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

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ABSTRACT

Radial velocity measurements and sine-curve fits to orbital velocity variations are presented for the ninth set of 10 close binary systems: V395 And, HS Aqr, V449 Aur, FP Boo, SW Lac, KS Peg, IW Per, V592 Per, TU UMi, and FO Vir. The first three are very close, possibly detached, early-type binaries, and all three require further investigation. Particularly interesting is V395 And, whose spectral type is as early as B7/8 for a 0.685 day orbit binary. KS Peg and IW Per are single-line binaries, with the former probably hosting a very low mass star. We have detected a low-mass secondary in an important semidetached system, FO Vir, at $q = 0.125 \pm 0.005$. The contact binary FP Boo is also a very small mass ratio system, $q = 0.106 \pm 0.005$. The other contact binaries in this group are V592 Per, TU UMi, and the well-known SW Lac. V592 Per and TU UMi have bright tertiary companions; for these binaries, and for V395 And, we used a novel technique of arranging the broadening functions into a two-dimensional image in phase. The case of TU UMi turned out to be intractable even using this approach, and we have not been able to derive a firm radial velocity orbit for this binary. Three systems of this group were observed spectroscopically before: HS Aqr, SW Lac, and KS Peg.

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

Online material: machine-readable table

1. INTRODUCTION

This paper is a continuation of a series of papers (Lu & Rucinski 1999; Rucinski & Lu 1999; Rucinski et al. 2000, 2001, 2002, 2003; Lu et al. 2001; Pych et al. 2004; hereafter Papers I–VI, VIII, and IX) of radial velocity studies of close binary stars and presents data for the ninth group of 10 close binary stars observed at the David Dunlap Observatory. For technical details and conventions, and for preliminary estimates of uncertainties, see the interim summary paper (Rucinski 2002a, hereafter Paper VII). Selection of the targets is quasi-random: at a given time, we observe a few dozen close binary systems with periods shorter than 1 day, brighter than 10–11 mag, and with declinations greater than $-20°$; we publish the results in groups of 10 systems as soon as reasonable orbital elements are obtained from measurements evenly distributed in orbital phases.

Whenever possible, we estimate spectral types of the program stars using our classification spectra. These are compared with the mean $(B - V)$ color indices 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 observations reported in this paper were collected between 1997 June and 2004 November. The ranges of dates for individual systems can be found in Table 1. All systems discussed in this paper, except three (HS Aqr, SW Lac, and KS Peg), have been observed by us for radial velocity variations for the first time. We have derived the radial velocities in the same way as described in previous papers. See Paper VII for a discussion of the broadening-function (BF) approach used in the derivation of the radial velocity orbit parameters: the amplitudes K_i, the center-of-mass velocity V_0, and the time-of-primary-eclipse epoch T_0.

The novelty of this paper is the treatment of binaries with very weak signatures of binarity in their BFs, resulting either from exceptionally weak Mg I λ5184 triplet lines (V395 And, § 2.1) or from the presence of a bright third star in the system (TU UMi, § 2.9), which limits the dynamic range in the BF. We use here an approach borrowed from image processing techniques in that we represent the BF information in the phase domain as a two-dimensional image in which smoothing in the phase coordinate restores the temporal correlation between successive BFs.

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TABLE 1
DAVID DUNLAP OBSERVATORY RADIAL VELOCITY OBSERVATIONS

HJD	V_1	W_1	V_2	W_2
HS Aqr				
2452507.6792	122.09	1.00	−143.05	1.00
2452507.7194	91.43	1.00	−104.07	1.00
2452507.7372	73.05	1.00	−99.45	0.50
2452507.7543	60.43	0.50	0.00	0.00
2452507.7744	38.30	0.50	0.00	0.00
2452507.7875	0.00	0.00	0.00	0.00
2452509.6398	84.74	1.00	−103.00	0.50
2452509.6551	95.57	1.00	−116.69	1.00
2452509.6704	108.27	1.00	−120.46	1.00
2452509.6863	115.38	1.00	−133.96	1.00

NOTES.—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. The table gives the radial velocities V_i and associated weights W_i for observations described in the paper. The first 10 rows of the table for the second program star, HS Aqr, are shown; this star is more typical than the first, V395 And, for which radial velocities were obtained from smoothed, averaged BFs as described in the text. There are no radial velocity data for TU UMi. In the table, velocities are expressed in km s^{-1}. Observations leading to entirely inseparable BF and correlation-function peaks are given zero weight; these observations may be eventually used in more extensive modeling of BFs. The radial velocities designated as V_1 correspond to the component that was stronger and easier to measure in the analysis of the BFs; it was 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.

This paper is structured in a way similar to that of previous papers, in that most of the data for the observed binaries are in two tables: Table 1 consists of the radial velocity measurements and Table 2 their preliminary sine-curve solutions. Table 1 contains data for nine stars, as we have not been able to derive individual radial velocities for the difficult case of TU UMi.

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. It also contains our new spectral classifications of the program objects. Section 2 of the paper contains brief summaries of previous studies for individual systems and comments on the new data. Figures 1 and 2 show the two-dimensional BF images for V395 And and TU UMi, while Figures 3 and 4 show the radial velocity data and solutions. Figure 5 shows the BFs for all systems; the functions have been selected from among the best-defined ones, usually around the orbital phase of 0.25, using the photometric system of phases counted from the deeper eclipse.

2. RESULTS FOR INDIVIDUAL SYSTEMS

2.1. *V395 And*

Photometric variability of V395 And was discovered by the *Hipparcos* satellite (Perryman et al. 1997); the star was

TABLE 2
SPECTROSCOPIC ORBITAL ELEMENTS

Name	Type, Spectral Type	Other Names	V_0	K_1, K_2	ϵ_1, ϵ_2	$T_0 - 2{,}400{,}000$, $(O-C)$ (days) [E]	P (days), $(M_1+M_2)\sin^3 i$	q
V395 And[a]	EA	HD 222900	+14.60(1.51)	133.35(2.55)	14.20	53,278.0000(30)	0.684656	0.879(25)
	B7/8:	HIP 117111		151.72(2.06)	9.09	+0.0332 [6978]	1.647(80)	
HS Aqr	EA	HD 197010	+19.34(0.64)	111.57(0.56)	3.36	52,507.7981(12)	0.710188	0.626(7)
	F6 V	BD −01°4025		178.24(1.46)	9.94	+0.0002 [10]	1.795(38)	
V449 Aur	EW(A)	HD 41578	+6.24(1.22)	128.27(1.45)	9.72	52,307.0853(24)	0.703648	0.730(15)
	A2/3 V	HIP 29108		175.61(2.15)	16.76	+0.0826 [5410]	2.051(73)	
FP Boo	EW(A)	BD +43°2523	−4.87(1.02)	26.88(0.98)	8.08	52,388.2227(36)	0.6404870	0.106(5)
	F0 V	HIP 76970		254.04(2.80)	14.28	−0.0114 [6070]	1.475(60)	
SW Lac	EW(W)	HD 216598	−10.32(1.17)	173.91(1.78)	10.11	52,484.1080(8)	0.3207158	0.776(12)
	G5 V	HIP 113052		224.14(1.70)	11.54	+0.0003 [−50]	2.101(55)	
KS Peg	SB1 (EB?)	HD 222133	−3.27(0.62)	25.19(0.80)	5.25	50,735.6405(28)	0.502103	
	A1 V	HIP 116611				−0.0059 [16115]		
IW Per	SB1 (EB?)	HD 21912	+11.44(0.31)	98.64(0.51)	3.46	53,031.4192(8)	0.91718	
	(A3 V)	HIP 16591				+0.0270 [4940]		
V592 Per	EW(A)	HD 29911	+27.92(1.04)	93.74(1.25)	9.42	52,516.8641(20)	0.715722	0.408(7)
	(F2 IV)	HIP 22050		229.97(1.85)	15.00	−0.0108 [5612]	2.521(72)	
TU UMi[b]	EW(W)	BD +76°544	−4.16(0.20)	35(15)	30	52,725.6262	0.377088	0.16(7)
	(F2)	HIP 73047		220(20)	40	0 [0]	0.65(27)	
FO Vir	EA/EB	HD 117362	−27.26(1.45)	33.84(1.02)	6.75	51,660.1839(25)	0.775568	0.125(5)
	(A7 V)	HIP 65839		269.91(2.95)	15.87	−0.0342 [4074]	2.257(89)	

NOTES.—The spectral types given in the second column relate to the combined spectral type of all components in a system; they are given in parentheses if taken from the literature, otherwise they are new. The convention of naming the binary components in the table is that the more massive star is marked by the subscript "1," so that the mass ratio is defined as always $q \leq 1$. 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_i) 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 on 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.

[a] The solution is based on 103 data points arranged in phase using the preliminary T_0 and period, as given in the text, and then with the BFs smoothed in the phase domain. Such averaged data points are given in Table 1.

[b] The data do not permit a solution; only very rough estimates are given. The value of V_0 is for the visual companion, while T_0 is from the photometric solution based on data obtained simultaneously with the spectroscopic program (Pych & Rucinski 2004). Because of the low contribution of the close binary to the total light, the (literature) spectral type is that of the visual companion.

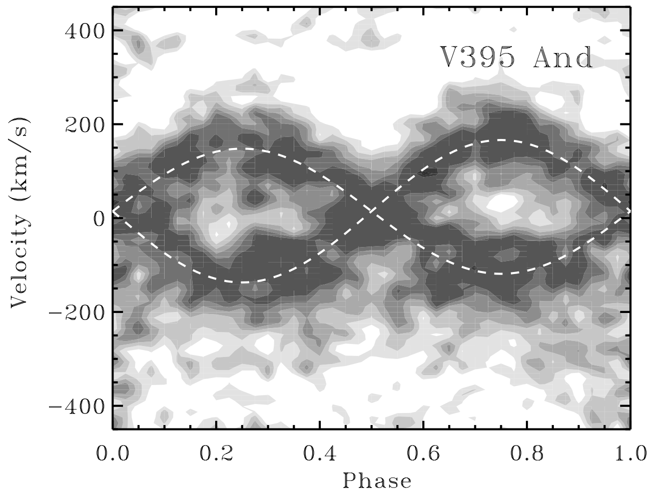

FIG. 1.—BF image for V395 And with the orbital solution superposed on the contour plot. The image has been smoothed in the phase domain with a Gaussian of FWHM = 0.025 in phase. A vertical section of the image at phase 0.75 is shown in Fig. 5.

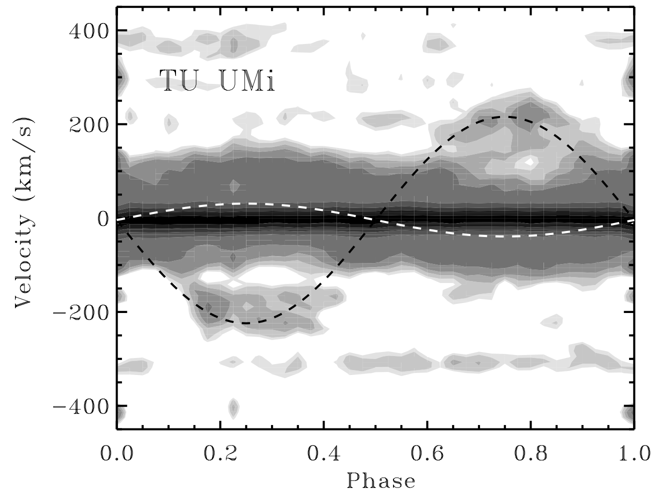

FIG. 2.—BF image for TU UMi with a very approximate guess at an orbital solution superposed on the contour plot. The image has been smoothed in the phase domain with a Gaussian of FWHM = 0.025 in phase. Sections at phases 0.25 and 0.75 are shown in Fig. 5.

assigned type RRc in the 74th Special Name-list of Variable Stars (Kazarovets et al. 1999) on the basis of the *Hipparcos* data. Duerbeck (1997) suggested that V395 And is a contact eclipsing system on the basis of the period-color relation. Light elements were calculated by Pribulla et al. (2003), HJD $= 2{,}448{,}500.4372 + 0.684656E$, using the *Hipparcos* photometric data and the doubled value of the original period.

V395 And was listed in Duflot et al. (1995) with spectral type estimated as B7 (this type is also quoted in the Washington Double Star Catalog[3] [Mason et al. 2001], hereafter WDS) and a radial velocity of -8 km s^{-1}; in the Henry Draper Catalogue the spectral type is A0. Our spectra of the magnesium triplet in V395 And showed an exceptionally weak, poorly defined, strongly broadened feature with a depth of only 2% of continuum with no discernible doubling. While we expected that the feature would be weak in a nominally A0-type star (SIMBAD), the particular weakness of the line was surprising.

The star is relatively bright, $V_{\rm max} = 7.55$. It is a member of a visual binary (WDS 23445+4623). The companion at a separation of 5$''$.7 is 2.2 mag fainter than V395 And. It is visible at the position angle 104° and thus is projected into our east-west spectrograph slit. Its presence may have produced weakening of the spectral lines by probably less than 15%.

Original estimates based on the very shallow and poorly defined BFs suggest that the star will be entirely intractable and may have to be abandoned. Our standard technique of measuring radial velocities requires that each BF for each spectrum give a peak or a pair of peaks for radial velocity centroid determination; such well-defined peaks simply did not exist for V395 And. However, a new approach, partly based on ideas used in image processing, worked relatively well: the BFs were ordered in columns in a two-dimensional image, with the *Y*-coordinate being the heliocentric radial velocity. The *X*-coordinate, the phase, is obviously unevenly filled, and the data can be interpolated into a regular grid of phases. At this point, we use the fact that the BFs are correlated in the temporal (phase) domain so we can use smoothing. Thus, horizontal cuts through the BF image were convolved with a Gaussian kernel with a FWHM of 0.025 in phase and then rebinned into a new uniform phase system with 40 phase points. The "BF image" is shown in Figure 1, while a section at phase 0.75 is shown in Figure 5, among the BFs for other stars of this group.

Even after the processing of all 103 available spectra of V395 And, as described above, only some of the smoothed BFs were measurable for individual radial velocities. They are listed in Table 1 as for other stars, but they should be used with considerable caution. The smoothed BFs were originally found at 0.025 intervals in phase, and heliocentric times were calculated for them using the T_0 prediction given above. Some of the smoothed BFs were still too poor and have been eliminated from the listing. The final solution was based on the data as listed in Table 1 and required a new value of the initial epoch T_0 as given in Table 2.

The star appears to be a very close pair with almost identical components, $q = 0.88 \pm 0.03$. The component potentially eclipsed at the primary minimum (corresponding to T_0) is less massive; its peak in the BF is slightly sharper and taller, indicating higher surface temperature and lower rotation rate. The very small amplitude of light variations, $\Delta V \simeq 0.04$, suggests that the eclipses will not actually be observed and that the binary is an "ellipsoidal variable" showing only proximity effects. Our classification spectra clearly indicate a spectral type as early as B7, which is difficult to reconcile with the close orbit with the period of 0.685 days. The two spectra that we obtained were not identical and showed some peculiar variability and emission at He I λ4009, He λ4027. No spectral estimate of $\log g$ was possible because of peculiarity of the spectra. Stars of spectral type B7 or B8 have masses around 2.8–3.0 $M_\odot$ and radii around 2.2–2.4 $R_\odot$. If the orbit has $i \simeq 40°$, then the current data would imply $A \simeq 6.0\ R_\odot$, which is just about possible for a contact system.

2.2. *HS Aqr*

HS Aqr is a detached or semidetached binary. Spectroscopic studies based on the high-quality echelle spectra were presented by Popper (1996, 1997, 2000). This was followed by an extensive discussion of the photometric and spectroscopic data by Clausen et al. (2001). The above sources provide the most extensive references to properties of the system. The value of T_0 was taken from Kreiner (2004): $T_0 = 2{,}452{,}500.6960 + 0.710188E$.

Our observations of HS Aqr give a good solution of the radial velocity orbit (Fig. 3), but perhaps not of such a high quality as

[3] The WDS catalog is available at http://ad.usno.navy.mil/wds.

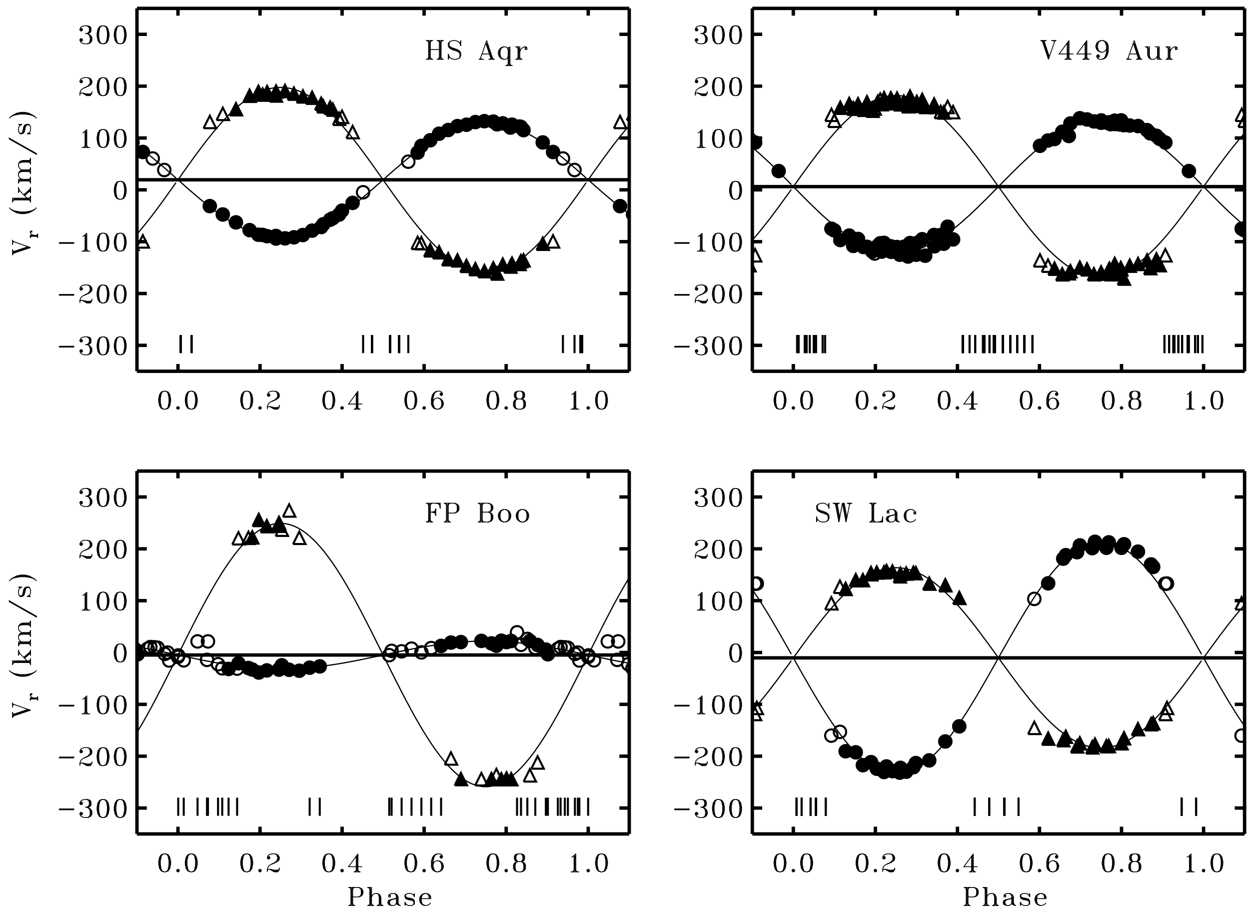

FIG. 3.—Radial velocities of the systems HS Aqr, V449 Aur, FP Boo, and SW Lac plotted in individual panels versus the orbital phases. The lines give the respective circular orbit (sine-curve) fits to the radial velocities. HS Aqr and V449 Aur are detached binaries, while FP Boo and SW Lac are contact binaries. The circles and triangles in this figure and in Fig. 4 correspond to components with velocities V_1 and V_2, respectively, as listed in Table 1. 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 open symbols indicate observations contributing half (or less) weight in the orbital solutions. Short marks at the bottom of each panel indicate phases of available observations that were not used in the solutions because of the blending of lines. All panels have the same vertical range, −350 to +350 km s^{-1}.

that of Popper, which was based on the echelle spectrograph spectra. However, since the main uncertainties in this field are not in random errors but in systematic differences in measuring techniques, we give our solution here for future reference.

The BF at phase close to 0.25 (Fig. 5) shows two well-defined peaks for detached components, with that for the secondary component a bit broader, indicating that this component is larger if this star is in rotation-revolution synchronism. This agrees with the supposition (Clausen et al. 2001) that the secondary component is close to or fills its Roche lobe.

Our new spectral type estimate of F6 V is slightly earlier than previously discussed (F8 V and G8–9), in better agreement with the Tycho-2 (Høg et al. 2000) color index $B - V = 0.52$. The binary is in a visual system (CCDM J20409−0036AB, ADS 14147AB), but the companion at 1.″6 separation is some 4 mag fainter than HS Aqr and thus of no consequence for the radial velocity orbit. The recent minimum prediction by Kreiner (2004) perfectly agrees with our determination of the initial epoch T_0. The star is bright, $V_{max} = 9.0$, but was not included in the *Hipparcos* database, so its parallax is currently unknown.

2.3. *V449 Aur*

V449 Aur was discovered photometrically by the *Hipparcos* mission. The primary eclipse prediction was the *Hipparcos* one, $T_0 = 2{,}448{,}500.2670 + 0.703648E$. The mean *uvby* data of Jordi et al. (1996), $V = 7.455$ and $b - y = 0.086$, suggest an early type no later than A5/6 V, while our spectral classification is A2 IV and, through a comparison with the color index, implies some reddening.

The binary type of the system is not clear at this moment; the BFs are partially blended, as in a contact binary, and somewhat difficult to measure for centroid determinations (see Fig. 5). On the basis of its very shallow *Hipparcos* light curve, but its rather well-defined eclipses, the binary was considered by Rucinski (2002b) to be detached (EA); the BFs would rather suggest a contact binary. However, the large widths of the peaks in the BFs and the resulting blending may result from rotational velocities higher than the synchronous ones. The mass ratio is not far from unity, $q = 0.730 \pm 0.017$, which is frequently encountered among early-type very close binaries. The scatter of the radial velocity observations of the slightly more massive component, which is eclipsed in the primary minimum, appears to be genuinely larger at phases around 0.2–0.4 (Fig. 3); we have no explanation for it.

2.4. *FP Boo*

FP Boo is another case of *Hipparcos* photometric discovery. The *Hipparcos* period and T_0 serve the current observations relatively well: $T_0 = 2{,}448{,}500.478 + 0.640487E$. The previous spectral type given by SIMBAD and in the *Hipparcos*

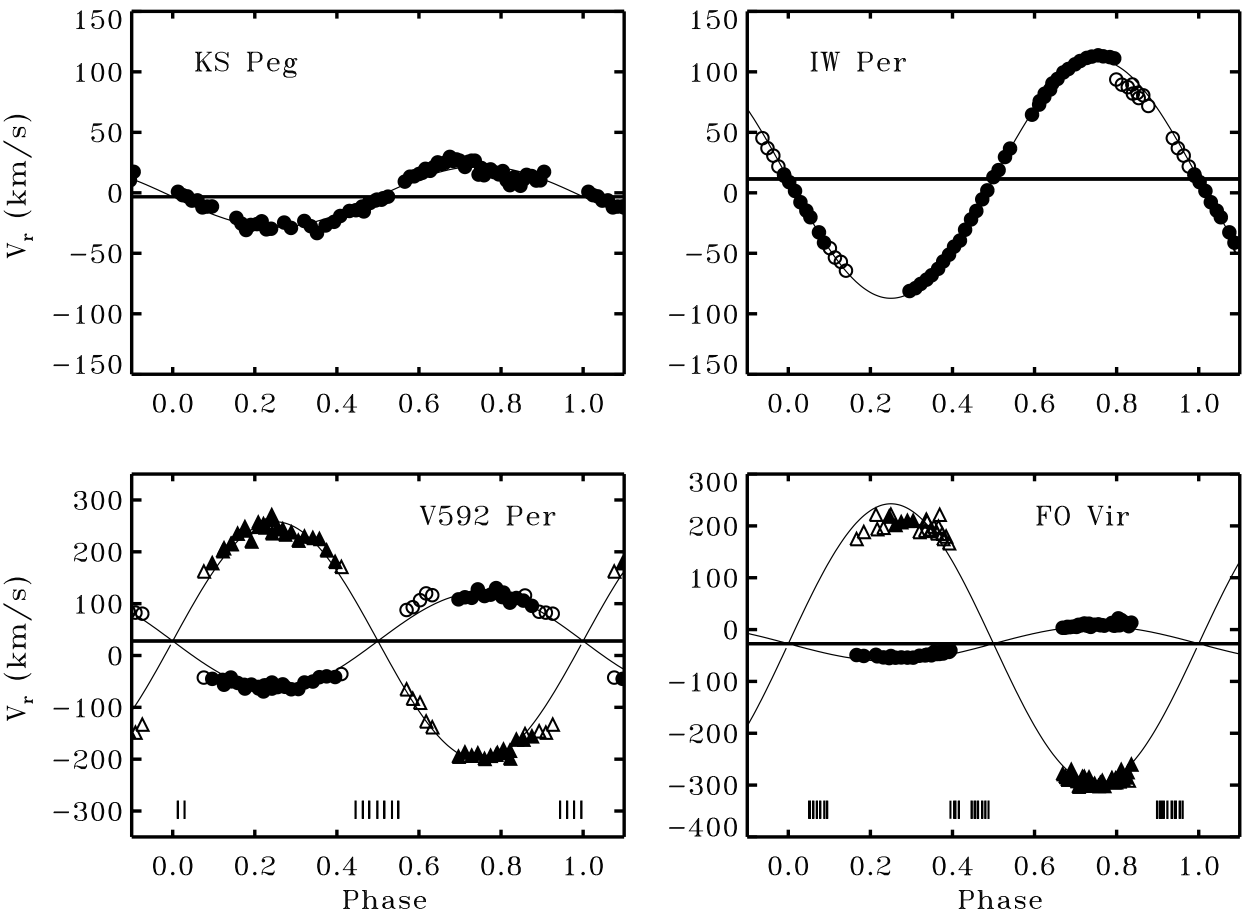

FIG. 4.—Same as Fig. 3, but for KS Peg, IW Per, V592 Per, and FO Vir. Note that the vertical scale is different and much expanded for the single-line binaries KS Peg and IW Per, while for FO Vir it is the same as for the other systems but shifted vertically by +50 km s^{-1}.

database, A5, does not agree with our estimate of F0 V; the latter would imply $B - V = 0.28$, whereas the Tycho-2 mean color index is even redder, $B - V = 0.35$, corresponding to F2 V.

The *Hipparcos* photometry was analyzed by Selam (2004) using a simplified approach. The mass ratio was estimated at $q_{\rm ph} = 0.1$, which is in surprisingly good agreement with the spectroscopic result, $q_{\rm sp} = 0.106 \pm 0.005$, taking into account that the light curve is shallow and does not show any obvious total eclipses. [This case is, in our view, an exception, a fortuitous coincidence. Normally, we do not trust the so-called photometric mass ratios because so many stars in our radial velocity program show $q(\rm sp) \neq q(\rm ph)$.] FP Boo was somewhat faint ($V_{\rm max} = 10.07$) for *Hipparcos* photometry, so the light curve could be easily improved. Since the velocity amplitudes are large and thus imply an orbital inclination close to 90°, it is likely that more precise photometry will show total eclipses. With its small mass ratio and spectral type of F0/2 V, the system is somewhat similar to the well-known contact binary AW UMa. The radial velocity orbit is shown in Figure 3, while a BF close to phase 0.25 is shown in Figure 5.

2.5. *SW Lac*

SW Lac is one of the most frequently photometrically observed contact binaries. It is a bright ($V_{\rm max} = 8.66$) binary with a large amplitude and an unstable light curve and thus is an easy target for investigations using small telescopes. Several discussions address the matter of evolving surface spots, the most recent being Albayrak et al. (2004), in which references to previous work can be found.

SW Lac is a late-type contact binary with a spectral type variously assigned as G3, G5, and K0. Our new classification is G5 V, which predicts a color index a bit less red than the observed $B - V = 0.73$; possibly G8 V would be a good compromise. From the moment of minima predictions, as well as the direct detection of faint spectral signatures (Hendry & Mochnacki 1998), the binary appears to have at least one, probably two, nearby low-mass companions (Pribulla et al. 1999). The system is known to change the orbital period. We used the moment of primary minimum of Kreiner (2004), HJD = 2,452,500.1435 + 0.3207158E, which ideally predicts our T_0.

Our observations form the third currently available set of radial velocity data (see Fig. 3). Zhai & Lu (1989) published the first radial velocity orbit, with $q = 0.797 \pm 0.010$. A similar but not identical result was obtained soon after by Hrivnak (1992), who published only the mass ratio, $q = 0.73 \pm 0.01$, without more details. In spite of the large brightness of the star and excellent definition of the individual peaks in the BFs, our mass ratio, $q = 0.776 \pm 0.012$, carries a larger error than that for most of our targets, probably because of the genuine changes in the BFs, which are caused by elevated stellar surface activity. What is important, however, is that radial velocity semiamplitudes in our orbit (Fig. 3) are larger than previously observed; our total mass estimate, $(M_1 + M_2) \sin^3 i = 2.10 \pm 0.06\ M_\odot$ (the primary 2.18 $M_\odot$, the secondary 0.92 $M_\odot$), is significantly larger than that for the orbit of Zhai & Lu (1989), $(M_1 + M_2) \sin^3 i = 1.74\ M_\odot$. Since most systematic effects result in a reduction of the radial velocity amplitudes, our result is more trustworthy, as it is based on the superior technique of the BFs. Thus, SW Lac

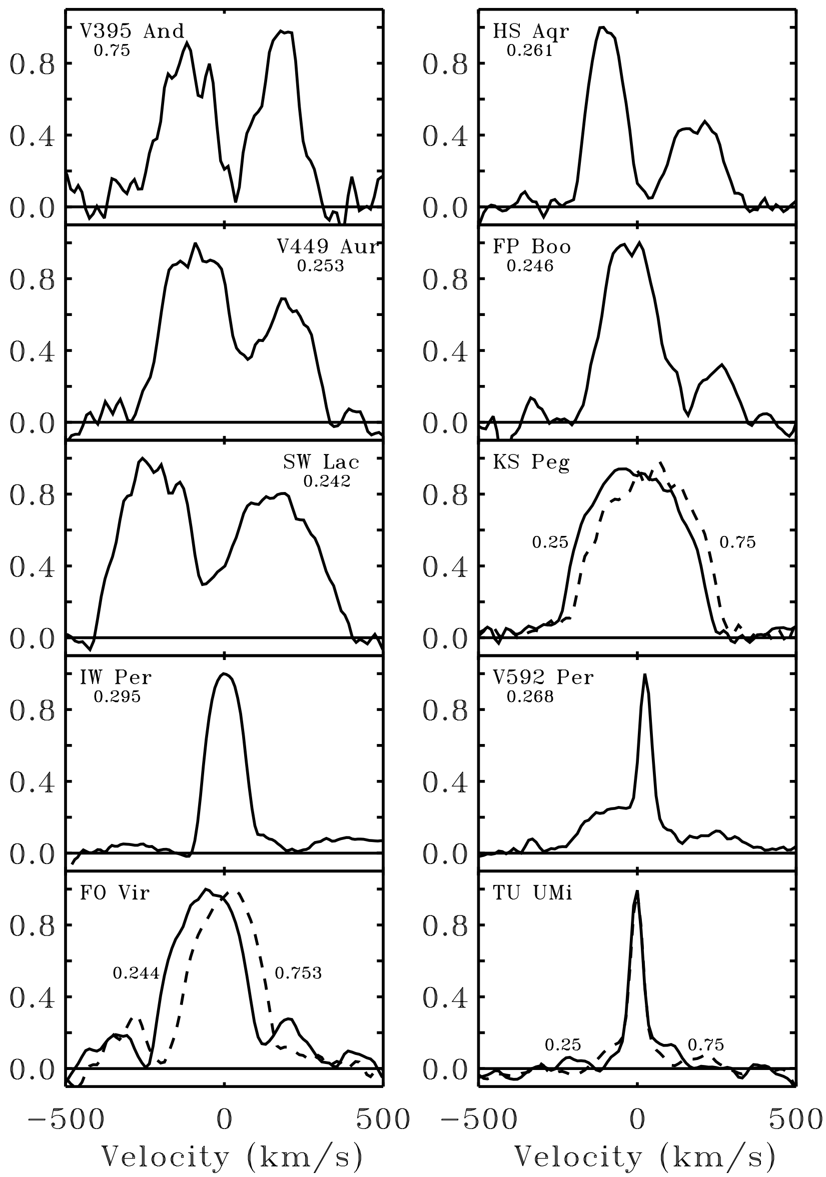

FIG. 5.—BFs for all 10 systems of this group. For most systems BFs at phases close to 0.25 have been selected. The phases are marked by numbers in individual panels; for KS Peg, FO Vir, and TU UMi the numbers are written above the locations of the secondary star peaks. For V395 And, KS Peg, and TU UMi the plots actually give sections of the BF images after Gaussian smoothing (FWHM = 0.025) in the phase domain. For V395 And the section at phase 0.25 was too poorly defined, so the section at phase 0.75 is shown instead. Note the high brightness of the secondary in SW Lac, which directly shows the W-type phenomenon; note that this could also be explained by the semidetached configuration of this binary (which otherwise is considered to be one of the most typical contact systems). The uneven baseline for IW Per is due to differences in continuum tracing for the star and the template. As described in the text, FO Vir showed spurious peaks (one is visible here), which were almost as strong as those for the secondary component but followed the motion of the primary component; we think it is because of the mismatch of the template with the low-metallicity spectrum of FO Vir and the continuum height difference for the template and for the star itself.

is a relatively massive but surprisingly cool system, a situation that was very clearly seen before in the case of another cool contact binary, AH Vir (Lu & Rucinski 1993). As in the case of AH Vir, the masses are characteristic for F-type stars, while the combined luminosity is in agreement with small star sizes—implied by the Roche geometry of a very short period system—and their low temperature (G5 V). Indeed, for SW Lac, the M_V calibration (Rucinski & Duerbeck 1997) predicts $M_V(\text{cal}) \simeq 4.5$, as compared with the parallax-based, observed $M_V(\text{obs}) = 4.1 \pm 0.2$, so that the geometry and photometric properties are those of a late-type, compact contact system but with masses that are too large.

We have not noticed in individual BFs any traces of the third component detected by Hendry & Mochnacki (1998) and apparently producing part of the time-of-minima perturbations (Pribulla et al. 1999; Kreiner 2004). However, the same spectra, when averaged in the heliocentric system, clearly show a late-type dwarf contributing about 1% to the total light at our 5184 Å spectral window (C. D'Angelo & M. van Kerkwijk 2005, private communication).

2.6. *KS Peg*

The bright star KS Peg ($V_{\max} = 5.48$, $B - V = +0.01$), also called 75 Peg, has been known as a radial velocity variable for a long time, since the work of Plaskett et al. (1920). Hube & Gulliver (1985) recognized the peculiar properties of this binary star, in particular the very small mass ratio of $q < 0.1$, making the velocity amplitude of the primary component small and the secondary component invisible in their spectra. The photometric variability was observed by Hube et al. (1988), while a good-quality light curve was provided by the *Hipparcos* (Perryman et al. 1997) project. The light curve, with an amplitude of only 0.1 mag, shows very wide minima with unusual, sharply peaked, brief light maxima.

We observed KS Peg in our standard way and, because the star is so bright, with particular attention to detection of the secondary component. In our series of observations, we have already detected several binaries with $q \simeq 0.1$, with some even below this limit, such as SX Crv at $q \simeq 0.07$ (Paper V), so we hoped to see a signature of the secondary. The spectral type of KS Peg is A1 V; we used a star of A2 V as the main template, but we also used another F8 V radial velocity standard to possibly capture the signature of the secondary component of later spectral type. None of these led to detection of any traces of the secondary, even when applying the technique of BF image smoothing described above for V395 And (§ 2.1), which permits detection of weak features correlating in the phase domain. Since the spectra of such a bright star result in particularly good determinations of the BFs, the nondetection of the secondary is puzzling and indicates that the secondary may be a very low mass star or even a massive planet, just able to enforce rapid rotation on the visible component but too faint to contribute light to the overall luminosity of the binary.

One of the panels of Figure 5 shows a comparison of BFs at both orbital elongations (averages of six BFs at each elongation). Rapid rotation of the primary component and its (small) orbital displacements are very clearly visible, but there is no sign of the secondary component. Note that systematic trends in the baselines are due to the rectification process, with inevitably different tracing of the continuum for the program and the standard template spectra. These trends may mask a very weak secondary component.

Our initial reference epoch was that of the *Hipparcos* photometry, $T_0 = 2{,}448{,}500.286 + 0.502103E$, which predicts our T_0 very well. In fact, with the same period as in the table, even the epoch of Hube & Gulliver (1985) is well predicted more than 16,000 cycles earlier. (The authors in fact suggested 0.5021035, which does not tie all observations that well.) The remarkable constancy of the orbital period may be one of the useful hints in interpretation of KS Peg.

KS Peg is an important object because it is a bright star and thus belongs to the complete, magnitude-limited *Hipparcos* sample of short-period binaries brighter than 7.5 mag (Rucinski 2002b). Its parallax is moderately large, 13.65 ± 0.75 mas, and the star is intrinsically bright, $M_V = +1.1 \pm 0.1$. The absolute magnitude agrees very well with the expected value for a main-sequence A1 star, $M_V \simeq +1.0$. The large projected rotational velocity of the primary component, $V_1 \sin i = 240 \pm 15$ km s^{-1}, implies that the orbital inclination cannot be far from 90°. Assuming $M_1 = 2.3 \pm 0.1\ M_\odot$ and $R_1 = 2.3 \pm 0.1\ R_\odot$, one can achieve a consistent picture, in terms of reproduction of K_1 and $V_1 \sin i$, with a relatively small secondary star with $M_2 = 0.18 \pm 0.01\ M_\odot$ and thus $q = 0.078 \pm 0.005$, in a binary with the orbital inclination $i = 80° \pm 3°$.

2.7. *IW Per*

IW Per is somewhat similar to KS Peg, described above: it is also a bright, $V_{\rm max} = 5.76$, small-amplitude, 0.04 mag, photometric variable. The variability was recognized by Morris (1985), but most of the research concentrated on the chemical peculiarities and Am characteristics (Abt & Morrell 1995; Adelman 1998; Pauzen & Maitzen 1998).

IW Per was not a lucky star in our observations. A new CCD system used for it failed after some time, and the data could not be related to those taken before or after, as our technique requires high consistency in observations of program and template stars. Later on, it was realized that the heavy Dewar of the CCD system induced flexure in the spectrograph of up to half a pixel in the detector focal plane. We decided to analyze and publish the available data for IW Per when it was realized that it is a single-line spectroscopic binary, precluding any in-depth studies of this system. In the final radial velocity solution, the spectra taken at large hour angles have been given half-weight to account for the spectrograph flexure. The period and the initial epoch for our observations have been taken from the *Hipparcos* database: $T_0 = 2{,}448{,}500.523 + 0.917180E$.

In contrast to KS Peg, IW Per is not a very low amplitude radial velocity variable; the half-amplitude $K = 98.6$ km s^{-1} indicates that the mass ratio is not very small, probably around $q \simeq 0.45-0.5$, and that the spectroscopically invisible component is a star with a mass only slightly smaller than solar. The visible component rotates with $V_1 \sin i \simeq 90 \pm 10$ km s^{-1}, which is consistent with synchronous rotation in a moderately wide binary with the orbital period of 0.917 days.

IW Per has the best-determined parallax among stars of the current group, 18.29 ± 0.81 mas. The implied luminosity, $M_V = 2.07 \pm 0.11$, the spectral type A3 V, and $B - V = 0.13$ are mutually consistent.

2.8. *V592 Per*

V592 Per is another photometric discovery of *Hipparcos*. It is a relatively bright, $V_{\rm max} = 8.22$, basically unstudied contact binary. The moment of primary eclipse from *Hipparcos*, HJD = $2{,}448{,}500.243 + 0.715722E$, serves well for the prediction of T_0. The star has been known to possess a visual companion at a separation of only 0.″16 (Heintz 1990). Data for WDS 04445+3953 indicate that the position angle changes rather rapidly, so the system is definitely a physical one. We rediscovered the companion spectroscopically. In the BFs its signature is strong because of its sharpness, but the companion is fainter than the binary with $L_3/(L_1 + L_2) = 0.60 \pm 0.06$, or $\Delta m = 0.55$ mag (in the WDS catalog, $\Delta m = 0.85$ mag).

To determine the close binary orbit, we analyzed our observations the same way as for triple systems, by first fitting three Gaussians to the whole BF, then subtracting the third star Gaussian, and then measuring the radial velocities of both binary components from the residual BFs. In spite of the presence of the visual companion, the contact binary orbit is well defined, with $q = 0.408 \pm 0.008$. The spectroscopic result is in total disagreement with the mass ratio estimated from the light curve of $q_{\rm ph} = 0.25$ (Selam 2004). Once again, we stress that, because of the very low information content of light curves, light curve solutions for partially eclipsing contact binaries have little validity, and they should not be attempted without supporting spectroscopic data.

Our observations are spread over time in that there is a gap of two full seasons. The radial velocities of the third component were estimated from all available spectra, giving an average value of $V_3 = +29.28 \pm 0.20$ km s^{-1} for the first season (2,451,870–2,451,957) and $V_3 = 27.92 \pm 0.18$ km s^{-1} for the second season (2,452,513–2,452,517). Our systematic uncertainties are at the level of 1.5–2.0 km s^{-1}, while measurements in the presence of the variable binary "background" are difficult, so we cannot claim that we see seasonal variation in V_3; it is basically identical to V_0 of the contact binary.

In view of similar luminosities, the spectral type F2 IV estimated by Grenier et al. (1999) probably applies to both stars, the contact binary V592 Per and the third star in the system. This spectral type does not agree with $(B - V) = 0.47$ estimated from the Tycho-2 data (Høg et al. 2000), which suggests F5–F6.

2.9. *TU UMi*

TU UMi is one of the *Hipparcos* photometric discoveries. A description of new photometric observations conducted concurrently with the spectroscopic observations is given by Pych & Rucinski (2004); the paper also contains references to work related to identification of the variability and of the determination of the period at twice the *Hipparcos* original period.

Pych & Rucinski (2004) was based on a short time interval and could not provide a new value of the period, which was estimated to only four significant figures. However, the *Hipparcos* period, which we use here, together with the new photometric epoch, JD(min) = 2,452,725.6262 (Pych & Rucinski 2004), indicate, when counted back to the *Hipparcos* epoch (additionally shifted by 1/4 of the period because the star was thought to be a pulsating one, so the time of its maximum light was used), JD(min) = 2,448,499.9747, a good stability of the period.

TU UMi is a case of a contact binary with a bright close companion. We were not aware that it had been known as a visual binary, WDS 14557+7618, with a separation of 0$''$.2 (well below the 1.88 m telescope resolution in our location) when we started the observations. The spectral lines of the close binary are very broad and, in fact, entirely invisible in individual spectra, being masked by the strong sharp spectrum of the companion.

With 70 individual spectra rather evenly covering orbital phases, we attempted to analyze the data using an approach similar to that described for V395 And (§ 2.1) by ordering in phase and smoothing the BFs. This case is much more difficult than that of V395 And because, even after averaging, the binary features are too weak and too poorly defined to be measured; most of the dynamic range in the BF is "wasted" on the sharp peak of the tertiary component (Fig. 5). We attempted to remove this peak from the BF. First, we followed our normal routines of approximating the third star feature by a Gaussian and subtracting it. This did not work, as the profile is not Gaussian at its base, where its shape is particularly important. Then we attempted to find the shape of the third star peak by combining all BFs and determining their lower envelope. This still did not provide a correct shape of the tertiary peak at the base, since none of the BFs was really free of the binary signature. Thus, we were unable to remove the tertiary and to determine individual radial velocities of components for TU UMi; this star does not have any data listed in Table 1. While this is disappointing, we feel that it is doubtful whether this star will ever permit a detailed parameter determination. In this situation, we present only very rough estimates from what can be derived from just an eyeball fit to the BFs in the two-dimensional representation (Fig. 2).

In plotting the expected changes in the BFs as a function of phase, we assumed the initial epoch as photometrically observed simultaneously by Pych & Rucinski (2004). The star appears to be a W-type contact system with a rather large amplitude of the secondary star variation, perhaps as large as $K_2 \simeq 220 \pm 20$ km s^{-1}. An estimate for the primary is $K_1 \simeq 35 \pm 15$ km s^{-1}. These amplitudes are shown on the BF image in Figure 2. Integrations of the wide binary feature at several phases indicate that the binary is in fact only marginally fainter than the third component, $L_3/(L_1 + L_2) = 1.25 \pm 0.15$, but the sharpness of its peak dominates in the combined spectrum of the system. The above estimate of the relative luminosity may carry a large systematic error, since it is strongly dependent on how the baseline of the BF is drawn; in fact, this luminosity ratio implies $\Delta m = -0.24 \pm 0.12$, which poorly agrees with the direct magnitude difference given in the WDS catalog ($\Delta m = -0.47$). The third component was observed to have a mean velocity of -4.16 ± 0.20 km s^{-1} (a single observation $\sigma = 1.7$ km s^{-1}).

2.10. *FO Vir*

FO Vir is a totally eclipsing detached or semidetached binary, with the larger component close to filling the Roche lobe; thus, it is possibly an object in the precontact state. An extensive discussion of its properties, following the photometric study of Schmidt & Fernie (1984), who established its binary character, was presented by Mochnacki et al. (1986). On the basis of photometry and radial velocities of the dominant A7 V component, they were able to infer many parameters of the system; in particular, they predicted the mass ratio, $q = 0.15 \pm 0.02$, in a semidetached system with the more massive component filling or almost filling its Roche lobe. Similar results were obtained by Poretti et al. (1987). FO Vir is a member of a visual binary, WDS 13298+0106, but the companion is some 6.5 mag fainter, so its presence was of no consequence for the spectroscopic observations.

We have been able to detect the secondary component of FO Vir, but with some difficulty, because it is relatively small and faint at the observed mass ratio $q = 0.125 \pm 0.005$ and is of a much later spectral type than that of the A7 V primary, probably early K. A somewhat indirect detection of the secondary was reported by Shaw et al. (1991), who observed the Lyα λ1216 emission moving in antiphase with the primary star and thus most likely related to the secondary; their $q = 0.16 \pm 0.04$ is in agreement with the current determination.

We experienced difficulties with measuring the radial velocities of both components in the first half of the orbit; this could be related to the previously reported strong and variable O'Connell effect (Shaw et al. 1991). In addition, the case of FO Vir confronted us with what may be a limitation of our BF approach: we observed relatively strong (similar to those of the secondary component), initially unexplained BF features moving in phase with the primary. We suspect that these "ghosts" may appear because of the low metallicity of the primary component (Mochnacki et al. 1986) and a mismatch between the spectra of program and template stars; we simply could not locate a proper, low-metallicity template among bright standard stars. Many tests and experiments with different templates give us assurance that the final orbital elements are secure ones, although a certain element of uncertainty still remains.

The radial velocity data for FO Vir may have to be reinterpreted when a better T_0 prediction for the duration of our observations (1997–2001) becomes available. With observations spanning four seasons, we could establish that the period must be shorter than that used by the *Hipparcos* project (0.775569), and we used one that was shorter than that by only one digit in the last place; however, the period may be, in fact, systematically changing so that a full discussion is clearly in order, especially in view of a possibly sporadic mass transfer in the system. Our T_0 is shifted by 50 minutes from the time predicted by the *Hipparcos* project. A rediscussion of a rather few available moments of minima for 1983–1991 gave JD(hel) = $2{,}452{,}500.1514 + 0.7755678E$, which we took as guidance for adopting a shorter period, but which nevertheless resulted in the spectroscopic T_0 for our program being too early by 40 minutes.

3. SUMMARY

This paper presents radial velocity data and orbital solutions for the ninth group of 10 close binary systems observed at the

David Dunlap Observatory. This group contains very interesting objects. KS Peg and IW Per are single-line (SB1) binaries without any traces of companions; the former may have a very small mass secondary ($q < 0.1$). V395 And, HS Aqr, and V449 Aur are very close, early-type binaries; the matter of them being detached systems requires further work. V395 And, with its spectral type of B7/8:, is particularly interesting because of its orbital period of only 0.685 days. FP Boo, SW Lac, V592 Per, and TU UMi are contact binaries. Two of them, V592 Per and TU UMi, have bright tertiary companions, while FP Boo is a very small mass ratio ($q = 0.11$) contact binary. The frequently observed system SW Lac is more massive than estimated before; its broadening functions show the large surface brightness and rather compact dimensions of its secondary component, both possibly indicating that it is really a semidetached binary and not a contact system. Finally, we have been able to detect the low-mass secondary in FO Vir ($q = 0.12$); the system was probably a semidetached binary before establishing contact.

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