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RADIAL VELOCITY STUDIES OF CLOSE BINARY STARS. XII.[1]

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ABSTRACT

Radial velocity measurements and sine-curve fits to the orbital radial velocity variations are presented for 10 close binary systems: OO Aql, CC Com, V345 Gem, XY Leo, AM Leo, V1010 Oph, V2612 Oph, XX Sex, W UMa, and XY UMa. Most of these binaries have been observed spectroscopically before, but our data are of higher quality and consistency than in the previous studies. While most of the studied eclipsing pairs are contact binaries, V1010 Oph is probably a detached or semidetached double-lined binary, and XY UMa is a detached, chromospherically active system whose broadening functions clearly show well-defined and localized dark spots on the primary component. A particularly interesting case is XY Leo, which is a member of visually unresolved quadruple system composed of a contact binary and a detached, noneclipsing, active binary with an 0.805 day orbital period. V345 Gem and AM Leo are known members of visual binaries. We found faint visual companions at about 2″–3″ from XX Sex and XY UMa.

Key words: binaries: close — binaries: eclipsing — stars: variables: other

Online material: machine-readable tables

1. INTRODUCTION

This paper is a continuation of a series of papers (Papers I–VI and VIII–XI) of radial velocity studies of close binary stars and presents data for the 11th group of 10 close binary stars observed at the David Dunlap Observatory (DDO). For full references to the previous papers, see Pribulla et al. (2006, Paper XI); for technical details and conventions, the presentation of the broadening functions approach, and preliminary estimates of uncertainties, see the interim summary paper by Rucinski (2002, Paper VII). The recent DDO studies use the very efficient program of Pych (2004) for removal of cosmic rays from the two-dimensional images.

While most of the data used in this paper were determined using the broadening functions (BFs) extracted, as in the previous papers, from the region of the Mg I triplet at 5184 Å, we also used a few observations of XY UMa from a region centered at 6290 Å. This experimental setup, which included telluric features, was used (1) because of concerns about flexure effects in our spectrograph and (2) to improve visibility of the late-type secondary component in this binary. The experiment provided a good check on the stability of our radial velocity system and, to a large extent, alleviated our concerns. We also found that the stellar lines around 6290 and 6400 Å were generally too weak to replace the 5184 Å feature for routine stellar BF determinations. The BFs for XY UMa extracted from the 6290 Å region were more noisy than those from the 5184 Å spectral region, and the detection of the secondary component was not improved.

In 2005 August a new grating with 2160 lines mm^{-1} was acquired to replace the previously most frequently used 1800 line mm^{-1} grating, which after many years of use lost its efficiency. This markedly improved the quality of the observed spectra and of the resulting BFs. The older grating was used only for 2005 observations of V1010 Oph and XY UMa.

The radial velocity (RV) observations reported in this paper were collected between 2005 April and 2006 April. The ranges of dates for individual systems can be found in Table 1. The selection of the targets in our program remains quasi-random: at a given time, we observe a few dozen close binary systems with periods usually shorter than 1 day, brighter than 10–11 mag, and with declinations greater than $-20°$; we publish the results in groups of 10 systems as soon as reasonable orbital elements are obtained from measurements evenly distributed in orbital phases. In this paper we reobserved several relatively bright systems (V1010 Oph, W UMa, and XY Leo) to ascertain possible systemic velocity changes which could indicate presence of a third body in the system. Similarly, as in our previous papers dealing with spectroscopically multiple systems (here the cases of XY Leo and V345 Gem), RVs for the eclipsing pair were obtained from BFs with the third-star sharp peaks removed first, as described most recently in Paper XI.

As in other papers of this series, whenever possible, we estimate the spectral types of the program stars using our classification spectra. These are compared with the mean $(B - V)$ color indices, usually taken from the Tycho-2 catalog (Høg et al. 2000)

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

TABLE 1
DDO Radial Velocity Observations

HJD − 2,400,000	V_1 (km s^{-1})	W_1	V_2 (km s^{-1})	W_2	Phase
53,590.6265...........	0.00	0.00	0.00	0.00	0.4984
53,590.6421...........	0.00	0.00	0.00	0.00	0.5292
53,590.6578...........	0.00	0.00	0.00	0.00	0.5602
53,590.6738...........	0.00	0.00	0.00	0.00	0.5917
53,590.6893...........	53.83	2.65	−181.89	1.05	0.6223
53,590.7049...........	72.29	5.60	−201.81	0.73	0.6531
53,590.7208...........	80.82	0.54	−212.17	0.45	0.6845
53,590.7362...........	92.63	0.74	−225.73	0.46	0.7149
53,590.7516...........	92.74	0.69	−229.77	0.34	0.7453
53,590.7669...........	92.44	0.65	−232.10	0.30	0.7754

Notes.— The table gives the RVs V_i and associated weights W_i for observations described in the paper. Table 1 is published in its entirety in the electronic edition of the *Astronomical Journal*. The first 10 rows of the table for the first program star, OO Aql, are shown. Observations leading to entirely inseparable broadening function peaks are given zero weight; these observations may eventually be used in more extensive modeling of broadening functions. 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 the values for T_0 and the periods given in Table 2.

and the photometric estimates of the spectral types using the relations published by Bessell (1979).

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 the sine-curve orbital solutions in Table 2. The RVs and the corresponding spectroscopic orbits for all 10 systems are shown in phase diagrams in Figures 1–3. The RVs are fitted without proximity effects taken into account. This results in systematic deviations of the fits close to the eclipses. A further improvement of the orbits can be obtained by simultaneous fitting of the RVs and photometry, taking into account the proximity effects end eclipses, but it has not been attempted in this paper. The measured RVs are listed in Table 1 together with their weights, determined from $1/\sigma^2$, as based on individual determinations of centroid velocities. This weighting scheme, which accounts for differences in the *relative* quality of observations, markedly improves the overall quality of the orbital solutions. However, these errors, resulting from nonlinear least-squares fitting, tend to stay at a level of a few 0.1 km s^{-1}, and therefore underestimate the real uncertainties. In turn, the errors of the unit weight, as given by the fit (Table 2, sixth column), combine the errors of the individual RVs with all systematic deviations (proximity effects, flexures of the spectrograph, mismatch of template spectral types, etc.), and thus overestimate the measurement uncertainties.

Table 2 also contains our new spectral classifications of the program objects. Section 2 of the paper contains brief 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 quadrature are shown in Figure 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 identified

TABLE 2
Spectroscopic Orbital Elements

Name	Type, Spectral Type	Other Names	V_0	K_1, K_2	ϵ_1, ϵ_2	T_0 − 2,400,000 $(O-C)$ [E]	P $(M_1+M_2)\sin^3 i$	q
OO Aql	EW(A)	HD 187183	−53.71(0.61)	153.03(0.93)	4.08	53,606.0845(6)	0.5067932	0.846(7)
	F9 V	BD +08 4224		180.81(1.14)	7.35	+0.0008 [+2182]	1.954(19)	
CC Com	EW(W)	GSC 1986-2106	−2.89(0.74)	124.83(1.34)	5.72	53,822.2339(3)	0.2206860	0.527(6)
	K4/5			237.00(1.09)	5.54	−0.0004 [+5990.5]	1.083(12)	
V345 Gem...........	EW(W)	HD 60987	+0.03(0.68)	41.54(0.96)	5.31	53,802.8329(3)	0.2747690	0.142(3)
	F7 V	HIP 37197		291.75(1.26)	6.90	+0.0505 [+4740.5]	1.054(13)	
XY Leo	EW(W)	HIP 49136	−51.24(0.64)	144.65(1.10)	6.95	53,812.1951(3)	0.2840978	0.729(7)
	(K0 V)	BD +18 2307		198.41(1.11)	6.92	+0.0022 [+4618.5]	1.188(12)	
AM Leo...............	EW(W)	HIP 53937	−7.25(0.62)	115.56(0.97)	6.49	53,787.5742(12)	0.3657989	0.459(4)
	F5 V	BD +10 2234		251.98(1.17)		+0.0003 [+3519.5]	1.882(18)	
V1010 Oph	EB(SB2)	HD 151676	−19.92(0.38)	110.46(0.45)	2.68	53,825.7086(19)	0.6614168	0.465(3)
	A7 V	HIP 82339		237.33(1.44)	6.48	+0.0009 [+2004]	2.883(30)	
V2612 Oph	EW(W)	HD 170451	−25.59(0.44)	71.33(0.66)	3.66	53,846.9204(3)	0.375307(3)	0.286(3)
	F7 V	BD +6 3809		249.09(0.89)	4.04	+0.0492 [+3709.5]	1.279(11)	
XX Sex	EW(W)	HD 89027	−36.75(0.39)	25.80(0.45)	2.28	53,824.4139(9)	0.540110	0.100(2)
	F3 V	BD −05 3027		258.51(1.54)	7.78	+0.0164 [+2795]	1.286(20)	
W UMa	EW(W)	HD 83950	−28.40(0.48)	119.21(0.68)	4.90	53,804.8472(3)	0.33363487	0.484(3)
	F5 V	HIP 47727		246.30(0.87)	3.40	−0.0006 [+3910.5]	1.688(12)	
XY UMa	EB(SB2:)	HD 237786	−7.68(0.24)	124.74(0.28)	1.67	53,821.6344(2)	0.4789961	
	K0 V	HIP 44998				+0.0000 [+2759]		

Notes.— The spectral types given in the second column relate to the combined spectral type of all components in the system; they are given in parentheses if taken from the literature, and otherwise 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 always defined to be $q \leq 1$. 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. 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 solar mass units. Ephemerides (HJD$_{\rm min}$ − 2,400,000 + period in days) used for the computation of the $(O-C)$ residuals are as follows: OO Aql, 52,500.2610 + 0.5067932; CC Com, 52,500.2158 + 0.22068583; V345 Gem, 52,500.24 + 0.274769; XY Leo, 52,500.0872 + 0.2840978; AM Leo, 52,500.1452 + 0.3657989; V1010 Oph, 52,500.231 + 0.661414; V2612 Oph, 52,454.7107 + 0.375296; XX Sex, 52,314.79 + 0.54011; W UMa, 52,500.1693 + 0.3336347; XY UMa, 52,500.0844 + 0.4789960.

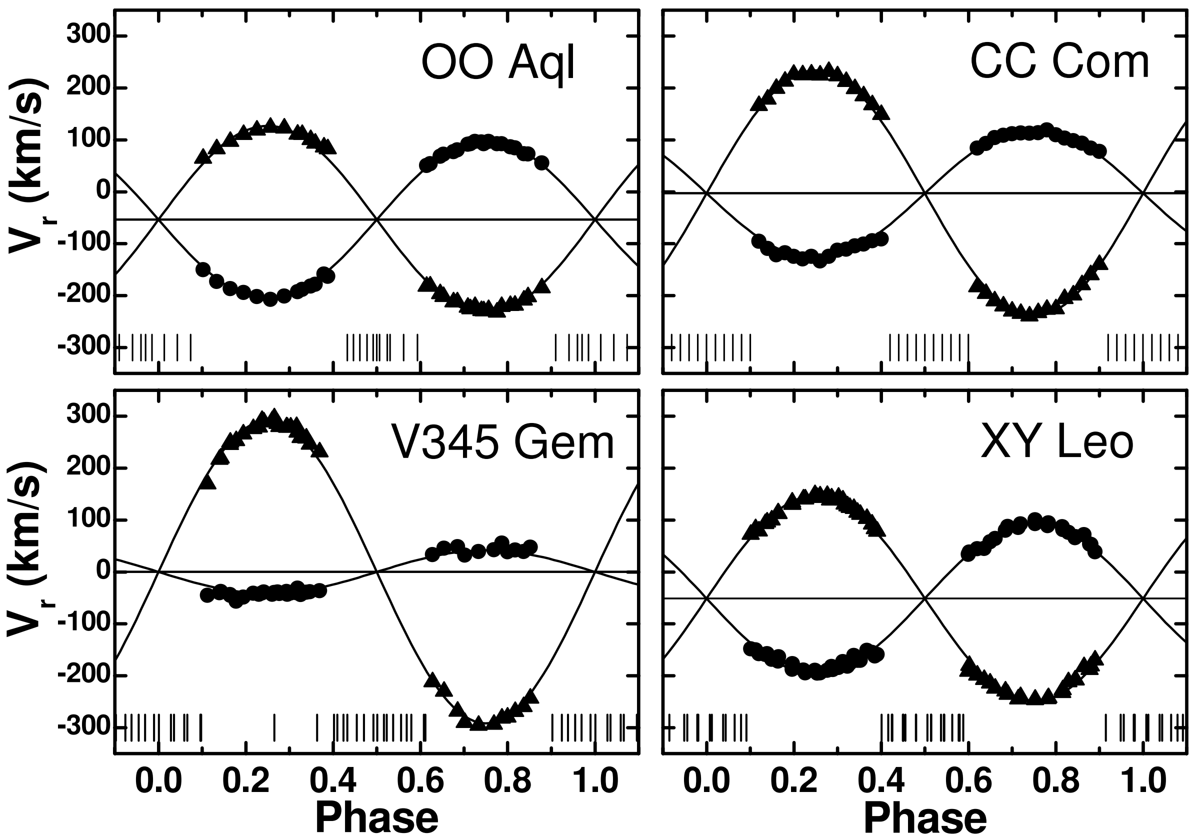

FIG. 1.—RVs of the systems OO Aql, CC Com, V345 Gem, and XY Leo, plotted in individual panels vs. the orbital phase. The lines give the respective circular-orbit (sine-curve) fits to the RVs. While all four systems are contact binaries, V345 Gem and XY Leo are members of multiple systems. The circles and triangles in this and in Figs. 2 and 3 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 bars in the lower parts of the panels show the phases of available observations that were not used in the solutions because of excessive spectral line blending.

with the primary, i.e., deeper 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. For XX Sex, the reference ephemeris was taken from Wils & Dvorak (2003); for the rest of the systems, the ephemeris given in the online version of Kreiner (2004)[2] were adopted. Because the online time-of-eclipse data are frequently updated, we give those used for the computation of the $O - C$ residuals below Table 2 (as of 2006 May). 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. *OO Aql*

This bright ($V_{max} = 9.50$) contact binary is quite unusual in that it has a mass ratio close to unity in spite of being an A-type system. It also shows a discrepancy between the spectral type and the color index. While Roman (1956) assigned a G5 V spectral type to the system, Hill et al. (1975) found a K0 type based on the classification spectra. The observed color indices $(B - V) = 0.76$ (Eggen 1967) and $(b - y) = 0.46$ (Rucinski & Kaluzny 1981) indicate a late spectral type of G8 to K0, but as pointed out by Eggen (1967), the reddening in this Galactic direction is very patchy and may reach $E_{B-V} \simeq 0.15$. Our classification spectra give discordant estimates: while the G band (4300 Å) gives about F9 V, the hydrogen lines are weak, indicating a late G type, perhaps G8 V.

In spite of its relatively high brightness, the system was not observed by the *Hipparcos* satellite, so no direct measure of the distance is available. Using the Rucinski & Duerbeck (1997) calibration and assuming a wide range of spectral types of F8 V to G8 V, we obtain a range of absolute magnitudes of $M_V = 3.06$ (F8 V) to $M_V = 3.66$ (G8 V), corresponding to minimum distances (no reddening) of 194 and 147 pc, respectively. A reddening of $E_{B-V} = 0.15$ would increase these estimates to 208 and 158 pc, respectively.

Mochnacki (1981) suggested that OO Aql may be considered as a prototype of a subgroup of contact binaries with components recently evolved into contact after a considerable angular momentum loss in the precontact stage. The view that the system represents a rare, transitional phase in the evolution of contact binaries was later shared by Hrivnak (1989), who presented a consistent, combined radial velocity and light-curve solution and showed that the orbital inclination of the system is close to 90°. A sine-curve approximation to the radial velocities obtained with the cross-correlation method led to a spectroscopic orbit with $V_0 = -46.4 \pm 0.9$ km s^{-1}, $K_1 = 147.3 \pm 1.4$ km s^{-1}, and $K_2 = 178.5 \pm 112.0$ km s^{-1}. This resulted in a large mass ratio of $q = 0.825 \pm 0.012$, which, with the proximity effects included, raised q to 0.843 ± 0.008. This value is very close the one obtained from our new spectroscopic orbit, $q = 0.846 \pm 0.007$.

The center-of-mass velocities of Hrivnak (1989) and the present result differ by about 7 km s^{-1}. In view of the typical differences found for contact binaries from analyses of different authors

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

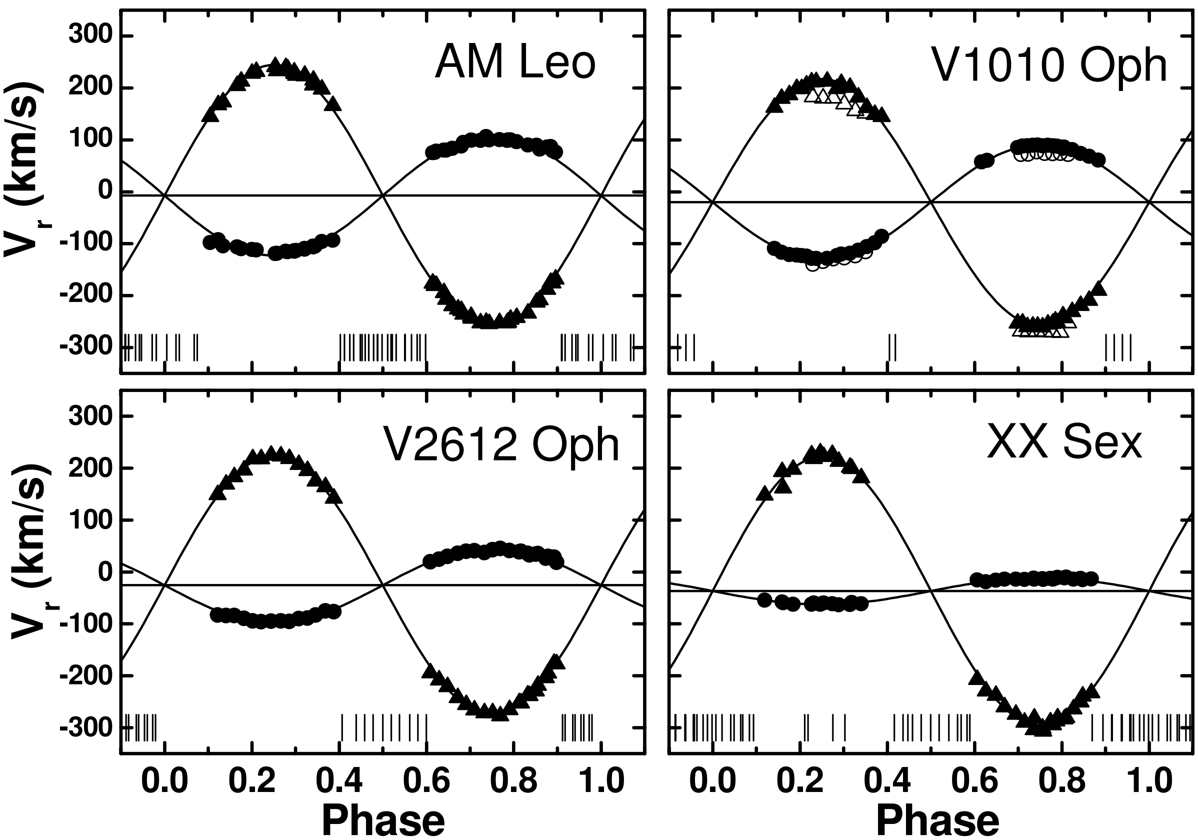

Fig. 2.—Same as Fig. 1, but for AM Leo, V1010 Oph, V2612 Oph, and XX Sex. While V1010 Oph is a double-lined detached or semidetached binary, AM Leo, V2612 Oph, and XX Sex are contact binaries. Open symbols correspond to observations not used for the spectroscopic orbit determination.

(Pribulla & Rucinski 2006), we regard this as a manifestation of a systematic effect which could be caused by differences in radial velocity standard systems or/and differences in methods used for radial velocity determinations (cross-correlation or broadening functions, combined with the RV determination via centroids, Gaussian profiles, or rotational profiles).

We see the OO Aql system practically edge-on, so the true masses are very close to the projected ones. With $(M_1 + M_2)\sin^3 i = 1.954 \pm 0.019\ M_\odot$ and the new mass ratio, we obtain $M_1 = 1.058 \pm 0.011\ M_\odot$ and $M_2 = 0.895 \pm 0.009\ M_\odot$. The mass of the primary component corresponds to the main-sequence spectral type G1 V (the secondary component would be G6 V, if not in contact). Thus, the primary spectral type, as estimated from its mass, is close to the hot end of the two extremes in the direct estimates, F8 V and G8 V. The distinctly red color of the system, $(B - V) = 0.76$, would then imply a surprisingly large reddening of $E_{B-V} \simeq 0.2$.

2.2. *CC Com*

CC Com is a totally eclipsing contact binary at the extreme short-period end of the currently available period distribution. With its period of only 0.22068 days, it held the record for a long time until a contact binary with a 0.215 day period was found in 47 Tuc by Weldrake et al. (2004). Because of its extreme

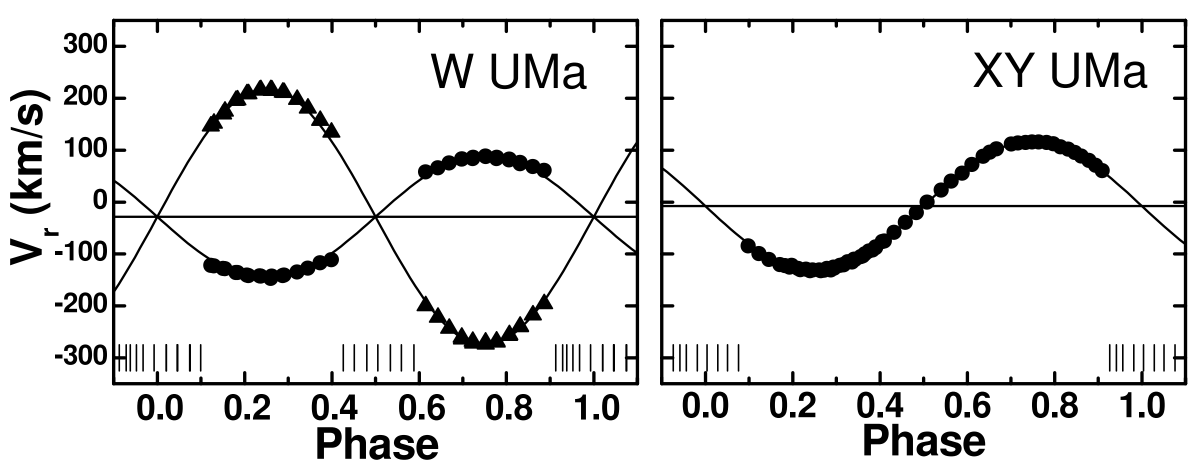

Fig. 3.—Same as Figs. 1 and 2, but for the two remaining systems, W UMa and XY UMa. While W UMa is the prototype contact binary, XY UMa is a very close but detached binary.

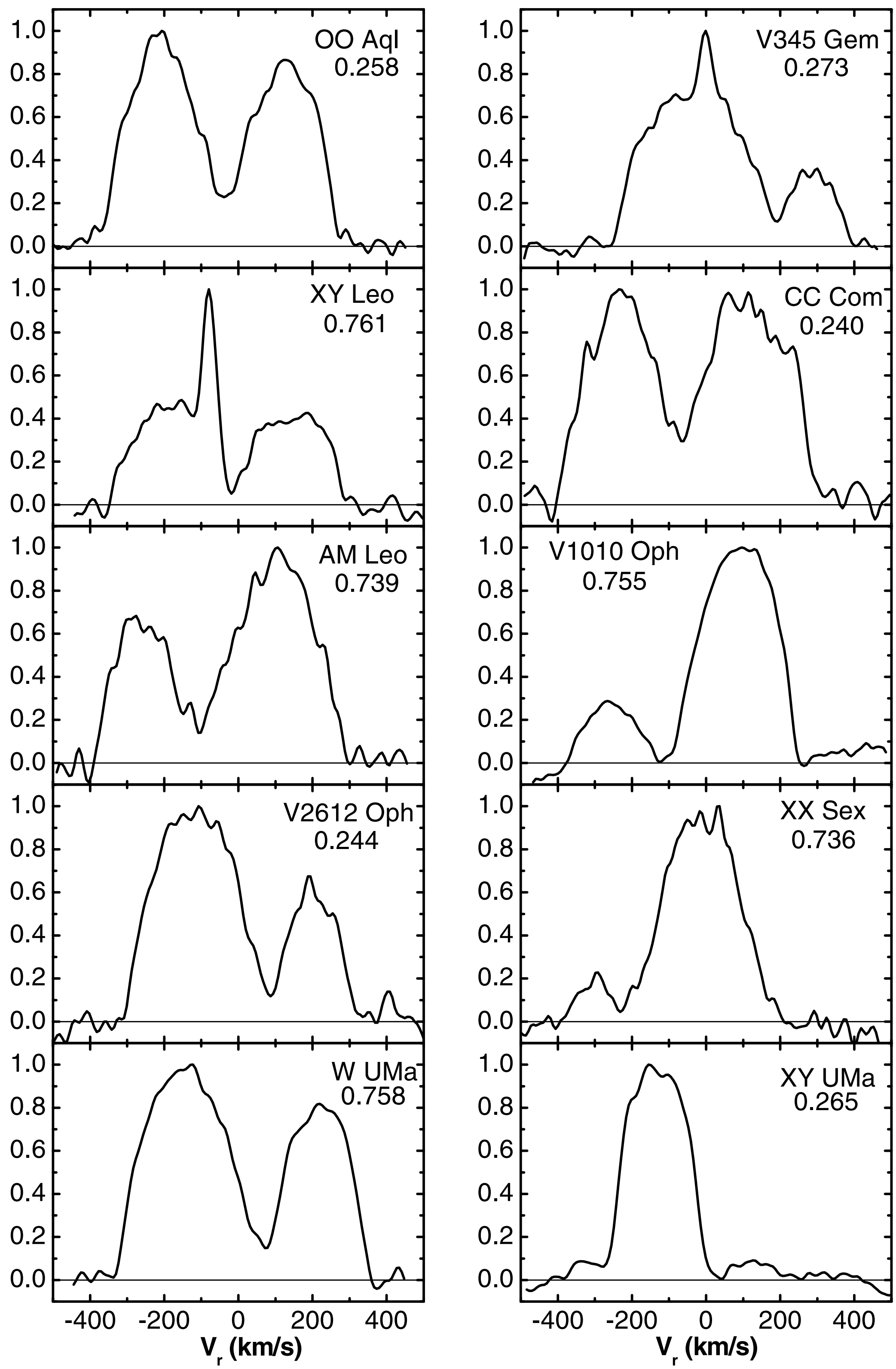

FIG. 4.— BFs for all 10 systems of this group, selected for phases close to 0.25 or 0.75. The phases are given by numbers in the individual panels. XY Leo is a quadruple system composed of a contact eclipsing binary and a detached, noneclipsing, close binary with an orbital period $P \approx 0.805$ days and with only one component visible as a relatively sharp peak in the BF (its orbit is shown in Fig. 5). The third star feature in the BF of the contact binary V345 Gem is also clearly visible. All panels have the same horizontal range, -500 to $+500$ km s^{-1}.

properties, it has been the subject of several photometric studies (e.g., Rucinski 1976; Linnell & Olson 1989) and of two spectroscopic studies (Rucinski et al. 1977; McLean & Hilditch 1983).

Using an old, now totally obsolete technique of measuring individual metallic lines in image-tube, 4 m telescope spectra, Rucinski et al. (1977) determined relatively reasonable spectroscopic parameters: $V_0 = -10.2 \pm 5.4$ km s^{-1}, $K_1 = 122.0 \pm 5.5$ km s^{-1}, and $K_2 = 235.9 \pm 4.8$ km s^{-1}, confirming the photometric mass ratio found from the timing of the eclipse inner contacts (Rucinski 1976). The broadening functions do not show any trace of a third component; hence, we regard the 7.3 km s^{-1} difference between the systemic velocities in Rucinski et al. (1977) and the present paper as resulting from systematic errors. The spectroscopic orbit in McLean & Hilditch (1983) based on a few rather poor measurements, while agreeing with the above, has been of a limited use.

A new determination of radial velocities was a real challenge for our 2 m class telescope due to the relatively low apparent brightness ($V_{\max} = 11.0$), red color, and very short period of the system. Even with relatively long exposures of 500 s (2.6% of the orbital period), the spectra were very noisy. Moreover, with the K5 V spectral type, the system is relatively faint at the Mg I triplet. We solved these difficulties by reobserving the quadrature segments of the orbit several times, with a total number of 134 spectra. As expected, individual BFs were poor, so we sorted them in the phase domain and then used temporal smoothing with a $\sigma = 0.02$ Gaussian filter, with subsequent rebinning to steps of 0.02 in phase. Consequently, Table 1 gives the radial velocities in equidistant phases, with the mean values of the HJD time equal to the average time of the contributing observations. Our new spectroscopic elements are within the errors of those determined by Rucinski et al. (1977). The total minimum mass of the system, $(M_1 + M_2)\sin^3 i = 1.088 \pm 0.014\,M_\odot$, is expected to be close to the true value because the orbit of the system is seen practically edge-on.

2.3. *V345 Gem*

The photometric variability of V345 Gem was discovered by the *Hipparcos* satellite (Perryman et al. 1997), which cataloged it as a periodic variable with a period of 0.1373890 days. Later, Duerbeck (1997) classified the system as a pulsating variable on the basis of the period-color relation. V345 Gem was subsequently included in the General Catalog of Variable Stars (Kazarovets et al. 1999) as a δ Scuti variable. Finally, the high-precision photometry of Gómez-Forrellad et al. (2003; with both components of the visual pair within the photometric aperture; see below) showed that the system is very probably a contact binary with twice the period (0.274778 days) and a photometric variation amplitude of 0.07 mag. These authors determined the first reliable ephemeris,

$$\text{Min. I} = \text{BJD } 2{,}448{,}362.7224(10) + 0.2747736(2)E,$$

by doubling the *Hipparcos* period.

V345 Gem is the member of visual binary WDS 07385+3343 (Mason et al. 2001), consisting of components with magnitudes $V_1 = 8.08$ and $V_2 = 9.35$, separated by 3.1″, and at present positioned practically perpendicular to our spectrograph slit. Kazarovets et al. (1999) commented that the photometric variability of V345 Gem might be due to the fainter component. In fact, it was the early spectral type of the dominant component (F0) which resulted in an incorrect classification of the star as a pulsating variable by Duerbeck (1997).

By mistake, our spectroscopic observations of V345 Gem were first focused on the primary component of the visual pair. After some time it became obvious that the primary component is a single, slowly rotating star and that the contact binary has to be identified with the fainter companion. The presence of the bright companion still remained obvious in the spectra of the close binary because, due to the relatively poor seeing at the DDO site of typically 1″–4″, the spectra of the fainter component were always contaminated by the visual companion. Although the companion spectral signature could be removed by fitting three Gaussian profiles to the extracted BFs, some persistent features most likely caused by the different levels and slopes of the continua in the two stars did remain. In spite of these difficulties, the resulting spectroscopic orbit of the contact pair is of a good quality, with a minimum mass of $(M_1 + M_2)\sin^3 i = 1.054 \pm 0.013\,M_\odot$, which is rather high for its orbital period of 0.275 days and mass ratio of $q = 0.143$. After a correction for the third light of the brighter visual companion, the photometric amplitude of the contact pair is about 0.33 mag, which implies a high inclination angle, so that the total mass is probably close to the above minimum-mass estimate.

The recent secondary minimum (HJD 2,453,731.9423; Nelson 2006) coincides in phase with the upper spectroscopic conjunction of the more massive component. Hence, V345 Gem is a contact binary of the W subtype.

The *Hipparcos* trigonometric parallax $\pi = 8.61 \pm 1.77$ mas may be affected by the visual binary character of the wide pair. If we take F7 V to be the spectral type, estimated for the fainter component of the visual pair from our classification spectra and the corresponding $(B - V)_0 = 0.50$, the absolute magnitude calibration of Rucinski & Duerbeck (1997) gives $M_V = 4.12$, which is very close to the absolute magnitude $M_V = 4.03$ determined from the parallax and the visual magnitude.

The radial velocity of the visual companion, $V_3 = -1.68 \pm 0.15$ km s^{-1}, determined from strongly contaminated spectra of the binary, $L_3/(L_1 + L_2) > 0.10$, is close to the center-of-mass velocity of the contact binary, $V_0 = 0.03 \pm 0.68$ km s^{-1}; however, this value may be affected by the asymmetric distribution of the third light across the spectrograph slit. A similar value, $V_3 = -2.55 \pm 0.73$ km s^{-1}, was found from 44 spectra of the third star that were observed by mistake but were well centered on the spectrograph slit. No RV variations of the brighter visual component have been found. This confirms the physical bond of the visual pair and indicates that the orbital motion in the visual orbit is very slow. The radial velocities of the bright visual component of V345 Gem are available in Table 3.

2.4. *XY Leo*

The bright contact binary XY Leo is a member of a quadruple system with an active binary and a contact binary in a 20 yr period mutual orbit (Barden 1987). The system has a long history of being recognized as somewhat unusual and abnormally bright in the X-ray (Cruddace & Dupree 1984) and in chromospheric Mg II emission (Rucinski 1985).

The multiple nature of the system was first indicated by periodic changes of the orbital period of XY Leo; the light-time effect (LITE) interpretation and the expected nature of the third body were extensively discussed by Gehlich et al. (1972). The authors deduced the minimum mass for the third body to be about 1 $M_\odot$. Struve & Zebergs (1959) obtained the first spectroscopic orbit for the contact binary and noted strong Ca II H and K emissions, which were thought to originate from the more massive component. Finally, Barden (1987) found the companion spectroscopically to be a BY Dra–type binary of mid-M spectral type

TABLE 3
Radial Velocity Observations of the Visual Companion to V345 Gem and the Third Component in XY Leo

HJD − 2,400,000	V_3 (km s^{-1})
53,780.81180	−0.884
53,780.82239	−0.987
53,780.82978	−0.787
53,781.79724	−1.586
53,781.80200	−1.760
53,781.81979	−1.672
53,781.82691	−1.783
53,785.51372	−2.312
53,785.52096	−2.789
53,785.52816	−3.365

Notes.—The RVs of V345 Gem until HJD 2,453,785 were derived from spectra in which the single, dominant component was centered on the spectrograph slit. After HJD 2,453,788 the spectrograph slit was centered on the fainter eclipsing binary, and the radial velocities were determined by Gaussian-profile fitting to the BFs with the light contamination $L_3/(L_1 + L_2) > 0.10$. Table 3 is published in its entirety in the electronic edition of the *Astronomical Journal*. Ten typical rows for the visual companion to V345 Gem are shown.

TABLE 4
Spectroscopic Orbital Elements of the Second Noneclipsing SB1 Binary in the Quadruple System XY Leo

Parameter	Value
P_{34} (days)	0.80476 ± 0.00003
e_{34}	0.00
ω (rad)	1.5708
T_0 (HJD)	2,453,814.5286 ± 0.0008
V_0 (km s^{-1})	−39.67 ± 0.27
K_3 (km s^{-1})	46.44 ± 0.38
$a_3 \sin i$ ($R_\odot$)	0.738 ± 0.006
$f(m)$ ($M_\odot$)	0.0084 ± 0.0002

Notes.—The table gives spectroscopic elements of the second binary in XY Leo: orbital period (P_{34}), eccentricity (e_{34}), longitude of the periastron passage (ω), time of the periastron passage (T_0), systemic velocity (V_0), semiamplitude of the RV changes (K_3), semimajor axis of the relative orbit ($a_3 \sin i$), and mass function [$f(m)$]. The elements were obtained assuming a circular orbit.

with its own short orbital period of 0.805 days. The lines of this component were seen as narrow absorption features in the red spectra, relatively easy to measure compared with the spectral lines of the contact binary. The light contributions of the third and fourth components at Hα were found to be 7.5% and 2.5% of the total light, respectively. The orbits of the two systems are not coplanar: while the inclination of the eclipsing pair is about 66°, the M-star binary orbit is seen at a 31° angle (Barden 1987). Unfortunately, the outer 20 yr period orbit has not yet been resolved either visually or astrometrically, although in the *Hipparcos* catalog it is suspected to be an astrometric double (the "S" flag in the H61 field).

Our new observations (2006 February to April) were obtained almost exactly one whole 20 yr period of the outer orbit after the spectroscopy of Barden (1987). Hence, we cannot provide any new insight into the outer orbit. The systemic (center-of-mass) velocity of the contact pair is expected to vary due to mutual revolution by ±6.23 km s^{-1} according to the most recent LITE solution (Pribulla & Rucinski 2006). An evenly distributed spectroscopic coverage of the 20 yr orbit would enable us to unambiguously determine the masses of all four components in the system, in the same way as was done for VW LMi (Paper XI).

The non-Keplerian solution (with proximity effects included) of Barden (1987), $K_1 = 124.1 \pm 2.8$ km s^{-1}, is significantly smaller than our value of 144.65 km s^{-1}. It is interesting to note that Hrivnak et al. (1984) obtained an even smaller K_1 than Barden (1987), only 108 ± 2 km s^{-1}. This systematic effect is probably due to the previous use of the cross-correlation technique and thus inadequate resolution, leading to a stronger influence of the third component, which is always close to the center-of-mass velocity of the close binary. As a result, our mass ratio for the contact pair is relatively large compared with the previous results, $q = 0.729(7)$.

At 5184 Å the light contribution of the fourth component (the secondary of the M-dwarf pair) is only about 1%–2%, so this component is not seen in our spectra; therefore, we could determine only a single-line orbit for the second pair (Table 4, Fig. 5). The parameters, $V_0 = -39.67 \pm 0.27$ km s^{-1} and $K_3 = 46.44 \pm 0.38$ km s^{-1}, are practically identical with those for the solution of Barden (1987). The light contribution of the third component estimated from the triple-Gaussian fits to our BFs around the quadratures of the contact binary is about $L_3/(L_1 + L_2) = 0.13$, which is much higher than that found in the photometric analysis of Yakut et al. (2003). We note that because of the different spectral continuum normalization levels for slowly and rapidly rotating components in spectroscopically multiple systems, the spectroscopic estimates tend to overestimate this ratio.

2.5. *AM Leo*

The contact binary AM Leo is the brighter component of the visual double star ADS 8024 (WDS J11022+0954), with a separation of 11.5″. The position angle of the fainter companion is 270°, i.e., along our spectrograph slit, so the light of both components entered the spectrograph and was recorded simultaneously. The radial velocity of the visual companion, $V_3 = -11.08 \pm 0.97$ km s^{-1}, was found to be stable and close to the systemic velocity of the eclipsing binary. Due to the relatively high brightness of the eclipsing pair, it was the subject of numerous photometric investigations (for references see Hiller et al. 2004; Albayrak et al. 2005). Hiller et al. (2004) analyzed the light curves of the system and found $q = 0.398$ and an inclination angle $i = 86°$. While AM Leo was included in the *Hipparcos* mission, the presence of the visual companion significantly deteriorated its

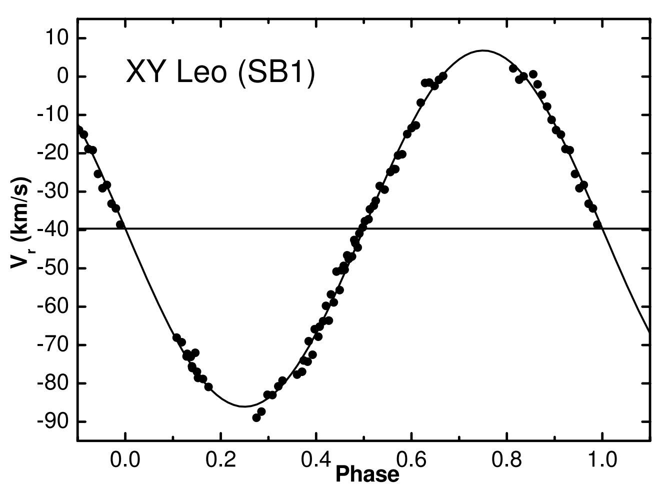

Fig. 5.—RVs of the third component of XY Leo and the corresponding fit to its orbital motion with a period of 0.805 days.

trigonometric parallax determination, leading to its large uncertainty, $\pi = 13.03 \pm 3.64$ mas.

The only spectroscopic orbit was presented by Hrivnak (1993), who performed a preliminary solution neglecting proximity effects and found a mass ratio of $q = 0.45$ with $M_1 + M_2 = 2.00\ M_{\odot}$. Our solution with $q = 0.459(4)$ is consistent with the above determination. The system is seen almost edge-on, so the minimum mass derived by us, $M_1 + M_2 = 1.882 \pm 0.018\ M_{\odot}$, is close to the true total mass of the system.

The recent period study of AM Leo (Albayrak et al. 2005) shows possible cyclic period variations, interpreted by the authors as a result of a LITE caused by an invisible third component with a minimum mass of 0.18 $M_{\odot}$. The authors estimated that this hypothetical body would be about 7 mag (i.e., more than 600 times) fainter than the contact binary. This component, if it really exists, cannot be identified with the known visual companion on the wide astrometric orbit. As expected with a 7 mag difference, we do not see any persistent feature close to the systemic velocity which could be interpreted as being caused by a faint nearby companion. In fact, in the DDO averaged spectra (D'Angelo et al. 2006), the brightness difference detection limit is about 5.2 mag.

2.6. *V1010 Oph*

V1010 Oph is a bright ($V_{\max} = 6.20$), early spectral type (A3 V), short-period, almost-contact, semidetached eclipsing binary. Its variability was discovered by Ströhmeier et al. (1964). The published spectroscopic studies of this system (Guinan & Koch 1977; Margoni et al. 1981; Worek et al. 1988) found V1010 Oph to be an SB1 system with $K_1 \simeq 100$ km s^{-1}. Margoni et al. (1981) observations led to a significant orbital eccentricity of 0.23 ± 0.03, which is highly unexpected for such a close binary, indicating a problem in the analysis. Later observations of Worek et al. (1988) gave a small eccentricity of $e = 0.02 \pm 0.02$, which is consistent with zero due to the biased character of the eccentricity estimates (it cannot be negative). While previous velocity semiamplitudes were consistent, the center-of-mass velocities were discordant, with $V_0 = -15 \pm 3$ km s^{-1} determined by Margoni et al. (1981) and $V_0 = -41 \pm 1.5$ km s^{-1} determined by Guinan & Koch (1977). The photometric analysis of Leung & Wilson (1977) based on the assumption of the Roche model, showed that (1) the primary eclipse is a transit, (2) the eclipses are total, and (3) the system is in marginal contact.

Our BFs of V1010 Oph (Fig. 4) clearly show the secondary component orbiting with a large semiamplitude (see Table 2). The well-determined mass ratio of $q_{\rm sp} = 0.465 \pm 0.003$ is in agreement with the photometric determination $q_{\rm ph} = 0.4891 \pm 0.0016$ of Leung & Wilson (1977). Note that this statement is a qualified one because very frequently we see large discordances between $q_{\rm sp}$ and $q_{\rm ph}$, and even in this case the error of $q_{\rm ph}$ must have been strongly underestimated. As expected, we do not see any indications of a nonzero eccentricity. It is interesting to note that all radial velocity determinations from 2005 (Fig. 2, *open symbols*) give a much smaller systemic velocity for the system, by $\Delta V_0 \simeq -30$ km s^{-1}, possibly indicating that the eclipsing pair orbits around a common center of gravity with a third star in the system. The system was included in the *Hipparcos* mission, with the resulting parallax of 13.47 ± 0.83 mas, so the system has a very well determined distance.

2.7. *V2612 Oph*

The variability of V2612 Oph (NSV 10892 in the General Catalog of Variable Stars) was first suspected by Hiltner et al. (1958). The authors gave $V = 9.50$, $B - V = 0.60$, and $U - B = 0.07$. *V*-band photometry of Koppelman et al. (2002) showed that it is a contact binary. The authors determined a preliminary ephemeris for the primary minimum:

$$\text{Min. I} = \text{HJD } 2{,}452{,}454.7107 + 0.375296E.$$

Their light curve is asymmetric, with the maximum following the primary minimum brighter by about 0.03 mag. New minima of V2612 Oph observed by Tas et al. (2004) gave a large $(O - C)$ shift, indicating a slightly longer orbital period. Therefore, in our spectroscopic solution we optimized both T_0 and P, leading to $P = 0.375307(3)$.

Yang et al. (2005) analyzed the light curve of Koppelman et al. (2002) and found the following parameters: $q = 0.323 \pm 0.002$, $i = 65.7° \pm 0.3°$, and $f = 0.23 \pm 0.04$. Our mass ratio $q = 0.286$ is not consistent with the photometric estimate, as frequently observed for partially eclipsing system with overinterpreted light-curve analyses. The value for T_0 in the ephemeris of Koppelman et al. (2002) coincides with an upper conjunction of the less massive component, so the system is clearly of the W subtype. The projected total mass of the system, $(M_1 + M_2)\sin^3 i = 1.279 \pm 0.011\ M_{\odot}$, is consistent with our spectral type estimate, F7 V, for a moderately low value of the orbital inclination.

V2612 Oph is located in the outskirts of the intermediate-age Galactic cluster NGC 6633. The star was included in the four-color photometry of NGC 6633 by Schmidt (1976), who found $(b - y) = 0.382$ and determined a large value for the interstellar reddening of $E(b - y) = 0.472$, which is inconsistent with the average cluster reddening of $E(b - y) = 0.124 \pm 0.017$. Similarly to Hiltner et al. (1958), the author did not accept the membership of the star in NGC 6633.

V2612 Oph was not observed by the *Hipparcos* satellite, and its trigonometric parallax is unknown, so the cluster membership cannot be reliably verified. Using the Rucinski & Duerbeck (1997) absolute magnitude calibration assuming an F7 V spectral type, we obtain $M_V = 3.52$. With the distance modulus of NGC 6633 of $V - M_V = 7.71$ mag (Kharchenko et al. 2005), the system should be as faint as $V_{\max} = 11.26$. Hence, it seems that V2612 Oph is in front of the cluster, although this is entirely inconsistent with the supposedly very large $E(b - y)$ reddening value.

The proper motion of V2612 Oph, $\mu_\alpha \cos\delta = 57.2 \pm 2.1$ and $\mu_\delta = 23.3 \pm 2.1$ mas yr^{-1} (Høg et al. 2000), does not correspond to the mean NGC 6633 motion of $\mu_\alpha \cos\delta = 0.10$ and $\mu_\delta = -2.0$ mas yr^{-1} (Kharchenko et al. 2005). On the other hand, the center-of-mass velocity of V2612 Oph, $V_0 = -25.59 \pm 0.44$ km s^{-1}, is close to the mean radial velocity of the cluster of $V_R = -25.43$ km s^{-1}, as given by Kharchenko et al. (2005). Recently, high-precision photometry of the cluster performed by Hidas et al. (2005) has led to the detection of several variable stars in NGC 6633. In particular, a W UMa variable V7 with a similar period of $P = 0.38673$ days, at $V_{\max} = 12.8$, is over 3 mag fainter than V2612 Oph. Hence, we reject the membership of V2612 Oph in NGC 6633.

2.8. *XX Sex*

The photometric variability of XX Sex (HD 89027) was found on the Stardial images (Wils & Dvorak 2003). The authors determined an approximate ephemeris for the primary minima:

$$\text{Min. I} = \text{HJD } 2{,}452{,}314.79 + 0.54011E.$$

The Third All Sky Automated Survey (ASAS-3) light curve shows that XX Sex is a totally eclipsing system with rather different depths of the minima. The orbital period in ASAS is slightly improved to 0.540111 days. No high-precision photometry of XX Sex has been published yet.

Our independent spectral type estimate of F3 V is slightly later than F0, as given in the SIMBAD astronomical database. XX Sex was not included in the *Hipparcos* mission; hence, its trigonometric parallax is unknown. During our spectroscopic observations we noted a faint visual companion to XX Sex separated by about 3″ in the northwest direction.

The upper spectroscopic conjunction of the more massive component observed by us coincides in phase with the deeper minimum in the ASAS-3 photometry, indicating that the system is of the A type. This is further supported by the low mass ratio determined by us, $q = 0.100 \pm 0.002$, and by the relatively long orbital period. For such a small mass ratio, eclipses remain total for a wide range of inclinations down to as low as 70°. This is actually indicated by the relatively small projected total mass of $(M_1 + M_2)\sin^3 i = 1.153 \pm 0.026\ M_\odot$ for the spectral type of F3 V.

In the analysis of the broadening functions we noted that while the peak of the secondary component is usually well defined around the second quadrature (phase 0.75), where it is sufficiently separated from the primary-component peak, its profile is flat and poorly defined around the first quadrature. These unexplained shape variations in the secondary component signature resulted in the rejection of four RV determinations for this component.

2.9. *W UMa*

The prototype contact binary W UMa has been intensively observed since its discovery in 1903 (Muller & Kempf 1903). The contact binary is the brighter ($\Delta m = 4.4$) component of the visual pair ADS 7494 (WDS J09438+5557), with a separation of 6.4″. The physical association of the components has not yet been demonstrated. The *Hipparcos* catalog lists W UMa as a suspected astrometric binary with an "S" flag in the H61 field.

Apart from numerous photometric observations and studies (Linnell 1991), the system has been observed several times spectroscopically (McLean 1981; Rucinski et al. 1993). The spectroscopic elements of the system are still poorly known, with large differences in the center-of-mass velocity, ranging from $V_0 = 0$ km s^{-1} (Binnendijk 1967) to $V_0 = -43$ km s^{-1} (Popper 1950). It is unclear whether these differences can be explained by very different and slowly improving methods of radial velocity determinations for contact binaries. In addition, W UMa shows unexplained, irregular orbital period changes, which probably indicate the simultaneous action of several mass and angular-momentum transfer processes within the contact system.

Our new spectroscopic orbit is based on 36 high-precision RV measurements extracted from very well defined BFs (see Fig. 4). The resulting parameters (Table 2) clearly supersede all previous determinations. The spectroscopic elements are well within previous determination uncertainties, as given in the last two studies (McLean 1981; Rucinski et al. 1993). During our observations covering 16 days we did not observe any center-of-mass velocity changes.

The trigonometric parallax of the system, $\pi = 20.17 \pm 1.05$, is very well defined. The absolute visual magnitude determined from the period-color-luminosity relation of Rucinski & Duerbeck (1997), $M_V = 3.86$, is rather severely inconsistent with the magnitude found from the parallax, $M_V = 4.82 \pm 0.11$. To obtain a reasonable accord, a substantial amount of reddening ($A_V = 0.96$) or a much later spectral type, perhaps as late as K1 V, would be required; both explanations are equally unlikely. This major discrepancy is entirely unexplained and puzzling for such a well-observed contact binary.

2.10. *XY UMa*

XY UMa is a highly chromospherically active system with an exceptionally short orbital period for a detached binary of only 0.479 days. The photometric variability of XY UMa was first noted by Geyer et al. (1955). The binary has been the subject of extensive photometric studies; for references see Pribulla et al. (2001). The spectroscopic orbit of the primary component was first obtained by the cross-correlation function technique by Rainger et al. (1991). To detect and measure the RVs for the secondary, Pojmanski (1998) applied a sophisticated modeling of the near-infrared spectra in the region of the Ca II infrared triplet. This led to the following parameters: $V_0 = -10.5 \pm 1.0$ km s^{-1}, $K_1 = 122.5 \pm 1.0$ km s^{-1}, and $K_2 = 202 \pm 6$ km s^{-1}. The chromospheric emission filling the Hβ and Hα lines was later studied by Özeren et al. (2001).

The system was suspected of being a member of a multiple system (Pribulla et al. 2001) with a third-body orbital period of about 30 yr. The H61 field of the *Hipparcos* catalog contains the flag "S" (as described in the catalog, "suspected nonsingle"), i.e., a plausible astrometric orbital solution for XY UMa was found. While our BFs do not show any trace of the third component, we noted during the current observations a faint ($\Delta m \approx 3$ mag) visual companion in the northwest direction about 2″–3″ from XY UMa. A spectrum of the companion taken on 2006 March 24 indicates that it may be a binary system, although contamination by the light of XY UMa is not excluded.

Our new spectroscopic observations consist of two runs: In the spring of 2005 we observed spectra centered at 6290 Å, in a spectral window which included a telluric molecular feature (later removed in the BF extraction), while in the spring of 2006 we used the standard setup around the Mg I λ5184 triplet. Neither of the runs revealed any obvious signatures of the secondary component, so at first we treated the orbit as that of a single-lined binary (SB1). An orbit based only on the 2006 observations, $V_0 = -7.68 \pm 0.24$ km s^{-1} and $K_1 = 124.74 \pm 0.28$ km s^{-1}, utilized 61 spectra (excluding spectra obtained within ±0.09 in phase around the primary eclipse). When we arranged the spectra in phase and smoothed them in the phase domain, a faint feature of the secondary component became visible (Fig. 6). Its semiamplitude was about $K_2 \simeq 178$ km s^{-1}, which is markedly smaller than the 202 km s^{-1} found by Pojmanski (1998). The discrepancy may be caused by the dominance of the reflection effect at 5184 Å, so that the effective line center on the secondary is shifted toward its irradiated hemisphere. We note that our BFs are very well defined for the primary component. They clearly show a dark, relatively small, well-localized spot visible around the second quadrature which migrates through the stellar profile following the stellar rotation of the primary component. A weaker similar spot was recorded around the first quadrature in some of the spectra.

The *Hipparcos* parallax of the system, 15.09 ± 1.48 mas, and the maximum visual magnitude $V = 9.62$, give the absolute visual magnitude $M_V = 5.51 \pm 0.22$, corresponding to a single G8 V main-sequence star. The light contribution of the secondary companion is just a few percent in the V passband.

The spectral type of XY UMa was estimated by analyzing the average spectrum of the system. The best template to fit the average spectrum was found to be K0 V (the next available templates were G8 V and K4 V). This template was the best even for individual spectra observed during the eclipses. The published

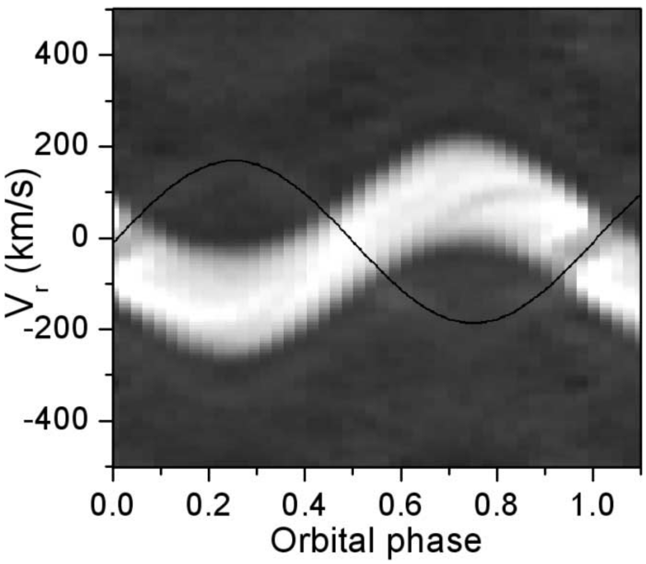

Fig. 6.—Gray-scale plot of the phase-domain-averaged BFs of XY UMa, showing faint features of the secondary companion, best visible after the secondary minimum. During the primary eclipse the secondary component is clearly visible as a moving dark feature within the primary component profile. Note also the dark spots on the primary, best visible in phases 0.7–0.8. An orbit of the secondary component, as observed in our spectral window at 5184 Å, is plotted by a solid line.

spectral types of the components are G3 V and K4–5 V (Pribulla et al. 2001), which appear to be much too early.

3. SUMMARY

With the new 10 short-period binaries, this paper brings the number of the systems studied at the David Dunlap Observatory to 110. The systems presented in this paper include (1) the quadruple system XY Leo, consisting of a contact binary and a BY Dra–type close binary consisting of two M-type dwarfs, (2) the very close, detached, chromospherically active system XY UMa, and (3) V1010 Oph, which is probably a detached or semidetached SB2 system. The remaining seven SB2 binaries are all contact ones: OO Aql, CC Com, V345 Gem, AM Leo, V2612 Oph, XX Sex, and W UMa. Six systems of this group have been observed spectroscopically before: OO Aql, CC Com, XY Leo, AM Leo, W UMa, and XY UMa, but our new data are of higher quality than in any of the previous studies.

Companions to the close binaries appear to be present in V345 Gem, XY Leo, AM Leo, XX Sex, and XY UMa, but all have been recognized as such before except for XX Sex and XY UMa, for which the faint companions are new detections. The case for the physical association of the visual companion to W UMa still remains open.

We point out that the red color of OO Aql is unexplained, unless it is very heavily reddened. We also note a large discrepancy in the absolute magnitude of W UMa between that predicted by the simple period-color-luminosity calibration and the one derived from the parallax.

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