hipparcos* satellite (European Space Agency 1997).

Y Sex was somewhat faint for the DDO instrumentation which together with its relatively early spectral type led to noisy BFs. The very close companion separated by 0″.49 was always within the seeing disk at DDO. Its light contribution $L_3/(L_1 + L_2) = 0.11 \pm 0.03$, as determined from the BFs close to the orbital quadratures of the eclipsing pair, is slightly larger than that inferred from the magnitude difference as cataloged in the WDS.

The 2MASS $J - K = 0.278$ index is consistent with the F5 classification while *Tycho-2* $B - V = 0.39$ corresponds to a slightly earlier spectral type F3/4V. The *Hipparcos* parallax, $\pi = 8.75 \pm 2.09$ mas is rather imprecise to be of any use. Our classification spectra indicate the spectral type F5/6.

3. BINARY STARS WITH INSUFFICIENT ORBITAL COVERAGE

Several targets were observed at DDO but a sufficient phase coverage was not achieved either due to low brightness (resulting in poor spectra), low sky elevation or the DDO closure before the conclusion of this program. Below, we describe systems for which RV data were collected, but usually only one orbital quadrature was adequately covered. Such data do not define the mass ratio reliably but can be used to estimate the total projected semiamplitude $(K_1 + K_2)$ and thus the total projected mass, or can be combined with future observations.

3.1. TT Cet

Properties of TT Cet (HIP 8294) are discussed and a preliminary orbit given in Duerbeck & Rucinski (2007). It is a close, but very probably a detached or semidetached binary. The system was found to be too faint and too low over the southern, city-illuminated sky for DDO ($\delta = -9°45'$, $V_{\rm max} = 10.9$). The quality of the extracted BFs was further deteriorated by the fairly early spectral type and thus a correspondingly weak Mg I triplet.

Most of the BFs extracted from the DDO spectra show only the primary component; the secondary is visible in only one BF, see Figure 3. Our RVs (Table 1) are given only for the primary component. The 2MASS color index $J - K = 0.25$ indicates the F4/5V spectral type, while the *Tycho-2* $B - V = 0.404$ corresponds to an F3/4 spectral type. Our own spectral classification confirms a spectral type of F4V.

3.2. AA Cet

For a full discussion of this system, see Duerbeck & Rucinski (2007). Because AA Cet (HIP 9258, HD 12180) was visible very low from DDO, we were able to take only 11 spectra of this system; unfortunately, most of them happened to be close to the conjunctions. Therefore, we are giving only a few RV determinations for AA Cet in Table 1. The extracted BFs show a systematic difference between the quadratures: while around the phase 0.25, the profile of the secondary is close to the expected rotational profile, the profiles for the phases around 0.75 appear narrower and triangular or irregular shape. Our classification spectra indicate the spectral type F4V.

3.3. CW Lyn

Variability of CW Lyn (HIP 42554) was discovered by the *Hipparcos* mission, where it was classified as a β Lyrae variable with 0.812389 days orbital period. Later, Selam (2004) analyzed the *Hipparcos* LC using the Fourier-coefficient method and found that the system is a genuine contact binary. The author determined the following preliminary parameters: a fill-out $f = 0.0$, mass ratio $q = 0.10$, inclination angle $i = 77°.5$. The *Hipparcos* LC with the amplitude of about $\Delta V = 0.25$ indicates a possibility of total eclipses for a low mass ratio system. No ground-based observations of the system have been published so far.

Our spectroscopy covers the second orbital quadrature only. The *Hipparcos* ephemeris does not satisfactorily predict phases of our spectroscopy indicating either a significant period change or a problem with the ephemeris. The BFs (see Figure 3) support the low mass ratio of the system but show some peculiarities similar to those seen in AW UMa (Pribulla & Rucinski 2008): (1) the secondary has a triangular shape and (2) the primary component has a wide base underneath a relatively narrow profile, in a clear disagreement with the Roche model.

The system was included in the *Hipparcos* mission, but its parallax, $\pi = 3.93 \pm 1.37$ mas, is of limited use. The BF strengths indicate the F3/4 spectral type which is fairly consistent with the 2MASS color $J - K = 0.263$. Our classification spectrum corresponds to the same spectral type, F4V.

3.4. V563 Lyr

Variability of V563 Lyr (NSV 11321) was noted by Hoffmeister (1966) and the system was later photometrically observed by Beltraminelli et al. (1999), who found it to be a contact binary with $P = 0.577639$ days, and estimated its spectral type as F5. The LC minima seemed to be of similar depth. The authors also noted that the components are very probably evolved because of the rather late spectral type for the orbital period. Except for a few minima observations, the system has never been studied in detail.

With a visual magnitude ranging between 10.96 and 11.47 (Beltraminelli et al. 1999), the system was difficult for the DDO spectral observations. Most of the spectra were noisy so that only eight observations during two nights of excellent seeing were useful for RV determinations (see Table 1). The BFs immediately show that the system is accompanied by a third component with a light contribution of about $L_3/(L_1 + L_2) = 0.15$. Unfortunately, only one orbital quadrature was covered with good observations preventing a reliable determination of the orbit. Assuming that the third component is physically bound, and that its velocity, $V_3 = \sim 14$ km s^{-1}, is identical to the center-of-mass velocity of the contact binary, we can roughly estimate the mass ratio at $q = 0.37$ and the total projected mass at a relatively high value of $(M_1 + M_2)\sin^3 i = 3.0\,M_\odot$.

The trigonometric parallax of V563 Lyr is unknown since it was not included in the *Hipparcos* mission. Its 2MASS infrared color $J - K = 0.216$ corresponds to the F2/3 spectral type while the *Tycho-2* color is $B - V = 0.456$, implying F5V is probably affected by the interstellar extinction.

3.5. CW Sge

CW Sge (HIP 98430) is a rather faint ($V_{\rm max} = 11.0$) contact binary. Its variability was noticed by Hoffmeister (1935) who classified the system as an RR Lyr variable with $P = 0.330223$ days. Later, Lange (1960) found it to be a W UMa variable with a 2 times longer period. In the catalog of Brancewicz & Dworak (1980), CW Sge is a close but detached binary with components filling, respectively, 86% and 85% of their Roche radii. No other photometric or spectroscopic study of the system has yet been published. The adaptive optics observations of Rucinski et al. (2007) showed that the binary is accompanied by a late-type companion separated by 1″.84. This companion most probably entered the slit of the DDO spectrograph during periods of bad seeing. CW Sge may, in fact, host an even closer companion as indicated by a large, 7.64 mas, "cosmic error" in the original *Hipparcos* astrometric solution (European Space Agency 1997), leading to a negative parallax, $\pi = -0.23 \pm 2.41$ mas.

CW Sge was found to be too faint for DDO and was abandoned. Only one orbital quadrature (phase 0.75) was observed making a reliable orbit determination impossible. The best template for the observed spectra is that of an F8 spectral type, which appears to be too late for a contact binary with orbital period as long as $P = 0.66$ days. The RVs show that the more massive component is the cooler one. Our own spectral classification spectrum suggests a spectral type of F6, which is moderately consistent with $J - K = 0.23$ which suggests type F3.

3.6. LV Vir

Variability of LV Vir (HIP 66078, HD 117780) was detected by the *Hipparcos* mission, where it was classified as a β Lyrae variable with orbital period $P = 0.409439$ days. LV Vir is a member of the relatively close visual binary WDS 13328−1746 consisting of $V = 9.09$ and $V = 9.43$ components, currently at the position angle $\theta = 27^\circ$ and the separation $\rho = 1''.2$. This resulted in the inclusion of both components into the DDO spectrograph slit. The Fourier analysis of the *Hipparcos* LC by Selam (2004) showed that LV Vir is a genuine contact binary. Except for speckle interferometry observations of the visual pair, no ground-based photometry or spectroscopy of the system has been published yet, in spite of the fairly large photometric amplitude of the variable ($\Delta V = 0.20$).

Because of the southern declination of the star, we were able to take only three spectra of the system. The resulting BFs (see Figure 3) show all three components (the binary and the visual companion) and support the contact configuration for the close binary system. Although we do not have a classification spectrum for the system, the best match to the observed spectra of LV Vir indicates the F6/7 spectral type. The 2MASS infrared color $J - K = 0.282$ corresponds to the F5 spectral type, while the *Tycho-2* $B - V = 0.521$ corresponds to the F7/8 spectral type.

3.7. MW Vir

MW Vir (HIP 69828, HD 125048) was found to be variable during the *Hipparcos* mission. The wavelike variation with $\Delta H_p = 0.03$ and $P = 0.246539$ days could either result from pulsations of a single star or from ellipsoidal variations in a close binary. Although the system is a very bright one, $V \simeq 7.0$, no ground-based observations of the star have been published yet. MW Vir was identified with an X-ray source both in the *Einstein* and *ROSAT* observations indicating a late-type companion to the moderately early-type star (Chisholm et al. 1999).

Nine spectra taken close to the conjunction show that MW Vir is definitely a binary star. Unfortunately, only one component is spectrally visible with determinable RV so that the secondary is probably a low-mass, late-type star. The rotational velocity of the primary is about $v \sin i \simeq 75$ km s^{-1}; its orbital RVs were observed to decrease by 33 km s^{-1} over the phase interval of 0.123 (see Table 1).

The system is relatively nearby, with the *Hipparcos* parallax of 12.40 ± 1.10 mas. The *Tycho-2* $B - V = 0.229$ corresponds to a spectral type of A7-8V, while the 2MASS $J - K = 0.186$ gives a substantially later type, F1V. Assuming that the system is a contact binary and using the absolute magnitude calibration of Rucinski & Duerbeck (1997) we find $M_V^{\rm cal} = 2.18$ (for $B - V = 0.23$), which is consistent with the absolute magnitude given by the *Hipparcos* parallax, $M_V = 2.42$.

4. DIFFICULT BINARY STARS

In this section, we present fragmentary results for binary systems where, although attempted, no reliable measurements of RVs could be obtained. Although only indicative, these results may lead to further research as some of the objects appear to be very interesting.

The problems that we encountered were as follows: (1) the target was observed too low on the DDO sky resulting in poor spectra; (2) the spectral type was found to be rather early making the lines of the Mg I triplet too weak; (3) the target was too faint for our telescope—spectrograph combination; (4) the close binary was found to be accompanied by a third, bright and dominant, rapidly rotating companion spectrally obscuring the binary; (5) the third component had a significantly different spectral type from the binary and suppressed the binary signature in the BFs.

4.1. GO Cyg

GO Cyg (HIP 101748, HD 196628) is a close but very probably detached eclipsing binary system; for references and details, see Sezer et al. (1993) and Oh et al. (2000). Its spectroscopic orbit based on RVs obtained by the cross-correlation function (CCF) method was presented in Sezer et al. (1993).

The system consists of components of different temperatures ($T_1 = 10{,}700$ K and $T_2 = 6200$ K) and thus it is not ideal for the BF approach; moreover, the primary is too early to have sufficiently strong lines in the Mg I region. Only four spectra of the system were taken, all close to the secondary minimum. In addition to the primary component of the binary, one can clearly see an additional component rotating with $v \sin i =\sim 35$ km s^{-1} (see Figure 4). It is interesting to note that the third component was not noted in the CCFs analysis presented by Sezer et al. (1993). A reliable analysis of the system would require a high-dispersion spectroscopy over the whole optical range for a spectral disentanglement of all components.

4.2. V857 Her

The variability of V857 Her (GSC 3070 345, $V_{\rm max} = 10$, sp. type A6) was noticed by Geyer et al. (1955), who proposed it to be a Cepheid pulsating star. No systematic observations of the system were performed until 1996, when Gomez-Forrellad & Garcia-Melendo (1996) obtained extensive CCD photometry of the system and found it to be a totally eclipsing W UMa binary with $P = 0.3825$ days. A preliminary solution of the LCs—mostly driven by the small photometric amplitude and the presence of total eclipses—led to a very low mass ratio, $q_{\rm ph} = 0.0725 \pm 0.050$, and a high fill-out factor $f = 0.80 \pm 0.10$. The authors also noticed cyclic LC changes. Later, Qian et al. (2005) determined an even smaller (in fact, a record small) mass ratio, $q_{\rm ph} = 0.0653$. No spectroscopic study of the system has been published so far.

Two sets of spectra of V857 Her were obtained at DDO, the older set using the 1800 lines mm^{-1} grating and THX chip and the more recent set using the 2160 lines mm^{-1} grating and the JY2 chip. The spectral lines in Mg I region are surprisingly shallow resulting in poor BFs for either of the DDO data sets; basically, no trustworthy RVs could be determined. Averaging of all available spectra for either of the data sets has resulted in reasonable mean BF when analyzed with an F2 template (Figure 4); the BFs corresponded to a single, relatively rapidly rotating star with a presumed presence of another component in the system. The secondary component was not visible due to a (possibly) low mass ratio and, obviously, to the averaging of the spectra. Subtracting the corresponding binary contribution (obtained by a convolution of the template spectrum with the BF) results in a residual spectrum resembling that of a late B-type or an early A-type star rotating at $v \sin i \simeq 50$ km s^{-1}. Because this approach involves an average spectrum, we cannot say if the early-type component detected that way is a binary or a single star. If this component is physically connected with the close binary, it must be a hot subdwarf, either a single or binary star. V857 Her did not appear to be a visual double on the spectrograph slit and is not listed in the WDS Catalog (Mason et al. 2001b).

The peculiarity of the system was noticed before by Pribulla & Rucinski (2006) in that it appeared too blue for its orbital period of 0.3825 days. The *Tycho-2* color index $(B - V) = 0.164$, corresponds to the A6 spectral type, while our classification spectrum indicates an A7 spectral type. The presence of an early-type component would explain the period–color discrepancy and the shallowness of the eclipses but would also put in doubt the very low mass ratio previously indicated by the LC modeling. V857 Her is a very interesting system and certainly deserves a dedicated study based on high signal-to-noise ratio, wide wavelength coverage (echelle) spectra.

4.3. V752 Mon

V752 Mon (HIP 34401, HD 54250) is a member of the visual binary WDS 07079−0441 ($V = 7.47 + 7.95$, $\theta = 24°$, $\rho = 1''.7$). During the *Hipparcos* mission, it was found that the object is a low-amplitude variable and was tentatively classified as a δ Scuti pulsator. The rather early spectral type, A9V–F0V, supported this classification. However, knowing how many *Hipparcos* short-period pulsating stars turned out to be close binaries, we included V752 Mon in our binary star program.

Unfortunately, the orientation of the visual pair was not convenient so that on most nights both components were simultaneously included in the spectrograph slit. The brighter component dominated in the spectra, but the extracted BFs do not show any changes when arranged versus the presumed pulsation period or versus a period 2 times longer. In fact, the BFs show only one rapidly rotating component with $v \sin i \sim$ 155–160 km s^{-1}, with no traces of the visual companion which would be expected for two almost identical components with only a 0.5 mag difference (Mason et al. 2001b).

The dominating star in the spectra appears to be a δ Scuti star. The BFs clearly show wavelike structures propagating on the surface of the rapidly rotating star which can be explained by nonradial modes with $m \simeq$ 8–10. We describe a similar case with very clear signatures of nonradial pulsations, CU CVn, in Section 5 (see Figure 5) where we comment on the applicability of the BF technique to pulsating stars.

At this point, we cannot exclude a possibility that the photometric (binary star) variability comes from the secondary component of the visual pair and that pulsations of the dominating star simply mask the spectral signatures of a close binary in that star. It is puzzling that the visual secondary is not present in our spectra at all. Its absence may be explained in two ways: (1) it is also a rapidly rotating star at the (almost) same RV as the primary so that the two broad profiles overlap or (2) it is in fact a close binary, but because our spectra—in the mediocre seeing conditions—were guided on the brighter component of the pair, the light contribution of the secondary to the spectra was lesser than expected. Obviously, only spectra of individual components of the visual pair will establish which component is variable and what is its type.

We note that if we were sure that a close binary is not hiding as the secondary of the visual pair, we would have included V752 Mon in Section 5, among pulsating stars serendipitously observed by us during our program.

4.4. V353 Peg

V353 Peg (HIP 116108) is a bright ($V_{\rm max} = 7.42$) low-amplitude ($\Delta H_p = 0.07$) variable discovered by the *Hipparcos* satellite and classified as a β Lyrae-type eclipsing binary with a period of 0.584557 days. The eclipsing pair is very probably accompanied by a third component because the system shows a nonlinear sky motion as indicated by its astrometric solution requiring an acceleration term (the "G" flag in H59).[11] Unfortunately, speckle interferometry of Mason et al. (2001a) could not resolve the visual pair. V353 Peg was observed spectroscopically as part of the ground-based spectroscopic support of the *Hipparcos* mission (Fehrenbach et al. 1997): the four RV observations showed a spread of 40 km s^{-1}. Otherwise, this bright variable has been rather neglected.

The BFs show a strong, dominating, slowly rotating component accompanied by very faint features of a close binary. The BFs extracted around the binary quadratures conclusively show the phase variations expected for a close binary. However, the binary is just barely distinguishable at the base of the strong peak of the companion (Figure 4) so its RVs could not be well determined. The BF analysis was further complicated by a significant difference in the spectral types of the binary and its bright companion resulting in a depression around the dominant component which affects the residual profile of the binary. The third component is significantly brighter than the eclipsing binary with $L_3/(L_1 + L_2) \simeq 2.5$ preventing a sound analysis of the system. The RV of the third component was found to be practically constant at $V_3 \simeq -5$ km s^{-1} (see Table 3).

The 2MASS infrared color $J - K = 0.158$ corresponds to the F0V spectral type which is fairly consistent with the *Tycho-2* $B - V = 0.21$ implying an A8 type. Our own, rather uncertain classification indicates a combination of spectral types, A7 and F2, possibly corresponding to the dominant third component and the eclipsing binary.

4.5. MS Vir

MS Vir (HIP 68881) is another *Hipparcos* discovery. The system was originally classified as a β Lyrae eclipsing binary with the variability period of $P = 0.31244$ days. According to Selam (2004), who modeled the *Hipparcos* photometry using the Fourier-coefficient method, MS Vir is not a β Lyr system but a contact binary with the geometric parameters: $q = 0.25$, $f = 1.00$, and $i = 52^\circ.5$.

Because the system was visible very low at DDO ($\delta = -17°41'$), we obtained only seven spectra of the system.

[11] In the new reduction of *Hipparcos* raw data (van Leeuwen 2007), there is "stochastic" solution for V353 Peg instead.

Table 3
RV Observations of the Third and Fourth Components of Multiple Systems

Target	HJD–2,400,000	V_3 (km s^{-1})	V_4 (km s^{-1})
ET Boo	53812.95453	−77.29	48.18
ET Boo	53842.77197		
ET Boo	53843.74628	−45.12	17.01
MR Del	54630.82080	−49.87	
MR Del	54638.68821	−50.06	
MR Del	54638.69974	−50.28	
MR Del	54638.71214	−50.20	
MR Del	54638.72308	−52.02	
MR Del	54638.73503	−49.74	
MR Del	54638.74573	−52.78	

Notes. The table gives the RVs V_i for the third and fourth components. The 10 rows of the table for the quadruple system, ET Boo, and the triple system MR Del are shown. Observations of quadruple systems leading to entirely inseparable BF peaks of components of the second binary have been omitted from the table and not used in computation of the orbits (the heliocentric Julian dates are, however, given). The first three RV observations of TV UMi (at HJD 2,452,694) were found to be incorrect in the original publication (Pribulla et al. 2006). Correct values for RV of third and fourth components are given here.
(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Although we attempted to obtain well-exposed spectra using 900 s exposures, the spectra and resulting BFs are too poor to enable reliable RV measurements. The BFs indicate that MS Vir is indeed a close binary composed of similar components. New spectroscopy from the Southern hemisphere is needed to derive reliable parameters of the system. We note that the *Hipparcos* parallax of the star is rather large, $\pi = 13.36 \pm 1.65$ mas, so that the system is nearby.

5. LOW-AMPLITUDE AND PULSATING VARIABLES

5.1. Low-Amplitude Variables

The *Hipparcos* mission has detected many low-amplitude variables with variability periods between 0.1 and 0.5 days. As the original analyses and subsequent studies have shown, the variables turned out to be mostly pulsating stars of δ Sct, RR Lyr, SX Phe, and γ Dor types with an admixture of contact binaries seen at low inclination angles. As was demonstrated by Rucinski (2001), the probability of very small amplitudes for contact binaries does not go to zero with $i \rightarrow 0$ but rather stabilizes at a finite value. Additionally, low amplitudes of some among the close binaries could be caused by the presence of a third component. In such cases, companions may force bluer colors of the combined systems making them more similar to pulsating stars; this would invalidate the period–color diagram approach of Duerbeck (1997) of finding contact binaries among small-amplitude variables. Our series and its companion investigations on triplicity of close binaries (Pribulla & Rucinski 2006; D'Angelo et al. 2006; Rucinski et al. 2007) have shown that the frequency of companions to close binaries is exceptionally high and may be approaching 100%. For that reason, we felt that many stars classified as pulsating by the *Hipparcos* project required checking for the possibility of being in fact binaries. In most cases, we stopped further observing after establishing that a star is a sharplined one and thus not a close binary. But, sometimes, when the presence of a dominating third component was suspected, we continued our observations. Thus, in this somewhat erratic way, we collected several RV observations which may be of use in the future.

Throughout the DDO close binary program, we stumbled upon 17 low-amplitude variables which were hard to classify and where only one spectral component seen at a constant RV was detected. For these systems we give mean RV, the projected rotational velocity, $v \sin i$, and estimated spectral type in Table 4. The individual RVs and rotational velocities are given in Table 5. Of course, we do not exclude a possibility that some of the constant velocity stars are in fact close binaries, possibly with companions. Here, we simply report our findings for any future use.

5.2. V752 Mon and CU CVn

The most obvious nonradially pulsating stars observed in this program are V752 Mon (this system may contain a close binary, Section 4.3) and CU CVn. Both variables show rapid rotation and in both, "bumps" or "ripples" are clearly present in their BFs when these are arranged in phase into two-dimensional displays (Figure 5). In both cases, the ripples move in the direction of the stellar rotation and are uniformly distributed along the stellar longitudes clearly indicating nonradial pulsations. Such ripples have been observed before in individual lines or in cross-correlation analysis studies of δ Sct stars (Mantegazza 1997, 2004). Here, we see them very well defined in the BFs which attests to the usefulness of this technique even for pulsating stars: apparently, all lines in our spectral window of some 240 Å behaved and traced the pulsations the same way.

We have more data for V752 Mon than for CU CVn (Figure 5), but the quality is poorer, possibly because of a more complex nature of the multiple system and the possible presence of the close binary (Section 4.3). It is very interesting that we can distinguish the very stable, practically totally unmodified ripple pattern after one year (exactly 342 days) separating the first and the last nights of the V752 Mon observations. The nonradial modes appear to be prograde ones with $m \simeq 8$–10.

In the case of CU CVn, the ripples are even better defined and can be easily measured for the temporal period of return of $P \sim 0.4$–0.5 days. Vidal-Sáinz et al. (2002) rejected the original *Hipparcos* classification of the star as a W UMa binary (which was the reason for us to observe the star) and gave the dominant pulsation period as 0.0678 days, i.e., one half of the *Hipparcos* period. The appearance of the ripples, compared with theoretical simulations (Kochukhov 2004), indicate sectoral mode with $l = m = 6$–8 and an axial inclination angle $i \sim 90^\circ$.

Both, V752 Mon and CU CVn, definitely deserve new high-resolution spectroscopy. We suspect a similar picture to emerge for IN Dra (see below) but—with only a few spectra for this star—we cannot state anything definitely.

5.3. Other Single or Pulsating Stars

The main spectroscopic results for low-amplitude variables observed during the DDO binary program are given in Table 4. Unambiguous variability classification have been possible only for a few of them because of the small number of spectra or short, one night durations of some of our observations. These limitations apply especially to HV Eri, V1359 Ori, and GG UMa, for which we cannot reject a possibility that they are eclipsing variables seen at low inclination angle; these systems could either be SB1 or observed close to either of the conjunctions.

In the pulsating star CC Lyn, the DDO data probably relate only to the brighter component of the visual pair. The RV of CC Lyn was found to vary between +15 km s^{-1} and +23 km s^{-1}.

Table 4
Low-amplitude Variable Stars Found to be Pulsating or of Unknown Type

Target	RV (km s^{-1})	$v \sin i$ (km s^{-1})	Sp. Type	No. of Obs.	ΔH_p	Period (days)	Class 1	Class 2
FH Cam	3.0	45	A8	36/1	0.07	0.272478		Puls.
CU CVn	−4.1	155	A7	18/1	0.08	0.135667		Puls.
V364 Cep	+8.9	153	(A0)	10/1	...	...		Puls.
V459 Cep	+1.2	97	(F7)	3/1	0.05	0.178805	EW or puls.	Puls.
V2129 Cyg	−22	54	(F8)	1/1	0.11	0.154876	Puls.	EW or puls.
GW Dra	var?	<15	(F2)	4/2	0.10	0.126184	Puls.	Puls.
IN Dra	var?	147	(F0)	5/3	0.06	0.137171	Puls.	Puls.
HV Eri	−8.1	83	(F4)	1/1	0.14	0.210948	EW or puls.	EW or puls.
PV Gem	var?	135:	F5-7	10/2	0.07	0.188065	EW or puls.	Puls.
V927 Her	−21	<15	(F4)	1/1	0.17	0.130528	Puls.	Puls.
UX LMi	var	60:	(F7)	3/3	0.12	0.150638		Puls. ?
CC Lyn	var	<15	F0-2	62/4	0.10	0.354622	EW	Puls + EW ?
V752 Mon	23	159	(F0)	75/7	0.05	0.231451	EW	Puls + EW ?
V1359 Ori	−20.8	60	(F7)	2/1	0.08	0.182158	EW or puls.	Puls. ?
V579 Per	−3.5	228	A4/5	65/6	0.10	0.232812	EW	Puls.
GG UMa	−16.5	60	(F6)	2/1	0.11	0.134841	Puls.	Puls.
GS UMa	−3.4	38	(F5)	4/1	0.07	0.164007	Puls.	Puls.

Notes. The table gives the mean RVs for stars which are very probably pulsating variables or for multiple systems with one dominant variable component. Projected rotational velocities are given when $v \sin i > 30$ km s^{-1}. Spectral types in parentheses have been taken from the literature, otherwise they are from our classification spectra. The extent of our observations can be judged from the column "No. of Obs." where the number of observations is given as: No. of spectra/No. of nights. The *Hipparcos* amplitude, ΔH_p (95th percentile − 5th percentile) and the variability period are taken from the *Hipparcos* photometry Annex. For three systems, FH Cam, CU CVn, and CC Lyn, originally classified as β Lyrae variables, this period corresponds to the double wave; for those stars, if definitely shown to be pulsating variables, one half of the *Hipparcos* period should be taken. The last two columns "Class 1" and "Class 2," give the variability classification following Duerbeck (1997) and our "best effort" estimate, respectively. Stars known to be members of visual pairs in Mason et al. (2001b) are HV Eri (the components about 30″ apart), PV Gem (the brighter component of a very wide visual pair, about 2′ apart), CC Lyn ($V = 6.62 + 8.26$, $\theta = 88°$, $\rho = 2\farcs2$), and V752 Mon ($V = 7.47 + 7.95$, $\theta = 24°$, $\rho = 1\farcs7$). The pulsating star V364 Cep was observed by us by mistake; it is the only variable listed in this table which was not discovered by the *Hipparcos* satellite mission.

Table 5
RV Observations of Single and Pulsating Stars

Target	HJD–2,400,000	RV (km s^{-1})	$v \sin i$ (km s^{-1})
FH Cam	51658.65601	1.32	44.75
FH Cam	51658.71993	3.12	42.96
FH Cam	51658.72485	3.43	44.44
FH Cam	51658.72974	5.44	45.62
FH Cam	51658.73760	2.52	44.71
FH Cam	51658.74251	2.73	43.88
FH Cam	51658.74740	1.98	43.47
FH Cam	51658.75230	2.88	44.33
FH Cam	51658.76016	1.55	43.53
FH Cam	51658.76505	2.46	44.58

Notes. Projected rotational velocity, $v \sin i$ is given only for rapidly rotating stars with $v \sin i > 30$ km s^{-1}. For V752 Mon BFs determined from observations around 6290 Å lead to very scattered RVs—those are not given in the table.
(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

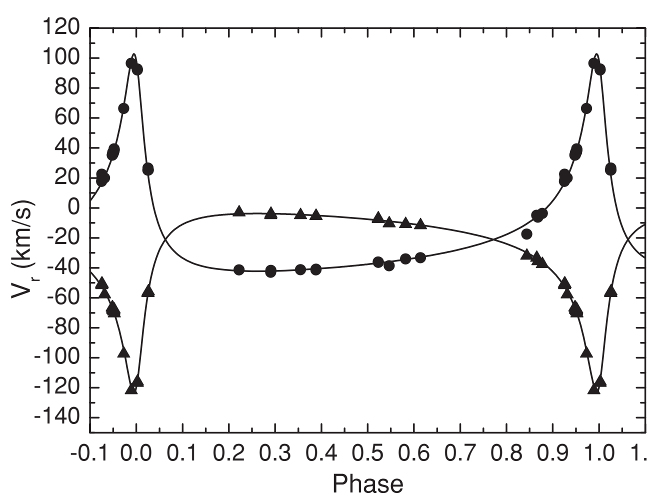

Figure 6. RVs of the third and fourth components of the quadruple system TV UMi. The corresponding spectroscopic orbital solutions are shown by continuous lines.

6. SPECTRAL CLASSIFICATIONS

During our program, we realized the value of independently acquired spectral classifications. For that reason, we planned to classify all binaries without available spectral types. Unfortunately, we have not been able to achieve this for all binaries of this series before the observatory closure. In addition to the data for the eight binaries which form the main results of this paper, as given in Table 2, we obtained classification spectra only for systems originally studied in the first paper of the series: Lu & Rucinski (1999, Paper I). The spectral types were determined for V417 Aql (F7V), LS Del (F5-8V), EF Dra (F8/9V), V829 Her (F6-9V), UV Lyn (G0V), BB Peg (F7V), and AQ Psc (F5-8V). Also, we determined the spectral types for three stars which were later found to be pulsating: FH Cam (A8V), CU CVn (A7V), and CC Lyn (F0-2V).

7. QUADRUPLE SYSTEMS

Four quadruple systems were previously observed and analyzed at DDO: ET Boo, XY Leo, VW LMi, and TV UMi (Pribulla et al. 2006, 2007). Because of the high significance of these results for our understanding of the stability of those tight

Table 6
Updated Spectroscopic Orbital Elements of the Second (Noneclipsing) Binaries in the Quadruple Systems ET Boo, XY Leo, and TV UMi

Parameter		Error
XY Leo		
P_{34} (days)	0.8047497	0.0000042
T_0 (HJD)	2 453 882.1270	0.0008
V_0 (km s^{-1})	−39.97	0.22
K_3 (km s^{-1})	46.44	0.34
$f(m)$ ($M_\odot$)	0.00839	0.00018
ET Boo		
P_{34} (days)	31.52135	0.00045
e_{34}	0.738	0.011
ω (rad)	2.952	0.026
T_0 (HJD)	2 452 930.737	0.027
V_0 (km s^{-1})	−24.09	0.43
K_3 (km s^{-1})	40.17	0.66
K_4 (km s^{-1})	57.31	0.67
$(M_3 + M_4)\sin^3 i$ ($M_\odot$)	0.928	0.052
TV UMi		
P_{34} (days)	31.18836	0.00037
e_{34}	0.757	0.006
ω (rad)	3.499	0.013
T_0 (HJD)	2 453 192.994	0.016
V_0 (km s^{-1})	−21.12	0.26
K_3 (km s^{-1})	59.84	0.52
K_4 (km s^{-1})	72.46	0.53
$(M_3 + M_4)\sin^3 i$ ($M_\odot$)	2.084	0.063

Notes. The table gives spectroscopic elements of the second binaries in the quadruple systems: orbital period (P_{34}), eccentricity (e_{34}), longitude of the periastron passage (ω), time of the periastron passage (T_0), systemic velocity (V_0), and semiamplitudes of the RV changes (K_3, K_4). The corresponding mass ratio q, and total mass ($(M_3 + M_4)\sin^3 i$) are given for ET Boo and TV UMi, where both components of the second binary could be measured. For the single-lined noneclipsing binary in XY Leo, only $f(m)$ is given. The orbit of the second binary in XY Leo is circular, thus $e_{34} = 0.00$ and $\omega_{34} = \pi/2$.

quadruple systems and to improve the orbits of the companion (not close) binaries, we continued acquisition of the spectra for these systems until the closure of the observatory.

New RV observations of VW LMi were published in a subsequent dedicated paper (Pribulla et al. 2008), while the data for the remaining systems are listed in Table 3. The corresponding orbital elements for ET Boo, XY Leo, and TV UMi are given in Table 6. For TV UMi, the new observations enabled us to determine the orbital period and the spectroscopic elements; we note that both were indeterminable in the original paper (Pribulla et al. 2006) of the DDO series. The RVs of TV UMi and their best fits are shown in Figure 6.

8. SUMMARY

With RV orbits for the last eight short-period binaries, this last paper of the DDO series brings the number of the systems studied at the DDO to 141. There have been 138 orbits contained in 14 of the 15 papers of this series (the seventh paper, Rucinski 2002, did not contain any new data) plus the separate investigations of W Crv (Rucinski & Lu 2000), AW UMa (Pribulla & Rucinski 2008), and GSC 1387 475 (Rucinski & Pribulla 2008).

This paper—in addition to the eight systems with the reliable orbits—summarizes all remaining, unpublished spectroscopic material obtained within the close binary project. The included material consists of systems with insufficient phase coverage, problematic systems (too faint, too southern for DDO or too complex multiples), and systems found or suspected to be pulsating variables. For most of the binaries of this paper, we are presenting the first spectroscopic observations. The highlights of the current study are (1) the discovery of four triple systems GO Cyg, V563 Lyr, DD Mon, V353 Peg; (2) the discovery of an underluminous, early-type component in V857 Her; (3) detection of prograde-rotating ripples in BFs of CU CVn and V752 Mon indicating nonradial pulsations.

Numerous discoveries and reliable solutions of triple and quadruple systems show that the BF deconvolution approach utilizing the singular value decomposition (SVD) method is a powerful and reliable technique which can be applied not only to close binaries but also to other types of spectral line broadening due to geometrical effects. A good example of the power of this technique is our detection of nonradial oscillations in two pulsating variables, CU CVn and V752 Mon. As far as we know, the nonradial pulsations have been detected only in the variability of line profiles of selected spectral lines (Zima et al. 2006) or in CCF studies; the latter obviously with a loss of information because the CCF technique reduces the effective spectral resolution. The only time the BF technique has been applied to a δ Sct star (EE Cam; Breger et al. 2007) indicated a potential for discovery of fine structure in line profiles, probably akin to the ripples seen in CU CVn and V752 Mon.

With the closure of the DDO observatory, this series has come to an end; only a dozen or so known W UMa-type eclipsing binaries brighter than about $V = 10$ and potentially accessible from DDO remain unobserved. Our analysis for several stars presented here may feel incomplete and unsatisfactory. We still hope that the material presented will still lead to or will supplement future followup observations of several binary stars described here.

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