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Spectroscopic Orbits for Late-type Stars. II

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Abstract

We have determined spectroscopic orbital elements for 13 systems—10 single-lined binaries and three double-lined binaries. For the three binaries with previously published spectroscopic orbits, we have computed improved or comparable elements. While two systems have relatively short periods between 10 and 19 days, the remaining systems have much longer periods ranging from 604 to 9669 days. One of the single-lined systems, HD 142640, shows both short-period and long-period velocity variations and so is triple. For three systems—HD 59380, HD 160933, and HD 161163—we have combined our spectroscopic results with *Hipparcos* astrometric observations to obtain astrometric orbits. For HD 14802 we have determined a joint orbital solution from spectroscopic velocities and interferometric observations. The orbits given here will be useful in combination with future interferometric and *Gaia* satellite observations.

Key words: binaries: spectroscopic – binaries: visual – stars: fundamental parameters – stars: late-type

Supporting material: machine-readable tables

1. Introduction

The present spectroscopic determinations of binary orbits are a continuation of the work reported in Willmarth et al. (2016, hereafter referred to as Paper I). As in Paper I, most of the stars discussed here were observed in the course of the solar-type star survey of Abt & Willmarth (2006) but not discussed therein after they were determined not to be within the survey boundaries. We therefore refer the reader to Paper I for details of the motivations and methods since this work is similar in all regards. Three stars from other sources have also been included in the present paper. HD 4935 was identified as a double-lined binary during a survey of A5–F5 stars, while HD 64427 and HD 161163 were discovered to be spectroscopic binaries during the course of other investigations.

Some basic information about the 13 systems included in this paper is given in Table 1. In that table we list our measurements of $v \sin i$ values for the stars in the binaries. We have determined spectroscopic orbits for the 10 single-lined binaries and three double-lined binaries and also computed astrometric orbits for four of the systems. After presenting those results we provide brief discussions of the individual systems.

2. Observations and Velocities

The radial velocities used here are mainly from the same sources described in Paper I: Kitt Peak National Observatory (KPNO) and Fairborn Observatory (Fekel et al. 2009, 2013). Additional data from other sources were used for a few orbits and are described in Section 4 as part of the discussions of the individual systems. In the past there have been several large velocity surveys that have produced many precise radial velocities, but regrettably some of those individual velocities have remained unavailable to us despite our inquiries. Tokovinin (2014) has noted that "The large volume of precise RV data accumulated in search of exoplanets remains, for the most part, unpublished and inaccessible, with a few exceptions…." The availability of such data would be of great benefit to the study of binary stars, especially visual binaries and others of long period.

3. Orbital Analyses

3.1. Spectroscopic Orbits

We refer the interested reader to Paper I and Fekel et al. (2017) for details concerning our period and orbit determinations. The symbols that we use for the orbital elements, P, T, e, ω, K, and γ, have their customary meanings of orbital period, time of periastron, orbital eccentricity, longitude of periastron, velocity semi-amplitude, and center-of-mass velocity, respectively. We have adopted the physical constants recommended by Torres et al. (2010) to determine the related parameters $a \sin i$, the projected orbital separation, $f(m)$, the mass function, and $m \sin^3 i$, the minimum mass, which are computed from the orbital elements. Our spectroscopic elements and the related parameters of our 13 systems are presented in Table 2 for the single-lined systems and Table 3 for those that are double-lined. In those tables, the $\sigma(O-C)$ quantity is the rms of the observed minus computed velocities.

3.2. Astrometric Orbits

Following the procedure described in Pourbaix & Boffin (2003), we examined the *Hipparcos* astrometric data (Perryman & ESA 1997) for the 13 binary systems in this paper. To determine the astrometric solutions, we adopted our spectroscopic values for P, T, e, and ω and solved for the other orbital parameters, the semimajor axis of the astrometric orbit, a_0, the orbital inclination, i, and the position angle of the line of nodes, Ω. Consistency is then required between the Thiele-Innes and Campbell orbital solutions (Pourbaix 2001; Pourbaix & Arenou 2001).

In the case of our single-lined binary systems HD 64427 and HD 134323, the *Hipparcos* astrometry remains well represented by the model of a single star. For five more systems—HD 10307, HD 142640, HD 152311, HD 188376,

Table 1
Basic Properties of the Program Stars

Name	HR	HD	HIP	Spectral Type[a]	V (mag)	$B-V$ (mag)	Parallax[b] (mas)	Parallax[c] (mas)	M_V[d] (mag)	$v \sin i$[e] (km s^{-1})	Period (days)
⋯	⋯	4935	4025	F1 V	6.72	0.33	11.24	10.59	1.84	11,7 ± 1,1	10.9089
⋯	483	10307	7918	G1 V	4.96	0.62	79.09	78.50	4.43	3 ± 1	7141
κ For	695	14802	11072	G0 V	5.19	0.61	45.60	45.53	3.48	3 ± 1	9669
⋯	2866	59380	36399	F6 V	5.85[f]	0.48[f]	35.95	36.71	3.67	8 ± 1	998.4
⋯	⋯	64427	38840	K III	8.35[f]	1.61[f]	1.78	1.63	−0.59	8 ± 1	604.4
⋯	5639	134323	74121	G/K III	6.14[f]	0.98[f]	5.60	7.33	0.47	4 ± 1	2088
⋯	5927	142640	78059	F6 V	6.32[f]	0.47[f]	15.64	16.18	2.36	8 ± 1	19.024[g]
⋯	6269	152311	82621	G2 IV–V	5.86[f]	0.69[f]	35.73	37.12	3.71	4 ± 1	2713
⋯	6598	160933	86184	F9 IV–V	6.42	0.58	23.53	21.89	3.12	4 ± 1	2222
⋯	⋯	161163	86642	G0 V	7.29[f]	0.63[f]	24.06	24.73	4.26	5,6 ± 1,2	2233
ω Sgr	7597	188376	98066	G5 IV	4.70	0.75	42.03	38.48	2.63	3 ± 1	1712.7
⋯	7902	196815	102032	G0/1 V	6.50[f]	0.59[f]	8.64	9.33	1.35	8,13 ± 1,3	2170
⋯	9107	225239	394	G2 V	6.11	0.63	27.18	25.52	3.14	2 ± 1	700.6

Notes.
[a] The reference for the listed spectral type is given in the discussion of each star in Section 4.
[b] Original *Hipparcos* parallax of Perryman & ESA (1997).
[c] Revised *Hipparcos* parallax of van Leeuwen (2007).
[d] Absolute magnitude computed with the parallax of van Leeuwen (2007).
[e] Determined from rotational broadening fits to the lines in the Fairborn Observatory spectra. If the star is a double-lined binary, the value for the secondary follows that of the primary.
[f] Values from Høg et al. (2000) as listed in SIMBAD; the rest are from SIMBAD.
[g] Radial velocities also show a change in velocity over a long period, estimated at 8500 days.

and HD 225239—although our new astrometric solution, which is constrained by our spectroscopic elements, yields an improved fit to the *Hipparcos* measurements, the new solution is poorly constrained by the spectroscopic results, and the reduction of χ^2 is not large enough to clearly favor our new solution. However, in the cases of HD 59380 and HD 160933, when we adopt our spectroscopic orbit values for P, T, e, and ω and solve for the other orbital parameters, a_0, i, and Ω, we obtain significantly improved elements. The resulting parallax and proper-motion components are then also examined.

For the single-lined system HD 14802, which is our binary with the longest period, the fit of the astrometric data with our spectroscopic binary elements is not significantly better than the original acceleration solution. However, the Fourth Catalog of Interferometric Measurements of Binary Stars (INT4) (see Hartkopf et al. 2001) lists a number of resolved speckle observations of this system. Thus, we obtained a simultaneous solution of the spectroscopic and speckle observations.

We similarly used our spectroscopic results in combination with the *Hipparcos* astrometric data and analyzed our three double-lined binary systems. In the case where the magnitude difference between components is not very large, there will be little shift in the photocenter and no orbital motion will be detected, as was the case for HD 4935. We also found no useful solution for HD 196815, which is one of our three most distant systems (Table 1). However, for HD 161163 we were able to obtain an improved solution.

Our results for HD 14802, HD 59380, HD 160933, and HD 161163 are discussed in the sections for those individual stars. The additional astrometric elements of the latter three stars are summarized in Table 4 while the solution of the spectroscopic and speckle observations for HD 14802 is given in Table 5.

4. Observational History and Results

A brief discussion of the individual stars follows with the final spectroscopic orbital elements for each system listed in either Table 2 or Table 3. In Table 2 previously published orbital elements for three of the systems—HD 10307, HD 14802, and HD 134323—are listed for comparison. The radial velocity observations used to compute the orbits for all stars except the triple system HD 142640 are tabulated in Table 6. Given in that table are the star name, heliocentric Julian date of mid-observation, orbital phase, radial velocity, observation weight (Wt), observed minus computed velocity, and source of the observation. Table 7 lists the observed and calculated velocities of HD 142640. In that table we list the heliocentric Julian date of mid-observation, the observed radial velocity, the observed minus computed residual for the combined fit of the two orbits, the long-period orbital phase, the computed long-period velocity, the short-period orbital phase, the computed short-period velocity, and source of the observation. In Figure 1 we have compared the velocities used to determine our spectroscopic orbits with the computed orbital curves.

4.1. HD 4935 = HIP 4025

HD 4935 is the brighter component of the visual binary ADS 702 AB = WDS J00516+1247. The B component has a separation of 5.″2 and a V magnitude of 12.8, which is about 6 mag fainter than the primary. The double-lined nature of HD 4935 was first noticed with our acquisition of a spectrum in 1988. From classification resolution spectra, Abt (2004) gave it an MK spectral type of F1 V. Shain (1951) reported the earliest known radial velocities but only provided an average of three observations and did not note the double-lined nature of the system. It appears that this first average radial velocity measurement is the only value previously published and is

Table 2
Orbital Elements for Single-lined Spectroscopic Binaries

HD	P (days)	T (HJD)[a]	e	ω (deg)	K (km s^{-1})	γ (km s^{-1})	$\sigma(O-C)$ (km s^{-1})	$a_1 \sin i$ (10^6 km)	$f(m)$ ($M_\odot$)
10307	7140.8	57677	0.4474	209.6	2.710	3.300	0.13	238.0	0.01054
	7.7	13	0.0051	1.0	0.018	0.013	…	1.7	0.00023
10307[b]	7122	43363	0.42	210.8	2.81	3.12	0.23	250	0.0123
	fixed	fixed	fixed	3.5	0.25	0.13	…	22	0.0033
10307[c]	6744	36381	0.34	193	2.52	3.25	…	219.8	0.0932
	33	125	0.04	6	0.16	0.10	…	…	…
14802	9669	56881	0.3293	262.4	5.454	16.834	0.03	684.7	0.1368
	111	18	0.0041	1.0	0.041	0.063	…	9.4	0.0035
14802[d]	7700	54466	0.0576	269.07	2.302	…	0.01424	1272	0.0097
	295	…	…	…	…	…	…	…	0.0032
14802[c]	7839	39587	0.30	263	3.95	18.13	…	406.17	0.04354
	32	684	0.04	12	0.26	0.66	…	…	…
14802[e]	25.81 (yr)	1988.89[f]	0.339	266.3	5.23	16.67	…	…	…
	0.15	0.17	0.013	1.0	0.13	0.06	…	…	…
59380	998.43	56077.4	0.5547	358.8	2.960	4.401	0.15	33.81	0.015453
	0.64	1.7	0.0071	1.2	0.020	0.019	…	0.30	0.000041
64427	604.42	56947	0.0488	261.2	6.597	8.112	0.26	54.77	0.01792
	0.88	12	0.0066	7.1	0.039	0.028	…	0.33	0.00032
134323	2088.3	56967	0.442	109.0	2.736	−47.312	0.17	70.5	0.00320
	9.9	11	0.012	2.0	0.040	0.021	…	1.2	0.00016
134323[b]	2059	46713	0.46	124.3	2.53	−47.94	0.24	63.5	0.00238
	22	45	0.04	7.6	0.20	0.07	…	7.4	0.00083
142640 Aa	19.023593	56452.4347	0.5786	312.51	9.565	…	0.22	20.0409	0.0009360
	0.000039	0.0072	0.0019	0.28	0.029	…	…	0.0071	0.0000098
142640 A	8500	50389	0.110	290	2.024	−2.911	0.16	235.09	0.0072
	fixed	256	0.043	13	0.052	0.034	…	28	0.0012
152311	2712.8	57056	0.239	223.6	3.556	−21.579	0.27	128.8	0.01158
	9.3	23	0.014	3.2	0.054	0.035	…	2.1	0.00055
160933	2222.4	56906	0.310	280.6	2.188	−55.035	0.18	63.6	0.002072
	4.3	14	0.012	2.5	0.029	0.020	…	0.90	0.000088
188376	1712.74	57549.31	0.8200	141.47	12.255	−19.332	0.08	165.22	0.06127
	0.29	0.20	0.0012	0.33	0.041	0.022	…	0.76	0.00084
225239	700.60	57696.63	0.7582	325.93	3.529	4.752	0.11	22.17	0.00084
	0.12	0.20	0.0020	0.44	0.017	0.012	…	0.13	0.000016

Notes.
[a] HJD = heliocentric Julian date − 2400000.
[b] Duquennoy & Mayor (1991).
[c] Abt & Willmarth (2006).
[d] Endl et al. (2002).
[e] Tokovinin (2013).
[f] Besselian years.

referenced elsewhere in the literature, for instance in the General Catalogue of Stellar Radial Velocities (Wilson 1953) and by Nordström et al. (2004).

With the addition of HD 4935 to the Fairborn Observatory observing list in 2016 December, sufficient data were soon obtained that allowed the determination of its 10.9089 day period. The Aa and Ab components have a mass ratio $M_{\mathrm{Aa}}/M_{\mathrm{Ab}} = 1.136 \pm 0.005$.

The ratio of equivalent widths of the two components, Aa/Ab, is 1.49, corresponding to a magnitude difference of 0.45 mag at about 6000 Å. This suggests spectral types of F0 V and F3 V for the primary and secondary components, respectively.

4.2. HD 10307 = HR 483 = HIP 7918

HD 10307 is the brighter component of the astrometric binary WDS J014148.08+4237AB. Keenan & McNeil (1989) and Gray et al. (2003) have both classified it as G1 V. From plates obtained with the Sproul 61 cm refractor, a photocentric orbit was calculated by Lippincott et al. (1983) with a period of 19.50 yr

Table 3
Orbital Elements for Double-lined Spectroscopic Binaries

HD	P (days)	T (HJD)[a]	e	ω (deg)	K (km s^{-1})	γ (km s^{-1})	$\sigma(O-C)$ (km s^{-1})	$a \sin i$ (10^6 km)	$m \sin^3 i$ ($M_\odot$)
4935 Aa	10.9088993	56663.6523	0.3021	279.71	49.576	1.652	0.34	7.089	0.620
	0.0000067	0.0067	0.0010	0.28	0.086	0.045	…	0.012	0.003
4935 Ab	…	…	…	…	56.32	…	0.38	8.054	0.546
	…	…	…	…	0.16	…	…	0.023	0.002
161163 Aa	2232.6	54635.3	0.2631	52.6	8.614	−44.284	0.21	255.2	0.921
	4.1	7.4	0.0057	1.3	0.036	0.039	…	1.2	0.017
161163 Ab	…	…	…	…	11.24	…	0.58	333.0	0.706
	…	…	…	…	0.13	…	…	3.8	0.010
196815 A	2169.6	56316	0.2284	155.4	11.446	−2.796	0.38	332.4	2.11
	2.9	12	0.0096	2.3	0.070	0.076	…	2.2	0.14
196815 B	…	…	…	…	14.77	…	0.91	429	1.632
	…	…	…	…	0.65	…	…	19	0.082

Note.
[a] HJD = heliocentric Julian date − 2400000.

Table 4
Additional Orbital Elements from Astrometric Solutions

HD	a_0[a] (mas)	i (deg)	Ω (deg)	m_1 ($M_\odot$)	m_2 ($M_\odot$)
59380	16.88	148.8	101.4	1.3[b]	0.7[c]
	0.06	1.1	2.2		
160933	19.7	30.0	169.7	1.3[b]	0.3[c]
	1.5	2.4	3.7		
161163	30.5	105.4	17.5	1.0	0.79
	1.2	4.7	3.8		

Notes.
[a] a_0 is the semimajor axis of the absolute photocentric orbit. For a single-lined spectroscopic binary it corresponds to a_1, the semimajor axis of the primary. However, for a double-lined binary those two parameters are not equivalent because the photocentric motion will be reduced as a result of light coming from the secondary.
[b] Primary mass estimation is given in the discussion of each star in Section 4.
[c] Secondary mass based on assumed primary mass and orbital elements.

Table 5
Combined Spectroscopic and Interferometric Solution for HD 14802

Parameter	Value
P (yr)	26.54 ± 0.047
T (Julian yr)	2014.597 ± 0.001
e	0.3294 ± 0.0011
a (mas)	534.4 ± 2.5
i (deg)	50.59 ± 0.48
ω_B (deg)	82.35 ± 0.14
Ω (deg)	319.68 ± 0.25
K (km s^{-1})	5.4640 ± 0.0058
γ (km s^{-1})	16.860 ± 0.010

(7122 days). Combined with the detection of the secondary with infrared speckle measurements, Lippincott et al. (1983) determined masses of the primary and secondary of $1.44 \pm 0.35\,M_\odot$ and $0.38 \pm 0.07\,M_\odot$ respectively. Further measurements by Henry & McCarthy (1993) produced a determination of the absolute magnitude of the secondary as $M_V = 11.8$ and a magnitude difference, ΔV, of 7.5. With a new parallax value, they determined component masses of 0.933 ± 0.231 and $0.280 \pm 0.071\,M_\odot$. Recently, Miles & Mason (2017) published a visual orbit from seven interferometric observations and determined a period of 18.12 yr (6618 days) and an eccentricity of 0.434.

HD 10307 was included in the radial velocity survey of Duquennoy & Mayor (1991), but because of its long period, they assumed the values of P, T, and e from Lippincott et al. (1983), and derived the other orbital parameters from their shorter time span of velocities. The survey of Nordström et al. (2004) also included HD 10307 with some 31 radial velocities obtained over a period of 7040 days, which would have included the entire orbital period, but we have been unable to access those individual velocities. Abt & Willmarth (2006) included the velocities of Duquennoy & Mayor (1991), Campbell & Moore (1928), and Beavers & Eitter (1986), along with their own measurements and derived an orbit with a period of 6744 days.

The present work includes radial velocities from the past 13 years, mainly from Fairborn Observatory by the first author (FF) as described in Paper I, a few velocities from the second author (DW) (open circles, Figure 1), who used KPNO spectrographs, also described in Paper I, velocities from the aforementioned work of Duquennoy & Mayor (1991) (pluses, Figure 1) and Abt & Willmarth (2006), plus four additional KPNO velocities to compute what we believe is the first orbit based only on radial velocities. While two radial velocities from DAO (Wright 1951) were included initially, their large errors precluded using them in the final orbit. These elements are presented in Table 2 along with the earlier spectroscopic orbits described above. The derived period of 7141 ± 8 days appears to agree well with the earliest astrometric orbit by Lippincott et al. (1983).

If we adopt our period of 19.56 yr, the semimajor axis of 0$''$.63 from Miles & Mason (2017), and the revised *Hipparcos* parallax of 78.50 mas from van Leeuwen (2007), then from Kepler's third law the sum of the masses is 1.35 $M_\odot$. Adopting a mass for the primary of 1.1 $M_\odot$ from its spectral type and an inclination of 98°.8 from Miles & Mason (2017), we find the mass of the secondary is 0.27 $M_\odot$ and thus the total mass of the binary is 1.37 $M_\odot$, which is in excellent agreement with

Table 6
Radial Velocities of Program Stars

HD	HJD[a]	Orbital Phase	RV (km s^{-1})	Wt	$(O-C)$ (km s^{-1})	Source[b]
4935 Aa	47430.8436	0.6446	−27.90	1.00	−0.13	KPNO(DW)
4935 Aa	47468.7769	0.1219	54.00	1.00	0.46	KPNO(DW)
4935 Aa	48209.6858	0.0397	34.40	1.00	0.29	KPNO(DW)
4935 Aa	48861.8918	0.8263	−45.40	1.00	−0.03	KPNO(DW)
4935 Aa	54408.7416	0.2964	33.06	1.00	0.49	KPNO(DW)
4935 Aa	54456.6701	0.6899	−34.26	1.00	0.02	KPNO(DW)
4935 Aa	54457.6666	0.7812	−43.77	1.00	0.27	KPNO(DW)
4935 Aa	54458.6172	0.8684	−42.35	1.00	0.05	KPNO(DW)
4935 Aa	54462.6306	0.2363	42.60	1.00	−0.46	KPNO(DW)
4935 Aa	56664.6438	0.0910	50.58	1.00	0.22	KPNO(DW)
4935 Aa	57766.7181	0.1162	53.20	1.00	−0.06	Fair(FF)
4935 Aa	57772.6311	0.6583	−29.83	1.00	−0.03	Fair(FF)
4935 Aa	57776.6160	0.0236	26.43	1.00	0.39	Fair(FF)
4935 Aa	57779.6341	0.3002	32.24	1.00	0.37	Fair(FF)
4935 Aa	57783.6724	0.6704	−32.20	1.00	−0.64	Fair(FF)

Notes.
[a] HJD = heliocentric Julian date − 2400000.
[b] KPNO = Kitt Peak National Observatory, Fair = Fairborn Observatory, And = Andersen et al. (1985), AW = H. Abt and D. Willmarth, DMH = Duquennoy et al. (1991), DW = D. Willmarth, FF = F. Fekel, JM = Jasniewicz & Mayor (1988), Lick = Campbell & Moore (1928), Nid = Nidever et al. (2002), Zech = Zechmeister et al. (2013).

(This table is available in its entirety in machine-readable form.)

the result from Kepler's third law. The secondary is thus an M dwarf.

4.3. HD 14802 = κ For = HR 695 = HIP 11072

This relatively bright, southern, solar-type star was classified as G0 V by both Keenan & McNeil (1989) and Gray et al. (2006). In a survey of X-ray-bright solar-type stars, Guedel et al. (1995) detected microwave radiation from a source 0″.23 south of HD 14802. They also noted that three unpublished CORAVEL velocities indicated that the star's velocity varies. Support for its binary status came from *Hipparcos* survey results (Perryman & ESA 1997) because HD 14802 received a "G" multiplicity flag, which indicates that higher-order terms were needed to obtain an adequate astrometric solution. Later, Gontcharov et al. (2000) determined a period of about 25 yr from the nonlinear motion of the photocenter in the *Hipparcos* astrometric data and measurements from other proper-motion catalogs. Precise radial velocities were measured by Nidever et al. (2002) (open box, Figure 1) and Endl et al. (2002) (open triangles, Figure 1), with a preliminary orbital period of 7700 days or 21.1 yr determined by the latter group. Abt & Willmarth (2006) also measured radial velocities; combined with the earlier data, they determined a period of 21.46 yr although a complete orbit had not yet been covered. More recently, Zechmeister et al. (2013) (open triangles, Figure 1) published a continuation of the work described in Endl et al. (2002) that confirmed that the period given in the latter paper was too short since the radial velocity continued a monotonic decline. They estimated a poorly constrained orbital period of 29.3 yr. In the same year, Tokovinin (2013) incorporated previous astrometric and spectroscopic data along with his own radial velocity and speckle measurements and computed a combined orbital solution that resulted in a period of 25.8 yr. After attempting to subtract the primary from his spectra, Tokovinin (2013) obtained correlations of the residual spectra that suggested that the secondary is a low-mass double-lined binary with a period of about 3.7 days. His paper also gives a comprehensive historical discussion of HD 14802.

The present work uses all of the radial velocities listed above except for the eight velocities from Tokovinin (2013) that overlap with our own data. Additional velocities, mainly from Fairborn Observatory, were used to compute an orbit with complete orbital coverage and a period of 9669 ± 111 days or 26.5 ± 0.3 yr. Our orbital elements are similar to those of Tokovinin (2013) although our errors are smaller.

Tokovinin (2013) used seven speckle observations in his joint orbital solution, but an increased number of observations, which now trace the orbital motion through periastron, are available in INT4 (see Hartkopf et al. 2001). Thus, we computed a new simultaneous solution with the radial velocities used in our new spectroscopic orbit and the resolved speckle observations listed in the interferometry catalog. The latter observations are listed in Table 8. The resulting orbital solution is given in Table 5, and the visual orbit shown in Figure 2.

As noted earlier, HD 14802 is a solar-type star with a spectral type of G0 V. Our result for the value of the mass function, 0.137 ± 0.004 $M_\odot$ (Table 2), is very large. Thus, if the secondary were a single star, we would expect to see evidence of its lines in our spectra (e.g., Stockton & Fekel 1992), especially near maximum velocity separation. Thus, we agree with the conclusion of Tokovinin (2013) that the secondary is actually a pair of low-mass stars.

4.4. HD 59380 = HR 2866 = HIP 36399

Both Houk & Swift (1999) and Gray et al. (2006) have classified HD 59380 as an F6 V star. Its radial velocity appears to have been first measured at Mount Wilson Observatory on three separate dates with velocity values ranging from 5.7 to 12.0 km s^{-1} as tabulated by Abt (1970), although the last value was obtained with much lower resolution. These measurements

Table 7
Observed and Calculated Radial Velocities of HD 142640 A,Aa

HJD[a]	Observed RV (km s^{-1})	$(O-C)$[b] (km s^{-1})	Orbital Phase $P_{\rm long}$	RV $P_{\rm long}$[c] (km s^{-1})	Orbital Phase $P_{\rm short}$	RV $P_{\rm short}$[d] (km s^{-1})	Source[e]
51960.0261	−6.38	0.14	0.1848	−0.69	0.8507	−5.55	KPNO(AW)
51981.9730	10.31	0.12	0.1874	−0.72	0.0043	11.15	KPNO(AW)
51983.9654	7.69	0.04	0.1876	−0.80	0.1091	8.53	KPNO(AW)
52073.7717	−6.85	−0.17	0.1982	−1.04	0.8299	−5.98	KPNO(AW)
52074.7734	−6.00	0.05	0.1983	−0.82	0.8825	−5.13	KPNO(AW)
52075.7654	−3.32	−0.13	0.1984	−1.00	0.9347	−2.45	KPNO(AW)
52076.7755	6.62	0.08	0.1985	−0.79	0.9878	7.49	KPNO(AW)
52118.6801	3.41	−0.03	0.2035	−0.92	0.1905	4.30	KPNO(AW)
52350.0232	−1.25	−0.06	0.2307	−1.07	0.3514	−0.24	KPNO(AW)
52371.9599	−3.85	−0.03	0.2333	−1.06	0.5045	−2.82	KPNO(AW)
52372.9529	−4.70	−0.17	0.2334	−1.19	0.5567	−3.67	KPNO(AW)
52373.9722	−5.37	−0.17	0.2335	−1.20	0.6103	−4.34	KPNO(AW)
52402.8732	6.36	0.17	0.2369	−0.88	0.1295	7.41	KPNO(AW)
52404.8898	1.85	0.16	0.2371	−0.89	0.2355	2.90	KPNO(AW)
55551.0524	−8.85	−0.17	0.6073	−4.59	0.6177	−4.43	Fair(FF)
55574.9804	−9.71	0.07	0.6101	−4.37	0.8755	−5.27	Fair(FF)
55588.0399	−8.04	−0.02	0.6116	−4.47	0.5620	−3.59	Fair(FF)
55604.9094	−6.32	0.09	0.6136	−4.38	0.4487	−1.86	Fair(FF)
55618.9055	0.30	0.20	0.6152	−4.28	0.1845	4.77	Fair(FF)
55631.0161	−10.32	−0.01	0.6167	−4.50	0.8211	−5.84	Fair(FF)

Notes.
[a] HJD = heliocentric Julian date − 2400000.
[b] Observed velocity minus computed combined velocity of the two orbits.
[c] Long-period radial velocity is the observed velocity minus the computed velocity of the short-period orbit.
[d] Short-period radial velocity is the observed velocity minus the computed center-of-mass velocity of the long-period orbit.
[e] KPNO = Kitt Peak National Observatory, Fair = Fairborn Observatory, AW = H. Abt and D. Willmarth, DW = D. Willmarth, FF = F. Fekel.

(This table is available in its entirety in machine-readable form.)

gave little reason to suspect that the star is a binary. A speckle observation by McAlister et al. (1993) did not reveal a companion nor have any subsequent speckle observations. However, the star did receive an "X" multiplicity flag from the *Hipparcos* survey, which indicates that their astrometric measures had excess scatter of unknown origin. Goldin & Makarov (2006) undertook fitting unconstrained Kepler orbits to such stars with *Hipparcos* stochastic solutions and derived 65 orbits, including one for HD 59380. The orbits for those stars were further refined in Goldin & Makarov (2007), where the period for HD 59380 was determined to be 1001± 26 days.

Our own investigation of HD 59380 began with spectroscopy in 1987 as reported in Abt & Willmarth (1992) although those velocities have not been published until now. Abt & Willmarth (2006) undertook another series of observations, but they also were not reported therein because the star was determined to be outside the survey boundaries. All of these radial velocities along with those from Fairborn Observatory are included in the present orbit determination. The latter include critical phases at the nodal points. We have not used the two earlier velocities from Mount Wilson that were obtained with higher resolution than the third observation because, even though they improve the errors in the period and time of periastron slightly, the errors of the other elements are increased. The independently determined astrometric period of 1001 days (Goldin & Makarov 2007) is in good accord with our much more precise value of 998.4 ± 0.6 days.

As indicated by the results of Goldin & Makarov (2007), the astrometric signature of the spectroscopic orbit in the *Hipparcos* data for HD 59380 (HIP 36399) is crystal clear, and our new analysis produces $a_0 = 16.88 \pm 0.06$ mas, $i = 148\overset{\circ}{.}8 \pm 1\overset{\circ}{.}1$, and $\Omega = 101\overset{\circ}{.}4 \pm 2\overset{\circ}{.}2$. With respect to the original stochastic solution, the parallax and proper motion are substantially revised, yielding a parallax of 38.63 ± 0.83 mas and proper-motion components of $\mu_\alpha \cos\delta = 59.57 \pm 0.86$ mas yr^{-1} and $\mu_\delta = 130.52 \pm 0.51$ mas yr^{-1}, which are in excellent agreement with the proper motions from Tycho-2 (Høg et al. 2000).

From the F6 V spectral type we adopt a mass of 1.3 $M_\odot$ for the primary of HD 59380. This value used with the mass function from Table 2 and inclination from the astrometric orbit (Table 4) results in a mass of 0.69 $M_\odot$ for the secondary, making it a K dwarf.

4.5. HD 64427 = HIP 38840

HD 64427 has garnered very little attention because there are only four references listed in SIMBAD's bibliographic survey since 1850, and there is no modern classification of its spectral type or measurement of its radial velocity. Its V and $B-V$ values are 8.38 and 1.603 mag, respectively (Perryman & ESA 1997). The revised *Hipparcos* parallax of van Leeuwen (2007) is 1.63 ± 1.00 mas. Our spectra show that it is a K giant. Given its small parallax, its $B-V$ color is likely significantly reddened.

Our observations of this binary are serendipitous because the star was mistakenly placed on our Fairborn observing list at the end of 2013, and shortly afterward it showed velocity variability. As a result, we continued to observe the star and we present its elements here. We find an orbital period of 604.4 ± 0.9 days and an eccentricity of 0.05, which is unusually small for such a long orbital period. The low eccentricity and long period of HD 64427 are orbital characteristics similar to those of barium stars (e.g., Boffin et al. 1993), which are stars that are believed to

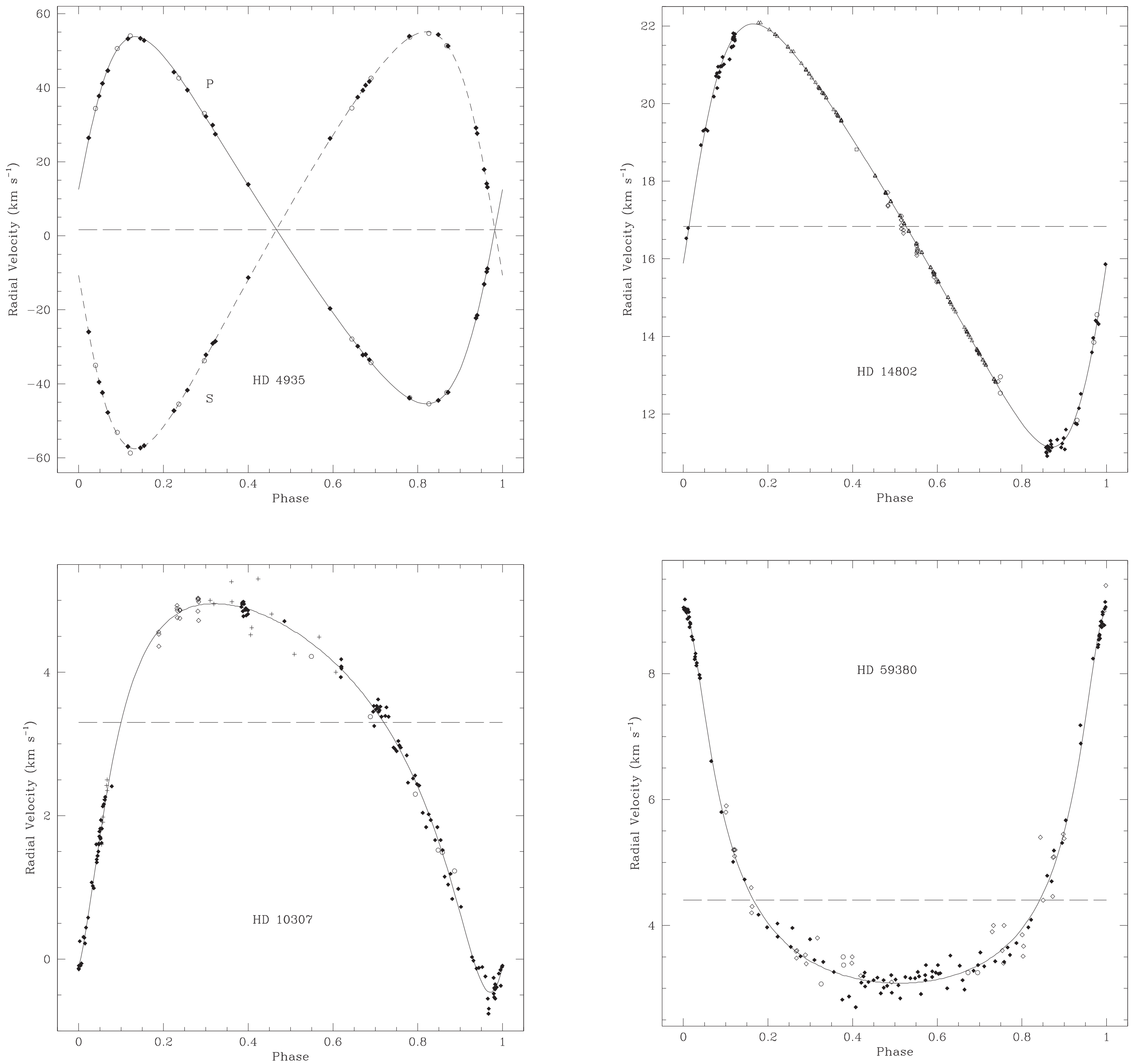

Figure 1. Radial velocities—filled diamonds from Fairborn Observatory (FF), open diamonds from KPNO (AW)—compared with the computed velocity curve (solid line) for each of the 13 systems. When velocities from other sources are used, the symbols for those velocities are identified in the text of Section 4 for the appropriate star. The horizontal dashed line in each plot is the center-of-mass velocity. For double-lined systems, P = primary and S = secondary.

have acquired peculiar abundances because of mass transfer from what is now a white dwarf companion. The somewhat larger than usual residuals as indicated by the rms of a single velocity, σ (Table 2), may be the result of pulsation (e.g., Henry et al. 2000).

4.6. HD 134323 = HR 5639 = HIP 74121

HD 134323 is listed with a G6 V classification in the Bright Star Catalogue (Hoffleit & Jaschek 1982). However, Heintz (1986) states "The classification G6 V is erroneous." Heintz (1986) also derived a parallax of 13 mas compared to the revised *Hipparcos* value of 7.33 ± 0.50 mas (Table 1). The absolute *V* magnitude (Table 1) from that parallax indicates that HD 134323 is a giant, and from our spectra we find that it is a late-G or early-K giant.

By 1939 some 12 radial velocities of HD 134323 had been published, although the three papers describing those data only listed the average velocity from each of their respective observations. Beavers & Eitter (1986) published a series of 18 radial velocity observations over 769 days, which, when plotted, show an upward trend of about 2 km s^{-1}, but the rms about the curve is also 2 km s^{-1}, and therefore those velocities do not lead to any degree of certainty about the reality of the variations.

Duquennoy & Mayor (1991) also noted the discrepancy in spectral type, stating that "the photoelectric colours do not support the classification as a dwarf." While they did not include

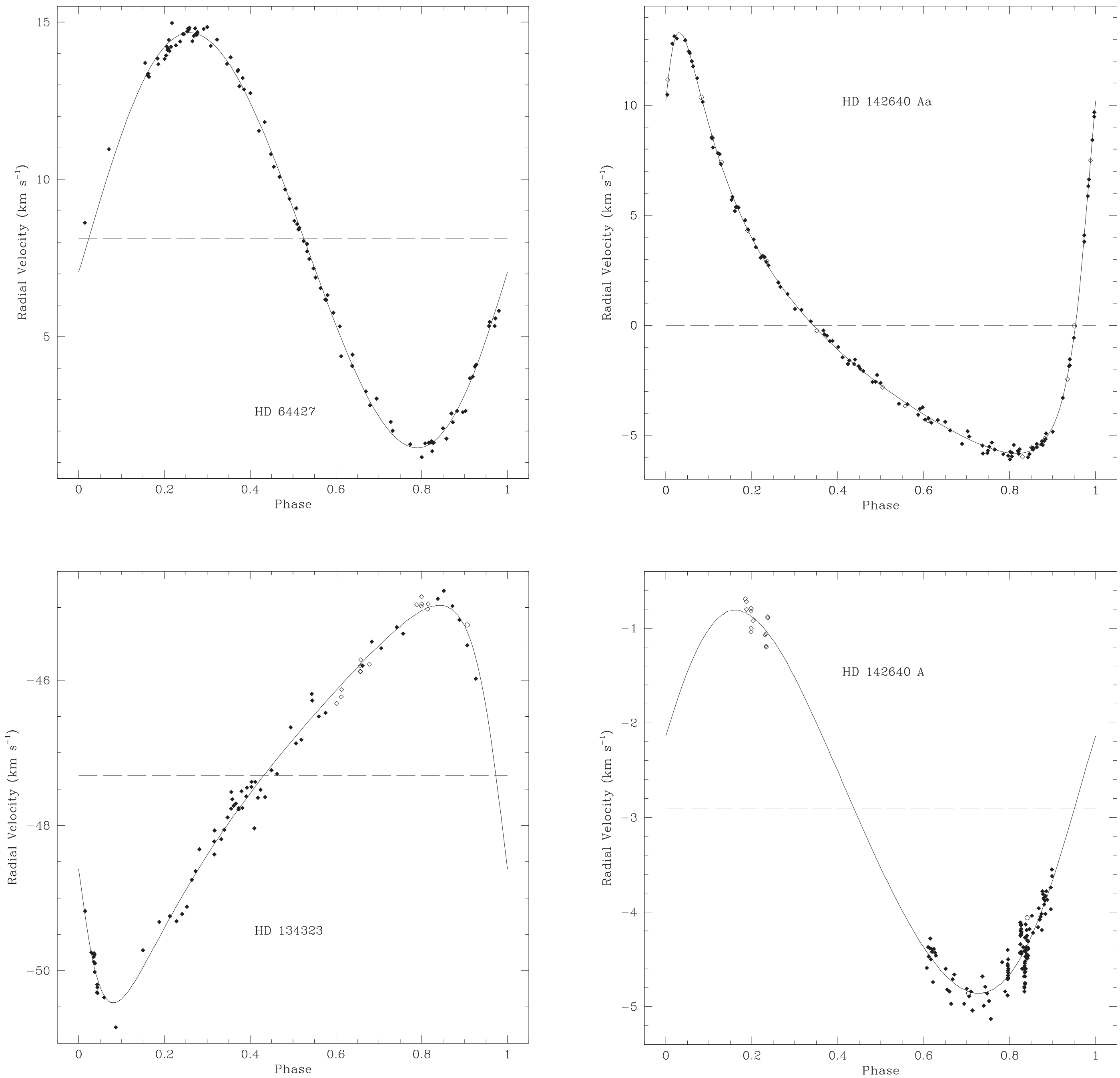

Figure 1. (Continued.)

it in the statistical analysis of their survey, they did calculate an orbit with a period of 2059 days. HD 134323 was observed in the survey of Abt & Willmarth (2006) as well but was also excluded from that paper because it was outside the bounds of the survey parameters. The present work initially included the radial velocities (Duquennoy et al. 1991) used in the orbit by Duquennoy & Mayor (1991), radial velocities obtained during the survey by Abt & Willmarth (2006), and radial velocities from Fairborn Observatory to derive an orbit with a period equal to that of Duquennoy & Mayor (1991) within the errors. It was apparent, though, that the $(O - C)$ residuals for the data from Duquennoy et al. (1991) were mostly negative despite our adding a correction of $+0.3\ \mathrm{km\ s^{-1}}$. This value had been determined during the survey of Abt & Willmarth (2006) by comparing radial velocities of constant-velocity stars common to both surveys. An orbit determined with the weights of the data of Duquennoy et al. (1991) set to 0.0 indicated an average $(O - C) = -0.74\ \mathrm{km\ s^{-1}}$ with respect to our data. Duquennoy et al. (1991) infer that corrections have been made to their velocities: "The corrections applied are generally less than $0.4\ \mathrm{km\ s^{-1}}$, but can reach $1.4\ \mathrm{km\ s^{-1}}$ for a star with $(B - V) = 1.0$." Because of this uncertainty and finding the errors of the orbital elements to be smaller (except for the period) without the data of Duquennoy et al. (1991), our final orbit uses only our data. We also note that we did not include the aforementioned data of Beavers & Eitter (1986) since their lower precision

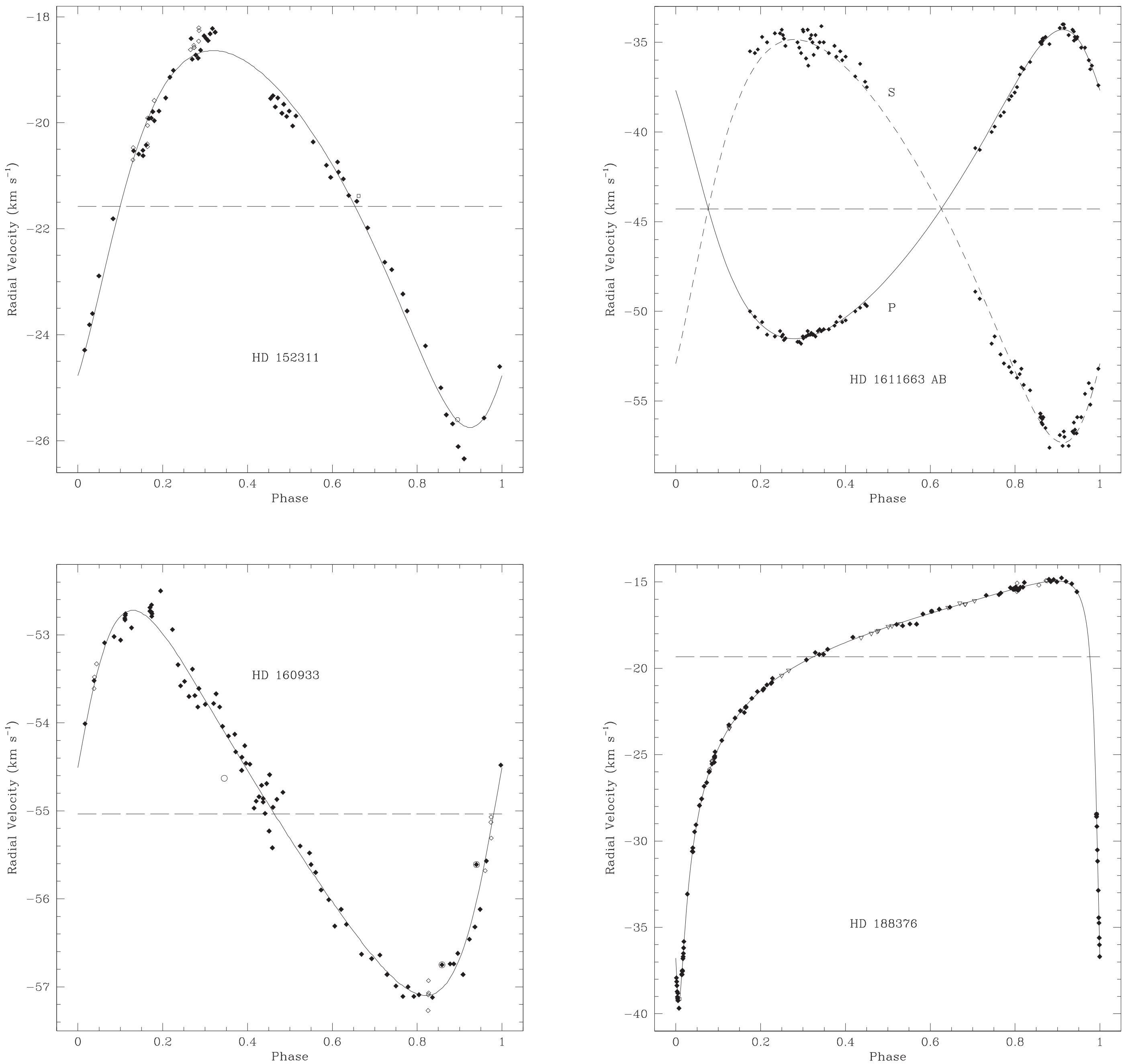

Figure 1. (Continued.)

increased the errors by a large factor. Our orbital period of 2088 ± 10 days is in good agreement with the value of 2059 days found by Duquennoy & Mayor (1991).

4.7. HD 142640 = HR 5927 = HIP 78059

Houk & Smith-Moore (1988) classified HD 142640 as an F6 V star, which is consistent with its $b - y$ color (Gronbech & Olsen 1976). HD 142640 has been little observed spectroscopically, with the only early work indicating an average radial velocity of -7 km s^{-1} and that its velocity is variable (Wilson & Joy 1950). The four individual velocities were later listed by Abt (1970). Holmberg et al. (2007) determined a mean radial velocity of 8.0 km s^{-1} from two observations over 646 days, and indicated a 0.0 probability of a constant radial velocity. HD 142640 was included in the velocity survey of Abt & Willmarth (2006) but was not discussed in that work after it was determined to be outside the sample criteria. It soon became obvious, though, that it is a short-period single-lined binary and a period of 19.024 days was derived but not published. It was subsequently added to the observing list at Fairborn Observatory as another of the "leftover" stars from the survey of Abt & Willmarth (2006).

As more observations from Fairborn Observatory became available, it soon became apparent that the new velocities did not fit well the orbit of the earlier data from the survey of Abt & Willmarth (2006). While the newer velocities produced an orbit with almost identical parameters to the one obtained from the data of Abt & Willmarth (2006), the systemic velocity of the preliminary Fairborn orbit was shifted by approximately

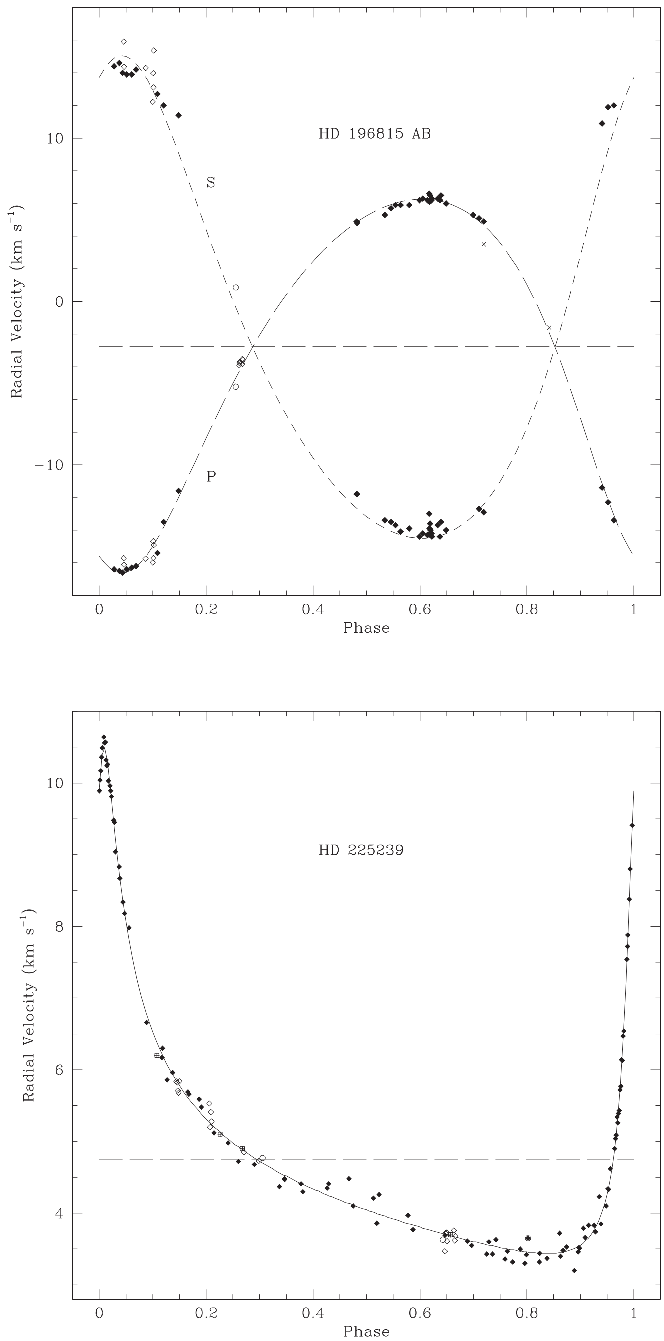

Figure 1. (Continued.)

$-3.6\,\mathrm{km\,s^{-1}}$. With the long time baseline between the data of Abt & Willmarth (2006) and the numerous radial velocities from Fairborn Observatory, we were able to determine orbits from data grouped in time intervals and found a smooth progression of the systemic velocity with time. While our time interval is not long enough to cover a complete cycle of the long-term velocity variation, those systemic changes in velocity appear to indicate a period of around 8500 days. With the aid of the general least-squares program of Daniels (1966) that solves for two orbits simultaneously, a range of periods from 6500 to 10,000 days was tried for the long-period orbit. For periods between 7500 and 10,000 days, the standard deviations of the orbits were at a minimum and changed little, leading us to adopt as a preliminary solution a long-period orbit having a period of 8500 days. While

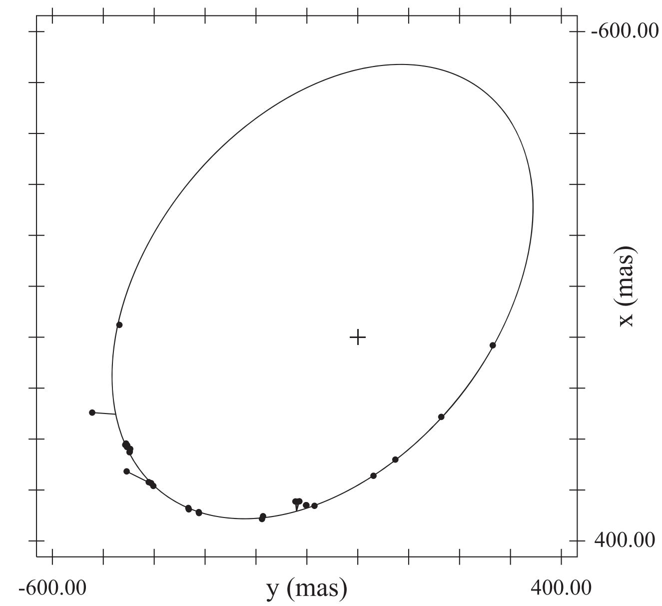

Figure 2. The relative visual orbit of HD 14802 (solid line) computed from the combined spectroscopic and speckle interferometric observations. Short lines connect the interferometric observations to their predicted positions. The orbital period is 26.54 yr and the motion is counterclockwise. North is down and east is to the right in the plot. The typical uncertainty of the position angle θ is 1°15 and that of the separation ρ is 0$''$0104.

Table 8
Speckle Observations of HD 14802

Date	θ (deg)	ρ (arcsec)
2005.6348	267.1	0.469
2007.8130	285.9	0.5424
2008.5407	294.7	0.5009
2008.5406	294.9	0.5034
2008.6061	295.5	0.5021
2008.6061	295.2	0.5003
2008.6061	295.2	0.5013
2008.6996	296.2	0.498
2008.7674	296.8	0.5021
2008.7674	296.7	0.5011
2009.6709	305.3	0.4969
2009.6709	304.8	0.4997
2009.7534	300.2	0.525
2009.7558	306.1	0.4966
2010.7174	315.6	0.4737
2010.7174	315.3	0.4725
2010.9655	317.8	0.4643
2010.9655	318	0.4653
2012.0989	332.3	0.4035
2012.0989	332.2	0.3977
2012.6706	340.5	0.342
2012.6706	339.3	0.345
2012.6706	339.9	0.344
2012.8300	343	0.345
2012.8300	343	0.3452
2012.8300	343.1	0.345
2012.9233	345.7	0.3418
2013.7477	6.6	0.2738
2014.0428	17.2	0.2513
2014.7634	46.5	0.2267
2015.7383	86.7	0.2657

the velocities in the long-period orbit have reached their minimum, it will require a number of years before the long-period orbit is well determined.

In Figure 1, each plotted velocity for the short-period orbit is the observed velocity minus its computed center-of-mass velocity in the long-period orbit. For the long-period orbit each plotted velocity is the observed velocity minus its calculated velocity in the short-period orbit.

4.8. HD 152311 = HR 6269 = HIP 82621

Houk & Smith-Moore (1988) classified HD 152311 as G5 IV, while Gray et al. (2006) gave it a slightly earlier spectral type of G2 IV–V. As with HD 142640, the earliest radial velocity measurements appear to have been published by Wilson & Joy (1950), who listed an average velocity of -17.2 ± 1.3 (p.e.) km s^{-1} from three spectra. Once again, Abt (1973) listed the individual velocities. Beavers & Eitter (1986) measured a series of 18 radial velocities that span 783 days, but no obvious trend in velocity is evident due to the relatively low velocity precision ($\sigma = 1.6$ km s^{-1}).

The first significant evidence that HD 152311 might be a long-period binary came from *Hipparcos* astrometric measurements. As a result of their analyses, Perryman & ESA (1997) gave the star a "G" multiplicity designation because extra acceleration terms were required to fit its astrometric motion. Subsequently, Nidever et al. (2002) found $\sigma = 0.354$ km s^{-1} from their three velocities that span 166 days, while their expected velocity error was 0.020–0.030 km s^{-1}. Our observations started about three years later (Abt & Willmarth 2006), and a monotonic trend of +2.4 km s^{-1} was evident in 423 days. Those velocities were also 0.7 km s^{-1} more positive than the one published velocity of Nidever et al. (2002) (open box, Figure 1). Continued observations at Fairborn Observatory plus the earlier data from the survey of Abt & Willmarth (2006) have enabled us to obtain radial velocities over a complete orbit and resulted in a period of 2713 ± 9 days. Our attempts to use the older data from Mount Wilson and Fick Observatories only degraded the orbital solution since the errors of measurement are comparable to the amplitude of the radial velocity curve.

Besides the *Hipparcos* detection of photocentric shifts, there have been two detections of the secondary by speckle interferometry. Tokovinin et al. (2010) measured a companion at $\rho = 0\farcs3593 \pm 0\farcs0029$ on 2008.5370 with $\Delta m = 5.4$ mag at 5510 Å. Tokovinin (2012) subsequently measured the secondary at $\rho = 0\farcs1851 \pm 0\farcs0029$ on 2012.354 with $\Delta m = 2.9$ mag at 7880 Å. It was noted that the secondary Δm was >5.11 mag at 5430 Å. From just the angular change over the time interval of these two measurements, the period could be approximately 24.4 or 4.6 yr, depending on the orbital geometry. Our derived period of 7.43 yr is 1.6 times longer than the short-period estimate.

4.9. HD 160933 = HR 6598 = HIP 86184

The spectral classifications of Cowley (1976), Abt (1986), and Gray et al. (2001) for HD 160933 are similar, being F9 V, F9 V, and F9 IV–V, respectively, and Abt (1986) also noted that its spectrum is weak-lined. In a survey of the radial velocities of 681 stars carried out at the David Dunlap Observatory (DDO), Young (1945) reported an average velocity of -53.3 km s^{-1} from four spectra. As with several other stars in this work, the system's velocity was also reported by Wilson & Joy (1950), who listed an average of -54.1 ± 0.7 (p.e.) km s^{-1}. Once again, the three individual velocities are listed in Abt (1973). Similar to the discussion for the previous binary, the precision of the DDO and Mount Wilson sets of measurements is comparable to the amplitude of the radial velocity curve, and the small orbital variation was not discernable, and so those velocities have not been used in our orbital solution. The series of 21 velocities determined by Beavers & Eitter (1986) should also be mentioned, but again, the precision of measurement is similar to those above, rendering them of little use for improving the orbit.

The binary nature of HD 160933 was suspected when it received a "G" multiplicity flag from the *Hipparcos* survey (Perryman & ESA 1997), but was confirmed over the span of 485 days during the survey of Abt & Willmarth (2006) when a change of +4 km s^{-1} was observed. That period of observation fortuitously covered almost all of the rise in velocity from its minimum value. Subsequent data from Fairborn Observatory and a few additional velocities from KPNO enabled us to determine a period of 2222 ± 4 days.

Table 8 of Tokovinin (2014) states that HD 160933 has an orbital period of 2235 days. The source of that information is a private communication with D. Latham, but no orbit has yet been published. That period is in excellent agreement with ours.

The *Hipparcos* astrometric data for HD 160933 (HIP 86184) were originally processed with an acceleration model, and the resulting proper motion was rather discrepant with the Tycho-2 one (Høg et al. 2000). Constraining the astrometric orbital fit with the spectroscopic solution significantly improves the agreement in proper motion, with our new values being $\mu_\alpha \cos\delta = -43 \pm 2$ mas yr^{-1} and $\mu_\delta = -208 \pm 1$ mas yr^{-1}. The resulting astrometric semimajor axis, orbital inclination, and longitude of the node are $a_0 = 19.7 \pm 1.5$ mas, $i = 30\fdg0 \pm 2\fdg4$, and $\Omega = 170° \pm 3\fdg7$, respectively.

The primary of HD 160933 is an F9 IV–V metal-poor star. If we adopt a mass of 1.3 $M_\odot$ for it and combine it with the mass function and astrometric inclination, the resulting mass of the secondary star is 0.33 $M_\odot$, corresponding to an M dwarf.

4.10. HD 161163 = HIP 86642

HD 161163 was identified in the *Hipparcos* and Tycho Catalogues (Perryman & ESA 1997) as a system that required a solution with additional nonlinear motion terms. As a result, it was given a "G" designation, and thus was likely an astrometric binary. Comparing the proper-motion results of the *Hipparcos* and Tycho-2 catalogs, Makarov & Kaplan (2005) reported that HD 161163 had a significant difference in at least one of its proper-motion components, supporting its identification as an astrometric binary.

The only known radial velocity measurements of HD 161163 heretofore appear to be an average value of -42.8 km s^{-1} from two measurements given by Nordström et al. (2004). However, Riddle et al. (2015) noted a 2012 private communication from D. Latham, who reported that the star is a double-lined spectroscopic binary with a 6 yr orbit. Riddle et al. (2015) associated this orbit with the close pair that they detected and also found that a fainter companion at $2\farcs23 \pm 0\farcs01$, identified as component B, is part of the system based on its fixed position relative to the Aa,Ab binary and its location in the color–magnitude diagram. The private communication from Latham noted a spectroscopic mass ratio of 0.52.

Our own spectra of HD 161163, which we began acquiring in 2002 at the KPNO, showed the system to be double-lined but with very blended components. Starting in 2009, additional spectrograms were obtained at Fairborn Observatory.

Because of the small velocity separation of the two components in the 6 yr binary, our velocity measurements and orbital results for HD 161163 require some explanation. The depth of the average secondary lines is only about 27% that of the average primary lines, and the lines of the components are always at least partially blended at our resolution. In the case of the components' maximum velocity separation, the bottom of the secondary line has separated from the primary. However, at the other node the bottom of the secondary line never completely separates from the primary. Therefore, using rotational broadening profiles for the two components (Fekel & Griffin 2011; Lacy & Fekel 2011), we simultaneously fit them with starting parameters for the line widths and depths that were determined from the average results for the components at the maximum velocity separation. The line blending due to the small velocity separation makes the resulting velocities of the secondary much more uncertain than those of the primary. Nevertheless, we obtained separate solutions of the primary and secondary velocities. The orbit for the primary appears to be well determined. In the case of the secondary, an acceptable orbit was also found for it with a center-of-mass velocity that differed from that of the primary by only 0.3 km s^{-1}. Thus, we obtained a combined orbital solution with all primary velocities weighted 1.0 and all secondary velocities weighted 0.1. The weights were assigned to the two components from the inverse of the variances of the two orbital solutions.

Our orbit for the Aa,Ab pair produced a period of 2233 $\pm$ 4 days (6.11 $\pm$ 0.01 yr) and a mass ratio $M_{\rm Aa}/M_{\rm Ab}$ = 1.30 $\pm$ 0.01. We adopted the V and $B - V$ values of 7.29 and 0.63 mag, respectively, for the combined Aa,Ab system (Table 1). We then estimated a ΔV mag difference of 2.0 $\pm$ 0.4 from our spectra, which results in $V = 7.45$ for component Aa. Using a slightly bluer $B - V$ of 0.60 mag to correct for the cooler secondary, we converted the $B - V$ to an effective temperature from Table 3 of Flower (1996). Then with the Stefan–Boltzmann law we obtained an absolute visual magnitude of 4.42, which is consistent with a G0 V star. If the spectroscopic binary secondary is 2 mag fainter, then it corresponds to a K1–2 V star. The mass ratio for two such stars is about 1.39, in reasonable agreement with our mass ratio.

The *Hipparcos* astrometric data for HD 161163 (HIP 86642) were originally processed with an acceleration model, and as noted by Makarov & Kaplan (2005) the resulting *Hipparcos* proper motion was significantly different than that found from the Tycho-2 data (Høg et al. 2000). Constraining the orbital model with our spectroscopic solution significantly improves the agreement, with our new *Hipparcos* values for the proper-motion components being $\mu_\alpha \cos\delta = -106 \pm 2$ mas yr^{-1} and $\mu_\delta = -116 \pm 1$ mas yr^{-1}. The resulting astrometric semimajor axis, orbital inclination, and longitude of the node are $a_0 = 30.5 \pm 1.2$ mas, $i = 105.^\circ4 \pm 4.^\circ7$, and $\Omega = 17.^\circ5 \pm 3.^\circ8$, respectively.

4.11. HD 188376 = ω Sgr = HR 7597 = HIP 98066

Both Keenan & McNeil (1989) and Gray et al. (2006) have classified HD 188376 as a G5 IV star. The luminosity class is consistent with its absolute V magnitude, which is determined from its parallax (Table 1).

The first known radial velocity measurements of this southern star appear to be from Lunt (1918), who determined a value -14.0 km s^{-1} from two spectra. A number of other measurements were made in subsequent years, and the star was suspected of having a variable velocity as early as 1928 (Campbell & Moore 1928). HD 188376 was included in a series of occultation measurements (Evans et al. 1986) with a possible detection of vector separations between $0.''0017$ and $<0.''0020$ in two filters. It also earned a *Hipparcos* "G" designation (Perryman & ESA 1997), requiring a model with a significantly nonlinear motion to fit the astrometric measurements and indicating that it was likely a binary. Murdoch et al. (1993) included HD 188376 in a survey search for substellar companions and confirmed that it was without doubt a spectroscopic binary, but the time span of their survey was not sufficient to derive an orbit. Our observations started in 2001 and soon showed a decrease of $\sim$10 km s^{-1}. Some earlier velocities by Beavers & Eitter (1986), those from Murdoch et al. (1993) (open, vertex down triangles, Figure 1), and our own enabled a preliminary orbit to be computed. An additional four radial velocities from Feast (1970) were initially included, but their zero-point is unknown, and they do not improve the orbit. A correction of -0.72 km s^{-1} was applied to the radial velocities of Murdoch et al. (1993) based on a comparison of them with the Fairborn velocities along the more or less linear part of the velocity curve. Continued observation at Fairborn Observatory covered the steep fall and rise of the velocity in its rather eccentric orbit. We have also included the single published velocity of Nidever et al. (2002) (open box, Figure 1), who found a change in velocity of 11.98 km s^{-1} in 430 days. Our orbital period of 1712.7 $\pm$ 0.3 days or 4.7 yr is significantly greater than their 1.2 yr time span.

4.12. HD 196815 = HR 7902 = HIP 102032

HD 196815 is a bright, southern, solar-type star. In her reclassification of the HD catalog stars Houk (1982) assigned it a spectral type of G0/1 V, while Malaroda (1975) gave it a slightly earlier type of F7 V. Perhaps because of its declination of -27°, it was not until 1980 that Beavers & Eitter (1980) published the first radial velocities for the system. From five observations they found a range of 10 km s^{-1} and so announced that it has a variable velocity. Following up on those initial observations, Beavers & Eitter (1986) compiled a long series of radial velocity measurements that, while not detecting the double-lined nature of the spectra, certainly confirmed the velocity variability. As part of a radial velocity survey, Andersen et al. (1985) obtained two observations of HD 196815 (crosses, Figure 1). The first was noted as the primary component, and the second indicated that the velocity was from blended components, so they were the first to identify the system as a double-lined spectroscopic binary.

Our observations of HD 196815 started in 2001 and quickly showed the very blended double-lined nature of the spectra. A preliminary orbit for the primary was calculated by the end of 2005 by including velocities from Beavers & Eitter (1986) (as the primary) and one velocity from Andersen et al. (1985) along with our own data. While those orbital elements were roughly similar to our final orbit, the errors are significantly higher because of the variable blending of the primary and secondary. The inclusion of radial velocities from Fairborn

Observatory, beginning in 2010, allowed the derivation of a doubled-lined orbit that determined $M_A/M_B = 1.16 \pm 0.05$.

As with HD 161163, our velocity measurements and orbital results for HD 196815 require some explanation. The depth of the average secondary line is only about 30% that of the average primary line, and the lines of the two components are always at least partially blended at our resolution. In the case of the components' maximum velocity separation, the bottom of the secondary line has separated from the primary line. However, at the other node the bottom of the secondary line never completely separates from the primary. Therefore, we used rotational broadening profiles for the two components (Fekel & Griffin 2011; Lacy & Fekel 2011) and once again simultaneously fit them with starting parameters for the line widths and depths that were determined from the average results for the components at the maximum velocity separation. This makes the resulting velocities of the secondary significantly more uncertain than those of the primary. Nevertheless, we obtained separate solutions of the primary and secondary velocities. The orbit for the primary appears to be well determined. An acceptable orbit was also found for the secondary. However, while some of its orbital elements are similar to those of the primary, others are significantly different. For example, while the periods of the primary and secondary velocities differ by 21 days or just 1%, the eccentricities of the two solutions differ by 0.07 and the longitude of periastron for the secondary differs by 147° rather than 180°.

These differences in orbital elements led us to wonder whether instead of seeing lines of the primary and secondary of a single binary, we might be seeing the primary components of two separate single-lined binaries. However, from the orbital elements of the primary the value of the mass function is 0.31 $M_\odot$. This value corresponds to the minimum mass of the secondary, and past experience indicates that a value greater than 0.1 $M_\odot$ for solar-type dwarfs and subgiants indicates that lines of the secondary should be visible. This argues that the star with the weaker lines in the spectrum is the secondary of the double-lined binary. Also, the solution for the secondary results in a value of the mass function of 0.65 $M_\odot$, which is the minimum mass of its companion. Such a very large value indicates that the companion of the secondary is much more massive, as would be the case if the two stars are part of a single, double-lined system.

Because of the differences in the orbital elements of the primary and secondary, we assigned weights of 0.01 to all the secondary measurements. Thus, we essentially used those velocities to determine only the semi-amplitude of the secondary. However, that combined solution showed a systematic offset in the secondary velocities, and so we have added 1.3 km s^{-1} to all secondary velocities in our final orbital solution, which produced an orbital period of 2170 ± 3 days.

Although not resolved with *Hipparcos*, subsequent speckle observations beginning in 1992 and listed in INT4 (see Hartkopf et al. 2001) have separations ranging from 0.″0319 (Tokovinin et al. 2016) to 0.″05 (McAlister et al. 1993), and $\Delta m = 0.7$ mag (5430 Å, Tokovinin et al. 2016) and 0.9 mag (7880 Å, Tokovinin et al. 2016). The combined system has an apparent magnitude, V, of 6.50 (Table 1). If we adopt ΔV of 0.7 mag from the interferometric result, then the apparent magnitude of the primary, V_A, is 6.96. The combined $B - V$ equals 0.59 mag (Table 1). The weaker lined and presumably cooler secondary will likely make the observed combined $B - V$ a bit too large, but not appreciably so. Using the Stefan–Boltzmann law, if we adopt $B - V = 0.56$ mag and the parallax of 9.33 mas (van Leeuwen 2007), then the absolute magnitude M_V for the primary is 1.81 and so corresponds to a subgiant rather than a dwarf. The composite spectral classifications of Malaroda (1975) and Houk (1982) would have M_V values ranging from 3.9 to 4.4. Given the large primary minimum mass of 2.1 $M_\odot$, the subgiant result is much more consistent.

4.13. HD 225239 = HR 9107 = HIP 394

Both Roman (1955) and Cowley et al. (1967) included HD 225239 in surveys of stars with high proper motion and classified its spectrum as G2 V. However, the absolute V magnitude of 3.14 (Table 1) determined from its parallax indicates that it is a subgiant.

A number of radial velocities of HD 225239 were obtained before the advent of CCD detectors, but none of them is precise enough to contribute towards the determination of the low-amplitude orbit of this star. The survey by Abt & Levy (1969), for instance, included HD 225239, but with an average $\sigma = 4.3$ km s^{-1} for survey stars with known constant velocity, it was not judged to be a binary. A subsequent similar survey by Abt & Willmarth (1987), now with a CCD detector and higher resolution coudé spectrograph, also did not produce sufficient evidence to conclude that the star has a variable velocity even though the velocity precision was improved to 0.9 km s^{-1}. The most likely reason for this non-detection was that the observing interval did not cover a complete cycle, and the change in velocity during that interval would have been only ~1.5 km s^{-1}.

As radial velocity precision improved with instruments such as CORAVEL and cross-correlation techniques, HD 225239 was suspected to be a velocity variable. Jasniewicz & Mayor (1988) (boxes with plus sign, Figure 1) found the ratio of the standard deviation of five CORAVEL measures to the expected error to be 2.2 and indicated "Var?" for the velocity. In their large survey of F and G dwarfs Nordström et al. (2004) found that HD 225239 definitely has a variable velocity. In an updated version of that survey, Holmberg et al. (2007) listed $\sigma = 1.5$ km s^{-1} for their velocity observations of HD 225239 compared to an expected velocity error of 0.3 km s^{-1}. Thus, they concluded that the probability of its velocity being constant is 0.0. Most recently, Tokovinin (2014) listed a period for HD 225239 of 699.7 days based on the private communication from D. Latham. There have not been any interferometric detections of the secondary component (INT4), but in the *Hipparcos* catalog (Perryman & ESA 1997) it is listed with an "X" multiplicity flag that indicates that the scatter of the astrometric observations was in excess of the measurement uncertainty but of unknown source, and so the star might possibly be a short-period astrometric binary.

As noted above, HD 225239 has been observed by some of the present authors for many years, but the data obtained during the survey of Abt & Willmarth (2006) finally enabled a preliminary period to be determined. Continued observations at Fairborn Observatory through all orbital phases allowed the determination of a definitive orbit with a period of 700.6 ± 0.1 days, in agreement with the result noted by Tokovinin (2014).

5. Summary and Conclusions

Combining our results from Paper I and this paper, we have determined spectroscopic orbits for 28 binary systems. Three of the systems have relatively short periods ranging from 8 to 19 days, while the other 25 have much longer periods ranging from 164 to 9669 days. We have provided first orbits for 16 of the systems and improved or comparable spectroscopic orbits for the rest. Three of the systems are double-lined spectroscopic binaries while the others are single-lined systems. For the single-lined binary HD 142640, we detected long-period changes in velocity that suggest a period of about 8500 days or more.

The proper-motion analyses of the *Hipparcos* astrometric data by the *Hipparcos* team (Perryman & ESA 1997) indicated that half of the 28 binary systems are known, probable, or possible binaries. Thus, we analyzed the *Hipparcos* astrometric data in combination with our spectroscopic results and obtained six astrometric orbits. In addition, for HD 14802 we determined a combined orbit using its spectroscopic and speckle observations. These results show that our spectroscopic orbits can be useful in determining combined orbits with future infrared interferometric observations and *Gaia* satellite astrometry. Such additional analyses will contribute to an increase in our knowledge of basic data for late-type stars.

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