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

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ABSTRACT

Radial-velocity measurements and sine-curve fits to orbital radial velocity variations are presented for 10 close binary systems: DU Boo, ET Boo, TX Cnc, V1073 Cyg, HL Dra, AK Her, VW LMi, V566 Oph, TV UMi, and AG Vir. With this contribution, the David Dunlap Observatory program has reached the point of 100 published radial velocity orbits. The radial velocities have been determined using an improved fitting technique that uses rotational profiles to approximate individual peaks in broadening functions. Three systems, ET Boo, VW LMi, and TV UMi, are found to be quadruple, while AG Vir appears to be a spectroscopic triple. ET Boo, a member of a close visual binary with $P_{\rm vis} = 113$ yr, was previously known to be a multiple system, but we show that the second component is actually a close, noneclipsing binary. The new observations have enabled us to determine the spectroscopic orbits of the companion, noneclipsing pairs in ET Boo and VW LMi. A particularly interesting case is VW LMi, for which the period of the mutual revolution of the two spectroscopic binaries is only 355 days. While most of the studied eclipsing pairs are contact binaries, ET Boo is composed of two double-lined detached binaries, and HL Dra is a single-lined detached or semidetached system. Five systems of this group have been observed spectroscopically before: TX Cnc, V1073 Cyg, AK Her (as a single-lined binary), V566 Oph, and AG Vir, but our new data are of much higher quality than in the previous studies.

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 of radial-velocity studies of close binary stars (Lu & Rucinski 1999; Rucinski & Lu 1999; Rucinski et al. 2000; Lu et al. 2001; Rucinski et al. 2001, 2002, 2003; Pych et al. 2004; Rucinski et al. 2005; hereafter Papers I–VI and VIII–X, respectively) and presents data for the 10th group of 10 close binary stars observed at the David Dunlap Observatory (DDO). For technical details and conventions, and for preliminary estimates of uncertainties, see the interim summary paper by Rucinski (2002, hereafter Paper VII).

In this paper we make use of broadening functions (BFs) extracted not only from the region of the Mg I triplet at 5184 Å, as in previous papers, but also from two regions containing telluric features centered at 6290 and 6400 Å. These experimental setups were used because of concerns about flexure effects in our spectrograph. While this experiment provided a good check on the stability of our radial-velocity system and, to a large extent, alleviated our concerns, we found that the stellar lines in these two regions were generally too weak to replace the 5184 Å feature on a routine basis. The BFs based on the 6290 and 6400 Å observations were rather poorly defined, especially for earlier spectral types; this was mostly due to the low efficiency of our diffraction grating in the red region. As a result, the BFs for AG Vir and DU Boo were poor, with the secondary component almost undetectable. Thus, in the end, we returned to the 5184 Å region for the subsequent observations. The flexure tests based on our telluric-lines template (Regulus = HD 87901) have shown that the standard wavelength calibrations provide a reasonable stability for our radial-velocity system, with the largest deviations within ± 3 km s^{-1}. The BFs obtained in the red region were used in the present study only to augment the data for the quadruple systems, ET Boo, VW LMi, and TV UMi, and only for observations at critical orbital phases of long-period systems when any spectrum was of use in defining the orbit.

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TABLE 1
DDO Radial Velocity Observations of Close Binary Systems

HJD − 2,400,000	V_1 (km s^{-1})	W_1	V_2 (km s^{-1})	W_2	Phase
53,480.5576	22.48	0.35	−168.48	0.03	0.6224
53,480.5803	25.78	0.47	−203.77	0.03	0.6439
53,480.6033	31.53	1.49	−209.61	0.14	0.6657
53,480.6261	34.74	1.09	−216.95	0.05	0.6873
53,480.6490	33.67	1.05	−227.17	0.08	0.7090
53,480.6717	40.69	1.00	−233.93	0.30	0.7305
53,480.6944	37.69	1.19	−235.97	0.13	0.7520
53,480.7172	38.72	0.89	−251.40	0.13	0.7736
53,480.7399	38.37	1.03	−237.67	0.10	0.7951
53,480.7626	40.39	1.32	−221.31	0.12	0.8165

Notes.—The table gives the RVs V_i and associated weights W_i for observations described in the paper. The first 10 rows of the table for the first program star, DU Boo, are shown. Observations leading to entirely inseparable BF peaks are given zero weight; these observations may eventually be used in more extensive modeling of BFs. The observations in the column V_1 correspond to the component that was stronger and easier to measure in the analysis of the BFs; it is not always the component eclipsed during the primary minimum at the epoch T_0 (see Table 2). The figures should help in identifying which star is which. Table 1 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

In 2005 August a new grating with 2160 lines mm^{-1} was acquired to replace the previously most frequently used grating, with 1800 lines mm^{-1}, which after many years of use lost its original efficiency. Thus, unfortunately, due to the changes described above, in combination with the necessarily very extended time coverage for triple and quadruple systems, the present data set is the least homogeneous since the start of this series of studies. The BFs used here were extracted from spectra obtained with four different CCD detectors and two different diffraction gratings. This lack of homogeneity does not seem to affect the final data, which have uncertainties similar to previously reported in this series of investigations.

Selection of the targets in our program remains quasi-random: at a given time, we observe a few dozen close binary systems that have periods usually shorter than 1 day, are brighter than 10–11 mag, and have 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. Whenever possible we estimate spectral types of the program stars using our classification spectra obtained with a grating of 600 lines mm^{-1} over a range of 635 or 890 Å (depending on the CCD detector) centered at 4200 Å. Our classifications are based on comparison with several spectral standards of the MK system observed on the same nights. They are 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 published by Bessell (1979).

The radial velocity (RV) observations reported in this paper were collected between 1997 June and 2005 September. The ranges of dates for individual systems can be found in Table 1. The present group contains three quadruple systems, ET Boo, VW LMi, and TV UMi, whose complex nature had been noticed several years ago but whose full orbital solutions required extended monitoring.

This paper is structured in a way similar to that of the 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 their preliminary sine-curve solutions in Table 2. RVs and the corresponding spectroscopic orbits for all 10 systems are shown in Figures 1–3. In this paper we changed the way how RVs are determined from the BFs: instead of Gaussian profiles, we now use single or double rotational profiles to fit the peaks in the BFs. This approach, which is described in § 3, gives much better results with smaller random errors. We stress that this is still not a full modeling of the BF shape (as attempted in Rucinski [1992], Lu & Rucinski [1993], and Rucinski et al. [1993]), which would be an optimal approach, but a more convenient and better working tool than with Gaussian profiles. The measured RVs are listed in Table 1 together with weights, determined as $1/\sigma^2$, as based on individual determinations of the central component velocity. This weighting scheme, which accounts for differences in relative quality of observations, improves the quality of the orbital solutions.

The data in Table 2 are organized in the same manner as in previous papers. In addition to the parameters of spectroscopic orbits, the table provides information about the relation between the spectroscopically observed epoch of the primary eclipse T_0 and the recent photometric determinations in the form of the $O - C$ deviations for the number of elapsed periods E. For HL Dra the reference ephemeris is taken from the *Hipparcos* catalog, and for DU Boo from Pribulla et al. (2005); for the rest of the systems, ephemerides given in the online version of the Atlas of $O - C$ Diagrams of Eclipsing Binary Stars[4] (Kreiner 2004) were adopted. Because the online ephemerides are frequently updated, we give those used for the computation of the $O - C$ residuals below Table 2 (status as of 2006 February).

The values of T_0 refer to the deeper eclipse, which for W-type systems corresponds to the lower conjunction of the more massive component; in such cases the epoch is a noninteger number. In the cases of ET Boo and VW LMi, for which observations covered several years and photometric data have been rather scanty, we optimized not only T_0 but also the orbital period.

Table 2 contains our new spectral classifications of the program objects. Independent classification was done for all systems except TX Cnc. Section 2 of the paper contains brief summaries of previous studies for individual systems and comments on the new data. The novel technique of fitting rotational profiles to peaks in the BFs is described in § 3. Examples of BFs of individual systems extracted from spectra observed close to quadrature are shown in Figure 4.

Similarly to our previous papers dealing with multiple systems, RVs for the eclipsing pair were obtained from BFs with the additional peaks removed. This task was performed by first fitting multiple Gaussian profiles to the combined BFs and then removing the signatures of the third (and sometimes fourth) component. While the final RVs of the close pair were determined by rotational profile fitting to such "cleaned" profiles, the velocities of the slowly rotating additional components were determined by the Gaussian fits (Table 3). Because the BF technique actually produces Gaussian profiles for intrinsically sharp signatures with $\sigma \simeq 15$ km s^{-1}, this approach is internally consistent.

2. RESULTS FOR INDIVIDUAL SYSTEMS

2.1. *DU Boo*

The photometric variability of DU Boo was discovered by the *Hipparcos* satellite (Perryman et al. 1997), by which the star was classified as an ellipsoidal variable of A2 spectral type. Later, Gomez-Forrellad & Garcia-Melendo (1997) observed the system photometrically and found that it is an eclipsing

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

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
DU Boo...........	EW(A)	HD 126080	−13.09(0.86)	53.59(1.02)	5.95	53,494.6896(39)	1.05588870	0.234(35)
	A7 V	HIP 70240		229.32(3.02)	11.22	+0.0068 [1173]	2.477(73)	
ET Boo............	EB	BD +47 2190	−23.35(0.51)	145.61(0.75)	9.09	52,701.5928(8)	0.6450398(7)	0.884(15)
	F7 V	HIP 73346		164.64(0.93)	10.09	−0.0008 [312]	1.996(17)	
TX Cnc	EW(W)	BD +19 2068	+33.97(0.52)	100.77(0.82)	4.09	51,807.9810(4)	0.38288273	0.455(11)
	(F8 V)			221.67(0.91)	5.66	+0.0008 [−1807.5]	1.330(12)	
V1073 Cyg......	EW(A)	HD 204038	−6.85(0.50)	66.45(0.61)	4.81	53,194.3876(12)	0.7858506	0.303(17)
	A9 V	HIP 105739		219.09(1.40)	6.63	+0.0025 [883]	1.896(25)	
HL Dra............	EB(SB1)	HD 172022	−29.36(0.43)	81.04(0.60)	1.88	53,166.8057(12)	0.944276	
	A6 V	HIP 91052				+0.0047 [4942]		
AK Her	EW(A)	HD 155937	+4.28(0.89)	70.52(1.12)	6.90	53,176.3946(19)	0.4215231	0.277(24)
	F4 V	HIP 84293		254.40(2.27)	13.90	+0.0009 [1604]	1.598(29)	
VW LMi[a]	EW(A)	HD 95660	. . .	105.41(0.83)	12.68	51,973.4117(4)	0.4775499(2)	0.416(4)
	F5 V	HIP 54003		253.21(0.84)	13.58	−0.0017 [−1103]	2.282(18)	
V566 Oph	EW(A)	HD 163611	−37.33(0.52)	71.08(0.69)	3.12	53,568.6298(4)	0.4096538	0.263(12)
	F4 V	HIP 87860		270.12(1.14)	6.63	+0.0037 [2608]	1.686(17)	
TV UMi	EW(W)	HD 133767	−9.70(0.67)	116.17(1.04)	7.57	52,454.0189(6)	0.41554935	0.739(21)
	F8 V	HIP 73474		157.09(1.19)	9.98	+0.0007 [−111.5]	0.879(12)	
AG Vir	EW(A)	HD 104350	−10.99(0.82)	93.39(1.06)	5.38	53,501.5388(13)	0.6426507	0.382(21)
	A5 V	HIP 58605		244.24(1.97)	10.81	+0.0030 [1558]	2.563(41)	

Notes.—The spectral types given in the second column relate to the combined spectral types 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 figures should help identify which component is eclipsed at the primary minimum. 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 minima are given by T_0. The corresponding $(O-C)$ deviations (in days) have been calculated from the available prediction for T_0, 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. The ephemerides ($HJD_{min} - 2{,}400{,}000$ + period in days) used for the computation of the $(O-C)$ residuals are as follows: DU Boo, 52,256.1254 + 1.0558887; ET Boo, 52,500.3407 + 0.6450413; TX Cnc, 52,500.0407 + 0.38288273; V1073 Cyg, 52,500.479 + 0.7858506; HL Dra, 48,500.189 + 0.944276; AK Her, 52,500.2709 + 0.42152292; VW LMi, 52,500.1516 + 0.4775505; V566 Oph, 52,500.249 + 0.4096538; TV UMi, 52,500.352 + 0.41555; AG Vir, 52,500.286 + 0.6426507.

[a] VW LMi: The contact binary revolves in a relatively short-period orbit around the second pair; therefore, the systemic velocity V_0 is not defined. See Table 5 for a full description of the system.

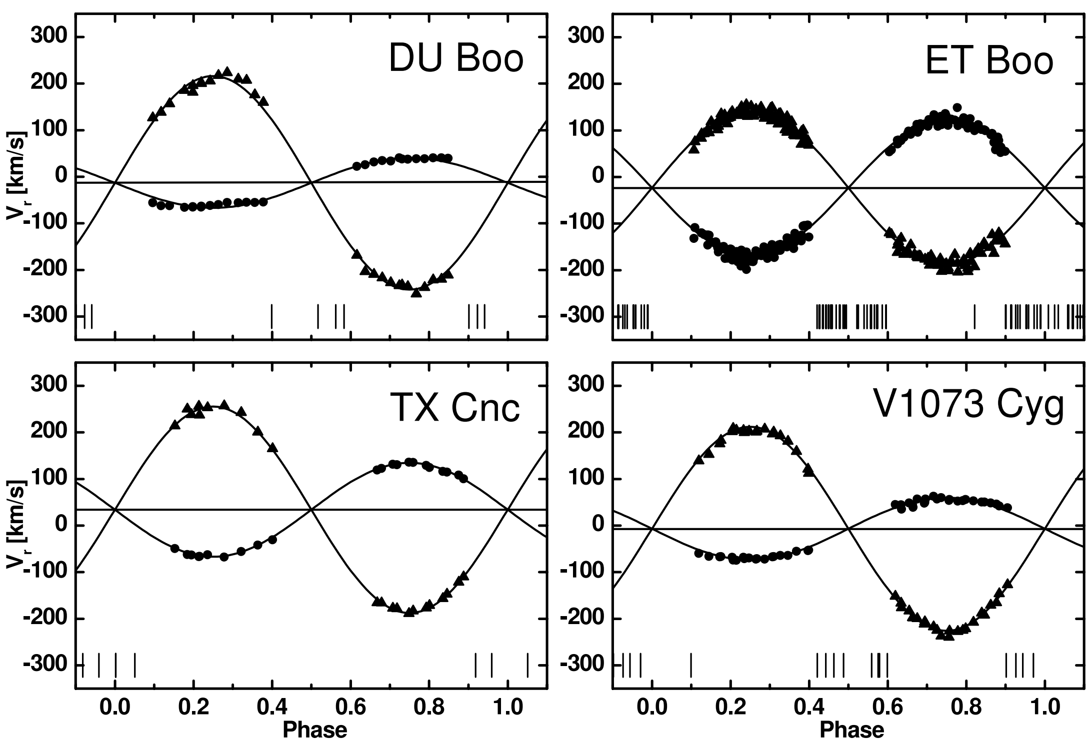

Fig. 1.—RVs of the systems DU Boo, ET Boo, TX Cnc, and V1073 Cyg vs. the orbital phases. The lines give the respective circular-orbit fits (sine curves) to the RVs. ET Boo is a quadruple system composed of a detached eclipsing pair and a detached noneclipsing pair with a much longer orbital period $P \approx 31.5$ days. DU Boo, TX Cnc, and V1073 Cyg 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 that shows negative velocities for the phase interval 0.0–0.5. The short bars in the lower parts of the panels show the phases of available observations that were not used in the solutions because of the blending of lines.

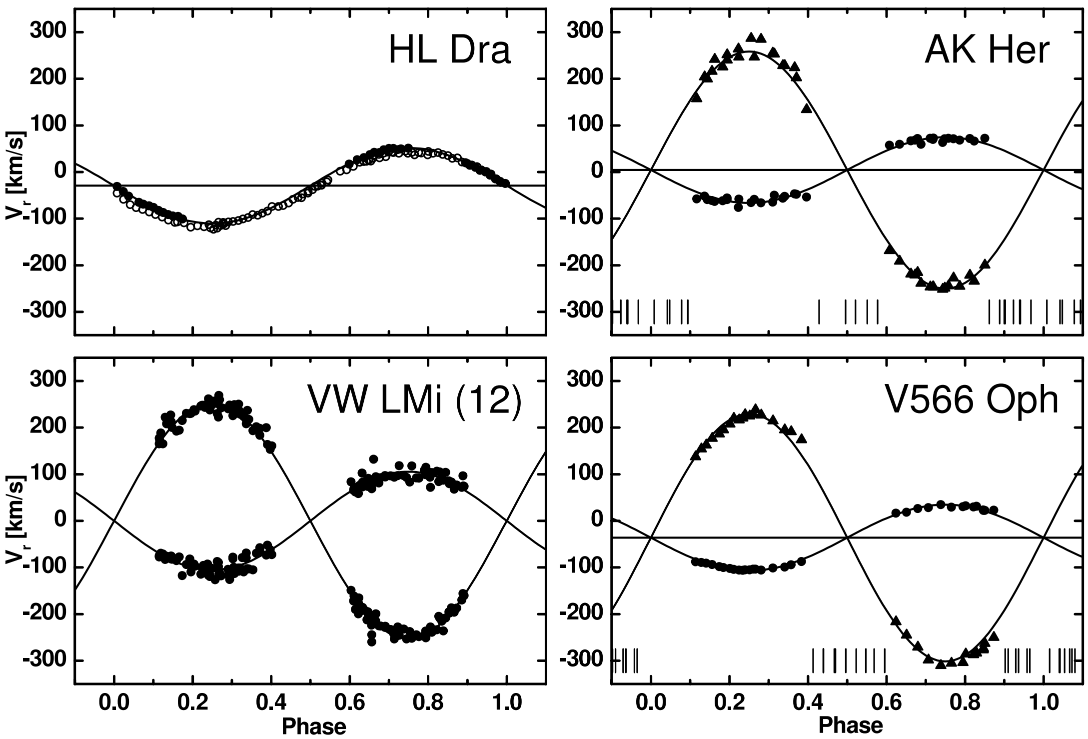

FIG. 2.—Same as Fig. 1, but for HL Dra, AK Her, VW LMi, and V566 Oph. HL Dra is a detached single-lined binary, while AK Her and V566 Oph are contact binaries. VW LMi is a quadruple system containing an eclipsing contact binary and a detached noneclipsing binary with a 7.93 day orbit. The study and interpretation of BFs is complicated by the fact that both binaries revolve in a relatively tight orbit with $P \approx 355$ days. We show additional data for VW LMi in Figs. 7 and 8.

binary with a large O'Connell effect amounting to the difference max. II $-$ max. I $= 0.10$ mag in the V passband. It is interesting to note that the light-curve asymmetry and the associated surface inhomogeneities have been very stable since the time of the *Hipparcos* discovery; this indicates that the solar-type dark-spots paradigm does not apply in this case. Recently, Pribulla (2004) analyzed the *UBV* photometry and found that DU Boo is a relatively long-period (1.0559 days) contact binary showing total eclipses; the derived photometric mass ratio was found to be $q = 0.194(2)$. Our spectroscopic mass ratio $q = 0.234(35)$ is consistent with the photometric determination, which documents the reliability of the photometric mass ratios derived from timing of the inner eclipse contacts for contact binaries showing total eclipses (Mochnacki & Doughty 1972a, 1972b).

The large O'Connell effect is reflected in the extracted BFs of DU Boo. While the primary component shows undisturbed BFs around quadratures, close in shape to the theoretical rotational profiles (§ 3), the BF profile for the secondary is always very deformed. This causes distortions of the observed RV curve and adversely affects the solution for the center-of-mass velocity. The peaks of the BFs are not fully separated, supporting the photometric solution of DU Boo as a contact binary. The system is clearly of the A type, with the more massive component eclipsed at the deeper minimum.

By combining our spectroscopic results with the inclination angle $i = 81\overset{\circ}{.}5$ (Pribulla 2004), we obtain the total mass of the system, $M_1 + M_2 = 2.56 \pm 0.07\, M_{\odot}$. Our new spectral type estimate of A7 V is definitely later than the spectral type given in the *Hipparcos* catalog (A2). The mean Tycho-2 color $(B - V) = 0.31$ is in better accord with our determination of the spectral type and requires only a small interstellar extinction. The orbital period of the system (1.0559 days) is rather long for a contact binary of A7 V spectral type, which indicates that the components of DU Boo may be evolved. The *Hipparcos* parallax is

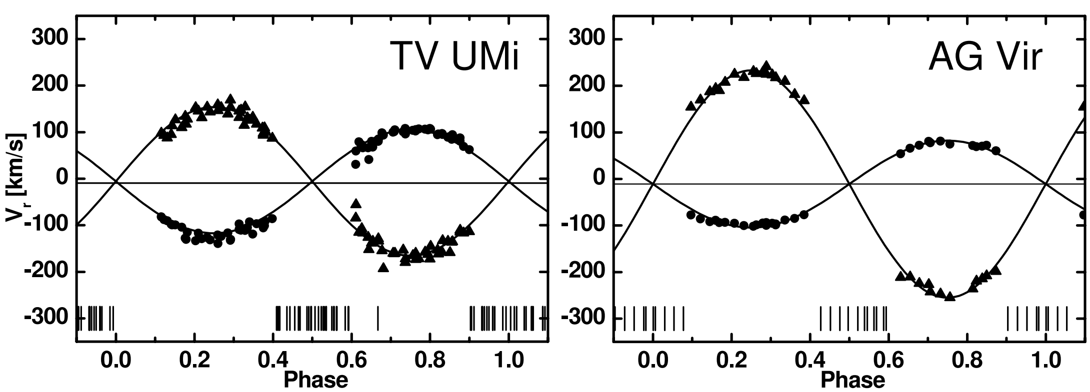

FIG. 3.—Same as Fig. 1, but for the two remaining systems, TV UMi and AG Vir. While AG Vir is a contact binary containing a third component, TV UMi is a quadruple system containing a contact binary and a detached noneclipsing binary with a period of about 31.2 days.

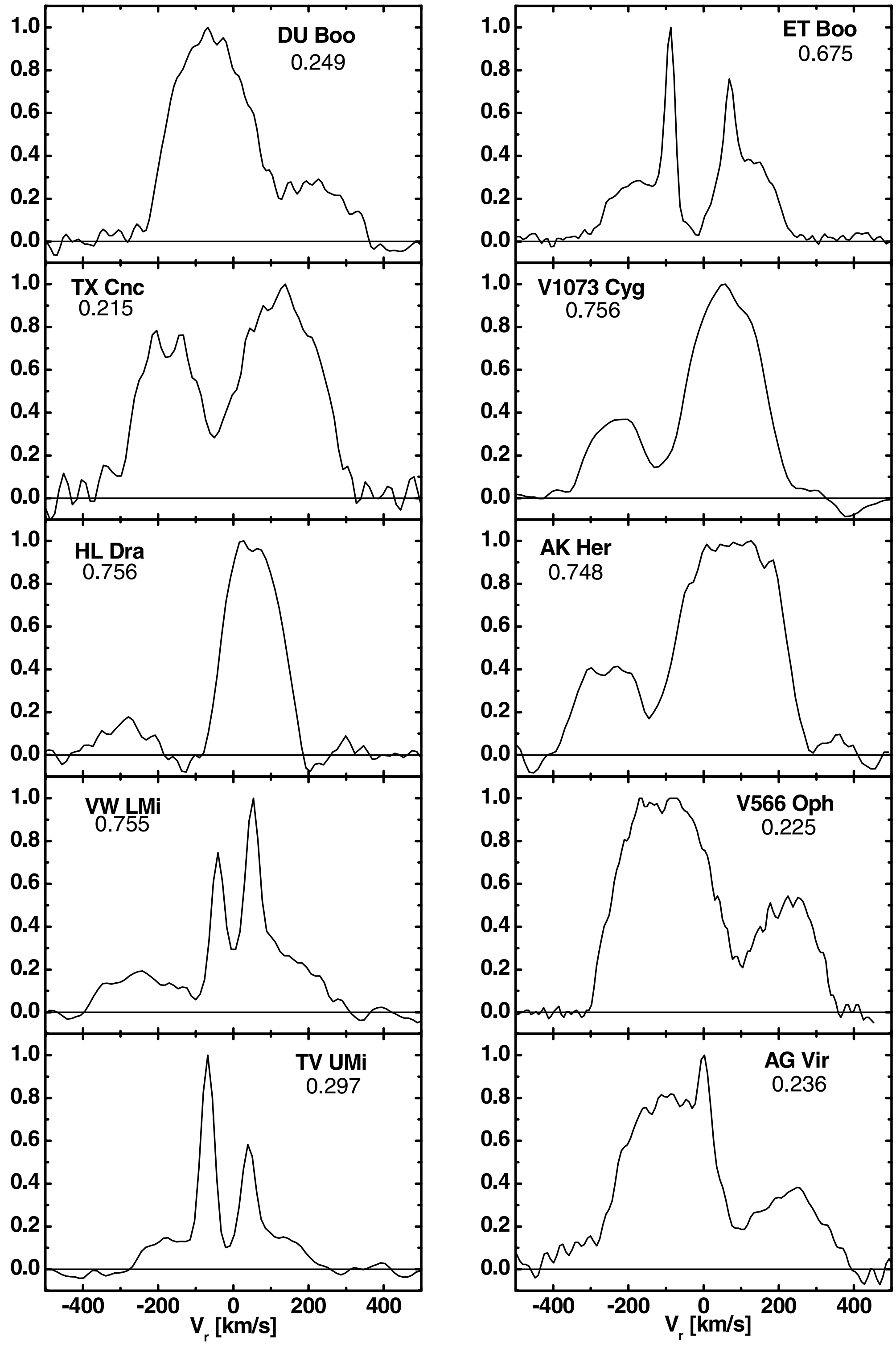

Fig. 4.—BFs for all 10 systems of this group, selected for phases close to 0.25 or 0.75. The phases are shown as numbers in the individual panels. For the three quadruple systems ET Boo, VW LMi, and TV UMi, we selected the BFs showing the second, noneclipsing pair. While the companion binary of VW LMi has an almost circular orbit and its lines are separated during most of the orbit, the lines of the companion binaries of ET Boo and TV UMi can be separated only during short intervals during the respective periastron passages. All panels have the same horizontal range, -500 to $+500$ km s^{-1}.

relatively small, $\pi = 2.58 \pm 1.03$ mas, and not precise enough for determination of the system luminosity.

2.2. *ET Boo*

The photometric variability of this star was discovered by the *Hipparcos* satellite (Perryman et al. 1997); it is cataloged as a β Lyrae eclipsing binary of F8 spectral type. ET Boo is a known member of the visual pair COU 1760 (ADS 14593+4649), with an orbital period of about 113 yr and a magnitude difference of $\Delta V = 0.86$ (see the Sixth Catalog of Orbits of Visual Binary Stars, currently available only in electronic form).[5]

[5] Washington Double Star Catalog (Mason et al. 2001; http://ad.usno.navy.mil/wds/orb6.html).

TABLE 3

Radial Velocity Observations of the Third and Fourth Components of Quadruple Systems

HJD − 2,400,000	V_3 (km s^{-1})	V_4 (km s^{-1})	Notes
ET Boo			
53,455.89155	−14.30	−42.26	b
53,455.90414	−14.30	−43.31	b
53,455.91510	−16.13	−42.56	b
53,455.92738	−12.09	−36.59	b
53,529.61628	−89.18	68.01	
53,530.73133	−63.86	44.00	
VW LMi			
50,852.78735	−75.68	51.31	
50,852.79458	−75.45	52.17	
50,853.69796	−54.16	29.50	
50,853.70383	−55.28	28.85	

Notes.—The table gives the RVs V_i for the third and fourth components. Ten typical rows of the table for the quadruple systems ET Boo and VW LMi are shown. Observations of quadruple systems ET Boo, VW LMi, and TV UMi leading to entirely inseparable BF peaks of components of the second binary are omitted from the table. RVs determined from partially blended profiles are marked by "b" in the last column. Table 3 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

TABLE 4

Spectroscopic Orbital Elements of the Second Noneclipsing Binary in the Quadruple System ET Boo

Parameter	Value
P_{34} (days)	31.5212 ± 0.0005
e_{34}	0.740 ± 0.011
ω (rad)	2.94 ± 0.03
T_0 (HJD)	2,451,354.66 ± 0.04
V_0 (km s^{-1})	−24.15 ± 0.44
K_3 (km s^{-1})	40.36 ± 0.67
K_4 (km s^{-1})	57.67 ± 0.69
$q = K_4/K_3$	0.70 ± 0.02
$(a_3 + a_4)\sin i$ (AU)	0.191 ± 0.003
$(M_3 + M_4)\sin^3 i$ ($M_\odot$)	0.93 ± 0.05

Notes.—The table gives the spectroscopic elements of the second binary in ET Boo: 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 and K_4). The corresponding mass ratio q, projected relative semimajor axis [$(a_3 + a_4)\sin i$], and total mass [$(M_3 + M_4)\sin^3 i$] are also given.

The close eclipsing binary producing the light variations (stars 1 and 2) is the brighter component of the visual pair. The observed separation of the visual components was 0.″1–0.″2 during the available astrometric observations (Mason et al. 2001), which is much less than the typical seeing at the DDO of 1″–3″; therefore, the spectra of both components were observed simultaneously. We discovered that the BFs (Figs. 4 and 5) show an occasional splitting of the third-component peak, indicating that it is in fact a close noneclipsing binary (stars 3 and 4) with a very strongly elliptical orbit. Thus, the system is a hierarchical quadruple with both components of the visual 113 yr period system being double-lined (SB2) close binaries. Our estimates of the combined brightness of the third and fourth components are $L_{34}/(L_1 + L_2) = 0.35 \pm 0.02$ for the spectral region around 5184 Å and $L_{34}/(L_1 + L_2) = 0.33 \pm 0.02$ at 6400 Å during the maximum light of the closer pair.

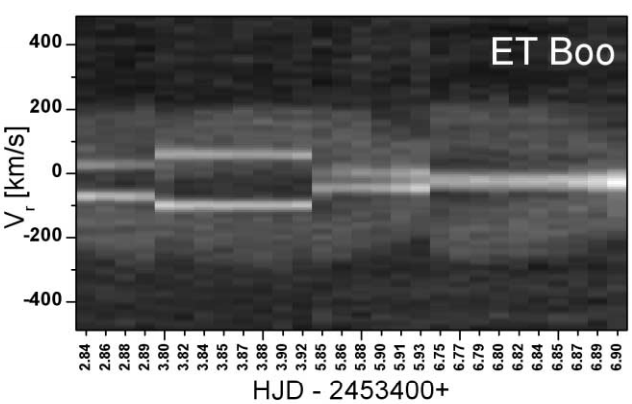

Fig. 5.—Gray-scale plot of BFs of ET Boo extracted from spectra taken in 2005 February around 6400 Å. The spectra were sorted in time. One bin in the *X*-axis corresponds to one spectrum, so the scale is not continuous. The signatures of the close, short-period binary are seen as relatively faint features in the background. The second binary is visible as a sharp feature in the BFs, which split into two components during the periastron passage on the second night of observations, on 2005 February 10.

The RV data for the close binary were handled in the standard way, by first removing the peaks (by preliminary fitting of Gaussian profiles) of the second binary and then measuring the positions of the RV peaks for the close pair. The novelty here is that instead of Gaussian profiles, as in previous papers, we used double rotational profiles for the close pair (§ 3). The results indicate that the brighter component of ET Boo is a semidetached or more likely a detached binary with a relatively large mass ratio, $q = 0.884$.

Only a small fraction of the available BFs show splitting of the visual companion peaks (components 3 and 4); this property gave us a hint of a highly eccentric orbit but also crucially helped in finding the orbital period. Because these stars have very similar brightness, the period ambiguity was resolved by consideration of the RV differences between the components. A preliminary orbital period found by trigonometric polynomial fitting to the data was later refined by the spectroscopic orbit solution (Table 4, Fig. 6) to give 31.521 days. The systemic velocity of the second binary, $V_0 = -24.15 \pm 0.44$ km s^{-1}, is close to the systemic velocity of the close pair, $V_0 = -23.52 \pm 0.52$ km s^{-1}, confirming the physical association of the two binaries. Since the orbital period of the wide pair is 113 yr, no orbital motion can be expected to be detected in the 5 yr of our observations.

2.3. *TX Cnc*

The photometric variability of TX Cnc, an apparent member of the Praesepe open cluster, was first announced by Haffner (1937). Whelan et al. (1973) were the first to obtain a good simultaneous fit to the photometric and spectroscopic data of the system on the assumption of the Roche model. A preliminary analysis of the DDO observations was published in a Ph.D. thesis (Blake 2002). The RVs used there were later redetermined using rotational profile fitting. Surprisingly, the BFs show the shape of a practically detached binary (see Fig. 4), although the orbital velocities are quite typical for a contact W-type system.

The spectroscopic elements of TX Cnc determined by Whelan et al. (1973) were $V_0 = 26.6 \pm 3$ km s^{-1}, $K_1 = 117.3 \pm 3$ km s^{-1}, and $K_2 = 189.8 \pm 4$ km s^{-1}, giving $q = 0.62$. A later

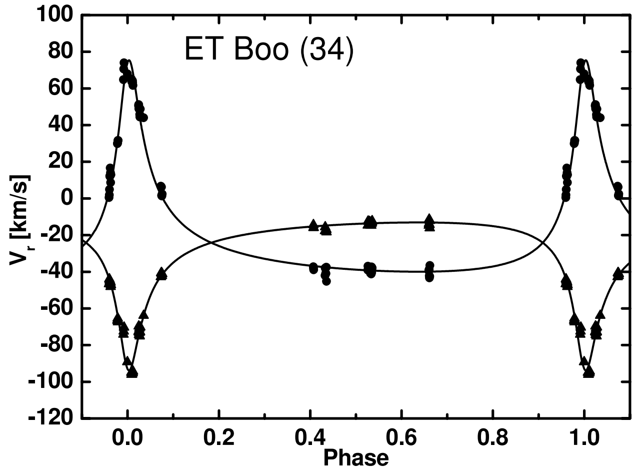

FIG. 6.—Radial velocities of the third and fourth components of ET Boo and the corresponding fits to an orbital motion with the period of 31.52 days.

RV solution published by McLean & Hilditch (1983), $V_0 = 29 \pm 6$ km s^{-1}, $K_1 = 96 \pm 8$ km s^{-1}, and $K_2 = 181 \pm 11$ km s^{-1}, was based on only eight photographic spectra. Our spectroscopic elements suggest a smaller mass ratio, $q = 0.455 \pm 0.011$, than derived before and a larger total mass, $(M_1 + M_2)\sin^3 i = 1.330 \pm 0.012\,M_\odot$; both changes are rather characteristic for an improved quality of the spectroscopic observations.

TX Cnc is of particular interest for our understanding of the evolution of contact binaries because it appears to belong to Praesepe, which is one of the youngest (900 Myr) open clusters containing such binaries (Rucinski 1998). All indications point to an advanced age for contact binaries, so confirmation of the membership of TX Cnc in Praesepe may provide a much needed lower limit on the time needed to form such binaries. Unfortunately, the system's parallax was not measured during the *Hipparcos* mission, so the membership must be judged by less direct means. Our RV data giving $V_0 = 34.0 \pm 0.5$ km s^{-1} are fully consistent with the mean velocity of the Praesepe cluster, $V = 34.53 \pm 0.12$ km s^{-1}, and the velocity dispersion of its spectroscopic binaries, $\sigma = 0.40$ km s^{-1} (Mermilliod & Mayor 1999).

In the Positions and Proper Motions Catalog, Röser & Bastian (1988) assign TX Cnc a parallax of 5.21 ± 0.79 mas. *Hipparcos* astrometry of Praesepe analyzed by van Leeuwen (1999) gives a cluster parallax of 5.32 ± 0.37 mas, i.e., a distance modulus of $m - M = 6.37 \pm 0.15$. With the maximum brightness of TX Cnc of $V_{\rm max} = 10.0$, we get $M_V = 3.63 \pm 0.15$, which is in perfect agreement with the absolute magnitude estimated from the Rucinski & Duerbeck (1997) calibration giving $M_V = 3.60$, for an assumed $(B - V)_0 = 0.54$ corresponding to spectral type F8 V.

This excellent agreement in RV, parallax, and luminosity distance is supported by proper-motion data. The careful photographic study by Jones & Stauffer (1991) showed that TX Cnc has a proper motion of ($\mu_x = -4.4 \pm 3.2$, $\mu_y = 0.5 \pm 1.4$) mas yr^{-1} relative to the center of motion of Praesepe, leading Jones & Stauffer (1991) to assign a 99% probability that TX Cnc belongs to Praesepe. The velocity dispersion contributes less than 1 mas yr^{-1}. The Tycho-2 work of Høg et al. (2000) yields ($\mu_\alpha \cos\delta = -36.2 \pm 1.2$, $\mu_\delta = -11.2 \pm 1.3$) mas yr^{-1} for the absolute proper motion of TX Cnc, compared with the mean center-of-mass motion of (-35.7 ± 0.4, -12.7 ± 0.3) mas yr^{-1} found by van Leeuwen (1999). We can therefore be very confident that TX Cnc is a member of Praesepe, and hence, it is an important system for testing theories of contact binary formation and evolution.

2.4. *V1073 Cyg*

The bright A-type contact binary V1073 Cyg has been the subject of several photometric studies (Sezer 1996; Morris & Naftilan 2000). There also exist two spectroscopic investigations: Fitzgerald (1964) published a spectroscopic orbit for the primary component with a marginal detection of the secondary, with $V_0 = -8 \pm 3$ km s^{-1}, $K_1 = 66 \pm 4$ km s^{-1}, and a mass ratio of $q = 0.34$. The author found a small eccentricity for the orbit, $e = 0.115 \pm 0.053$, which cannot be significant when one applies the arguments of Lucy & Sweeney (1971, 1973) about the statistics of eccentricity determinations.

Ahn et al. (1992) obtained an apparently more reliable, circular orbit solution for both components, with resulting spectroscopic elements of $V_0 = -0.8 \pm 1.1$ km s^{-1}, $K_1 = 66.7 \pm 1.3$ km s^{-1}, and $K_2 = 210.2 \pm 1.2$ km s^{-1}. Our results, $V_0 = -6.85 \pm 0.50$ km s^{-1}, $K_1 = 65.53 \pm 0.64$ km s^{-1}, and $K_2 = 218.9 \pm 1.5$ km s^{-1}, are superior to the previous ones thanks to the BF extraction technique and the rotational profile fitting. The relatively large formal rms errors are mainly caused by the simple sine-curve solution used by us. When combined with a high-precision light curve, the BF modeling can provide high-quality absolute parameters of the system.

Our spectral type estimate, F0 V, is much later than the original classification by Fitzgerald (1964), who estimated the spectral type as A3 Vm; it confirms the classification of Hill et al. (1975). The Tycho-2 color $B - V = 0.375$ and our spectral type indicate a nonnegligible amount of reddening. The *Hipparcos* parallax, $\pi = 5.44 \pm 0.95$ mas, is not sufficiently precise to draw conclusions about the physical properties of the system.

2.5. *HL Dra*

The variability of HL Dra was detected during the *Hipparcos* mission. The system was classified as a β Lyrae eclipsing binary with an orbital period of 0.944276 days. The primary component is of the A5 spectral type. No ground-based photometric study of the system has been published yet. Also, no recent minima after the *Hipparcos* mission are available. Our time of the spectroscopic conjunction shows only a small shift (+0.0047 days) with respect to the time predicted by the original *Hipparcos* ephemeris, so the orbital period of the system appears to be very stable.

We have not been able to detect spectral signatures of the secondary component in our data. The BFs close to quadratures show only small humps on either side of the primary peak, which cannot be identified with the secondary component because they do not show any orbital motion. The system is clearly a detached or semidetached pair with a low-luminosity secondary component.

HL Dra was observed during two seasons in two different wavelength regions, in 2004 at 5184 Å and in 2005 at 6290 Å. The latter data set is of relatively poor quality due to the low number and weakness of spectral lines found in the red spectral regions of early-type stars. The orbital single-line solutions resulting from the two data sets are in good accord except for the center-of-mass velocity of $V_0 = -29.3 \pm 0.4$ km s^{-1} for the 2004 data and $V_0 = -36.5 \pm 0.6$ km s^{-1} for the 2005 data. The shift is well outside the formal errors and may be caused by motion of the eclipsing pair around the barycenter with a third body. The 2004 data are of much better quality, so the orbital parameters listed in Table 1 correspond to this data set.

Our new spectral type determination is slightly later, A6 V, than that previously published. The Tycho-2 color index $(B - V) = 0.222$ corresponds to the A8 V spectral type, so the reddening appears to be small.

2.6. *AK Her*

AK Her is a W UMa–type contact binary discovered by Metcalf (see Pickering 1917). It is the brighter component in the visual binary ADS 10408. The companion, located at a separation of 4″.2, is 3.5 mag fainter than AK Her at its maximum light. The position angle of 323° is almost perpendicular to our fixed, east-west spectrograph slit, so this component was not detectable in the BFs.

The system is known to show a cyclic variation in the moments of eclipses that is probably caused by the light-time effect induced by an undetected companion on an orbit of about 57 yr (Awadalla et al. 2004). The perturbing star cannot be identified with the known visual companion and must be much closer to the binary. The complex multiplicity of the system is supported by *Hipparcos* astrometry in the following way: (1) the system shows a stochastic astrometric solution (the X flag in the catalog field H59); (2) it is suspected not to be single (the S flag in H61); (3) the trigonometric parallax of 10.47 ± 2.77 mas has much too large an error for the brightness of the system. Our individual spectroscopic data do not show any contribution from this putative third (or rather fourth) component. It is possible that such a companion will be seen in a detailed analysis of averaged spectra (D'Angelo et al. 2006), but this approach is outside the scope of the present paper.

Our RV solution is the first to treat the star as a double-lined binary system (SB2). Sanford (1934) observed the RV curve of the primary component and determined $f(m) = 0.0208\,M_{\odot}$. His RV solution ($V_0 = -13$ km s^{-1}, $K_1 = 79$ km s^{-1}) is fairly consistent with our solution.

Our spectral classification gives an earlier spectral type for the system, F4 V, than previously discussed, F8 V. It is not fully consistent with the Tycho-2 color index $(B - V) = 0.490$ and implies some interstellar reddening.

2.7. *VW LMi*

The photometric variability of VW LMi was found by the *Hipparcos* mission. It was classified in the *Hipparcos* catalog (Perryman et al. 1997) as a W UMa–type eclipsing binary with an orbital period of 0.477547 days. The first photometric observations of the system were published by Dumitrescu (2000). Later, the light curve of the system was analyzed by Dumitrescu (2003), who found the mass ratio $q_{\rm ph} = 0.395$ and inclination $i = 72.4°$; we show later that these values are incorrect, as they do not take into account the presence of the relatively bright binary companion.

VW LMi has been observed spectroscopically at DDO since 1998. It was realized from the beginning that the system is a quadruple one, consisting of two spectroscopic binaries. While the eclipsing pair can be identified with a short-period contact binary, the second spectroscopic binary is a detached one with a period of about 7.9 days (see below how we arrived at the more exact value). The light contribution of the second spectroscopic binary at the maximum brightness of the contact pair is $L_{34}/(L_1 + L_2) = 0.42$.

The study of the quadruple system VW LMi is complicated by the mutual orbital motion of both binaries, so changes in the respective V_0 values cannot be neglected. Another complication is the similar brightness of the components of the second, noneclipsing binary, making derivation of its orbital period very difficult. We worked first with the RV differences of the components of the second pair to find its orbital period. Trigonometric polynomial fits to the data led to the orbital period $P_{34} = 7.9305$ days, which explained all data very well. An attempt to find the orbit of the contact pair (after removing the contribution of the second binary) resulted in poor quality of the spectroscopic orbit. In fact, the residuals from both preliminary orbits showed a clear anticorrelation between the velocities of the contact pair (components 1 and 2) and of the noneclipsing binary (components 3 and 4), indicating the mutual orbital motion of the two binaries. The period analysis revealed only one feasible period of about 355 days, hence close to 1 yr. Since the data span 7 yr and the observing season for VW LMi is from late November to mid-May, the phase coverage of the mutual orbit is partial and has gaps.

A further improvement of all three orbits was achieved by simultaneous fits to all four data sets of the RVs of the form

$$V_i = V_0 + (-1)^i K_i\left[e_j \cos\omega_j + \cos(\omega_j + \nu_j)\right] + (-1)^j K_{2j-1,\,2j}[e_3 \cos\omega_3 + \cos(\omega_3 + \nu_3)],$$

where V_0 is the center-of-mass velocity of the whole quadruple system, K_i is the respective velocity semiamplitude of the individual components, e_j is the orbital eccentricity, ω_j is the longitude of the periastron, and ν_j is the true anomaly. The index i corresponds to the component number ($i = 1$–4), while the index j takes the value of 1 for the contact binary, 2 for the detached binary, and 3 for the mutual orbit of the two systems. Thus, for the components of the contact binary, $j = 1$ and $i = 1, 2$, while for the components of the detached binary, $j = 2$ and $i = 3, 4$. So, $K_{2j-1,2j}$ for $j = 1$ should be read as K_{12}, while for $j = 2$ it should be read as K_{34}, where K_{12} and K_{34} are the semiamplitudes of the RV changes of the centers of mass of the contact and the detached binary, respectively.

All results of the simultaneous fits are presented in Table 5, while the orbital elements of the contact pair are also given with the remaining binaries of this study in Table 2. For simplicity, all measurements were assigned the same weight, although the velocities for the detached pair were determined by Gaussian fits, while those of the contact pair were determined by rotational profile fits. The sine-curve fits to the data for the contact binary, corrected for the motion on the outer orbit, are shown in Figure 2. While the secondary component is usually not blended with the peaks of the second spectroscopic binary, the primary of the contact pair is always visible projected against the "background" of the profiles of the third and fourth components. This circumstance caused an enhanced scatter of the velocities of the primary component.

The corrected RVs of the second binary with the corresponding fits are plotted in Figure 7. The final orbital period for this binary is 7.93044 days, and the orbit is nearly circular. The velocities of all four components corrected for the corresponding orbital motions in the inner orbits and their best fits are plotted in Figure 8. These residual RVs represent the orbital motion of the centers of mass of both binaries.

Because the outer orbit has a relatively short period of 355 days, it is of interest to inquire into the mutual orientation of the three orbits. This can be estimated from the projected masses of the components in a sort of a "bootstrap" process started with the derived inclination of the contact, eclipsing system. A preliminary solution of unpublished photoelectric data obtained at the Stará Lesná Observatory of the Astronomical Institute of the Slovak Academy of Sciences was used to estimate the inclination angle

TABLE 5

Spectroscopic Orbital Elements of All Three Orbits Defined by RVs of Four Resolved Components of VW LMi

Parameter	Value
Contact (Eclipsing) Pair: Circular Orbit	
P_{12} (days)	0.47754988 ± 0.00000020
T_0 (HJD)	2,451,973.4117 ± 0.0004
K_1 (km s^{-1})	105.41 ± 0.83
K_2 (km s^{-1})	253.21 ± 0.84
$(M_1 + M_2) \sin^3 i_{12}$ ($M_\odot$)	2.282 ± 0.018
Detached Noneclipsing Pair	
P_{34} (days)	7.93062 ± 0.00014
e_2	0.033 ± 0.010
ω_2 (rad)	5.01 ± 0.09
T_0 (HJD)	2,452,282.44 ± 0.11
K_3 (km s^{-1})	65.44 ± 0.76
K_4 (km s^{-1})	64.15 ± 0.76
$(M_3 + M_4) \sin^3 i_{34}$ ($M_\odot$)	1.788 ± 0.033
Mutual Wide Orbit	
$P_{12\text{-}34}$ (days)	355.0 ± 0.5
e_3	0.14 ± 0.03
ω_3 (rad)	2.35 ± 0.22
T_0 (HJD)	2,452,703 ± 11
K_{12} (km s^{-1})	19.96 ± 0.84
K_{34} (km s^{-1})	21.76 ± 0.79
$(M_1 + M_2 + M_3 + M_4) \sin^3 i_{12-34}$ ($M_\odot$)	2.67 ± 0.16
V_0 (km s^{-1})	1.29 ± 0.39

Notes.—This table gives the spectroscopic elements for the three observed orbits of VW LMi. The designation of parameters is as in the previous table. The index "12" refers to the orbit of the contact pair, while the index "34" refers to the orbit of the second, detached binary. Parameters of the mutual orbit of these binaries are indexed as "12-34." The orbit of the contact pair is assumed to be circular ($e_1 = 0$, $\omega_1 = \pi/2$).

of the eclipsing pair. Fixing the third light at $L_{34}/(L_1 + L_2) = 0.42$ (see above) and using the spectroscopic mass ratio of $q = 0.42$ led to the inclination angle $i_{12} = 80.1° \pm 0.2°$. This is, as expected, a much larger inclination than the one obtained by Dumitrescu (2003; $i = 72.4°$) without assumption of a third light. Using our estimate of the inclination angle and the projected total mass of the contact pair $(M_1 + M_2) \sin i_{12} = 2.28\ M_\odot$, we obtain $(M_1 + M_2) = 2.39\ M_\odot$. The outer, 355 day orbit defines the mass ratio for the two pairs, $(M_1 + M_2)/(M_3 + M_4) = 1.09$. Therefore, the true (not the projected) mass of the second spectroscopic binary is $(M_3 + M_4) = 2.19\ M_\odot$. Using the projected mass $(M_3 + M_4) \sin i_{34} = 1.79 \pm 0.03\ M_\odot$, we estimate the inclination of the orbit of the second pair to be about 69°. The outer, 355 day orbit is even less inclined to the sky, since with $(M_1 + M_2 + M_3 + M_4) = 4.58\ M_\odot$ and a projected total mass of only 2.67 $M_\odot$, we obtain $i_{12\text{-}34} = 57°$. Obviously, we could not determine whether these values were all in the same quadrant or were complements to 180°; a determination of the sense of the revolution could only come from interferometric observations.

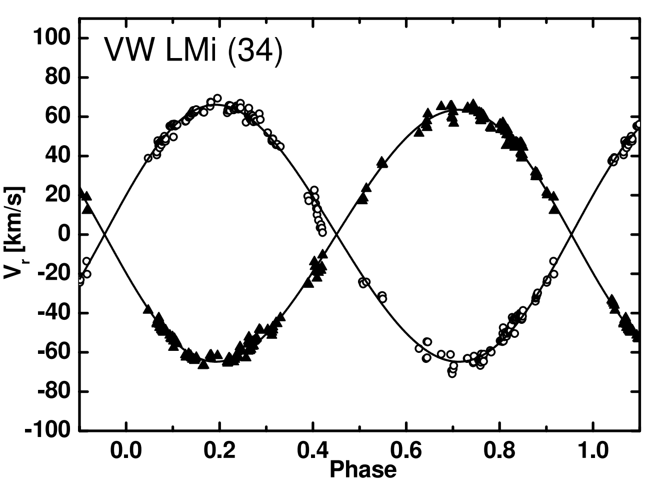

Fig. 7.—Radial velocities of the third and fourth components of VW LMi, plotted in a phase diagram with the period of 7.93 days, after being corrected for the motion on the outer, 355 day period orbit.

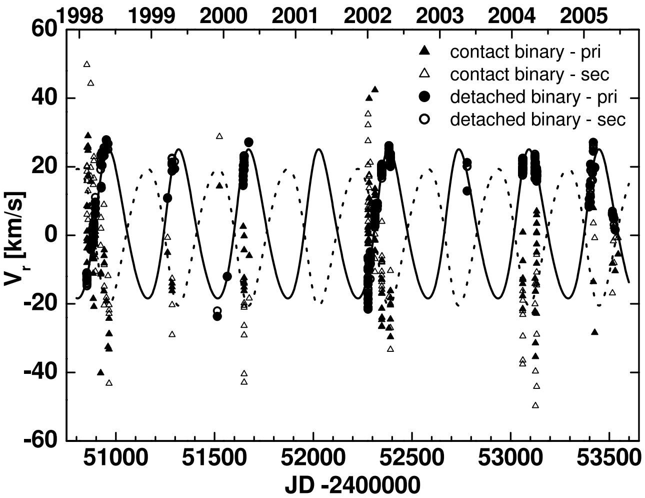

Fig. 8.—RVs of all four components of VW LMi corrected for orbital motion in both close orbits, showing the motion of the centers of mass in the wide, 355 day orbit. The phases are counted from the periastron passage. Because the orbital period is close to 1 yr, the seasonal observing interval slowly moved in the orbital phases between 1998 and 2005.

The noneclipsing, detached binary, with $(M_3 + M_4) = 2.19\ M_\odot$, is composed of two almost identical ($q_{34} = M_3/M_4 = K_4/K_3 = 0.980 \pm 0.017$), most probably main-sequence stars. Their masses correspond to about F9 V–G0 V spectral types, and their similarity is also reflected in the luminosity ratio $l_3/l_4 \approx 1.04$. The evolutionary status of the components can be guessed from a comparison of their rotational and orbital velocities. If we assume a synchronous rotation and take the rotational velocities of the components estimated from Gaussian profile fits to be about 12 km s^{-1} and the semiamplitudes of the RVs to be about 60 km s^{-1}, we see that the fractional radii of the components are $r/a < 0.2$. With the semimajor axis of the absolute orbit of about 10 $R_\odot$, their radii are $<2\ R_\odot$. The similar spectral types of all the components of the quadruple system of VW LMi result in a very good quality of extracted BFs, as can be judged in Figure 4.

It is interesting to note that the multiplicity of VW LMi was not identified astrometrically during the *Hipparcos* mission in spite of the relative proximity of the system at $\pi = 8.04 \pm 0.90$ mas. This is probably caused by the orbital period of the two pairs around each other being close to 1 yr, thus mimicking the parallactic motion.

Because of the small size of the mutual (355 day) orbit of only 0.62 AU, the chances of resolving the two astrometric components are rather small even with advanced techniques, because the expected maximum angular separation will be only 10 mas. The situation is little bit more optimistic with the expected light-time effect of the eclipse timing of the contact binary, as the expected full amplitude is about 0.0074 days, which should be relatively easy to detect with the observed photometric amplitude of 0.42 mag.

2.8. *V566 Oph*

The W UMa–type binary V566 Oph was discovered by Hoffmeister (1935). The system is bright ($V_{\max} = 7.46$), and therefore, it has been the subject of numerous previous photometric (for references see Twigg 1979) and spectroscopic observations. An interval of constant light observed during the secondary eclipse indicates an A type. Mochnacki & Doughty (1972b) published the first light curve analysis of V566 Oph based on the Roche model. The total eclipses permitted the determination of reliable geometric elements: the fill-out $F = 1.25 \pm 0.05$ ($f = 0.25$), mass ratio $q = 0.238 \pm 0.005$, and inclination $i = 80° \pm 2°$.

There exist three previous spectroscopic studies of the system. Two of these are based on photographic observations (Heard 1965; McLean 1983), and a more recent one is based on the Reticon data (Hill et al. 1989). The latter study used direct fitting of the synthetic profiles to the cross-correlation functions (CCFs). The spectroscopic elements obtained in their study, $V_0 = 38.5 \pm 1.1$ km s^{-1}, $K_1 = 72.6 \pm 1.5$ km s^{-1}, and $K_2 = 272.9 \pm 1.3$ km s^{-1}, are practically within the errors of our results, $V_0 = 37.3 \pm 0.5$ km s^{-1}, $K_1 = 71.1 \pm 0.7$ km s^{-1}, and $K_2 = 270.1 \pm 1.1$ km s^{-1}. The current improvement of the orbit is mainly due to the use of the BF extraction technique and of the rotational-profile fitting. The orbit can be still improved by taking proximity effects into account. Our new determination of the mass ratio, $q = 0.263 \pm 0.012$, is in moderately good agreement with the photometric mass ratio of Mochnacki & Doughty (1972b), confirming the utility of the photometric approach to systems with total eclipses.

The orbital period of the system is rather unstable. In spite of the possible light-time effect orbit found by Pribulla & Rucinski (2006), we did not find any traces of the third component in the extracted BFs.

V566 Oph is a relatively nearby system with a good *Hipparcos* parallax, $\pi = 13.98 \pm 1.11$ mas. The absolute magnitude determined using the calibration of Rucinski & Duerbeck (1997), $M_V = 3.07$, using $(B - V) = 0.406$ from the Tycho-2 catalog (Høg et al. 2000), is in good agreement with the visual absolute magnitude determined from the *Hipparcos* parallax, $M_V = 3.19 \pm 0.17$. Our new spectral classification, F4 V, indicates a slightly later spectral type than the F2 V found by Hill et al. (1989).

2.9. *TV UMi*

TV UMi is another discovery of the *Hipparcos* mission. The system was classified as a β Lyrae eclipsing binary with an orbital period of 0.415546 days, although the classification was obviously complicated by the low amplitude of the light variations of only about 0.08 mag. The eclipses are very wide and of almost the same depth. For that reason we suspected that the variability was caused by a contact binary of the W UMa type.

Prolonged spectroscopic observations of TV UMi at the DDO showed that the system is a quadruple one and consists of two spectroscopic binaries. The second close binary in TV UMi is almost as bright as the contact pair, but its components are difficult to analyze because of the strong eccentricity of the orbit and the very short duration of periastron passages when the spectral signatures could be potentially resolved. In fact, the components of the second pair could not be separated in most of our spectra; such a separation took place on only three occasions. The largest observed separation of the components of the second binary on 2001 June 8 of more than 100 km s^{-1} had to be close to periastron passage. One of the BFs from that night is included in Figure 3. During this event, the stronger component had a more negative RV. A period analysis of line separations indicates a 31.2 day orbital periodicity for the second pair. Reliable determination of the orbital parameters and confirmation of the preliminary orbital period would require more observations, preferably with a larger spectroscopic resolution to separate the components even outside the periastron passages. The TV UMi system resembles ET Boo in that its companion binary also has an eccentric orbit with a similar orbital period. Our RV observations cover a shorter time base and are less numerous than in the case of VW LMi, so we have not been able to find the mutual orbital motion of the binaries. During intervals when we observed the narrow blend of the peaks of the third and fourth components, the combined RV was about -15 km s^{-1}, slightly less than the systemic velocity of the contact binary (-9.7 km s^{-1}). This indicates a possible slow orbital motion of both pairs.

The light contribution of the second binary is large, $L_{34}/(L_1 + L_2) = 0.90$. As observed during the periastron passage on 2001 June 8, its components have slightly unequal brightness: $L_3/(L_1 + L_2) = 0.58$ and $L_4/(L_1 + L_2) = 0.32$. Using the measured RVs of the third and fourth components during the periastron passage, $\mathrm{RV}_3 = -67.94 \pm 1.13$ km s^{-1} and $\mathrm{RV}_4 = 37.21 \pm 1.03$ km s^{-1}, and the mean RV of the blend of the two components giving the approximate systemic velocity of the second pair, -15 km s^{-1}, we see that the mass ratio of the second binary is close to unity. The observed photometric amplitude of the contact system, $\Delta m = 0.083$, when corrected for light contribution of the companion binary, remains small at $\Delta m = 0.163$.

It is interesting to note that the system was not detected nor even suspected as a multiple one from the *Hipparcos* astrometric data. Chances to resolve both binaries by direct imaging are higher than in VW LMi because no rapid orbital motion of the contact binary was observed, indicating a longer orbital period and thus a larger separation of both binaries. According to the *Hipparcos* astrometry TV UMi is relatively nearby, with $\pi = 7.64 \pm 0.78$ mas.

Clearly, the current data for the second close binary system in TV UMi are inadequate for determination of full orbital parameters for the whole system. Such a determination would require a long-term monitoring program with one or two spectra obtained per night over a period of a few months.

2.10. *AG Vir*

The variability of AG Vir was discovered by Guthnick & Prager (1929). Since then it has been subject to several photometric investigations (for references see Bell et al. 1990). The system is very similar to DU Boo (§ 2.1) in that the first light maximum is always the brighter of the two by about 0.08 mag. A simultaneous photometric and spectroscopic analysis by Bell et al. (1990) showed that a reliable determination of the geometric elements was complicated by the strong asymmetry of the light curve. The system is of the A type with an undeterminable degree of contact (could be marginal or deep). The spectral type is A7 V (our new determination suggests A5 V), so the observed photospheric brightness inhomogeneities may be quite different from the solar-type dark spots.

The period analysis of Blanco & Catalano (1970) indicated the presence of a light-time effect in the eclipse timing caused by a third component on a 40 yr orbit. However, later observations

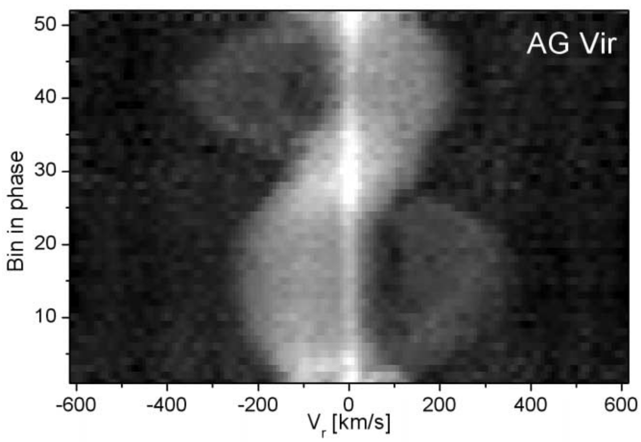

FIG. 9.—Gray-scale plot of the BFs of AG Vir. The spectra have been sorted in phase but not rebinned to the proper phase durations. While individual BFs do not show the third component very clearly, the gray-scale plot shows a continuous, bright ridge line close to the systemic velocity.

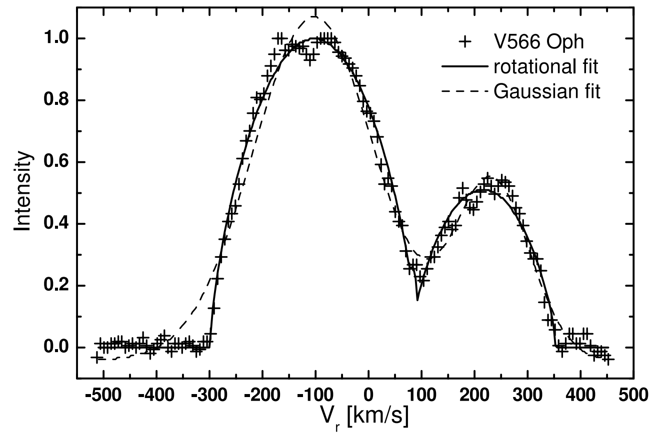

FIG. 10.—Comparison of double-Gaussian and -rotational fits to the BF of V566 Oph extracted from a spectrum taken close to the orbital quadrature. The RV is better defined in the steep portions of the rotational profile branches.

did not confirm any cyclic behavior, although the observed times of minima do show a large scatter. This can be interpreted either as light-curve variations caused by the presence of surface spots or as a light-time effect caused by a body on a short-period orbit. In fact, our BFs do show a well-defined signature of the third component, with $L_3/(L_1 + L_2) \approx 0.05$ (see Fig. 9). However, this star has a rather different RV (+2.9 ± 2.5 km s^{-1}) from the systemic velocity of the contact binary (−10.99 ± 0.82 km s^{-1}). Unfortunately, the uncertainties of the RVs are quite large, and only our better quality 2005 spectra (as used in this paper) show the presence of this component. A close inspection of the published CCFs of Bell et al. (1990) reveals the marginally defined presence of a third component close to the systemic velocity of the binary, but, as expected, the definition of the CCFs was inferior to that of the BFs.

The *Hipparcos* parallax (1.33 ± 1.18 mas) is too small and inconsistent with the estimated absolute magnitude for an A5 V star, $M_V = +2.1$, and the observed maximum visual magnitude, $V_{\rm max} = 8.50$. It is possible that this inconsistency is caused by a transverse motion of the eclipsing pair around the third component.

3. MEASUREMENTS OF RADIAL VELOCITIES USING ROTATIONAL PROFILES

While the previous papers of this series (Papers I, II, III, IV, V, VI, VIII, IX, and X) reported RV measurements obtained by Gaussian fits to the extracted BFs, in this paper we use a novel technique of extracting RVs by rotational profile fits. While neither Gaussian nor rotational profiles can replace the full modeling of BFs that will hopefully take place one day, the rotational profiles are as simple to implement as the Gaussian profiles but offer an improvement in the quality of the RV measurements, with a much better convergence to the final result and noticeably smaller random errors.

The BF of a rigidly rotating star (Gray 1976) is described by four parameters: the overall strength or the amplitude of the BF, a_0, the central velocity, a_1 (identified with the light centroid velocity of the star), and the half-width $a_2 = V \sin i$; the additional parameter is the vertical background displacement, a_3, which can usually be traced to different continuum and pseudocontinuum levels for the standard and program stars during the spectral normalization step. For a double-peaked profile, the first three parameters (a_0 to a_2) appear twice so that the fit involves seven unknowns. By using auxiliary quantities, $c_1 = 1 - u$ and $c_2 = \pi u/4$, the profile can be written as

$$I = a_0 + \frac{a_1 \left\{ c_1 \sqrt{1 - (x - a_1)^2/a_2^2} + c_2 \left[1 - (x - a_1)^2/a_2^2 \right] \right\}}{c_1 + c_2}. \tag{1}$$

The profile depends only slightly on the limb-darkening coefficient u. We assumed $u = 0.7$ in our measurements. As opposed to the Gaussian profile, the rotational profile (see an example in Fig. 10) has rather steep sides and, by definition, is exactly zero for velocities larger than the projected equatorial velocity $V_{\rm rot} \sin i$. These properties are crucial to the improvement in the determination of the parameter a_1, the light centroid for each component.

Although rotational profiles represent the BF profiles of double-lined binaries much better than Gaussian profiles, a practical application may encounter the same complications:

1. If the secondary shows a very faint peak in the BF, its width must usually be fixed at a reasonable value to improve the stability of the solution and to give consistent results.
2. The BF profiles for contact binaries are rather different from those of single, rigidly rotating stars, particularly in the "neck" region between the stars where an additional light is present. Obviously, these asymmetric deviations cannot be fitted by rotational profiles nor by Gaussian profiles. Normally, this leads to underestimates of the velocity semiamplitudes.

In the case of close binary stars, the combined rotational profiles can be applied to BFs strictly only outside the eclipses, as a proper representation of the data should involve inclusion of the eclipse and proximity effects (Rucinski 1992). However, a simple upper envelope of the two individual profiles works well even during partial eclipse phases. We found that double rotational profiles converge faster to the final results and describe the data much better than Gaussian profiles. This is well illustrated in the case of TX Cnc, for which a preliminary orbit defined by RVs obtained through Gaussian fits had almost twice as large standard errors of the spectroscopic elements. While the rms errors for the velocities derived from the Gaussian fits are $\sigma_1 = 8.4$ km s^{-1} and $\sigma_2 = 8.3$ km s^{-1}, the errors for the RVs derived by rotational profile fitting are $\sigma_1 = 4.1$ km s^{-1} and $\sigma_2 = 5.7$ km s^{-1}.

4. SUMMARY

With 10 new short-period binaries, this paper brings the number of systems studied at the David Dunlap Observatory to a round number of 100. The systems presented in this paper include three quadruple systems for which we have been collecting data for several years in the hope of being able to study variability of RVs on timescales ranging from a fraction of a day to several years. This has been achieved for ET Boo and VW LMi, where we can say much about all the components of these hierarchical binaries. ET Boo is a known visual binary with a period of 113 yr, with each component being a close binary. VW LMi is a particularly interesting system, with a period of mutual revolution of both binaries of only 355 days. Starting with a preliminary photometric solution of the light curve of VW LMi that gave the orbital inclination of the close binary, we were able to determine the orbital inclinations of all involved binaries in this system and thus to derive masses for all components. We have been less successful for the quadruple system TV UMi, for which the second pair requires a very prolonged monitoring for analysis of the 31.2 day orbit.

We have found that AG Vir appears to be a triple system, although there is inconsistency in the velocity of its companion. For AK Her we were able to obtain data free of contamination from the known third component; there are indications that this binary has another faint companion causing the light-time effect in eclipse timing. The systems DU Boo, TX Cnc, V1073 Cyg, and V566 Oph are relatively mundane double-lined contact binaries, while HL Dra is a single-lined binary of an unknown variability type.

All RVs for close binaries analyzed in this paper have been determined by using a novel technique of rotational profile fitting to the BFs. This technique, while still not perfect in reproducing asymmetries and intricacies of real BFs, is much more advantageous and accurate than the Gaussian fitting previously used in our studies.

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REFERENCES

Ahn, Y. S., Hill, G., & Khalesseh, B. 1992, A&A, 265, 597
Awadalla, N., Chochol, D., Hanna, M., & Pribulla, T. 2004, Contrib. Astron. Obs. Skalnaté Pleso, 34, 20
Bell, S. A., Rainger, P. P., & Hilditch, R. W. 1990, MNRAS, 247, 632
Bessell, M. S. 1979, PASP, 91, 589
Blake, M. 2002, J. R. Astron. Soc. Canada, 96, 168
Blanco, C., & Catalano, F. 1970, Mem. Soc. Astron. Italiana, 41, 343
D'Angelo, C., van Kerkwijk, M., & Rucinski, S. M. 2006, AJ, 132, 650
Dumitrescu, A. 2000, Inf. Bull. Variable Stars, 4952, 1
———. 2003, Romanian Astron. J., 13, 119
Fitzgerald, P. 1964, Publ. David Dunlap Obs., 2, 417
Gomez-Forrellad, J. M., & Garcia-Melendo, E. 1997, Inf. Bull. Variable Stars, 4469, 1
Gray, F. D. 1976, The Observation and Analysis of Stellar Photospheres (New York: Wiley)
Guthnick, P., & Prager, R. 1929, Beob. Zirk Astron. Nachr., 11, 32
Haffner, H. 1937, Z. Astrophys., 14, 285
Heard, J. F. 1965, J. R. Astron. Soc. Canada, 59, 258
Hill, G., Fisher, W. A., & Holmgren, D. 1989, A&A, 218, 152
Hill, G., Hilditch, R. W., Younger, F., & Fisher, W. A. 1975, MmRAS, 79, 131
Hoffmeister, C. 1935, Astron. Nachr., 255, 401
Høg, E., et al. 2000, A&A, 355, L27
Jones, B. F., & Stauffer, J. R. 1991, AJ, 102, 1080
Kreiner, J. M. 2004, Acta Astron., 54, 207
Lu, W., & Rucinski, S. M. 1993, AJ, 106, 361
———. 1999, AJ, 118, 515 (Paper I)
Lu, W., Rucinski, S. M., & Ogłoza, W. 2001, AJ, 122, 402 (Paper IV)
Lucy, L. B., & Sweeney, M. A. 1971, AJ, 76, 544
———. 1973, Observatory, 93, 37
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466
McLean, B. J. 1983, MNRAS, 204, 817
McLean, B. J., & Hilditch, R. W. 1983, MNRAS, 203, 1
Mermilliod, J. C., & Mayor, M. 1999, A&A, 352, 479
Mochnacki, S. W., & Doughty, N. A. 1972a, MNRAS, 156, 51
———. 1972b, MNRAS, 156, 243
Morris, S. L., & Naftilan, S. A. 2000, PASP, 112, 852
Perryman, M. A. C., et al. 1997, The *Hipparcos* and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Pickering, E. C. 1917, Harvard Circ., 201
Pribulla, T. 2004, in ASP Conf. Ser. 318, Spectroscopically and Spatially Resolving the Components of Close Binary Stars, ed. R. W. Hilditch et al. (San Francisco: ASP), 117
Pribulla, T., & Rucinski, S. M. 2006, AJ, 131, 2986
Pribulla, T., et al. 2005, Inf. Bull. Variable Stars, 5668, 1
Pych, W., et al. 2004, AJ, 127, 1712 (Paper IX)
Röser, S., & Bastian, U. 1988, A&AS, 74, 449
Rucinski, S. M. 1992, AJ, 104, 1968
———. 1998, AJ, 116, 2998
———. 2002, AJ, 124, 1746 (Paper VII)
Rucinski, S. M., & Duerbeck, H. W. 1997, PASP, 109, 1340
Rucinski, S. M., & Lu, W. 1999, AJ, 118, 2451 (Paper II)
Rucinski, S. M., Lu, W., Capobianco, C. C., Mochnacki, S. W., Blake, R. M., Thomson, J. R., Ogłoza, W., & Stachowski, G. 2002, AJ, 124, 1738 (Paper VI)
Rucinski, S. M., Lu, W., & Mochnacki, S. W. 2000, AJ, 120, 1133 (Paper III)
Rucinski, S. M., Lu, W., Mochnacki, S. W., Ogłoza, W., & Stachowski, G. 2001, AJ, 122, 1974 (Paper V)
Rucinski, S. M., Lu, W.-X., & Shi, J. 1993, AJ, 106, 1174
Rucinski, S. M., et al. 2003, AJ, 125, 3258 (Paper VIII)
———. 2005, AJ, 130, 767 (Paper X)
Sanford, R. F. 1934, ApJ, 79, 89
Sezer, C. 1996, Ap&SS, 245, 89
Twigg, L. W. 1979, MNRAS, 189, 907
van Leeuwen, F. 1999, A&A, 341, L71
Whelan, J. A. J., Worden, S. P., & Mochnacki, S. W. 1973, ApJ, 183, 133