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SPECTROSCOPIC ORBITS FOR 15 LATE-TYPE STARS

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ABSTRACT

Spectroscopic orbital elements are determined for 15 stars with periods from 8 to 6528 days with six orbits computed for the first time. Improved astrometric orbits are computed for two stars and one new orbit is derived. Visual orbits were previously determined for four stars, four stars are members of multiple systems, and five stars have *Hipparcos* "G" designations or have been resolved by speckle interferometry. For the nine binaries with previous spectroscopic orbits, we determine improved or comparable elements. For HD 28271 and HD 200790, our spectroscopic results support the conclusions of previous authors that the large values of their mass functions and lack of detectable secondary spectrum argue for the secondary in each case being a pair of low-mass dwarfs. The orbits given here may be useful in combination with future interferometric and Gaia satellite observations.

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

Supporting material: machine-readable tables

1. INTRODUCTION

In the course of the solar-type multiplicity survey of Abt & Willmarth (2006), a number of stars with radial velocity (RV) measurements were found to be outside the 25 pc volume-limited survey. Therefore, those stars, which included a number of binary systems, were not reported in that work. However, observations of the excluded binaries were continued to determine orbital elements. Fekel et al. (2015) recently computed a spectroscopic orbit for one of those binaries, HR 2692, and orbits for an additional 11 previously excluded systems are presented here. The results from continuing observations of four stars in the Abt & Willmarth (2006) survey—HD 73752, HD 197214, and HD 212697/8—which had a significant scatter of velocities or evidence of orbital motion, as well as HD 120690, for which Abt & Willmarth (2006) determined a preliminary orbit, are also given.

The significance of combined spectroscopic and astrometric orbits was emphasized by Fekel et al. (2015) and references therein. Because all but one of the binaries in the present paper have periods greater than 150 days, we also examined the *Hipparcos* astrometric data of our systems.

Since the work of Abt & Willmarth (2006), a number of the orbits of the binaries analyzed in this paper were published by others. Nevertheless, we include our results for those stars. For several of them we provide improved orbital elements. In addition, if the RVs of the other orbits were obtained at different epochs from ours, comparing our orbits with those previously published may enable center-of-mass velocity variations to be discerned, indicating the possibility of additional components in the systems. Some basic information about the 15 stars discussed in this paper is given in Table 1. In addition to determining the spectroscopic and astrometric orbits for our binaries, we also provide brief discussions of the individual systems.

2. OBSERVATIONS AND VELOCITIES

The radial velocities used here are mainly from four sources: those obtained during the aforementioned work of Abt & Willmarth (2006), an earlier survey of solar-type stars (1986–1990, Julian Days 2,546,708–2,550,885) reported in Abt & Willmarth (1992), subsequent observations by the first author (DW) using the same spectrograph, and observations by the second author (FF) that were acquired at Fairborn Observatory (Fekel et al. 2009).

The observations of Abt & Willmarth (2006) were obtained with the Kitt Peak National Observatory (KPNO) 0.9 m auxillary coudé feed telescope and the coudé spectrograph, which was originally built for the KPNO 2.1 m telescope. The observations reported in Abt & Willmarth (1992) employed the same equipment, except the "B" grating was used yielding approximately half the resolution used in Abt & Willmarth (2006). Further details are given in those papers, but it is worth noting that many of the stars measured were among the stars determined to have constant velocity by Nidever et al. (2002), and therefore served as velocity standards to correct for any systematic velocity shifts. Subsequent observations obtained by DW used either the "A" grating as in Abt & Willmarth (2006) or a 31.6 grooves mm^{-1} echelle grating cross-dispersed by grisms. The latter combination yields a resolving power $\lambda/\Delta\lambda = 72{,}000$ for 2 pixels.

Spectroscopic observations with the 2 m Tennessee State University telescope and fiber-fed echelle spectrograph at Fairborn Observatory in southeast Arizona were described in detail in Fekel et al. (2015), and provide the majority of the more recent RVs. For the stars in the present paper, we note that we used a solar-type star line list and fitted those lines with a rotational broadening function (Fekel & Griffin 2011; Lacy & Fekel 2011). In those cases where blended double lines were present, we simultaneously fitted the blended profiles with two separate rotational broadening functions, and allowed the depth, width, and velocity of the fits to vary.

Observations of stars appearing to be constant in velocity for both the data of Abt & Willmarth (2006) and those from Fairborn Observatory indicate a precision of approximately 0.1 km s^{-1} and were weighted 1.0 in the orbital solutions. However, a few of the early observations from the survey of

Table 1
Basic Properties of the Program Stars

Name	HR	HD	Spectral Type[a]	V[b] (mag)	$B - V$[b] (mag)	Parallax[c] (mas)	M_v (mag)	$v \sin i$ (km s^{-1})	Period (days)
..	1406	28271	F7 III	6.38	0.547	19.38	2.82	32.8 ± 1.0	460.14
63 Eri	1608	32008	K0 III–IV	5.39	0.797	18.53	1.73	4.1 ± 1.0	894.2
..	3430	73752	G5 IV + K0 V	5.05	0.720	51.55	3.61	<2	211.8
38 LMi	4168	92168	G0 IV	5.85	0.595	19.11	2.26	14.5 ± 1.0	7.799216
..	4285	95241	F7 V	6.04	0.539	22.55	2.80	3.2 ± 1.0	5245
..	4498	101563	G2 II–IV	6.44	0.651	23.12	3.25	3.9 ± 1.0	6528
..	5209	120690	G5 V	6.43	0.703	51.35	4.98	4.9 ± 1.0	3827
..	5213	120787	K0 III	5.97	0.974	7.95	0.47	2.9 ± 1.0	1779
49 Lib	5954	143333	F7 V	5.47	0.517	28.40	2.74	9.6 ± 1.0	1142
..	7477	185657	K0 III	6.47	0.990	7.13	0.53	3.9 ± 1.0	4204
..	7801	194215	G8 II–III	5.86	1.101	6.50	−0.08	4.3 ± 1.0	376.27
..	...	197214	G6 V	6.95	0.671	44.83	5.21	1.8 ± 1.0	164.28
4 Equ	8077	200790	F8 V	5.94	0.538	20.44	2.52	6.2 ± 1.0	1975.8
53 Aqr	8544/5	212697/8	G5 V/G1 V	6.29/6.39	0.71	49.80	4.78/4.88	7.8/6.4 ± 2.0	257.3
34 Peg	8548	212754	F8 IV–V	5.76	0.519	26.21	2.85	8.4 ± 1.0	929.9

Notes.
[a] Spectral type source is given in the Section 4 discussion of each star.
[b] Perryman & ESA (1997).
[c] van Leeuwen (2007).

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

Abt & Willmarth (2006) were obtained with a slit entrance to the spectrograph instead of the fiber optic feed, and were of somewhat lower precision. These spectra obtained from HJD 2,551,885–2,552,118 were weighted 0.5. A few slit observations by DW were also weighted 0.5, except for those obtained with the echelle grating mentioned above. Those high resolution spectra were weighted 1.0. The RVs from the Abt & Willmarth (1992) survey had precisions on the order of 0.4–0.5 km s^{-1} and were weighted 0.2. The weighting of a small number of velocities from a few other sources is described within the discussions for the relevant stars.

As noted in Fekel et al. (2015), the Fairborn velocities have been shifted to the zero point of Scarfe et al. (1990). In addition, Fekel et al. (2015) showed that the shifted Fairborn velocities and the KPNO velocities of Abt & Willmarth (2006) have the same zero points to within 0.1 km s^{-1}. This zero point agreement is confirmed by separate orbits for HD 92168 that used only Fairborn or KPNO velocities and have center-of-mass velocities that agree to 0.06 km s^{-1}.

Projected rotational velocities for the stars were determined from the average fit of the rotational broadening function to the lines once the instrumental broadening was removed.

3. ORBITAL ANALYSES

3.1. Spectroscopic Orbits

For all but two stars, initial orbits were computed with a Fortran program (Monet 1979) that executes a period search, calculates a preliminary orbit, and then improves it with Lehmann-Filhes iteration. For HD 73752 and HD 212697, a period-finding program (Fekel et al. 2015) was used that fits sine waves to trial periods of the RV observations to find the optimal period. A Fortran program BISP (Wolfe et al. 1967), which uses the Wilsing–Russell Fourier analysis method (Wilsing 1893; Russell 1902), then determined the initial elements that were improved in the program SB1 (Barker et al. 1967), which iterates the elements with differential corrections and outputs the predicted RV versus orbital phase for constructing the velocity curve plots.

We note that the symbols used for the orbital elements, P, T, e, ω, K, and γ, refer to orbital period, time of periastron, orbital eccentricity, longitude of periastron, velocity semiamplitude, and center-of-mass velocity, respectively. The physical constants used to determine the related parameters $a \sin i$, the projected orbital separation, and the mass function $f(m)$—which are computed from the orbital elements—were recommended by Torres et al. (2010). The orbital elements and related parameters of our 15 systems are presented in Table 2.

3.2. Astrometric Orbits

Following the procedure described in Pourbaix & Boffin (2003), we examined the *Hipparcos* astrometric data (Perryman & ESA 1997) for the binary systems in this paper. This procedure requires consistency between the Thiele-Innes and Campbell orbital solutions. For the majority of our systems, the *Hipparcos* observations are well represented by a single star model. However, for three systems—HD 32008, HD 143333, and HD 212754—we obtain excellent astrometric solutions by adopting P, T, e, and ω from our spectroscopic solutions and solving for the remaining 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. Our results are presented in the discussions for those three stars and are summarized in Table 3.

4. OBSERVATIONAL HISTORY AND RESULTS

4.1. HD 28271 = HR 1406 = HIP 20904

HD 28271 is the brighter component of the visual binary ADS 3243. That system has a current separation of 14.″8 and a magnitude difference of about 1.8. Tokovinin & Gorynya (2001) discovered that the visual binary primary, component A, is a spectroscopic binary. They also determined an orbit with a period of 461 days for the spectroscopic primary Aa, discussed

Table 2
Spectroscopic Binary Orbital Elements

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)	$f(m)$ ($M_\odot$)
28271	460.137	52288.3	0.2406	141.76	18.304	−42.899	0.34	112.41	0.2680
	0.070	1.1	0.0033	0.87	0.063	0.044		0.40	0.0028
28271[b]	460.7	50456	0.314	143	19.35	−41.58	3.06	116.384	0.295
	3.5	8	0.048	7	0.88	0.59		5.7	0.037
32008	894.17	52138.7	0.1352	156.1	5.166	−15.836	0.14	63.94	0.01245
	0.57	5.8	0.0044	2.0	0.020	0.016		0.25	0.00015
32008[c]	898.1	51240	0.173	155.1	5.20	−15.749	0.49	63.25	0.0125
	2.7	21	0.025	8.2	0.14	0.092		1.7	0.001
32008[d]	903	50384	0.3	171	4.8	−14.8	...	56.86	0.0090
	5	51	0.06	22	0.5	0.4		6	0.0029
73752	211.76	56372.6	0.210	142.9	3.102	48.417	0.27	8.83	0.006122
	0.17	2.7	0.016	4.9	0.057	0.038		0.16	0.000034
92168	7.799216	51983.57	0.0056	183	24.315	7.463	0.14	2.6077	0.011643
	0.0000054	0.38	0.0014	17	0.036	0.027		0.0039	0.000052
92168[e]	7.7991499	20165.164	0.023	285.56	24.10	6.05	1.59	2.585	0.01134
	0.0000037	1.470	0.034	68.51	0.73	0.55		...	...
95241	5245.2	55743.3	0.8183	111.73	4.454	−8.001	0.12	184.6	0.00912
	1.3	1.2	0.0028	0.78	0.030	0.027		1.8	0.00026
95241[f]	5244	55736.5	0.823	107.9	4.40	−6.91	0.21	181	0.0085
	4	2.6	0.006	1.5	0.09	0.03		5	0.0007
101563	6528	53738	0.072	230.7	4.559	−10.539	0.13	414.5	0.0659
	43	102	0.012	5.5	0.029	0.027		3.8	0.0013
120690	3827.3	54923	0.3586	140.3	6.276	5.242	0.16	308.34	0.0797
	7.0	12	0.0056	1.3	0.050	0.028		2.72	0.0021
120690[g]	3830	54911	0.3462	137.5	6.06	5.38	...	...	...
	22	10	0.0080	1.4	0.25	0.10		...	...
120787	1778.6	53299	0.501	302.0	1.611	−13.019	0.16	34.1	0.000499
	7.8	20	0.023	3.6	0.055	0.028		1.3	0.000056
143333	1142.4	57025	0.110	69.4	3.847	−20.111	0.14	60.06	0.00661
	1.1	22	0.012	7.4	0.051	0.036		0.80	0.00026
143333[h]	1144.18	53576.22	0.1054	61.50	3.805	...	0.0245	59.53	0.00642
	0.64	8.49	0.0038	2.44	0.012	...		0.244	0.00008
185657	4204	55695	0.3898	166.6	4.704	−87.507	0.16	250.4	0.0354
	10	14	0.0086	2.1	0.061	0.064		3.5	0.0014
194215	376.270	52409.42	0.1238	252.92	14.143	−8.115	0.15	72.61	0.10776
	0.029	0.81	0.0016	0.80	0.021	0.017		0.11	0.00049
194215[i]	374.88	53649.711	0.12329	258.14	14.1155	−8.14	0.047	72.210	0.10676
	0.18	0.074	0.00078	0.77	0.0056	0.14		0.063	0.00018
194215[j]	377.60	30279.9	0.0687	0.00	11.19	−7.25	2.26	58.0	0.0546
	0.38	16.2	0.0207	14.19	0.42	0.30		...	...
197214	164.278	55873.96	0.5919	1.01	7.011	−19.044	0.12	12.765	0.003072
	0.014	0.12	0.0026	0.37	0.33	0.015		0.066	0.000048
200790	1975.76	51004.2	0.3937	14.22	10.585	−19.873	0.15	264.4	0.1886
	0.94	4.2	0.0047	0.83	0.061	0.036		1.6	0.0035
200790[k]	1976.6	52976.8	0.389	14.2	10.54	−18.85	0.22	264.0	0.1881
	0.8	2.7	0.003	0.6	0.05	0.03		1.3	0.0028
200790[l]	1921	45095	0.25	17	10.7	−19.50	1.51	273	0.220
	59	87	0.14	17	1.2	0.70		34	0.80
212697/8	257.31	56143.16	0.626	128.0	5.13	−2.129	0.44	14.15	0.00171
	0.22	0.98	0.013	3.1	0.13	0.074		0.42	0.00015
212754	929.91	53293.9	0.4358	188.5	5.060	−16.110	0.16	58.24	0.00910
	0.46	3.2	0.0062	1.1	0.054	0.025		0.65	0.00030
212754[m]	931.3	53283.9	0.432	184.4	4.96	−14.60	0.30	57.3	0.0087
	1.1	3.3	0.010	1.9	0.07	0.04		0.9	0.0004

Notes.
[a] HJD = heliocentric Julian date −2400000.
[b] Tokovinin & Gorynya (2001).
[c] Massarotti et al. (2008).
[d] Vennes et al. (1998).
[e] Ginestet et al. (1974).
[f] Griffin (2014).
[g] Tokovinin (2012).
[h] Katoh et al. (2013).
[i] Hearnshaw et al. (2012).
[j] Bopp et al. (1970).
[k] Griffin (2011).
[l] From data of Beavers & Eitter (1986).
[m] Griffin (2010).

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

Table 3
Additional Orbital Elements From Astrometric Solutions

HD	a_0 (mas)	i (deg)	Ω (deg)	m_1[a] ($M_\odot$)	m_2[b] ($M_\odot$)
32008	7.6	96.0	44.2	2.0	0.43
	0.3	6.5	6.3		
143333	21.0	143.0	163.5	1.4	0.45
	1.1	2.0	2.8		
212754	9.50	94.0	101.6	1.4	0.29
	0.3	5.1	4.6		

Notes.
[a] Primary mass estimation is given in each star's discussion, Section 4.
[b] Secondary mass based on assumed primary mass and orbital elements.

the probable errors introduced in the parallax by the motion of the Aa–Ab pair, and concluded that Aa is actually an F7 III star, while Ab, the unseen secondary, is approximately an F2 V star or perhaps a pair of low-mass dwarfs. Both Cowley (1976) and Abt (1985) classified the visual binary primary as F7 V.

Table 4 contains our RVs and their times of observation along with the residuals of the RVs from the derived orbit. The standard error of the $O - C$ values is 0.34 km s^{-1}, which is somewhat larger than the 0.1–0.2 km s^{-1} that usually results from our measurements. As noted by Tokovinin & Gorynya (2001), both A and B have large $v \sin i$ values compared to typical solar-type stars. Ammler-von Eiff & Reiners (2012) list a $v \sin i$ value of 33.2 ± 1.7 km s^{-1} for HD 28271, which is in agreement with our value of 32.8 ± 1.0 km s^{-1}. Table 2 gives our orbital elements and related parameters along with those of Tokovinin & Gorynya (2001). Figure 1 compares our RV measurements with the computed orbital velocity curve.

Comparing our orbit of component Aa (Table 2) with that of Tokovinin & Gorynya (2001), we find that the periods are very similar: 460.1 versus 460.7 days. However, we determine a somewhat lower eccentricity, 0.24 versus 0.31, and our orbital element uncertainties are about an order of magnitude better. The difference in the center-of-mass velocities of the two orbits is 1.3 km s^{-1}, but the uncertainty of the Tokovinin & Gorynya (2001) orbit value makes this just a 2σ difference. Thus, the center-of-mass velocity difference provides no strong evidence of a wide component with a period intermediate to that of Aa and its common proper motion (CPM) visual binary secondary, component B.

From our orbit for HD 28271 the mass function, $f(m)$, is equal to 0.268 $M_\odot$ (Table 2). The value of the mass function depends on the mass of the primary, the mass of the secondary, and the orbital inclination (Batten et al. 1989). Stockton & Fekel (1992) have shown that for single-lined dwarf binaries with mass function values as small as ~0.05 $M_\odot$, lines of a spectroscopic binary secondary can be detected at red wavelengths in favorable cases. The mass function value for HD 28271 is more than five times larger than that value. If we adopt a mass of 1.4 $M_\odot$ for the primary from its spectral class and absolute magnitude, then the minimum mass of the secondary, corresponding to $i = 90°$, is 1.23 $M_\odot$, making it a late-F dwarf; decreasing i to 60° makes the unseen component the more massive star of the spectroscopic binary. The spectral lines of such relatively massive secondary stars should be visible in our spectra, but there is no obvious evidence of such lines. This result lends strong support to the suggestion of Tokovinin & Gorynya (2001) that the spectroscopic secondary may not be a single star but rather a pair of low-mass dwarfs.

A spectrum of ADS 3243B yields $V_r = -42.91 \pm 0.05$ km s^{-1} compared to our Aa–Ab system center-of-mass velocity of -42.90 ± 0.04 km s^{-1} (Table 2), reinforcing the CPM status of the wide pair. So far there has been no speckle interferometry detection of the Ab component.

4.2. HD 32008 = HR 1608 = HIP 23221

Although it is listed with a spectral type of G4 V in the Bright Star Catalog (Hoffleit & Jaschek 1982), HD 32008 is evolved. Landsman et al. (1993) obtained its *IUE* spectra, discovered that it had a white dwarf companion, and reviewed various studies that suggested a spectral type of K0 IV. Vennes et al. (1997) classified it as K0 III–IV with the luminosity class determined from the Wilson-Bappu relation (Wilson 1976) because the late-type star has Ca II H and K in weak emission. Massarotti et al. (2008) considered the late-type star to be a giant based on its $B - V$ color and luminosity. Ammler-von Eiff & Reiners (2012) determined a $v \sin i$ value of 4.8 ± 0.2 km s^{-1} in agreement with our value of 4.1 ± 1.0 km s^{-1}.

Three previous spectroscopic orbits have been determined for HD 32008 as well as an astrometric orbit. Beavers & Eitter (1988) reported deriving the orbital elements for 18 bright stars, but the specific results were not published. Some of the elements appear to have been used in a subsequent study by Vennes et al. (1998), where their 24 RV measurements were combined with the P and e values of Beavers & Eitter (1988) to determine the elements shown in Table 2. Their goal was to determine the properties of white dwarf companions, which is what the secondary of HD 32008 is thought to be. More recently, Massarotti et al. (2008) determined a more precise orbit that is also included in Table 2 with our orbit. The orbits of Vennes et al. (1998) and Massarotti et al. (2008) are in general agreement with our significantly more precise results. For example, while our period of 894 days agrees with the period of 898.1 days found by Massarotti et al. (2008), our eccentricity is about 25% smaller. The center-of-mass velocities of the orbit by Massarotti et al. (2008) and of our orbit are in excellent agreement, so there is no evidence for a third component in the system from a change in systemic velocity. Table 4 lists our observational data, which have a JD range of more than 6000 days, as well as the residuals of the RVs from the derived orbit. Figure 1 compares our RV measurements with the computed orbital velocity curve.

In the *Hipparcos* and Tycho Catalogs (Perryman & ESA 1997), the system HD 32008 (HIP 23221) has a stochastic solution, meaning that some *cosmic* noise was assumed to fit the observations with a single star model. With the help of the spectroscopic orbit of Vennes et al. (1998), Ren & Fu (2013) determined an orbit for HD 32008 based upon the *Hipparcos* astrometric data. They determined a value of $109\overset{\circ}{.}5 \pm 5\overset{\circ}{.}9$ for the orbital inclination.

With our greatly improved spectroscopic orbit, we obtain a revised astrometric solution with a semimajor axis of the photocentric orbit, $a_0 = 7.6 \pm 0.3$ mas and inclination $i = 96\overset{\circ}{.}0 \pm 6\overset{\circ}{.}5$. The resulting proper motion is in excellent agreement with the value from Tycho-2 (Hog et al. 2000). Our analysis of the astrometric data results in a parallax of 17.90 ± 0.67 mas, which is identical within the errors to the

Table 4
Radial Velocities of Program Stars

HD	HJD[a]	Orbital Phase	RV (km s^{-1})	Wt	$(O - C)$ (km s^{-1})	Source[b]
28271	51885.8240	0.1253	−61.99	0.5	0.08	KPNO(AW)
28271	51886.7855	0.1274	−61.90	0.5	0.01	KPNO(AW)
28271	51887.8573	0.1297	−61.45	0.5	0.28	KPNO(AW)
28271	51957.6075	0.2813	−46.68	0.5	0.39	KPNO(AW)
28271	51959.5956	0.2856	−47.14	0.5	−0.47	KPNO(AW)
28271	52192.9711	0.7928	−32.35	1.0	−0.13	KPNO(AW)
28271	52193.9422	0.7949	−32.39	1.0	−0.02	KPNO(AW)
28271	52194.9159	0.7970	−32.54	1.0	−0.01	KPNO(AW)
28271	52195.9571	0.7993	−32.69	1.0	0.01	KPNO(AW)
28271	52196.9473	0.8014	−32.49	1.0	0.38	KPNO(AW)
28271	52197.9712	0.8036	−33.09	1.0	−0.05	KPNO(AW)
28271	52241.8564	0.8990	−44.61	1.0	−0.03	KPNO(AW)
28271	52545.9839	0.5600	−29.30	1.0	0.41	KPNO(AW)
28271	52547.0029	0.5622	−29.29	1.0	0.35	KPNO(AW)
28271	52547.9852	0.5643	−29.99	1.0	−0.41	KPNO(AW)
28271	52556.9678	0.5838	−29.30	1.0	−0.25	KPNO(AW)
28271	52557.9428	0.5860	−29.06	1.0	−0.06	KPNO(AW)
28271	52558.9369	0.5881	−28.72	1.0	0.23	KPNO(AW)
28271	53682.8402	0.0307	−63.88	1.0	−0.30	KPNO(AW)
28271	53753.6797	0.1846	−57.10	1.0	−0.45	KPNO(AW)
28271	55498.8347	0.9773	−58.21	1.0	−0.57	Fair(FF)
28271	55505.9930	0.9929	−59.50	1.0	0.34	Fair(FF)

Notes.
[a] HJD = heliocentric Julian date−2400000.
[b] KPNO = Kitt Peak National Observatory, Fair = Fairborn Observatory, MtWilson = Abt (1970), Nid = Nidever et al. (2002), DMH = Duquennoy et al. (1991).
(This table is available in its entirety in machine-readable form.)

value of 18.29 ± 1.09 from the original *Hipparcos* reduction (Perryman & ESA 1997).

From Table 1, the resulting absolute magnitude of HD 32008 from its parallax, combined with its $B - V$ color, argues that the star is near the end of the Hertzsprung Gap. Comparison with the solar composition theoretical tracks of Girardi et al. (2000) confirms this and indicates a mass for the primary of 2.0 $M_\odot$. Adopting that value and our orbital inclination, we find a mass of 0.43 $M_\odot$ for the secondary using the mass function.

Based on their analysis of the *IUE* spectrum of HD 32008, Vennes et al. (1998) concluded that their derived white dwarf parameters are not consistent with the original *Hipparcos* parallax value of 18.29 ± 1.09. They suggested that the cause of the discrepancy is that the parallax is affected by the orbital motion. However, as noted above, our new orbital solution produces a parallax that is not significantly different from the original *Hipparcos* value. Recently, Barstow et al. (2014) analyzed a FUSE spectrum of the DA white dwarf companion to HD 32008. Both their effective temperature and log g values for the white dwarf were significantly lower than those determined by Vennes et al. (1998).

4.3. HD 73752 = HR 3430 = HIP 42430

HD 73752 has been known as a close visual binary since 1874 (Heintz 1990) and cataloged as ADS 6814 AB. Edwards (1976) determined separate spectral types of G3 V + K0 V for the two components. A single classification for the combined system was given by Houk & Smith-Moore (1988) as G3/G5 V, as well as Abt (1981), who gave a spectral type of G6 IV, and Gray et al. (2006), who classified it as G5 IV.

A visual orbit by Heintz (1990) has a period of 123.0 years, while the orbit by Söderhjelm (1999) incorporating *Hipparcos* data has a period of 127 years. On the basis of high resolution, high signal-to-noise echelle spectra, and the visual orbits, Fuhrmann et al. (2011) determined that the visual pair consists of a 1.21 $M_\odot$ G-type subgiant primary and a 1.04 $M_\odot$ G-dwarf secondary with a visual magnitude difference of 1.45. Their modeling of the composite spectrum found unresolved line profiles that would have been only 5.4 km s^{-1} apart at the time of their observations. They further cited speculations from as far back as 1943 that the RV showed larger excursions than might be expected from the visual orbit. They noted the RV curve by Abt & Willmarth (2006) with a velocity range of $\simeq$5 km s^{-1} in just 80 days as a strong indication that HD 73752 is a triple system with an Aa, Ab inner subsystem and an orbital period of a few hundred days. Ammler-von Eiff & Reiners (2012) measured a $v \sin i$ value of 3.3 ± 0.1 km s^{-1} compared to our value of <2 km s^{-1}.

The present work (Table 4) shows that the primary is a single-lined spectroscopic binary with $P = 211.76 \pm 0.17$ days (Table 2). The somewhat larger than usual observed $\sigma(O - C) = 0.27$ km s^{-1} is almost certainly due to the influence of the B component ($\Delta V = 1.45$) in the spectrum as discussed previously. Our spectra show the lines of the two visual components to be completely blended. At the maximum velocity separation, the blended profile shows a very modest blueward asymmetry, which indicates that the lines of component B are much weaker than those of Aa; this is consistent with the magnitude difference estimated by Fuhrmann et al. (2011). While we used two rotational broadening profiles to measure the velocities of the two components simultaneously, the velocities are not completely

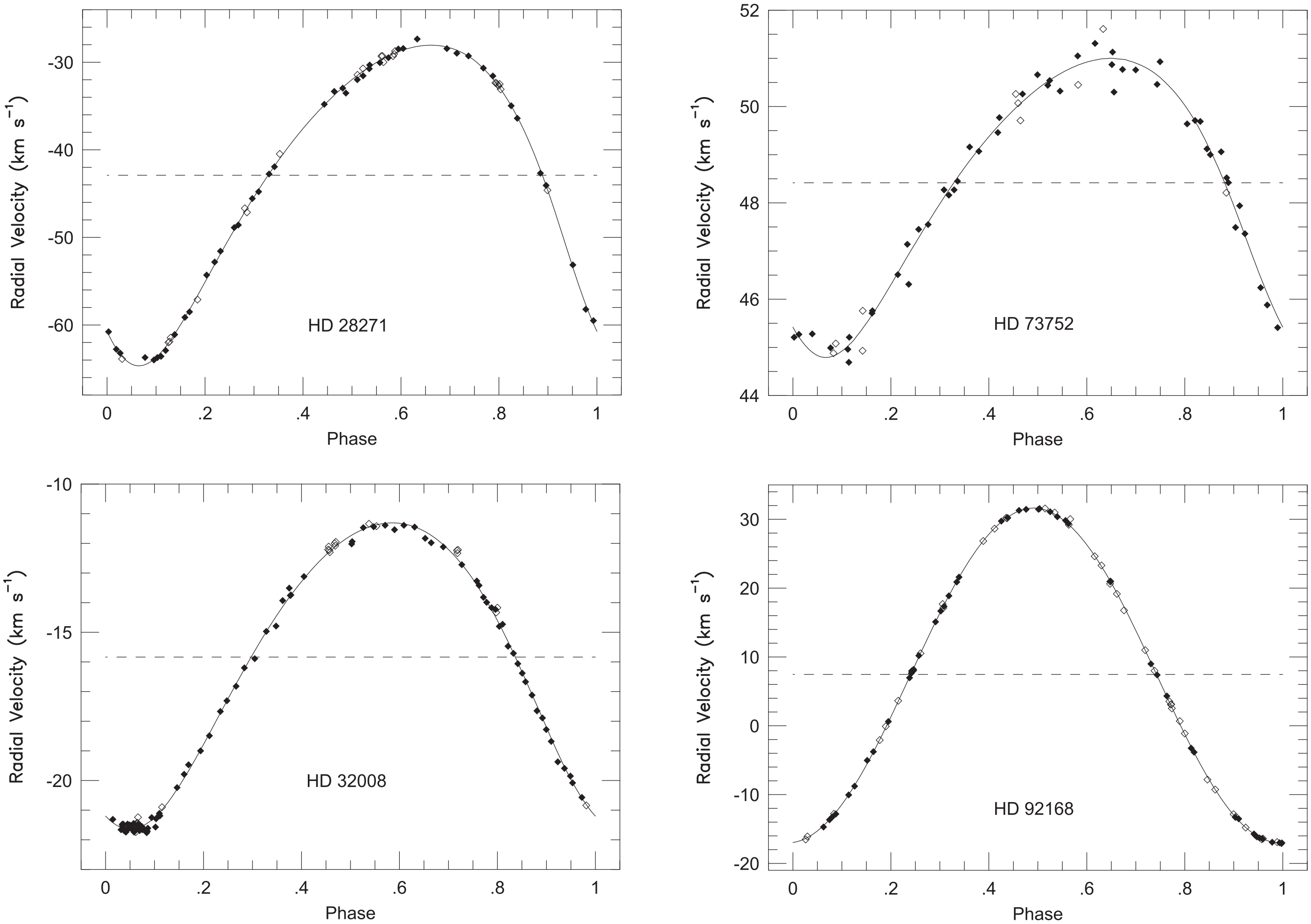

Figure 1. Radial velocity data points compared to the computed velocity curves. Filled diamonds from Fairborn Observatory (FF) and open diamonds from KPNO (AW). Other symbols are described in the text for each star in Section 4.

disentangled because our velocities of B show very low amplitude variability in phase and with the same period as that of Aa. Nevertheless, we believe that our orbital elements of Aa are reasonably well determined. Figure 1 compares our RV measurements with the computed orbital velocity curve.

It would be interesting to try to determine the mass of the invisible Ab component by assuming that the orbital angular momenta of the inner and outer orbits are aligned, but the study by Tokovinin (2008) concludes that the correlation is stronger when the ratio of the outer to inner orbits, P_L/P_S, is close to 5, the dynamical stability limit. For HD 73752, $P_L/P_S = 219$. This value, coupled with the very different values of i (31°.8 and 83°) derived for the AB orbits mentioned above, renders the exercise inconclusive.

4.4. HD 92168 = HR4168 = HIP 52139

Although classified as F9 V by Cowley & Bidelman (1979) and F8 V by Sato & Kuji (1990), the star is more evolved, and Abt (2009) assigned it a spectral type of G0 IV. The subgiant luminosity class is in agreement with its absolute magnitude from its parallax (Table 1), and the subgiant classification is also more in line with its significant $v \sin i$ of 14.1 km s^{-1} (Schroeder et al. 2009) and our value of 14.5 ± 1.0 km s^{-1}.

Noting that in the RV catalog of Wilson (1953) HD 92168 is reported as a spectroscopic binary, Ginestet et al. (1974) began observing it and determined an orbit with a period of 7.799150 days. Thus, it has by far the shortest orbital period of the 15 stars we discuss in this work. The orbit of Ginestet et al. (1974) —derived from a combination of RVs spanning 58 years from Observatoire de Haute-Provence, Mount Wilson Observatory, and Dominion Astrophysical Observatory—is listed in Table 2 along with the orbit from the present set of RVs, which span over 28 years (Table 4). The elements are not greatly different and the periods equal within three times their respective sigmas. The eccentricity of Ginestet et al. (1974), 0.023 ± 0.034, is consistent with a circular orbit. Separate solutions of our KPNO RVs and our Fairborn RVs produced even smaller eccentricities. While the KPNO orbital eccentricity and its uncertainty, 0.0035 ± 0.0024, are consistent with a circular orbit according to the precepts of Lucy & Sweeney (1971), the Fairborn orbital eccentricity of 0.0060 ± 0.0010 argues that the orbit may be slightly eccentric. The solution with our combined RVs results in a very small but still significant orbital eccentricity of 0.0056 ± 0.0014, so we retained the eccentric orbit rather than adopting a circular one.

The center-of-mass velocities of our combined solution (Table 2) and that of Ginestet et al. (1974) differ by 1.5 km s^{-1}, a 3σ result, but this difference is likely the result of different

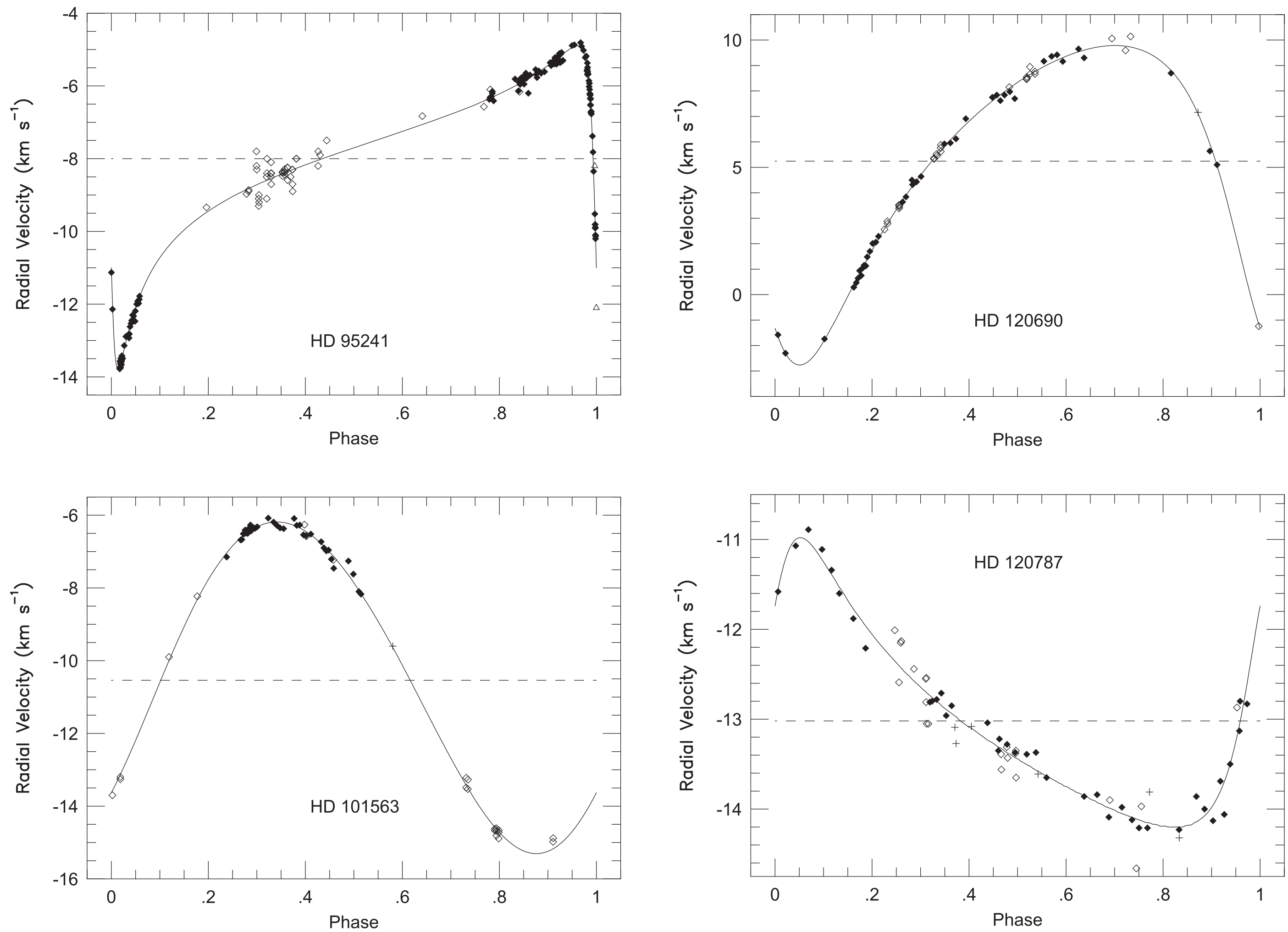

Figure 1. (Continued.)

velocity zero points for the observatories, rather than evidence for a third component. Figure 1 compares our RV measurements with the computed orbital velocity curve.

4.5. HD 95241 = HR 4285 = HIP 52791

Cowley (1976) classified HD 95241 as F9 V, while Cowley & Bidelman (1979) gave it a slightly earlier type of F7 V. However, as discussed in Griffin (2014), the *Hipparcos* parallax indicates that the star is approximately one magnitude more luminous than the typical F7 V star. Griffin (2014) found a $v \sin i$ of 4.52 km^{-1} with a formal mean standard error of 0.15 km s^{-1}, but cautioned that all the broadening in that value was assumed to be the result of rotation. Our smaller result of 3.2 ± 1.0 km s^{-1} removed an estimate for macroturbulence from the broadening.

For a substantial introduction to this star, see Griffin (2014), who provided a very detailed description and history for HD 95241. He previously presented a preliminary orbit (Griffin & Suchkov 2003) that had a period of 3949 ± 22 days, with the recognition that his observations did not cover a complete cycle. Subsequently, Griffin (2014) determined a period of 5258 ± 34 days using just his own Cambridge observations. After then including two Mount Wilson RVs (Abt 1970) that appear to have fallen fortuitously during the limited phase of steep decline in RV, Griffin (2014) found a period of 5244 ± 4 days.

The 5267 ± 50 day period from only our RVs (Table 4) is in agreement within the errors with that of Griffin (2014) using just his Cambridge RVs (above). Likewise, the inclusion of the two Mount Wilson RVs with our data produces a period of 5245.2 ± 1.3 days, which is very similar to that computed by Griffin (2014). Using the aforementioned catalog of the Mount Wilson velocites compiled by Abt (1970), we compared 66 RVs of 16 nearby stars in that catalog—which are also listed in Nidever et al. (2002) as constant in velocity—and found an offset of 0.6 ± 0.5 km s^{-1}, with which we adjusted the two included RVs. The 66 Mount Wilson RVs also yielded a standard deviation of 4.3 km s^{-1}, not leading to a high weight for the two observations from that observatory in the orbital solution, especially considering the derived value of $K = 4.45$ km s^{-1}. Griffin (2014) noted that the period will be ascertainable to within ± 2 days during the next steep RV decline in 2025, even without the inclusion of the somewhat uncertain Mount Wilson RVs. The orbits from Griffin (2014) and the present work are given in Table 2. Figure 1 compares our RV measurements with the computed orbital velocity curve. The two Mount Wilson RVs are indicated by triangles near phase 1.0.

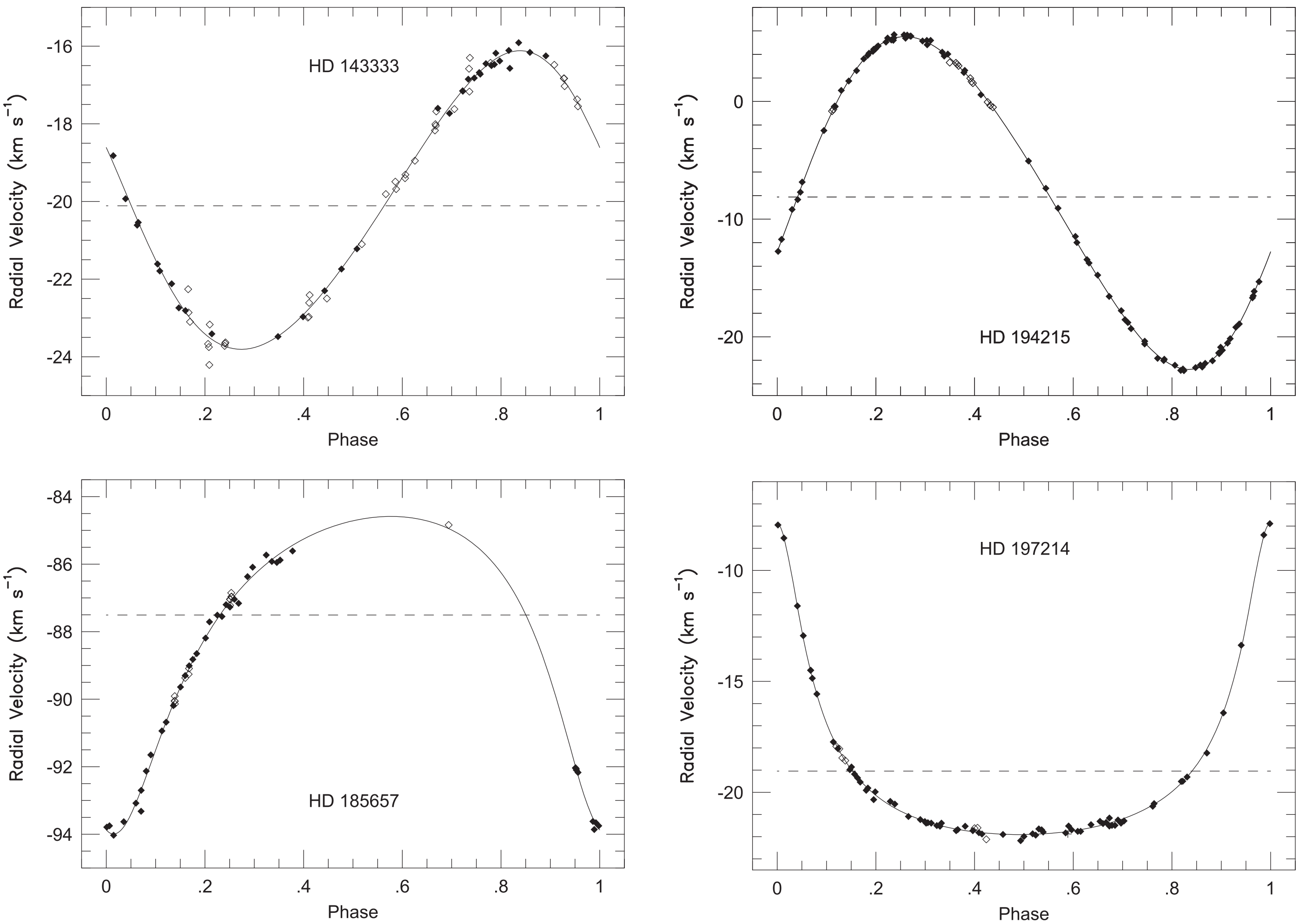

Figure 1. (Continued.)

The center-of-mass velocities of the two orbits differ by about $1\ \mathrm{km\ s^{-1}}$. Our observations cover roughly the same Julian date range as those of Griffin, so the difference is primarily the result of different velocity zero points.

4.6. HD 101563 = HR 4498 = HIP 57001

In his search for solar analogs Hardorp (1982) examined HD 101563 but found it a poor ultraviolet match to the Sun. In a more recent search for solar twins, Porto de Mello et al. (2014) examined it photometrically and analyzed its spectrum before concluding that compared to the Sun it is "much more massive, more evolved, and poorer in metals." While Malaroda (1975) assigned HD 101563 a spectral class of G0 V, Houk (1982) classified it as G2 III/IV, which was in better agreement with the results of Porto de Mello et al. (2014)

HD 101563 has the longest period in our current group of binaries at 6628 ± 43 days (18.15 ± 0.12 years). It received a "G" multiplicity designation from *Hipparcos* measurements, as well as being noted by Nidever et al. (2002) as having a RV rms > $0.1\ \mathrm{km\ s^{-1}}$ from their precision RV survey. Their one published RV measurement is included with our RVs and listed in Table 4. Figure 1 compares our RV measurements with the computed orbital velocity curve. The RV measurement of Nidever et al. (2002) is indicated by a plus sign and, due to its high precision, was weighted 2.0 in the orbital solution.

The orbital parameters, which we believe are now determined for the first time, are given in Table 2. The eccentricity of 0.072 ± 0.012 appears to be unusually low for this spectral type when compared to plots given in Duquennoy & Mayor (1991) and more recently in Ragahavan et al. (2010). Figure 14 of the latter reference appears to show a zone of avoidance of e values less than ∼ 0.15 between approximately $\log P$ (days) = 2–4, although the sample size is only 127 systems.

4.7. HD 120690 = HR 5209 = HIP 67620

HD 120690 is a solar-type star within 20 pc of the Sun. Its spectral classifications of G5 V (Houk & Smith-Moore 1988), G5a V (Keenan & McNeil 1989), and G5+ V (Gray et al. 2006) are in good agreement and indicate that it is slightly cooler and less massive than the Sun.

Like the two preceding binaries, HD 95241 and HD 101563, HD 120690 has a period of more than 10 years. From limited data Abt & Willmarth (2006) computed an initial spectroscopic orbit with a period of 3762 days. Tokovinin (2012) combined speckle measurements, RVs from Abt & Willmarth (2006), and one RV from Nidever et al. (2002) and derived a combined visual-spectroscopic orbit with a period of 3830 days. His spectroscopic orbit is similar to our present orbit, which has a period of 3827 days, although at the time of the Abt & Willmarth (2006) study, RVs had not been obtained near the

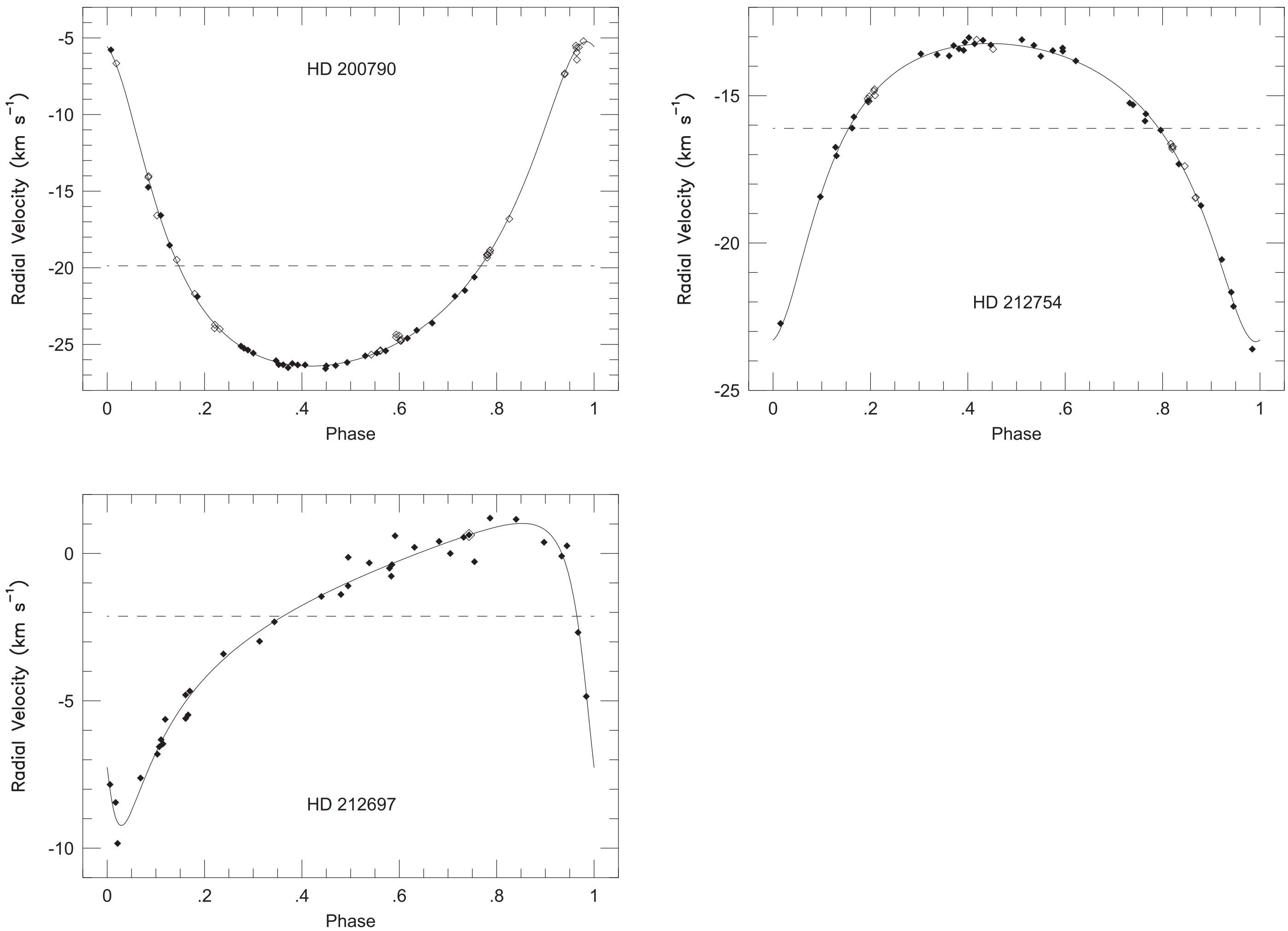

Figure 1. (Continued.)

phases of minimum RV. Table 4 contains our RV measures and Table 2 lists the derived orbits from Tokovinin (2012) and the present work. Figure 1 compares our RV measurements with the computed orbital velocity curve. The RV measurement from Nidever et al. (2002) is indicated by a plus sign and was given a weight of 2.0 in accordance with its higher precision.

Using the values of $M_1 = 0.99$ and $i = 96^{\circ}\!.4$ from Tokovinin (2012) and our value for the mass function, we find $M_2 = 0.59 M_{\odot}$. This value of M_2 is slightly smaller than the value 0.63 $M_{\odot}$ found by Tokovinin (2012) due to our improved value of the semiamplitude K and the third power dependence of the mass function $f(m)$ on K. In agreement with the magnitude difference $\Delta y = 3.5$ mag from Tokovinin (2012), these values of M_1 and M_2 indicate that the secondary would be about 3.4 mag fainter than the primary. We do not see any evidence of lines of the secondary in our spectra.

4.8. HD 120787 = HR5213 = HIP 67485

Duquennoy & Mayor (1991) recognized the binary nature of HD120787, but apparently did not have enough phase coverage to derive an orbit. Despite citing evidence from Gliese (1969) that the star is not a dwarf, it seems to be included in the results of their survey. Its *Hipparcos* parallax and V magnitude (Table 1) certainly indicate that it is a late-type giant. The *Hipparcos* results also give it a "G" multiplicity flag. Takeda et al. (2008) included it in a spectroscopic analysis of the stellar parameters and elemental abundances of late-G giants. They determined its effective temperature and gravity, which correspond to a K0 III.

We included the RVs from Duquennoy et al. (1991) after adding a correction of 0.3 km s^{-1} based on the 32 stars in common between that survey and Abt & Willmarth (2006). A weight of 0.3 was used based on the stated precision of $\leqslant$0.3 km s^{-1}. These RVs and those from the present work are listed in Table 4. We determined an orbital period of 1778.6 ± 7.8 days and provide the full set of elements in Table 2. Figure 1 compares our RV measurements with the computed orbital velocity curve. The RV measurement of Duquennoy et al. (1991) are indicated by plus signs.

4.9. HD 143333 = HR 5954 = HIP 78400

Cowley et al. (1967) classified HD 143333 as F8 V, while Cowley (1976) gave it a slightly later spectral type of F9 V, and both Houk & Smith-Moore (1988) and Gray et al. (2006) assigned it a slightly earlier spectral type of F7 V. The absolute visual magnitude from its *Hipparcos* parallax (Table 1) indicates that it is either near the end of its main-sequence lifetime or just beginning to cross the Hertzsprung gap.

Ammler-von Eiff & Reiners (2012) reported a $v \sin i$ value of 8.2 ± 0.2 km s^{-1}, while our value is about 15% larger, 9.6 ± 1.0 km s^{-1}.

HD 143333 has a fairly long history as a binary star suspect. As far back as 1924, Adams et al. (1924) listed it as having variable velocity, although because of the lower precision of those observations, it seemed to be varying much more wildly at the time (-36 to -11 km s^{-1}). Much later, Abt & Levy (1976) derived an orbit with a period of 3100 ± 9.3 days. But Morbey & Griffin (1987) reexamined the data of Abt & Levy (1976) and concluded that although HD 143333 may show real velocity variations, other periods are possible. The inclusion of older data and insufficient phase coverage contributed to the spurious period result. Including just the data obtained by Abt & Levy (1976) in our present orbit computation shows fair agreement, but those RVs do not improve the elements and were not used in the final orbit. Our RVs are given in Table 4 and Figure 1 compares our RV measurements with the computed orbital velocity curve.

Recently, Katoh et al. (2013) computed an orbit based on high-precision RVs. We did not include their measurements in our orbit calculation because their center-of-mass velocity is not given and their RVs appear to be on an arbitrary scale that varies from star to star. Our results are listed in Table 2 along with those of Katoh et al. (2013), whose errors were increased by a factor of 1.5 as noted by Griffin (2013) to convert their probable errors to standard errors. As can be deduced from Table 2, the orbital elements are in close agreement ($<1\sigma$) and our uncertainties are just 2–3 times larger even though their mean $O - C$ is one-sixth as large.

In the *Hipparcos* and Tycho Catalogs (Perryman & ESA 1997), the system HD 143333 (HIP 78400) was analyzed with a nine-parameter acceleration solution (i.e., including terms up to the time derivative of the proper motion). Adopting the elements from our spectroscopic orbit, the *Hipparcos* astrometric data yield an excellent astrometric solution and the resulting proper motion perfectly matches the Tycho-2 value (Hog et al. 2000). The semimajor axis of the photocentric orbit is 21.0 ± 1.1 mas and the orbital inclination is $143° \pm 2\overset{\circ}{.}0$. With this inclination and an adopted primary mass of 1.4 $M_\odot$ from a comparison with evolutionary tracks, the mass function of HD 143333 produces a secondary mass of 0.45 $M_\odot$.

4.10. HD 185657 = HR 7477 = HIP 96572

Using a probablistic neural network model, Mahdi (2008) classified HD 185657 as K0 III. Atmospheric parameters determined by Prugniel et al. (2011) indicate a similar classification.

Prior to the survey of Abt & Willmarth (2006), there was little reason to suspect a binary nature for HD 185657. A plot of the 13 RVs obtained by 2004, however, revealed a smoothly varying change of ~4 km s^{-1} over an interval of ~450 days. Our subsequent observations now span a complete cycle and enable us to determine an orbital period of 4204 ± 10 days (11.510 ± 0.027 years). The RVs are listed in Table 4, and the orbital elements derived from them are given in Table 2. Figure 1 compares our RV measurements with the computed orbital velocity curve.

The very large negative velocity of HD 185657—our center-of-mass value is -87.5 km s^{-1}—indicates that it is a halo object. It was included in a survey of duplicity for halo stars (Lu et al. 1987) with negative results and was classified as a Population II star in the Vilnius photometric system (Bartkevicius & Lazauskaite 1996).

4.11. HD 194215 = HR 7801 = HIP 100738

Although listed with a spectral type of K3 V in the fourth edition of The Bright Star Catalog (Hoffleit & Jaschek 1982), Houk (1982) classified the star as G8 II/III. The resulting absolute visual magnitude from the *Hipparcos* parallax (Table 1) supports a giant luminosity class.

Evidence for the binary nature of HD 194215 came mainly from RVs obtained with the Radcliffe 74-inch reflector at Pretoria, South Africa, from about 1959–1965. Bopp et al. (1970) used these measurements to derive an orbit with a period of 377.60 ± 0.25 days, which is very close to our present value of 376.270 ± 0.029 days. However, the other elements of Bopp et al. (1970) suffered from a lack of phase coverage near the minimum velocity, as well as low RV precision.

Hearnshaw et al. (2012) clearly remedied the latter issue with high-precison RV measurements obtained with the Hercules fiber-fed vacuum spectrograph at Mount John University Observatory. While their RVs are relative to one spectrum of HD 194215, they established the RV of that template by cross-correlating it with a standard star. The elements from their work, those of Bopp et al. (1970), and our present study are given in Table 2, while our RV measurements are listed in Table 4. The elements from Hearnshaw et al. (2012) agree closely with ours. Figure 1 compares our RV measurements with the computed orbital velocity curve.

The more than 800 day span during which Hearnshaw et al. (2012) acquired their velocities is included in our much longer range of more than 5000 days. The center-of-mass velocities of our orbit and that of Hearnshaw et al. (2012) are essentially identical (Table 2).

The value of the mass function, 0.11 $M_\odot$, is relatively large. However, there is no evidence of spectral features of the secondary in our spectra, likely because of the large magnitude difference between the giant primary and presumed main-sequence secondary.

4.12. HD 197214 = HIP 102264

Houk (1982) gave HD 197214 a spectral type of G3/G5 V. Later, Gray et al. (2006) classified it as G6 V. Although it is less than 25 pc from the Sun and thus a close neighbor, it is the only star in our list that is not in The Bright Star Catalog (Hoffleit & Jaschek 1982).

Concrete evidence for the binary nature of HD 197214 was established in the precision RV survey of Nidever et al. (2002), where an rms velocity scatter of 4.096 km s^{-1} over 437 days was found. Later, Abt & Willmarth (2006) detected a similar variation and it has been observed frequently at Fairborn Observatory in the interim. All these RVs are listed in Table 4, including one measure given by Nidever et al. (2002). The period is among the shorter ones in our sample at 164.278 ± 0.014 days, and the eccentricity fairly high, 0.5919 ± 0.0026. The full list of orbital elements can be found in Table 2. Figure 1 compares our RV measurements with the computed orbital velocity curve. The RV measurement listed by Nidever et al. (2002) is indicated by a plus sign and was given a weight of 2.0 in the orbital solution due to its high precision.

More recently, in a search for visual companions of solar-type stars, Chini et al. (2014) detected a CPM companion at 17."6 distance from HD 197214 with a J magnitude ~6 magnitudes fainter, implying an M star about 390 au from the primary.

4.13. HD 200790 = 4 Equ = HR 8077 = HIP 104101

Both Harlan (1974) and Cowley (1976) classified HD 200790 as F8 V. However, the absolute magnitude from the parallax (Table 1) indicates that the star is somewhat evolved. The star has modest rotation. Balachandran (1990) found a $v \sin i$ value of 5 km s^{-1} while Griffin (2011) measured 5.7 (stating an rms deviation of <1 km s^{-1}); both are in reasonable agreement with our value of 6.2 ± 1.0 km s^{-1}.

While HD 200790 earned only a "c" quality rating for its average RV in the General Catalog of Stellar Radial Velocities (Wilson 1953) based on eight measurements, it became a binary supect during a survey by Andersen & Kraft (1972) for low amplitude spectroscopic binaries among main-sequence F-type stars. They determined a $\sigma_{\rm RV} = 1.68$ km s^{-1} from six spectra, however the individual measurements were not given. From 14 velocities obtained over a period of 2965 days, Nordström et al. (2004) determined a mean RV of −22.2 km s^{-1} with a standard deviation of the mean of 5.1 km s^{-1}, indicating that the star is a binary.

An abstract by Beavers & Eitter (1988) references an orbit of HD 200790, but its elements were never published outside of the meeting for which the abstract was written. They did, however, publish their RVs (Beavers & Eitter 1986), from which we have determined an orbit (Table 2) using the quality values listed therein. While that orbit is roughly similar to our present orbit, for example their period of 1921 days compared with our period of 1976 days, the $\sigma(O - C)$ values are more than 10 times larger than those from our orbit. For this reason, we did not use their data in our orbit computation.

Shortly after the above work, Abt & Willmarth (1992) commenced an RV survey of F8–G1 IV, V stars, which included HD 200790. Those data (1986 October to 1990 December) clearly indicated a variable velocity (−25.4 to −5.5 km s^{-1}) and are given here for the first time. Further observations resumed in 2001 June as reported in Abt & Willmarth (2006), but Griffin (2011) had already begun a long series of observations starting in 1993 and ending in the determination of an orbit. That orbit, along with a much more detailed observational history, can be found in Griffin (2011), with the elements listed in our Table 2. The orbit from the present work includes the aformentioned RVs from Abt & Willmarth (1992, 2006), and Fairborn Observatory. All these RVs are presented in Table 4 and the orbital elements in Table 2. Figure 1 compares our RV measurements with the computed orbital velocity curve. Table 2 shows that our orbital elements agree closely with those of Griffin (2011) except for the systemic velocity. This is most likely due to zero point differences as discussed in Section 4.15.

Our non-detection of any secondary spectrum reinforces the finding of Griffin (2011) that the relatively large mass function results from a system consisting of the observed star together with a closer pair of low-mass dwarfs. This system is similar to that of HD 28271, which has a somewhat larger mass function.

Finally, we note that HD 200790 has a "G" flag for multiplicity in the *Hipparcos* survey, which might account for the uncharacteristically high parallax error value of 1.68 mas.

4.14. HD 212697/8 = HR 8544/5 = HIP 110778 = ADS 15934

HD 212697/8 is a close visual binary with solar-type components of similar brightness (Hoffleit & Jaschek 1982). Cowley & Bidelman (1979) classified the combined spectrum as G0 V, while Abt (1985) gave spectral types of G0 V to both components. Gray et al. (2006) classified the components separately. For HD 212698 they determined G1 V and adopted G5 V for HD 212697, so the former star is the brighter one. Pallavicini et al. (1987) obtained separate spectra of the two close visual components and noted that both stars are chromospherically active, rotating rapidly, and have high lithium abundances. Based on their lithium abundances and X-ray activity, Zuckerman et al. (2013) estimated an age between 100 and 300 Myr for the stars. According to Cutispoto et al. (2002) CORAVEL velocities suggest that HD 212697 is a possible single-lined spectroscopic binary. Torres et al. (2006) give $v \sin i$ values of 8 and 9 km s^{-1} for HD 212698 and HD 212697, respectively. From our blended spectra we find $v \sin i$ values of 6.4 ± 2.0 and 7.8 ± 2.0 km s^{-1}, respectively, for the same two stars.

The visual binary had a separation of 2."2 at the start of the survey by Abt & Willmarth (2006). According to the orbit of Hale (1994) and its ephemeris from ORB6 (Hartkopf et al. 2001) the system is currently near minimum separation of 1."27. Thus, our spectra contain the light of both stars. An examination of our spectra shows that the lines of the two visual components never completely separate, but the strength and width of the combined blended profiles change with time. With the exception of one KPNO spectrum obtained with the echelle grating, our KPNO spectra are not of high enough resolution to effectively deblend the two components. Our double fit to the blended profiles of the Fairborn spectra indicates that the fainter star, HD 212697, is indeed a spectroscopic binary with a period of 257.31 days. Thus, the system is triple.

We can estimate the maximum RV separation between A and B using the equation

$$K^3 = m \sin^3 i / 4P (1.0361 \times 10^{-7})(1 - e^2)^{3/2}$$

assuming $K_1 = K_2 = K$, $m_1 = m_2 = m = 1 M_\odot$. Using values of $i = 44^\circ\!.13$, $e = 0.9$ and $P = 3500$ years from Hale (1994), we find K = 2.0 km s^{-1}, so even with the maximum separation between A and B of 4 km s^{-1}, the components in a combined spectrum would not be separable.

Our observations are listed in Table 4 and the orbital elements in Table 2. The orbit is based completely on the Fairborn observations, except for the one coude echelle spectrum described above. Figure 1 compares our RV measurements with the computed orbital velocity curve.

4.15. HD 212754 = 34 Peg = HR 8548 = HIP 110785

While Cowley & Bidelman (1979) classified HD 212754 as F7 V, both Abt (1985) and Gray et al. (2001) gave it a spectral type of F8 IV–V. That the star is somewhat evolved is in agreement with its absolute visual magnitude of 2.85 in Table 1. Like a number of late-F stars, HD 212754 has a modest rotational velocity. Soderblom et al. (1989) determined a $v \sin i$ value of 7.9 ± 0.7 km s^{-1} and Griffin (2010) determined 8.6 ± 0.13 km s^{-1}; both are in good agreement with our result of 8.4 ± 1.0 km s^{-1}. However, Griffin (2010) notes that his value does not take into account other sources of line broadening and may not be as accurate as the quoted standard error of the mean.

According to Griffin (2010), HD 212754 had not been observed for RVs since 1922 until that author began observing it in 2000, which is the year before our own observations commenced. At the time of the publication of their survey of F-type stars, Griffin & Suchkov (2003) demonstrated the binary nature of HD 212754 but had insufficient phase coverage for a complete description of the orbit. Our observations continued while Griffin (2010) discussed the voluminous history of work on the star and published its orbit. The elements determined by that author are essentially identical to ours except for his systemic velocity, which is 1.5 km s^{-1} more positive than ours, but the errors of our elements are somewhat smaller. Griffin's RV system is tied to a different zero point than ours, and a comparison of several orbits in common suggests that Griffin's zero point is about 1 km s^{-1} more positive than ours. Our observations are tabulated in Table 4, and the derived orbital elements are given in Table 2 along with those of Griffin (2010). Figure 1 compares our RV measurements with the computed orbital velocity curve.

In the *Hipparcos* and Tycho Catalogs (Perryman & ESA 1997), the system HD 212754 (HIP 110785), like HD 32008, has a stochastic solution. A preliminary astrometric orbit was derived from the *Hipparcos* observations by Goldin & Makarov (2007), but Griffin (2010) concluded that except for the period and almost edge-on orbital inclination, the elements are nearly indeterminate. Assuming sin $i = 1$ from that astrometric orbit, Griffin (2010) adopted a primary mass of 1.1 $M_{\odot}$ and with his mass function value obtained a secondary mass of 0.25 $M_{\odot}$. The astrometric orbit of Goldin & Makarov (2007) barely overlaps with our spectroscopic solution. Using the latter yields an excellent astrometric solution and the resulting proper motion agrees very well with the Tycho-2 value (Hog et al. 2000). The semimajor axis of the photocentric orbit is 9.5 ± 0.3 mas and the inclination is $94\overset{\circ}{.}0 \pm 5\overset{\circ}{.}1$. Comparison of the effective temperature and luminosity of HD 212754 with the solar abundance evolutionary tracks of Girardi et al. (2000) indicates a mass of 1.4 $M_{\odot}$. That mass, the inclination from our photocentric orbit, and our mass function value lead to a secondary mass of 0.29 $M_{\odot}$.

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REFERENCES

Abt, H. A. 1970, ApJS, 19, 387
Abt, H. A. 1981, ApJS, 45, 437
Abt, H. A. 1985, ApJS, 59, 95
Abt, H. A. 2009, ApJS, 180, 117
Abt, H. A., & Levy, S. G. 1976, ApJS, 30, 273
Abt, H. A., & Willmarth, D. 2006, ApJS, 162, 207
Abt, H. A., & Willmarth, D. W. 1992, in IAU Coll. 135, ASP Conf. Ser. 32, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McCalister & W. I. Hartkopf (San Francisco, CA: ASP), 82
Adams, W. S., Joy, A. H., & Sanford, R. F. 1924, PASP, 36, 137
Ammler-von Eiff, M., & Reiners, A. 2012, A&A, 542, A116
Andersen, K. S., & Kraft, R. P. 1972, ApJ, 172, 631
Balachandran, S. 1990, ApJ, 354, 310
Barker, E. S., Evans, D. S., & Laing, J. D. 1967, RGOB, 130, 355
Barstow, M. A., Barstow, J. K., Casewell, S. L., Holberg, J. B., & Hubeni, I. 2014, MNRAS, 440, 1607
Bartkevicius, A., & Lazauskaite, R. 1996, BaltA, 1, 82
Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, PDAO, 17, 1
Beavers, W. I., & Eitter, J. J. 1986, ApJS, 62, 147
Beavers, W. I., & Eitter, J. J. 1988, BAAS, 20, 737
Bopp, B. W., Evans, D. S., & Laing, J. D. 1970, MNRAS, 147, 355
Chini, R., Fuhrmann, K., Barr, A., et al. 2014, MNRAS, 437, 879
Cowley, A. P. 1976, PASP, 88, 95
Cowley, A. P., & Bidelman, W. P. 1979, PASP, 91, 83
Cowley, A. P., Hiltner, W. A., & Witt, A. N. 1967, AJ, 72, 1334
Cutispoto, G., Pastori, L., Pasquini, L., et al. 2002, A&A, 384, 491
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Duquennoy, A., Mayor, M., & Halbwachs, J.-L. 1991, A&AS, 88, 281
Edwards, T. W. 1976, AJ, 81, 245
Fekel, F. C., & Griffin, R. F. 2011, Obs, 131, 283
Fekel, F. C., Tomkin, J., & Williamson, M. H. 2009, AJ, 137, 3900
Fekel, F. C., Williamson, M. H., Muterspaugh, et al. 2015, AJ, 149, 63
Fuhrmann, K., Chini, R., Hoffmeister, V. H., et al. 2011, MNRAS, 411, 2311
Ginestet, N., Pédoussaut, A., Carquillat, J.-M., & Nadal, R. 1974, A&AS, 15, 133
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Gliese, W. 1969, VeARI, 22, 109
Goldin, A., & Makarov, V. V. 2007, ApJS, 173, 137
Gray, R. O., Corbally, C. J., Garrison, R. F., et al. 2006, AJ, 132, 161
Gray, R. O., Napier, M. G., & Winkler, L. I. 2001, AJ, 121, 2148
Griffin, R. F. 2010, Obs, 130, 17
Griffin, R. F. 2011, Obs, 131, 294
Griffin, R. F. 2013, AJ, 146, 13
Griffin, R. F. 2014, Obs, 134, 245
Griffin, R. F., & Suchkov, A. A. 2003, ApJS, 147, 103
Hale, A. 1994, AJ, 107, 306
Hardorp, J. 1982, A&A, 105, 120
Harlan, E. A. 1974, AJ, 79, 682
Hartkopf, W. I., Mason, B. D., & McAlister, H. A. 2014, Fourth Catalog of Interferometric Measurements of Binary Stars, http://ad.usno.navy.mil/wds/int4.html
Hartkopf, W. I., Mason, B. D., & Worely, C. E. 2001, Sixth Catalog of Orbits of Visual Binary Stars, http://ad.usno.navy.mil/wds/orb6/orb6.html
Hearnshaw, J. B., Komonjinda, S., Skuljan, J., & Kilmartin, P. M. 2012, MNRAS, 427, 298
Heintz, W. D. 1990, A&AS, 82, 65
Hoffleit, D., & Jaschek, C. 1982, The Bright Star Catalogue, Fourth Revised Edition (New Haven, CT: Yale Univ. Obs.)
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 335, L27
Houk, N. 1982, Michigan Spectral Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 3 (Ann Arbor, MI: Univ. Michigan Press)
Houk, N., & Smith-Moore, M. 1988, Michigan Spectral Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 4 (Ann Arbor, MI: Univ. Michigan Press)
Katoh, N., Itoh, Y., Toyota, E., & Sato, B. 2013, AJ, 145, 41
Keenan, P. C., & McNeil, R. C. 1989, ApJS, 71, 245
Lacy, C. H. S., & Fekel, F. C. 2011, AJ, 142, 185
Landsman, W., Simon, T., & Bergeron, P. 1993, PASP, 105, 841
Lu, P. K., Demarque, P., Van Altena, W., McAlister, H. A., & Hartkopf, W. I. 1987, AJ, 94, 1318
Lucy, L. B., & Sweeney, M. A. 1971, AJ, 76, 544
Mahdi, B. 2008, BASI, 36, 1
Malaroda, S. 1975, AJ, 80, 637
Massarotti, A., Latham, D. W., Stefanik, R. P., & Fogel, J. 2008, AJ, 135, 209
McAlister, H. A., Mason, B. D., Hartkopf, W. I., & Shara, M. M. 1993, AJ, 106, 1639

Monet, D. G. 1979, ApJ, 234, 275
Morbey, C. L., & Griffin, R. F. 1987, ApJ, 317, 343
Nidever, D. L., Marcy, G. W., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2002, ApJS, 141, 503
Nordström, B., Mayor, M., Andersen, J., et al. 2004, A&A, 418, 989
Pallavicini, R., Cerruti-Sola, M., & Duncan, D. K. 1987, A&A, 174, 116
Perryman, M. A. C. & ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200 (Noordwijk: ESA)
Porto de Mello, G. F., da Silva, R., da Silva, L., & de Nader, R. V. 2014, A&A, 563, A52
Pourbaix, D., & Boffin, H. M. J. 2003, A&A, 398, 1163
Prugniel, Ph., Vauglin, I., & Koleva, M. 2011, A&A, 531, A165
Ragahavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Ren, S., & Fu, Y. 2013, AJ, 145, 81
Russell, H. N. 1902, ApJ, 15, 252
Sato, K., & Kuji, S. 1990, A&AS, 85, 1069
Scarfe, C. D., Batten, A. H., & Fletcher, J. M. 1990, PDAO, 18, 21
Schroeder, C., Reiners, A., & Schmitt, J. H. M. M. 2009, A&A, 493, 1099
Soderblom, D. R., Pendleton, J., & Pallaviccini, R. 1989, AJ, 97, 539
Söderhjelm, S. 1999, A&A, 341, 121
Stockton, R. A., & Fekel, F. C. 1992, MNRAS, 256, 575
Takeda, Y, Sato, B., & Murata, D. 2008, PASJ, 60, 781
Tokovinin, A. 2008, MNRAS, 389, 925
Tokovinin, A. 2012, AJ, 144, 56
Tokovinin, A. A., & Gorynya, N. A. 2001, A&A, 374, 227
Torres, C. A. O., Quast, G. R., Da Silva, L., et al. 2006, A&A, 460, 695
Torres, G., Andersen, J., & Giménez, A. 2010, ARA&A, 18, 67
van Leeuwen, F. 2007, A&A, 474, 653
Vennes, S., Christian, D. J., Mathioudakis, M., & Doyle, J. G. 1997, A&A, 318, L9
Vennes, S., Christian, D. J., & Thorstensen, J. R. 1998, ApJ, 502, 763
Wilsing, J. 1893, AN, 134, 89
Wilson, O. C. 1976, ApJ, 205, 823
Wilson, R. E. 1953, General Catalogue Of Stellar Radial Velocities, Publication 601 (Washington, DC: Carnegie Institution of Washington)
Wolfe, R. H., Jr., Horak, H. G., & Storer, N. W. 1967, in Modern Astrophysics, A memorial to Otto Stuve, ed. M. Hack (New York: Gordon and Breach), 251
Zuckerman, B., Vican, L., Song, I., & Schneider, A. 2013, ApJ, 778, 5