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

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ABSTRACT

Radial velocity measurements and sine-curve fits to the orbital velocity variations are presented for the fourth set of 10 close binary systems: 44 Boo, FI Boo, V2150 Cyg, V899 Her, EX Leo, VZ Lib, SW Lyn, V2377 Oph, Anon Psc (GSC 8-324), and HT Vir. All systems are double-lined spectroscopic binaries, with only two of them not being contact systems (SW Lyn and GSC 8-324) and five (FI Boo, V2150 Cyg, V899 Her, EX Leo, and V2377 Oph) being the recent photometric discoveries of the *Hipparcos* project. Five of the binaries are triple-lined systems (44 Boo, V899 Her, VZ Lib, SW Lyn, and HT Vir). Three (or possibly four) companions in the triple-lined systems show radial velocity changes during the span of our observations, suggesting that these are in fact quadruple systems. Several of the studied systems are prime candidates for combined light and radial velocity synthesis solutions.
Key words: binaries: close — binaries: eclipsing — stars: variables: general
On-line material: machine-readable tables

1. INTRODUCTION

This paper is a continuation of the radial velocity studies of close binary stars by Lu & Rucinski (1999, hereafter Paper I), Rucinski & Lu (1999, hereafter Paper II),[3] and Rucinski, Lu, & Mochnacki (2000, hereafter Paper III). The main goals and motivations are described in these papers. In short, we attempt to obtain radial velocity data for close binary systems that are accessible to 1.8 m class telescopes at a medium spectral resolution of about $R = 10{,}000$–15,000. Selection of the objects is quasi-random in the sense that we have started with short-period (mostly contact) binaries, and we attempt to slowly progress to longer periods as the project continues. We publish the results in groups of 10 systems as soon as reasonable orbital elements are obtained from measurements evenly distributed in orbital phases.

This paper is structured in the same way as Papers I–III, in that most of the data for the observed binaries are in two tables with the radial velocity measurements (Table 1) and their sine-curve solutions (Table 2). Section 2 of the paper contains brief summaries of previous studies for individual systems. The special feature of this paper, which distinguishes it from the previous three papers, is a discussion of close spectroscopic/visual companions to five close systems in § 3. We found many similarities in these triple-lined systems and decided to publish them together in one installment of our series. Table 3 lists the radial velocity data for the companions, which we always call the "third components" of the systems. In this spirit, we will discuss their luminosities in relation to those of the close binaries, L_3/L_{12}. We use the conventional naming of such components in visual systems, with "A" signifying the brighter component in a close visual pair (HT Vir turns out to be an exception).

The observations reported in this paper have been collected between 1997 February and 2000 October; the ranges of dates for individual systems can be found in Table 1. Eight systems discussed in this paper have been observed for radial velocity variations for the first time. 44 Boo and SW Lyn have been observed before; for both, we are providing much improved radial velocity orbits.

We derive the radial velocity data using the *broadening function* (BF) approach of the linear singular value decomposition (SVD), as described in Rucinski (1999).[4] The two peaks of the BF are fitted by Gaussians giving the radial velocities of the components. Then, variations of the radial velocities are represented by sine curves giving the center-of-mass velocity, V_0, the two semiamplitudes, K_1 and K_2, and the phase of the primary eclipse, T_0. Since our initial goals were the values of V_0 and of the mass ratio $q = K_1/K_2$, this approach was deemed adequate when we started the program. We are aware that the amplitudes and hence the masses may be biased by the Gaussian approximation, but we are unable to do the full modeling (as was done for AW UMa, AH Vir, and W UMa; Rucinski 1992; Lu & Rucinski 1993; Rucinski, Lu, & Shi 1993) without knowledge of the degree of contact and of the orbital inclination, which are derivable from light curves. Thus, we continue using the Gaussians, recognizing that one day our values of the semiamplitudes may have to be corrected for the systematic inaccuracies of our measurements.

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[3] In Paper II, the residuals ΔV listed in Table 1 for SV Equ are incorrect and do not agree with Figure 1 and the quoted value of the error per single observations, as given in Table 2. The correct residuals can be computed from the original data and the spectroscopic elements.
[4] Practical advice and detailed suggestions are available also at http://www.astro.utoronto.ca/~rucinski/.

TABLE 1
DDO OBSERVATIONS OF THE FOURTH GROUP OF 10 CLOSE BINARY SYSTEMS

HJD −2,400,000	Phase	V_1	ΔV_1	V_2	ΔV_2
44 Boo B:					
50,939.6513......	0.1943	91.3	3.3	−241.5	−6.3
50,939.6543......	0.2055	92.5	2.1	−243.7	−3.5
50,939.6572......	0.2164	94.5	2.2	−246.6	−2.5
50,939.6602......	0.2276	89.7	−4.0	−247.8	−0.9

NOTES.—Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Velocities are expressed in kilometers per second. Observations leading to entirely unseparable broadening and correlation function peaks are marked by ellipses; these observations may be eventually used in more extensive modeling of BFs.

[a] These data have not been used in the orbital solution.

[b] These data have been given half-weight in the orbital solution.

[c] The data for the secondary component of SW Lyn, between phases 0.5–1.0, have been given quarter-weight in the orbital solution.

The data in Table 2 are organized in the same manner as before. 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. It also contains our new spectral classifications of the program objects (unless taken in parentheses when we use other spectral type estimates). For further technical details and conventions used in the paper, please refer to Papers I–III of this series.

2. RESULTS FOR INDIVIDUAL SYSTEMS

2.1. *44 Boo B*

With the large parallax of $p = 78.4 \pm 1.0$ mas (ESA 1997, hereafter HIP), 44 Boo B[5] is the nearest contact binary and one of the nearest close binaries. Because of its brightness, it has been one of the most frequently photometrically observed variable stars in the sky. 44 Boo B is the fainter component of a relatively close (currently 1″.7) visual double that is attracting vigorous observational activity in the fields of stellar interferometry and speckle interferometry. We do not relate to these studies because our radial velocity data have been obtained in a short interval of only 10 days, so that they contribute only one radial velocity data point of the long-period (225 yr) visual orbit.

Several studies attempted to determine a radial velocity orbit for 44 Boo B. These efforts are summarized in Hill, Fisher, & Holmgren (1989). Here we present results far superior to any previous attempts. The success is mostly due to the extraction of the component velocities using the BF approach (see § 3), which permitted excellent separation of the three spectral components in the system. In particular, we provide an accurate estimate of the mass ratio for 44 Boo B, $q_{sp} = 0.487 \pm 0.006$, which should be of much help in future photometric studies of the contact system. The radial velocity orbit is shown graphically in Figure 1.

Since the discovery (Schilt 1926), the presence of the brighter companion created problems in studies of the close pair. The most extensive study of 44 Boo system by Hill et al. (1989) discussed efforts of decoupling of the spectral and photometric signatures of the visual pair, but even such basic data as spectral types or color indices were difficult to derive. The reanalysis of the *Hipparcos* data for close visual binaries (Fabricius & Makarov 2000) gave reliable magnitudes and color indices for both components: $V^A = 5.28$, $(B-V)^A = 0.65$ and $V^B = 6.12$, $(B-V)^B = 0.94$; the magnitudes are the average ones, so they do not take into account the variability of component B. The color index for component A agrees with the estimate of the spectral type by Hill et al. (1989) of G1 V, while the color index for component B points at a much later spectral type than was considered before, around K2 V, in accordance with the well-known high magnetic activity of the contact system.

The magnitude difference at maximum of 44 Boo B relative to component A was estimated by Hill et al. (1989) to be $\Delta V = 0.63$, so that $V^B(\max) = 5.91$. For this brightness, the absolute magnitude predicted from the parallax is $M_V^B = 5.38 \pm 0.04$, whereas the prediction of the $M_V(\log P, B-V)$ calibration (Rucinski & Duerbeck 1997, hereafter RD97) is $M_V^B(\mathrm{cal}) = 5.50$. These estimates would agree at $M_V^B = 5.38$ if we use $(B-V) = 0.90$ in the calibration, assuming that the maximum light $B-V$ is slightly smaller (bluer) than the average value given by Fabricius & Makarov (2000). We note that 44 Boo B, in spite of its proximity, was used in the first $M_V(\log P, B-V)$ with some reservations (Rucinski 1994) because its color index was poorly know at that time. It is gratifying to see now a much better agreement of the directly determined M_V for 44 Boo B with the calibration.

2.2. *FI Boo*

FI Boo is a new discovery from the *Hipparcos* mission. Duerbeck (1997) included it in the list of possible contact binaries. The period reported in the *Hipparcos* catalog is equal to one-half of the orbital period that we find, and the zero epoch T_0 was given in the catalog for the maximum light. With our spectroscopic results, the contact system is of the W type, with the less massive component eclipsed at the eclipse given by T_0, which has been selected to be one-quarter of the orbit before the maximum given in HIP.

The radial velocity orbit for FI Boo is very well determined (Fig. 1). The small value of $(M_1 + M_2)\sin^3 i = 0.343 \pm 0.010\ M_\odot$ is consistent with the small photometric amplitude of about 0.15 mag in suggesting a low orbital inclination.

Assuming $V_{max} = 9.57$ on the basis of the average V in Hog (2000, hereafter TYC2) and the amplitude in HIP with the parallax of $p = 9.52 \pm 2.10$ mas, we obtain $M_V = 4.41 \pm 0.49$. The RD97 calibration gives $M_V(\mathrm{cal}) = 4.17$.

2.3. *V2150 Cyg*

V2150 Cyg has been discovered by the *Hipparcos* mission. It shows a small photometric amplitude of 0.12 mag, suggesting a low orbital inclination. This is in accord with the low value of $(M_1 + M_2)\sin^3 i = 1.376 \pm 0.018\ M_\odot$ for an early spectral type of the binary, which suggests a rather massive system. Abt (1981) estimated the spectral type to be A5 V; our independent estimate is A6 V. The orbital period is 0.591 days, and the HIP light curve looks like that of a genuine contact binary, which is a rare occurrence among such early-type systems.

Although the system is a visual double (ADS 14835), its orientation relative to the spectrograph slit was such that

[5] The star 44 Boo has another name, i Boo. Frequently, these are combined, which is incorrect and makes electronic searches difficult. We use only the former name in this paper.

TABLE 2

SPECTROSCOPIC ORBITAL ELEMENTS OF THE FOURTH GROUP OF 10 CLOSE BINARY SYSTEMS

Name	Type (Spectral Type)	Other Names	V_0	K_1, K_2	ϵ_1, ϵ_2	T_0 −2,400,000, $O-C$, and [E]	P (days), $(M_1 + M_2)\sin^3 i$	q
44 Boo B[a]	EW/W	HD 133640B	−17.89 (0.40)	231.31 (0.65)	5.50	50,944.6878 (2)	0.267818	0.487 (6)
	(K2 V)	HIP 73695	...	112.70 (0.46)	3.29	+0.0002 [8]	1.132 (11)	...
FI Boo[b]	EW/W	HD 234224	−30.55 (0.72)	148.65 (1.10)	5.17	51,718.3951 (7)	0.389998	0.372 (21)
	G3 V	HIP 75203	...	55.27 (0.90)	4.52	+0.0926 [8,252]	0.343 (10)	...
V2150 Cyg	EW/A	HD 202924	−12.82 (0.45)	125.43 (0.55)	3.18	51,386.3434 (7)	0.591856	0.802 (6)
	A6 V	HIP 105162	...	156.40 (0.66)	5.69	+0.0195 [4,876]	1.376 (18)	...
V899 Her B[a]	EW/A	HD 149684	−16.84 (1.30)	135.97 (2.04)	14.9	51,533.8405 (11)	0.421173	0.566 (18)
	F5 comp.	HIP 81191	...	240.37 (2.12)	14.5	−0.0046 [7,203]	2.331 (77)	...
EX Leo	EW/A	BD +17°2269	−11.05 (1.10)	51.28 (1.07)	3.23	51,615.6025 (13)	0.408604	0.199 (36)
	F6 V	HIP 52580	...	257.98 (1.85)	20.1	−0.0110 [7,625]	1.255 (36)	...
VZ Lib A[a]	EW/A	...	−31.11 (2.30)	68.54 (3.84)	18.5	51,091.4297 (15)	0.358263	0.237 (68)
	G0 comp.	HIP 76050	...	289.25 (4.55)	27.7	−0.0814 [17,593]	1.704 (120)	...
SW Lyn A[a,c]	EB	HD 67008	+32.39 (1.35)	116.73 (1.65)	11.2	51,400.1795 (25)	0.644066	0.524 (28)
	(F2 V)	HIP 39771	...	222.75 (3.20)	19.1	−0.0062 [801]	2.617 (112)	...
V2377 Oph	EW/W	HD 159356	−25.79 (0.38)	159.64 (0.70)	3.18	51,720.3294 (5)	0.425401	0.395 (12)
	G0/G1 V	HIP 85944	...	62.99 (0.62)	3.16	+0.0128 [7,570]	0.487 (9)	...
Anon Psc	EB? EA?	GSC 8-324[d]	−27.85 (0.73)	131.62 (0.55)	4.44	51,794.1921 (4)	0.308550	0.702 (14)
	(K4/K5 V)	...	...	187.55 (1.80)	11.6	−0.0188 [1,110]	1.042 (23)	...
HT Vir B[a]	EW/A	HD 119931	−23.38 (0.68)	169.39 (1.00)	9.32	51,068.7101 (6)	0.407670	0.812 (8)
	F8 V comp.	HIP 67186	...	208.54 (1.00)	9.45	+0.0382 [17,230]	2.285 (38)	...

NOTES.—The spectral types given in column (2) are new, except those in parentheses, which are either taken from the literature or estimated from color indices. The convention of naming the binary components is that the subscript 1 designates the component that is eclipsed at the deeper minimum and is therefore the hotter one. The standard errors of the circular solutions in the table are expressed in units of the last decimal places quoted; they are given in parentheses after each value. For example, the last table entry for the mass ratio q, 0.812 (8), should be interpreted as 0.812 ± 0.008; the mass ratio is defined to be always $q \leq 1$. The center-of-mass velocities (V_0), the velocity amplitudes (K_i), and the standard unit-weight errors of the solutions (ϵ) are expressed in kilometers per second. The spectroscopically determined moments of primary minima are given by T_0; the corresponding $O-C$ deviations (in days) have been calculated from the most recent available ephemerides, 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.

[a] Spectroscopically triple system.

[b] FI Boo: The period is twice the value given in the *Hipparcos* catalog in which the time of maximum light is given as the initial epoch. The large $O-C$ reflects this difference.

[c] The solution for SW Lyn A is based on both observational seasons. See the text for discussion concerning the possible influence of the motion around the common center of mass in the triple system.

[d] The Guide Star Catalogue number is written in an abbreviated form in the table. The correct number is GSC 00008-00324.

TABLE 3

OBSERVATIONS OF THE SPECTROSCOPIC COMPANIONS OF CLOSE BINARY SYSTEMS

HJD −2,400,000	V	Weight
44 Boo A:		
50,939.6449	−35.3	1.0
50,948.6671	−34.2	1.0
50,949.6755	−35.3	1.0

NOTES.—Table 3 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Velocities in the second column are expressed in kilometers per second. Weights have been assigned on the basis of the quality of the radial velocity determinations from the BFs. A weight equal to zero means that we were not able to use this spectrum for radial velocity determination.

we were able to avoid the faint ($\Delta m = 3.4$) companion at the separation of 3″.7.

Our radial velocity orbit is very well determined (Fig. 1). The contact system consists of two very similar components with $q = 0.802 \pm 0.006$ with a more massive component eclipsed at the primary minimum (type A). The only previous radial velocity measurements of V2150 Cyg, found in a survey by Grenier et al. (1999), showed scatter among three measurements, indicating a radial velocity variability of $V = 31.4 \pm 16.8$ km s^{-1}. The nominal accuracy of this survey was 3.0 km s^{-1} on the basis of spectra with resolutions about 8 times lower than ours.

In spite of a good solution of the radial velocity orbit, we found one disturbing feature of the solution for V2150 Cyg: The radial velocity amplitudes depend on the spectral type of the template star used to derive the BFs. This is unusual because for most W UMa–type systems we have not seen any dependence of the amplitudes on the spectral type. Normally, with some spectral type mismatch of the template, the BF could change its intensity scale and its quality of determination, but the radial velocity amplitudes would stay constant. We selected several sharp-line standards from the list of F. Fekel (1997, private communication). Over the range of the template spectral types within the A type, we see a change of up to 7% in both semiamplitudes, K_i, with larger amplitudes obtained with templates of earlier spectral types. While the mass ratio remained perfectly constant, the systematic uncertainty in the amplitudes would obviously affect the derived values of masses. We have no explanation of the effect, but we note that V2150

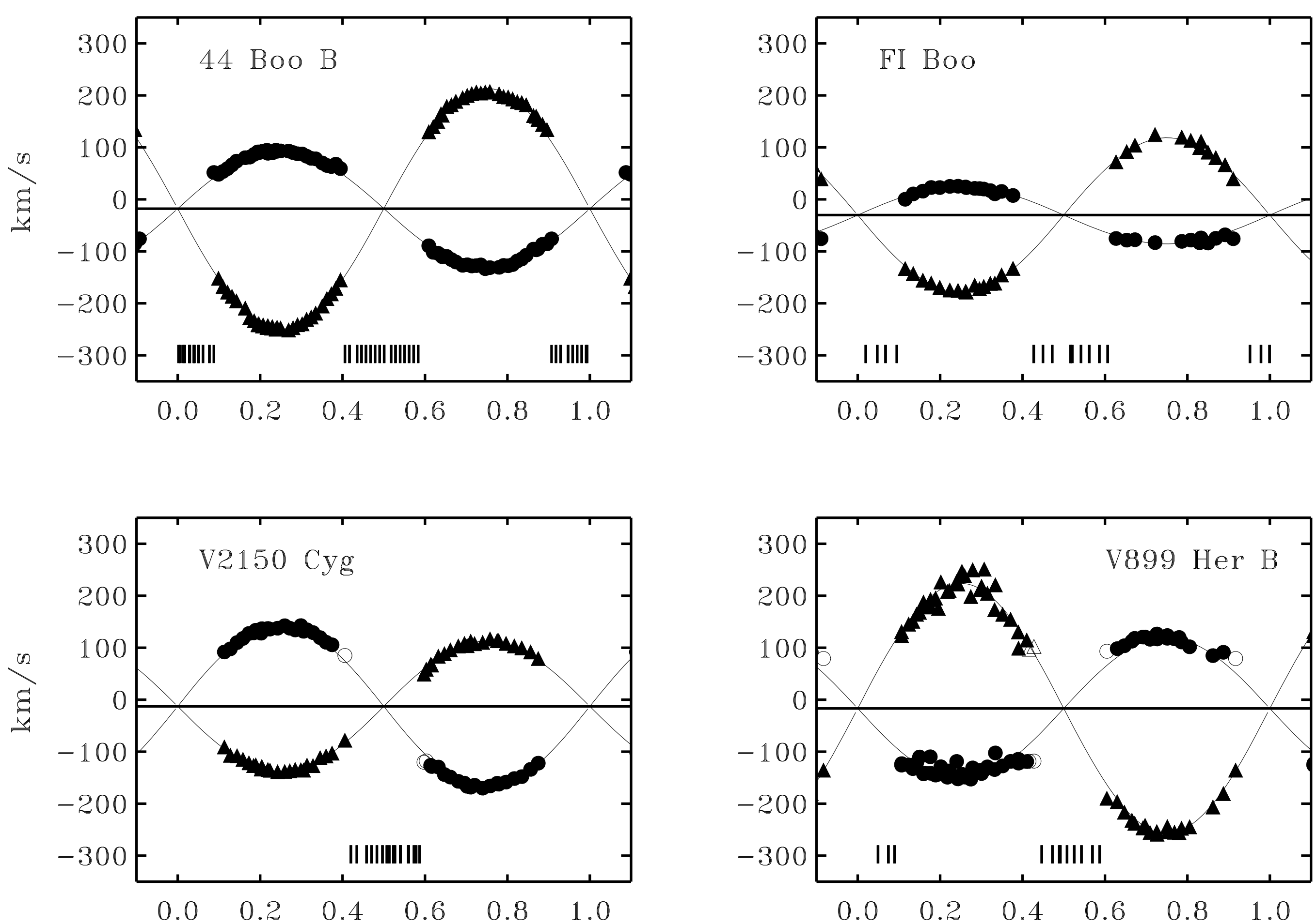

FIG. 1.—Radial velocities of the systems 44 Boo B, FI Boo, V2150 Cyg, and V899 Her B are plotted in individual panels vs. orbital phases. The lines give the respective circular orbit (sine-curve) fits to the radial velocities. 44 Boo B and FI Boo are W-type systems, while V2150 Cyg and V899 Her B are A-type systems. Short marks in the bottom sections of the panels show the phases of available observations that were not used in the solutions because of the blending of lines. Open symbols in this and the next two figures indicate observations given half-weights in the solutions. All panels have the same vertical scales.

Cyg is of the earliest spectral type among binary systems analyzed by us so far.

The system of V2150 Cyg is important because it may provide a crucial extension of the absolute magnitude calibration $M_V(\log P, B-V)$ toward early spectral types. With $V_{\max} = 8.06$ estimated from the average data in TYC2 and the amplitude and with the parallax $p = 4.7 \pm 1.6$ mas, we obtain $M_V = 1.43 \pm 0.74$, while the RD97 calibration, pushed to a color index as blue as $(B-V) = 0.25$, gives $M_V(\mathrm{cal}) = 1.89$. A big question is obviously the amount of reddening for this relatively distant (about 210 pc) system. The color index, when compared with the spectral type A5/A6 V, suggests a moderate reddening of about $E_{B-V} = 0.07$. In this case, the absolute magnitude derived from the parallax is $M_V = 1.21 \pm 0.74$, while $M_V(\mathrm{cal}) = 1.67$.

2.4. *V899 Her B*

V899 Her is the next *Hipparcos* discovery. Although it is classified in the *Hipparcos* catalog as an EB light-curve system (with unequal minima), it seems to be a genuine contact binary with a low-amplitude (0.14 mag) EW light curve and practically equally deep eclipses. Apparently, the light-curve classification was driven by one deviating point, possibly a photometric error. We have kept the *Hipparcos* ephemeris, which leads to an A-type contact system.

We discovered that V899 Her is a spectroscopically triple system in which the contact binary is the fainter component, so we designate the contact system as component B. The BF was an indispensable tool in separating the three spectral components; without it, the system would probably be unsolvable (see § 3). The presence of the bright companion explains the inconsistency between large radial velocity amplitudes of the components of V899 Her B, leading to a large value of $(M_1 + M_2) \sin^3 i = 2.33 \pm 0.08\ M_\odot$ (and thus an indication of the orbital inclination close to 90°) and the small photometric amplitude of the W UMa–type light curve, which appears to be "diluted" in the total systemic light.

The spectral type that we estimated from our low-resolution classification spectra is F5 V, with indications of a contribution from the fainter G-type component. Because of the dominance of the third component, there is no point in applying the RD97 calibration to this case. The maximum brightness and the color index, $V_{\max} = 7.87$ and $(B-V) = 0.48$, almost certainly reflect the properties of the third star rather than that of the close binary.

Because of the presence of the bright companion, the radial velocity orbit of V899 Her B is not as well defined as for other close binaries (Fig. 1). The bright companion A is itself a radial velocity variable because we noticed well-defined variations within the 250 day span of our observations (see § 3). We do not see these variations in the systemic velocity of the close pair, so we assume that the visual companion is itself an independent spectroscopic binary.

2.5. *EX Leo*

EX Leo has been found by *Hipparcos*. Our solution (Fig. 2) describes a rather typical contact binary of the A type with a small mass ratio, $q = 0.199 \pm 0.036$. Our estimate of the spectral type, F6 V, agrees very well with $(B-V) = 0.53$ from TYC2. The light curve has an amplitude of about 0.25 mag and is quite well defined but perhaps a bit sparsely covered by the HIP data.

The parallax $p = 9.84 \pm 1.11$ mas with $V_{\max} = 8.17$ leads to $M_V = 3.13 \pm 0.26$, so that it agrees with the RD97 calibration, $M_V(\mathrm{cal}) = 3.45$.

2.6. *VZ Lib A*

VZ Lib has been known as a contact binary since the work of Tsesevich (1954). Claria & Lapasset (1981) published the last currently available photometric study of the system.

We have detected a spectroscopic companion to VZ Lib, about 5 times fainter than the contact binary. We discuss it in § 3. Here we note that this component may have a slowly variable radial velocity, but these variations are not reflected in the systemic velocity of the close binary.

It is impossible to derive the correct $V_{\max}$ for the contact binary value because of the poorly known contribution of the third component to the total systemic light. The observed combined brightness, $V_{\max} = 10.36$ and $(B-V) = 0.61$ (Claria & Lapasset 1981), is in accord with our estimate of the spectral type, G0 (composite). These data, together with the HIP parallax $p = 4.92 \pm 1.96$ mas imply $M_V = 3.59 \pm 0.88$ for the whole system, while the RD97 calibration for the contact system predicts $M_V(\mathrm{cal}) = 3.94$, which is in agreement with some contribution of the third star to the systemic brightness.

Because of the faintness of the system, the presence of the third component, and the difficulties of measuring velocities of the close binary, our radial velocity solution is relatively poor (Fig. 2). The system appears to be a contact binary of the A type with a moderately small mass ratio of $q = 0.24 \pm 0.07$. The orbit is probably oriented close to edge-on because the sum of the masses is relatively large, $(M_1 + M_2) \sin^3 i = 1.70 \pm 0.12\ M_\odot$.

We note that our spectroscopically derived moment of the primary eclipse deviates by about 2 hr from the ephemeris of Claria & Lapasset (1981), either because of period changes or accumulated errors in the period over the long time since the last photometric observations.

2.7. *SW Lyn A*

The binary was discovered as a variable star by Hoffmeister (1949). Major photometric studies were done by Vetešnik (1968, 1977). Recently, Ogłoza et al. (1998) rediscussed the extant data; the discussion was to a large extent guided by the spectroscopic results of Vetešnik (1977), in that a mass ratio was assumed to be around $q \simeq 0.35$, in spite of photometric solutions that tended to converge to $q \simeq 0.5$–0.6. In fact, our spectroscopic results do give $q_{\mathrm{sp}} = 0.52 \pm 0.03$.

From the spectroscopic point of view, SW Lyn is quite complex: It appears to be a very close, short-period Algol system with a faint but detectable secondary. We also clearly see a third component, about 3 times fainter than the close binary, that has not previously been detected spectroscopically (see § 3). Possibly, it is the same star that is producing the 2128 day periodicity in the eclipse timing (Ogłoza et al. 1998).

Our radial velocity orbit is entirely different from that of Vetešnik (1977), which was obtained at a very low spectral resolution. Thus, we do not confirm any manifestations of apparent eccentricity, which were explained by gas streams. In view of our results, the detailed discussion of the physical properties of the system by Ogłoza et al. (1998) may have to be revised. We did experience difficulties in measuring

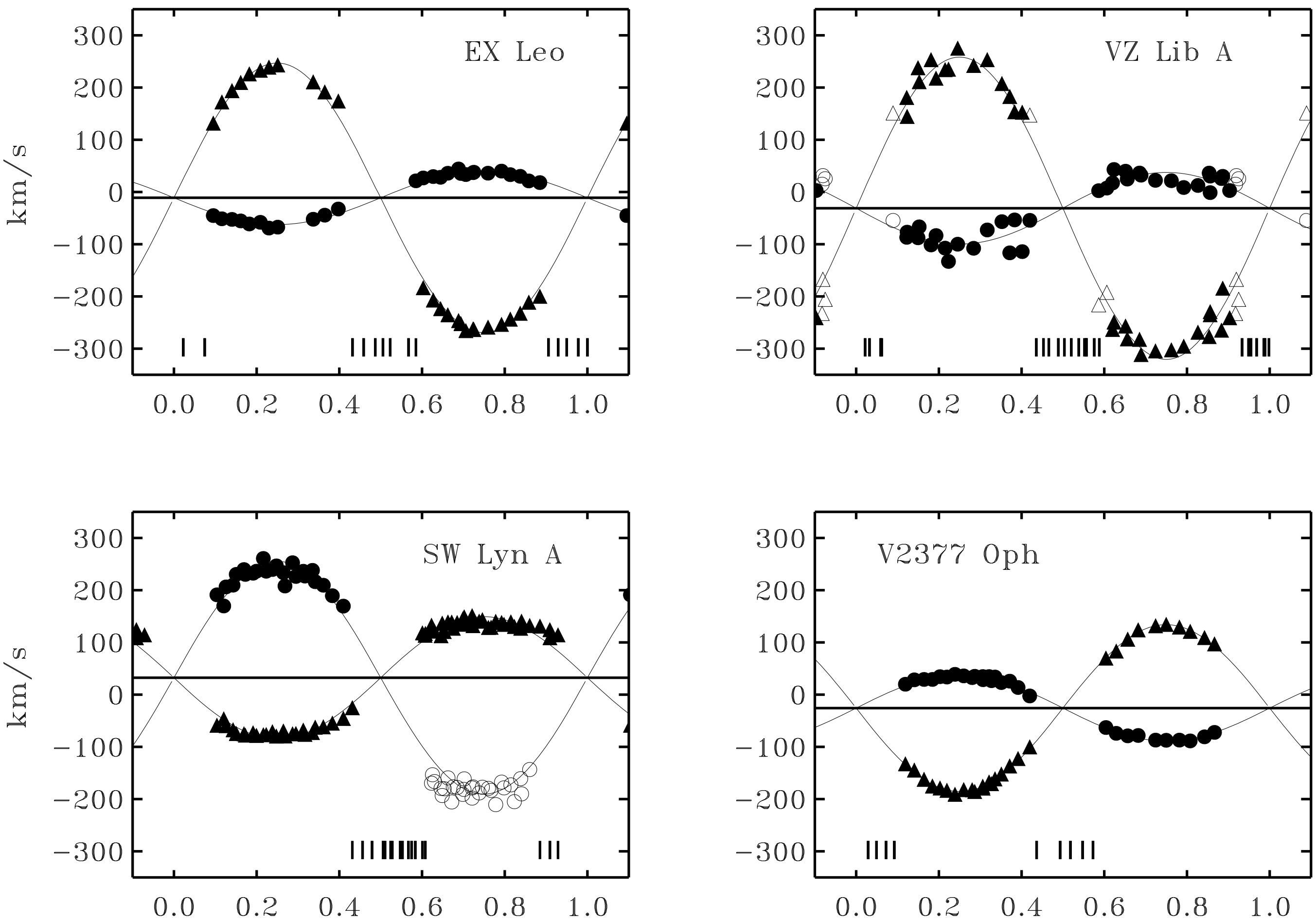

FIG. 2.—Radial velocities of the systems EX Leo, VZ Lib A, SW Lyn A, and V2377 Oph. Only V2377 Oph is a W-type system. SW Lyn A is most probably a short-period Algol system, and EX Leo and VZ Lib A are contact systems of the A type.

velocities of the secondary component, whose signal in the BF is very weak in comparison with the third star and the primary component (see § 3). These difficulties were especially severe in the second half of the orbit. Thus, in order not to affect the systemic velocity V_0 in our combined orbital solution, which takes into account the velocities of both stars, we assigned weights of one-half and one-quarter to all measurements of the secondary within the first and second halves of the orbit, respectively (Fig. 2).

Our observations were obtained in two groups (16 and 55 observations) separated by one year, which—in view of the presence of the third star—poses the question of whether the observations of the close binary could be combined into one solution. Accordingly, we obtained one solution based on all observations and one based only on the 55 observations of the second season (the phase distribution for the first season did not permit a separate solution). The results do not differ significantly, indicating that the center of mass of the close binary probably did not move much between the seasons. However, the conjunction times came out different but within the combined errors of both solutions. For reference, we give here the results of the solution based only on the second season: $V_0 = +31.11$ (1.26), $K_1 = 116.09$ (1.52), $K_2 = 222.87$ (3.60), and $T_0 = 2{,}451{,}400.1752$ (22).

The photometric properties of SW Lyn are rather poorly known. Vetešnik (1968) estimated $V_{max} = 9.2$ and $(B-V) =$ 0.38. The color index corresponds to the spectral type of F2 V. However, TYC2 suggests the mean $(B-V) = 0.23$. With its period of 0.644 days, SW Lyn is of interest to studies of the short-period Algol systems. Our spectroscopic value of T_0 agrees very well with the recent photometric timing of Ogłoza, Dróżdż, & Zoła (2000).

2.8. *V2377 Oph*

The binary has been discovered by *Hipparcos*. It appears to be a fairly uncomplicated W-type contact binary, and our solution is very well defined (Fig. 2). The small value of $(M_1 + M_2) \sin^3 i = 0.487 \pm 0.009$ $M_\odot$ is in accordance with the small amplitude of photometric variations (0.04 mag), both resulting from a low inclination angle.

Our spectral type G0/G1 V is in slight disagreement with the TYC2 color index of $(B-V) = 0.67$, so some reddening of about $E_{B-V} \simeq 0.07$ is possible. The system is relatively distant (about 100 pc) and has a parallax of $p = 10.09 \pm 1.22$ mas, which implies $M_V = 3.53 \pm 0.27$ for the case of no reddening, while the RD97 calibration predicts $M_V(\text{cal}) = 3.79$. For $E_{B-V} = 0.07$, the absolute magnitudes would be $M_V = 3.32$ and $M_V(\text{cal}) = 3.58$, respectively.

2.9. *Anon Psc = GSC 8-324*

This very interesting close binary has been discovered recently by Robb et al. (1999). It does not yet have a variable star name, so we are using here an abbreviated one, GSC 8-324.[6]

The system appears to be a very close pair of two detached K-type dwarfs on tight orbit, with an orbital period of $P = 0.3086$ days. We included the system in our program soon after learning about its discovery, led by an expectation that this is a new case of a V361 Lyr–like binary that is evolving rapidly into contact (Hilditch et al. 1997) but is some 4 mag brighter, therefore easier for detailed studies. Recent correspondence with R. Robb (2000, private communication) indicated that the spots on the surface of GSC 8-324 have moved between the seasons, so the system is *not* similar to V361 Lyr, in which the high stability of the accretion region strongly suggests a stable flow of matter between components. However, because the system is so very tight and yet detached—as judged by short duration of eclipses—and also relatively nearby (14 ± 8 pc, see below), it is one of the most interesting among recently discovered close binaries.

Because of the late type of the components, K4–K5 V (see the references in Robb et al. 1999), we feared that the magnesium triplet lines would not be as well suited for radial velocity observations as for F–G stars. For that reason, we made a change in our observational setup, and in addition to the observing the same region centered at 5185 Å as for other stars, we also obtained observations in the region centered at 5303 Å. The results of independent solutions were identical, so we made a combined solution for both spectral regions. However, we list the two series of observations separately in Table 1. The phased observations of the system are shown in Figure 3.

The radial velocity data for the primary component are well defined for both spectral regions. In contrast, the secondary-component peaks in the BF are weak, and the radial velocity data are correspondingly poorer. Yet, the mass ratio is very well determined, $q_{sp} = 0.702 \pm 0.014$. The value of $(M_1 + M_2) \sin^3 i = 1.04 \pm 0.02\ M_{\odot}$, together with the presence of deep eclipses, suggests a possibility of a reliable combined solution for absolute elements of the system. If not for the presence of large photospheric spots, the system could serve as one of the lower main-sequence calibrators.

The epoch of the superior conjunction (the primary eclipse) indicates that the orbital period could be slightly adjusted relative to the value given by Robb et al. (1999), but we leave this matter open, since we cannot exclude period changes in such a short-period system.

The system was included in the Tycho-1 catalog (HIP). The parallax has a large error but does suggest a relatively nearby system, with $p = 72 \pm 40$ mas. With the data in Robb et al. (1999), $M_V = 9.9 \pm 1.2$. The system has a large and relatively well defined proper motion, $\mu_{RA} \cos \delta = -108.2 \pm 2.2$ mas yr^{-1} and $\mu_{decl} = -201.1 \pm 2.1$ mas yr^{-1} (TYC2), undoubtedly because of its proximity.

2.10. *HT Vir B*

HT Vir belongs to a very close visual binary, a situation somewhat similar to that of 44 Boo, except that the separation is smaller, below 1″, and the brightnesses of the visual components are similar, with the contact binary being fainter only during the eclipses. We retain the designation of B for the contact system for consistency with the previous investigations. The close visual binary is currently the subject of numerous interferometric and speckle-interferometry studies.

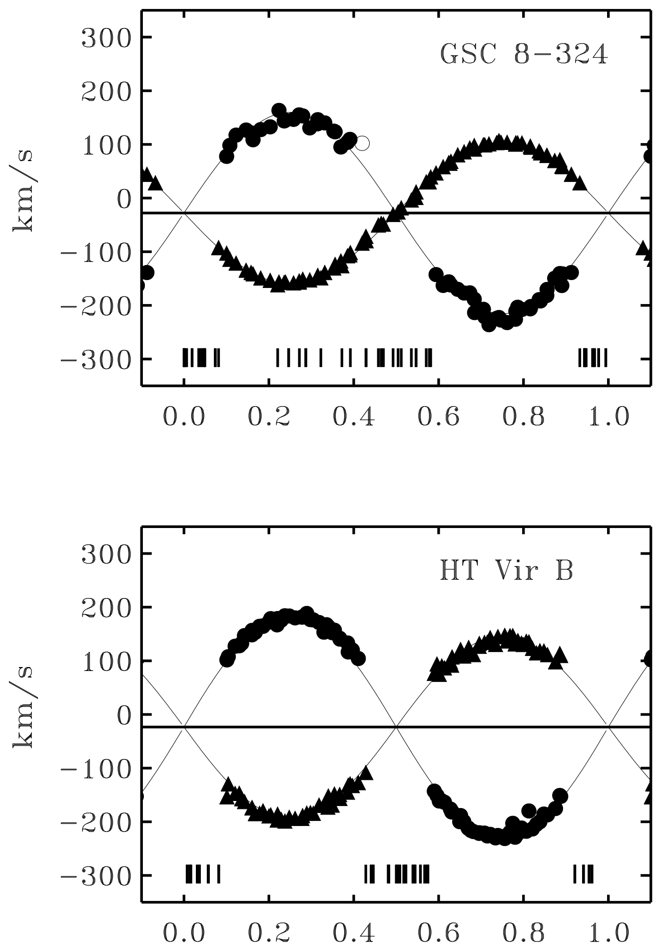

FIG. 3.—Radial velocities of the systems GSC 8-324 and HT Vir B. The first is a very close but detached or semidetached system, while HT Vir B is a contact A-type system with a surprisingly large mass ratio.

The reanalysis of the *Hipparcos* data for visual binaries (Fabricius & Makarov 2000) gave reliable magnitudes and color indices for both components at the time that the separation was only 0″.56: $V^A = 7.80$, $(B-V)^A = 0.64$ and $V^B = 8.30$ (average magnitude), $(B-V)^B = 0.56$. Our combined spectral type, with a strong contribution of the third component, is F8 V; this does not agree very well with its color index, which suggests a later-type star.

HT Vir was discovered by Walker (1984) and then studied photometrically by Walker & Chambliss (1985). The photometric solution suggests that the third component provides about as much light as the eclipsing system at its light maxima. Our BF results confirm the strong presence of the third component; we discuss this further in § 3. We found that the third component is in fact a radial velocity variable with a period of 32.45 days. Thus, the system is really a quadruple one, with lines of three systems visible in the spectra. We give a preliminary solution for the single-lined (SB1) system HT Vir A in § 3 and in Table 4.

[6] The name GSC 8-324 is in fact incorrect, which may complicate electronic searches. It should be GSC 00008-00324. The notation used by Robb et al. (1999), who used a different numbers of leading zeros, is also incorrect.

TABLE 4

PRELIMINARY SPECTROSCOPIC ORBIT FOR HT VIR A

Element	Unit	Value
Period......	Days	32.450 ± 0.012
V_0..........	km s^{-1}	−23.15 ± 0.17
K_1.........	km s^{-1}	10.10 ± 0.24
e...........	...	0.232 ± 0.028
ω..........	Radians	4.204 ± 0.088
T_0..........	JD	2,451,194.33 ± 0.45
σ...........	km s^{-1}	1.65

Because we have been able to isolate the signatures of HT Vir A from those of the contact binary, the radial velocity solution for HT Vir B is very well defined (Fig. 3). We note that the binary is of the A type yet has a surprisingly large mass ratio for such a system, with $q = 0.812 \pm 0.008$. It is interesting to note that, although our determination of q for HT Vir B is the first one, Walker & Chambliss (1985) postulated a value not far from unity on the basis of the ratio of radii derived from their photometric analysis. The large mass ratio would be in accord with the relatively large amplitude of light variations of HT Vir. Walker & Chambliss (1985) estimated that $L_3/(L_{12} + L_3) \simeq 0.44$ and thus $L_3/L_{12} \simeq 0.79$ at light maxima of the close binary; HT Vir A would be then the slightly fainter of the two visual components. The light variation amplitude observed by Walker & Chambliss (1985) of about 0.42 mag, when corrected for the contribution of HT Vir A to the total systemic brightness would be then about 0.92 mag. Such a large amplitude can be generated only by a contact system with the orbit seen edge-on, but also with a mass ratio close to unity. Integrations of the individual spectral features in our BFs (§ 3) suggest $L_3/L_{12} \simeq 0.52 \pm 0.05$ at the light maxima of the contact system, so that HT Vir A was observed by us to be fainter relative to the contact binary than before; its spectral signature was always better defined in the spectra and in the BFs because of its slow rotation.

The parallax of the system is the largest in this group after that of 44 Boo, with $p = 15.39 \pm 2.72$ mas. With $V^B_{\rm max} = 8.1$ and $(B-V)^B = 0.56$, this implies that $M^B_V = 4.0 \pm 0.4$. The RD97 calibration predicts that $M^B_V(\rm cal) = 3.54$.

Our spectroscopic determination of T_0 shows a relatively large $O-C$ deviation, a result of using the ephemeris of Walker & Chambliss (1985). Similarly to VZ Lib, HT Vir has not been observed for eclipse timing for a long time.

3. BROADENING FUNCTION APPROACH AND SPECTROSCOPIC COMPANIONS

3.1. *Broadening Functions*

The spectroscopic signatures of the visual/spectroscopic companions are particularly well defined in BFs, which give a projection of a system into the velocity space (Rucinski 1999). While the close binaries of our program have short periods and thus have their rotation/revolution signatures spread over wide ranges of radial velocities, the third components—which rotate slowly—show sharp peaks in the BF. We can easily model these sharp peaks by applying the BF derivation to other sharp-line stars.

Figure 4 shows the BFs for the five triple systems, 44 Boo, V899 Her, VZ Lib, SW Lyn, and HT Vir, all at phases close to orbital quadratures of the close pairs. In one case of HT Vir, we show elements of the BF decomposition into the third component and the binary itself (Fig. 4, *top and bottom right*). Of particular importance is that the third component can be cleanly subtracted from the BF, leaving a very well defined signature of the contact system. The success of the decomposition is due primarily to the linear properties of the BF derived through the SVD formalism (Rucinski 1999), in contrast to the cross-correlation function, which is nonlinear. This permits subtraction of the third component from the BF, which is simple and mathematically correct. Then, through separate integration of the sharp and broad components, we can determine the brightness of the companion in relation to that of the close binary, L_3/L_{12}. Thanks to the linear SVD-BF approach, we have been able to determine radial velocities for components in close binary systems that would present a totally insurmountable challenge if handled with the cross-correlation function, such as V899 Her, VZ Lib, or SW Lyn.

The linear deconvolution technique that we use to obtain the BFs is not the only one available for determination of accurate radial velocities from blended spectra showing lines of several components. In recent years, a powerful technique called TODCOR has been developed for close binaries by Zucker & Mazeh (1994) and then extended into the case of triple-lined systems by Zucker, Torres, & Mazeh (1995); the latter modification has been already successfully applied in some difficult cases of multilined systems (Jha et al. 2000). We did not use this technique for several reasons. It is not only that we feel more comfortable with a tool developed by ourselves, but (1) so far, TODCOR has not been demonstrated to work for very broad lines of contact binaries, and (2) our case of mixed very broad and narrow spectral signatures is even more difficult and would require even more extensive testing. We fear, in particular, that the nonlinear nature of the cross-correlation would complicate the derivation of relative brightnesses of components for systems with components showing very different degrees of rotational broadening.

In three (V899 Her, SW Lyn, and HT Vir), possibly four (VZ Lib), of the triple-lined systems, the third component appears to be a radial velocity variable. We will comment on each system in the separate subsections below.

3.2. *44 Boo A*

The observations were too short in the case of 44 Boo A to note any long-term radial velocity changes. However, since we wanted to obtain the best radial velocity data for the close binary 44 Boo B, the presence of the bright companion did require some additional precautions. In particular, an attempt was made during the observations to place the brighter component 44 Boo A as much outside the spectrograph slit as possible. The separation is currently about 1″.7, so that it is comparable to the width of our slit (1″.8), which cannot be rotated. Because the component A is about 1.8 times brighter than B (Hill et al. 1989) and its lines are sharp and very well defined, its signature is always visible in the BF (first panel of Fig. 4). By attempting to place its image outside the slit, we partly succeeded in suppressing its contribution (to the level of $L_3/L_{12} \simeq 0.4$–0.7, depending on the seeing, as measured in the BFs), but we did not eliminate it totally, achieving only a modification of its relative intensity in the BF. Its radial velocity derived from the BF is also incorrect (by up to 12 km s^{-1}) because the light was always spilling over from one side of our

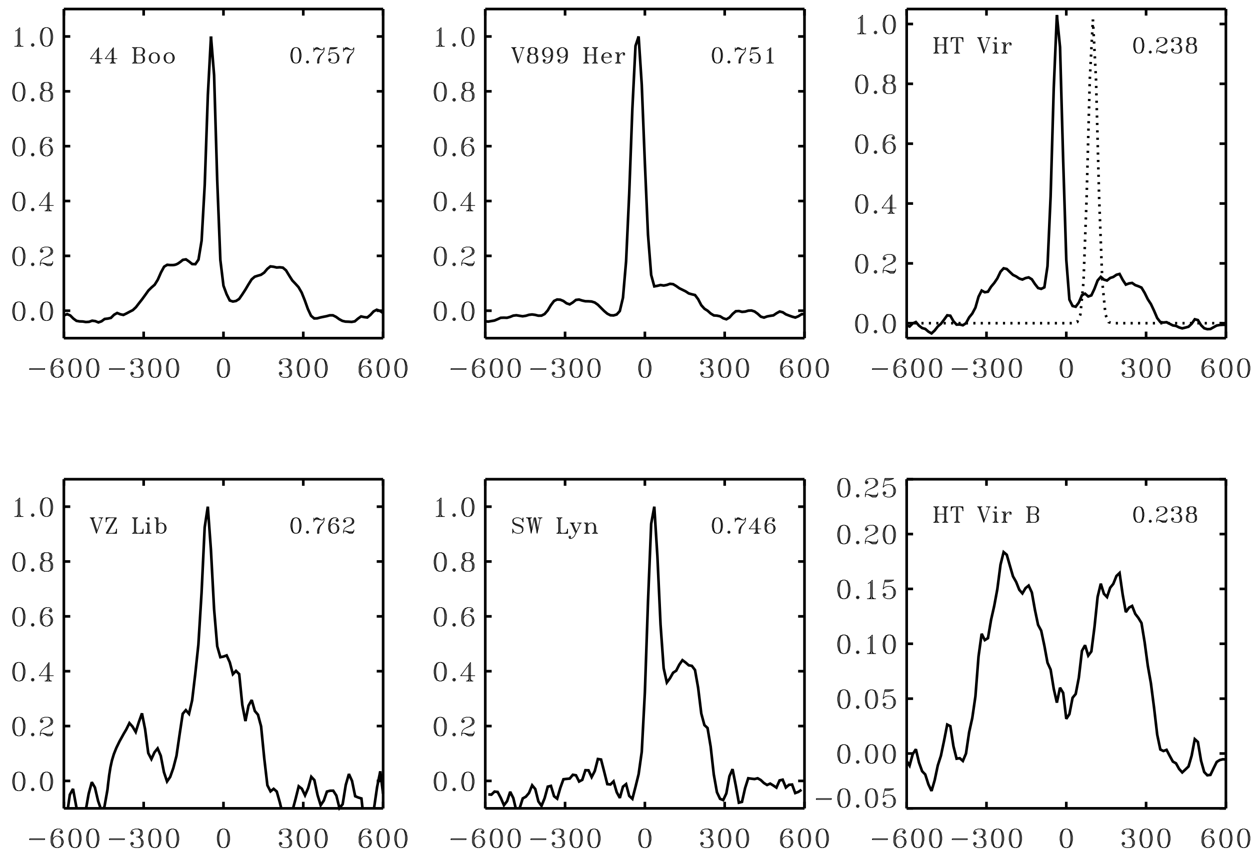

FIG. 4.—BFs for five close binary systems with spectroscopic companions. For HT Vir, we show (1) the full BF with the signature of a sharp-line template shifted for clarity by 100 km s^{-1} (*top right*, *dotted line*, shifted to right for clarity) and (2) the same function with the sharp-line component subtracted, leaving only the signature of the contact binary HT Vir B (*bottom right*). In each panel the number gives the orbital phase selected to be close to the orbital quadrature.

relatively wide slit. To derive an unbiased velocity of 44 Boo, we made three additional observations of this component at the slit center and measured the velocity of this component separately. Its average velocity for the epoch HJD = 2,450,945.996 is $V^A = -34.93 \pm 0.64$ km s^{-1}. The detailed data are given in Table 3.

3.3. *V899 Her A*

There exist no earlier reports of the presence of a third component in this star, which has been only recently discovered as a variable star. As we can see in the second top panel of Figure 4, the third component dominates the BF of V899 Her, so we call it the component A. The ratio of brightnesses at phases close to orbital quadratures is $L_3/L_{12} = 1.5 \pm 0.1$. The spectrum of the system, F5 V, is also dominated by this component, and we see only weak signatures of the broadened G-type spectrum in the BF. Only thanks to the linearity of the BF determination have we been able to study this interesting system.

We found that V899 Her A slowly changes its radial velocity. These variations are not reflected in the systemic velocity of the close pair, so that the companion A itself is probably a wide spectroscopic binary. The radial velocity data for V899 Her A are shown in Figure 5. We had many observations for this star, so we could group them into nightly average values. These in turn permitted us to obtain independent estimates of measurement errors for individual observations, after all stages of the combined standard and BF processing and component separation. For such a sharp-line star, the errors of the nightly averages are small at a level typically 0.5–1.0 km s^{-1}.

3.4. *VZ Lib B*

We have detected a spectroscopic companion of VZ Lib. The BF (Fig. 4, *bottom left*) indicates that in this case the brightness of the companion is lower than that of the close binary, with $L_3/L_{12} = 0.20 \pm 0.04$. Because the close binary has a relatively small mass ratio, the BF peak of the third star is usually merged with the broadening lobe of the primary, more massive component of the W UMa–type system of VZ Lib.

The radial velocities of the third component show a nightly spread of 2.6–4.3 km s^{-1}, whereas errors for sharp-line stars are typically ≤ 1 km s^{-1}. This may be an indication that the spectroscopic companion is itself a close binary, although we found that the derivation of the velocities for all three stars in this case was very difficult because of the relative faintness of the system and the extensive blending of the components in the BF. The variations of the third component appear to be slow (Fig. 5) but may result from grouped sampling of more rapid changes. The system requires further radial velocity observations to confirm that the companion has a variable radial velocity and that the system is actually a quadruple one.

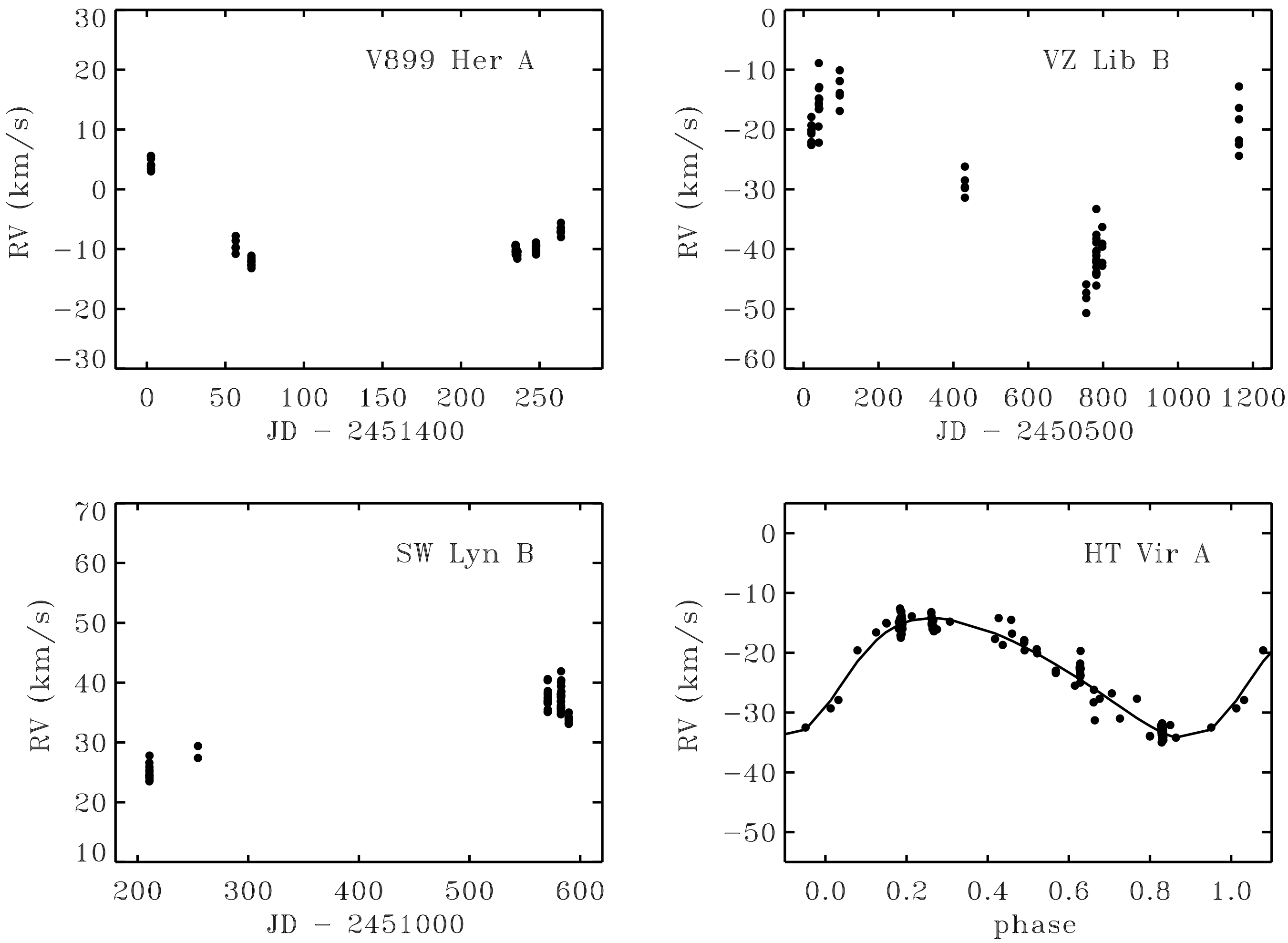

FIG. 5.—Radial velocity variations of the spectroscopic companions of V899 Her A, VZ Lib B, SW Lyn B, and HT Vir A. For HT Vir A, we show the radial velocity data phased with a period of 32.45 days, together with our preliminary single-line orbital solution. The vertical scale in all panels has the same span of 60 km s^{-1}, but the time axis is different for each panel.

3.5. *SW Lyn B*

We have detected a third star in the system of SW Lyn. It is well visible in the BF in Figure 4 (*bottom middle*). As mentioned in the description of the close binary in § 2, the presence of the signal from the third star, as well as the dominant role of the massive and bright primary component of the Algol system, resulted in difficulties with the radial velocity measurements of the secondary star of the close system.

The third star in SW Lyn is moderately bright, with $L_3/L_{12} = 0.33 \pm 0.05$ (for the contact system at the orbital quadrature), and is a radial velocity variable, so the whole system is a quadruple one. The radial velocity changes of the third component are slow and certainly compatible with the orbital period of 2128 days, which is noticeable in the eclipse timing for the close pair (Ogłoza et al. 1998). However, we see no direct indication that this is the same star. Unfortunately, contrary to V899 Her or VZ Lib, we have been unable to check whether seasonal data would give the complementary systemic velocity variation for the close pair; we could only solve the second season or all the data together. As we described in § 2, the orbital solutions for the close pair based on all the observations from both seasons and separately on the observations from the second season, gave identical sets of orbital parameters (within the errors). This would suggest that the spectroscopic companion and the eclipse timing perturber are not the same object.

3.6. *HT Vir A*

HT Vir has been known as a close visual binary with a separation of less than 1″ (Walker 1984; Walker & Chambliss 1985). In terms of the overall properties, the system is somewhat similar to 44 Boo. Walker & Chambliss (1985) determined that the component A had a brightness comparable to that of the close binary ($L_3/L_{12} \simeq 0.79$). By integration of the separate components of the BF (Fig. 4, *top right*), we obtained $L_3/L_{12} \simeq 0.52 \pm 0.05$, so that we found that HT Vir A was about 2 times fainter than the contact binary at its light maxima. In fact, we derived the ratio of the luminosities to be about 0.48 ± 0.03 for phases around 0.25 and about 0.56 ± 0.03 for phases around 0.75; this may reflect either an asymmetry in the light maxima of HT Vir B or systematic errors in our estimates of L_3/L_{12} for the mutually oppositely orientated peaks in the BF. After subtraction of the scaled peak of the third component, we obtained an excellent radial velocity orbit for HT Vir B (as described in § 2).

We discovered that HT Vir A is a relatively close, single-lined (SB 1) binary, so the HT Vir system is a quadruple one. The data for this star showed a scatter of about 20 km s^{-1}, which we analyzed for periodicity. Solution of the radial velocity data, using the program of Morbey (1975) with a preliminary orbital period of 32.45 days, leads to an eccentric orbit with the parameters listed in Table 4. We show the solution for HT Vir A in the bottom right panel of Figure 5.

4. SUMMARY

This paper gives radial velocity data and orbital solutions for the fourth group of 10 close binary systems that we observed at the David Dunlap Observatory. Only 44 Boo and SW Lyn have been observed spectroscopically before; for both, we provide much improved spectroscopic orbits. All systems are double-lined (SB 2) binaries with visible spectral lines of both components. We give the values of $(M_1 + M_2) \sin^3 i = (1.0385 \times 10^{-7})(K_1 + K_2)^3 P$ (day) $M_\odot$ in Table 2. As in the previous papers of this series, we have not been able to convert them into the sums of masses because in most cases the inclination angle is either unknown or not trustworthy. We note that the photometric discoveries of the *Hipparcos* project (FI Boo, V2150 Cyg, EX Leo, and V2377 Oph) tend to have small values of $(M_1 + M_2) \sin^3 i$, in accord with their small photometric amplitudes; both features are apparently due to low orbital inclinations. However, we also found that some of the newly discovered systems may have small photometric amplitudes because of the dilution of light in a triple system; the perfect example is V899 Her. By discovering low photometric amplitude binary systems, the *Hipparcos* mission has therefore contributed substantially to rectifying the statistics of bright contact binaries; these statistics had been known to be skewed toward large amplitude variables (Rucinski & Kałużny 1994; Rucinski 1997).

Five system in the current group are members of close visual and/or spectroscopic triple-lined systems (44 Boo, V899 Her, VZ Lib, SW Lyn, and HT Vir); among them, three, and possibly four, companions are themselves close binaries. We have been able to provide good data for these systems mostly because of the superior capabilities of the linear SVD-BF approach (Rucinski 1999) in resolving individual components in the triple-lined spectra.

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