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Radial-Velocity Standard Stars

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Abstract. We review the history of the IAU Radial Velocity Standard Stars and give a status report on recent efforts at the Harvard-Smithsonian Center for Astrophysics to establish an absolute velocity zero point for these stars and to improve their usefulness for intercomparing the results from different instruments and observatories.

1. Introduction

Radial velocity standard stars were originally proposed for two main purposes:

1. Intercomparisons between instruments. Stars designated as standards were meant to be well-suited for intercomparing results from different instruments and observatories. This purpose implied several desirable characteristics for sets of standard stars:

- They should be located near the celestial equator and distributed evenly around the sky in right ascension so that they are accessible to observatories located in both hemispheres at any time of the year or night.
- They should be well-established as constant stars so that variability does not have to be taken into account.
- Important parameters such as spectra type, velocity, and apparent brightness should be well covered.

2. Absolute velocity zero point. The absolute velocity zero point of the system should be well established, so that observations of the standards can be used to calibrate instrumental zero points.

Radial velocities of bright stars were being mass produced already in the early 1900s. However, recent improvements in the instruments and techniques used to measure radial velocities have put new demands on the performance expected from standard stars. In this paper we summarize the history of the IAU Radial Velocity Standard Stars, and give a status report on recent efforts at the Harvard-Smithsonian Center for Astrophysics (CfA) to improve the performance of the standards. We confine our discussion to stars with spectral types later than F5.

2. History of the IAU Standards

The stars in the current "official" list of IAU Radial Velocity Standard Stars were drawn from three sources. There is also a fourth list (Evans 1967) of southern-hemisphere stars that we will not consider here.

1. Bright Standards (Pearce 1957). 25 stars observed at 14 different observatories; reduced to the Lick velocity system; brighter than V magnitude 4.3; spectral type F0 and later; dwarfs and giants; number of observations per star: 19 to 528.

2. Faint Standards (Pearce 1957). 35 stars observed at 7 different observatories; fainter than V magnitude 4.3 and brighter than 8.0; spectral type F0 and later; dwarfs and giants; number of observations per star: 7 to 38.

3. Heard-Fehrenbach Standards (Evans 1967, Bouigue 1973). 21 stars observed at the David Dunlap Observatory, the Observatoire de Haute Provence and the Dominion Astrophysical Observatory; V magnitude 7 to 9 (the magnitudes were originally given as 8.2 to 9.7, but these are off by about one magnitude); spectral types F to K; dwarfs and giants; number of observations per star: 7 to 18.

These 81 stars are the "official" list of IAU Radial Velocity Standard Stars. They are a smorgasbord of spectral types and luminosity classes, with velocities drawn from several observatories, using different techniques and dispersions, and covering various time spans and numbers of observations. It is not surprising that a list derived in this manner would present difficulties, particularly as modern velocity methods covering very long time spans are applied to new determinations of their velocities. Many have proven to be velocity variables.

To appreciate some of the difficulties associated with the official standards, it is helpful to review briefly some history (see also Batten 1978, 1985; Batten et al. 1983).

Shortly after the above stars were proposed as standards there were reports that several of the stars, particularly among the brighter giants, showed velocity variations larger than 1 km s^{-1}. For example, HD 20902 and HD 45348 from the Bright list were rejected as standards in the 1958 IAU Commission 30 report to the General Assembly (Heard 1960). Other stars from the Bright and Faint lists were suspected of being variables and were recommended to be deleted from the standard list. Some of these have indeed been shown to be variable, but others have not been confirmed as variables.

The Heard-Fehrenbach list was derived from a survey of 1041 late-type stars started by F. Hogg and completed by J. Heard at the David Dunlap Observatory (Heard 1956). Twenty-four stars from that survey were originally proposed as standards by Heard as reported by Evans (1967). The 24 stars in the Evans list were subsequently observed by Heard and Ch. Fehrenbach at the David Dunlap, Haute Provence and Dominion Astrophysical Observatories (Heard & Fehrenbach 1972). Three stars were found to be variable, and ultimately orbital solutions were obtained for all three: HD 160952, $P = 182$ days and $K = 2.64$ km s^{-1} (Radford & Griffin 1976); BD $+29^{circ}1553$, $P = 892$ days and $K = 4.72$ km s^{-1} (Stefanik, private communication); HD 204934, $P = 144$ days and $K = 5.90$ km s^{-1} (Radford & Griffin 1975, Bassett 1978). The remaining 21 stars were adopted as IAU standards as reported by Bouigue (1973). The adopted velocities

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were arrived at by shifting the velocities from each observatory to the IAU system defined by the Bright and Faint stars and averaging.

Thirteen of the Heard-Fehrenbach stars were observed by Griffin (1975), who found an additional variable star, HD 14969, which he later showed to be a spectroscopic binary (Griffin 1980). Griffin combined his observations with those of Heard & Fehrenbach (1972), weighted by their respective errors, to suggest an "improved" list of velocities reduced to the IAU system. Griffin (1969, 1975) also criticized the method being used to establish a velocity system and adopted four of his own velocity standards, often referred to as the Griffin Standards.

Clear evidence for velocity variation among several more of the IAU standards was slowly accumulating, and the introduction of modern spectroscopic techniques promised to reveal additional problems. This was indeed the case. The first modern update of the IAU standards was presented at IAU Colloquium No. 88 by Mayor & Maurice (1985) based on CORAVEL observations. They reported that the IAU velocities for the Bright and Faint standards were on different systems with a zero-point shift of 0.8 km s^{-1}, and they noted that four of the IAU standards were variable, and three were possible variables. An orbit for one of the possible variables, HD 114762, was published in 1989 by Latham et al., with $P = 84$ days and $K = 0.59$ km s^{-1}. In 1990 Scarfe, Batten, & Fletcher published an update of the velocities for the IAU standards based on observations made at the Dominion Astrophysical Observatory. It was clear that the IAU standards still included velocity variables, and a comparison of the results from different observatories showed systematic trends both with stellar color and velocity.

Because of these problems IAU Commission 30 formally addressed the issues of variability among the IAU standards and the zero-point of the IAU velocity system. It set the objective of establishing a new set of late-type IAU Radial Velocity Standard Stars with individual mean velocities and an absolute zero point of the entire system good to 100 m s^{-1}. An observational campaign to monitor the IAU standards from several observatories was undertaken, including efforts with the Dominion Astrophysical Observatory (Victoria) spectrometer, the CORAVELs, and the CfA Digital Speedometers.

The status of this effort was summarized in the report of Commission 30 to the 1990 General Assembly (Latham & Stefanik 1991). In that report the results from the three observatories along with the official IAU velocities were reported for 72 of the IAU standards. Removed from that summary, in addition to the three variables mentioned above, were stars found to be variable with a semi-amplitude larger than 1 km s^{-1} or whose IAU velocity appeared to be in error by more than 1 km s^{-1}: HD 36673, 156014, 35410, 44131, and 115521. Also removed was HD 184467, which McClure (1983) had shown to be a spectroscopic binary. Even with these removals, a number of suspected variables remained. And, a systematic color dependence between the velocities from the CORAVELS compared to Victoria and CfA was clearly evident.

At the 1988 General Assembly it had been agreed that an effort should be made to establish some additional G dwarfs as standards. The primary argument for concentrating on G dwarfs was that any absolute velocity zero point that was established by observing minor planets would most safely transfer to stars with essentially the same spectrum as the sun. The hope was that the impact of the color problem could be minimized this way. Indeed, comparisons between CfA and the CORAVELS gave the smallest differences for G dwarfs. Furthermore, good candidates could be drawn from the samples of G dwarfs that had been monitored for many years. The status of the results for 25 new G dwarf candidates was reported by Latham & Stefanik (1991). Included were 18 stars chosen from the sample of G dwarfs monitored with the CORAVELS (Duquennoy & Mayor 1991) and 7 from the sample observed using a hydrogen-fluoride gas absorption cell on the Canada-France-Hawaii Telescope (Campbell, Walker, & Yang 1988; Walker et al. 1989). These G dwarf candidates all had a large number of observations covering long time spans, and showed no velocity variations. All appear to be good candidates for adoption as official standards, although it should be pointed out that subsequently a spectroscopic orbit with $K = 0.06$ km s^{-1} was published for one of them, HD 217014 = 51 Peg (Mayor & Queloz 1995)

3. Comparison of the CfA and Victoria Results

As a step towards improving the performance of the IAU standards, a careful comparison was made between the CfA and Victoria results during a visit of Scarfe to the CfA in 1993. A total of more than 9100 observations were compared, 6442 from the CfA Digital Speedometers, 1058 made by Scarfe with the DAO spectrometer, and 1606 made by McClure with the same instrument. These velocities have a typical precision of 0.4 or 0.5 km s^{-1} and covered a span of 10 to 15 years. The differences between the Victoria and CfA results showed no trends with mean velocity, right ascension, declination, magnitude, or spectral type.

This comparison disclosed clear evidence for velocity variations in four stars. HD 156014 and 115521 were confirmed as low-amplitude variables. HD 115521 shows a long-term variation with a timescale longer than 6000 days, and also a short term oscillation with period of about 470 days. HD 140913 gave a spectroscopic orbit with low amplitude (Stefanik et al. 1994; Mazeh, Latham, & Stefanik 1996), and HD 171232 showed a decrease of 5 km s^{-1} over a period of 16 years. There was also a hint that HD 29587 was variable, and eventually a low-amplitude spectroscopic orbit was published for this star (Mazeh et al. 1996).

Two additional variables are HD 123782, which has a semi-amplitude of 0.95 km s^{-1} and period of 493 days, and HD 42397, which was discovered by Scarfe (1992) to be a double-lined spectroscopic binary with long period and high eccentricity. This has been confirmed by additional CfA observations.

4. Status of the CfA Effort

For more than 15 years there has been an active program at the CfA to monitor the velocities of standard stars using the CfA Digital Speedometers (Latham 1985, 1992) on the 1.5-m Wyeth Reflector at the Oak Ridge Observatory located in the town of Harvard, Massachusetts, and on the 1.5-m Tillinghast Reflector and MMT, both located at the F. L. Whipple Observatory atop Mt. Hopkins, Arizona.

1. Templates. For the first several years of operation of the CfA Digital Speedometers we used observed spectra as the templates for our cross-correlation velocity reduction procedures. Most of the time we used an observed spectrum of the dusk sky as the template, but we also used observed spectra of an A star or an M star for extreme cases. For most of the 1990s we used templates drawn from an extensive library of synthetic spectra calculated by Jon Morse using Kurucz model atmospheres (e.g. Nordström et al. 1994). A new and improved library of synthetic spectra has recently become available (Morse & Kurucz in preparation), and we have been using these for templates since 1997.

2. Run-to-Run Velocity Shifts. We monitor the velocity zero point of the CfA Digital Speedometers using exposures of the dawn and dusk sky every night we observe. Usually these exposures show that it is sufficient to use a single correction for the zero point during an entire month's run, although occasionally there are significant shifts during a run due to changes in the instrument such as swapping detector packages. During the first few years of operation we did not monitor the dawn and dusk sky. To bring observations from those years onto the CfA sky-calibrated system we have solved for the run-to-run shifts using a global solution of 23572 observations of 1002 stars that have been observed since the beginning, including many IAU standards and stars in various binary surveys.

3. Absolute Velocity Zero Point. To establish the absolute velocity zero point of the CfA system and as an independent check of the long-term stability achieved using sky exposures for the run-to-run corrections, we have been monitoring minor planets for more than 13 years and have accumulated 1245 exposures of 35 different minor planets. The observed velocities are compared to velocities predicted from the astrometric orbit by the IAU Minor Planet Center (Marsden & Bardwell, private communication). These observations confirm that there is no drift in the velocity zero point based on the sky exposures, but the sky calibration gives velocities which are too positive by 81 m s^{-1} when the old templates are used and by 136 m s^{-1} when the new templates are used (because we have chosen to continue to use the same old synthetic template for the sky velocity reductions, and there is a shift of 55 m s^{-1} between the old and new synthetic template for the sun). The formal uncertainty (the standard deviation of the mean) in these velocity shifts is 14 m s^{-1}, but undoubtedly the systematic errors are larger. In particular, the gravitational redshift is not included in our synthetic spectra, so the CfA velocities for giants are systematically blueshifted by values on the order of 0.2 km s^{-1}.

4. Standard Star Results. The status of the CfA observations of IAU standards and new G dwarf candidate standards are summarized in Tables 1 and 2, respectively. These velocities were derived using the new synthetic templates, so 136 m s^{-1} should be subtracted in order to transfer to the absolute velocity zero point established by the CfA observations of minor planets. Columns 1 to 3 give the star identifications; columns 4 and 5 the J2000 coordinates; column 8 and 9 the number of observations and the time spanned in days; column 10 the mean velocity; columns 11 and 12 the standard deviation of the mean and the standard deviation of an individual observation from the mean; column 13 the source of the star; and column 14 a recommendation for stars that should

be rejected. Notes on the stars that are recommended for rejection are given below.

HD 14969. Griffin (1980) reported a spectroscopic orbit with P = 1935 days and $K = 4.43$ km s^{-1}.

HD 20902. Shortly after being proposed as a standard, this star was reported to have velocity variations larger than 2 km s^{-1} and was rejected (Heard 1960).

HD 29587. Mazeh et al. (1996) reported a spectroscopic orbit. A new CfA solution, updated to include the recent observations, gives $P = 1470$ days and $K = 0.89$ km s^{-1}.

HD 35410. The combined CfA and Victoria velocities give a spectroscopic orbit with $P = 1493$ days, $K = 1.96$ km s^{-1}, and $e = 0.72$.

HD 36673. The CORAVEL team reported this star to have velocity variations larger than 1 km s^{-1}.

HD 42397. Scarfe (1992) reported this star to be a double-lined spectroscopic binary with long period and high eccentricity. Recent CfA observations confirm that the spectrum is composite.

HD 44131. Duquennoy & Mayor (1991) reported a spectroscopic orbit with $P = 3393$ days and $K = 1.18$ km s^{-1}.

HD 45348. Shortly after being proposed as a standard, this star was reported to have velocity variations larger than 3 km s^{-1} and was rejected (Heard 1960).

HD 114762. Latham et al. (1989) reported a spectroscopic orbit with P = 84 days and K = 0.59 km s^{-1}. Mazeh et al. (1996) updated the orbital solution.

HD 115521. Many observers have reported that the velocity of this star is variable. There is a long-term variation, probably due to orbital motion with $P > 6000$ days and $K \sim 4$ km s^{-1}. There is also a short-period oscillation with $P = 470$ days.

HD 123782. Duquennoy & Mayor (1991) reported a spectroscopic orbit with $P = 494$ days and $K = 0.87$ km s^{-1}.

HD 140913. Stefanik et al. (1994) reported a spectroscopic orbit based on the combined CfA and Victoria velocities. Mazeh et al. (1996) reported an updated orbital solution with $P = 148$ days and $K = 1.93$ km s^{-1}.

HD 156014 = α Her. This supergiant is a member of a quadruple system surrounded by a circumstellar envelope. The visual companion is itself a double-lined spectroscopic binary with $P = 51.6$ days, and is separated by 4.7$''$ from the primary. The primary itself has a speckle companion at a separation of 0.19$''$ and expected period longer than 100 yr. The velocity variations of the primary exceed 1 km s^{-1}, but show no clear periodicity.

HD 171232. The combined CfA and Victoria velocities show a slow drift downward of 5 km s^{-1} over the past 16 yr.

HD 184467. McClure (1983) reported that this star is a double-lined spectroscopic binary. CfA observations yield an orbit with $P = 493$ days and $K = 7$ km s^{-1}.

HD 206778. The CfA velocities show a recent decrease of about 1.5 km s^{-1}.

HD 223094. The CfA velocities show a variation with $P \sim 500$ days and $K \sim 0.6$ km s^{-1}.

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Table 1.: CfA Native Velocities of IAU Radial-Velocity Standard Stars

HD	HR	Name	α (J2000)	δ	V	Sp	N	Span	RV	err	sd	List	Rej
693	33	6 Cet	00:11:15.9	−15:28:05	4.89	F5 V	70	5880	+14.50	±0.04	0.33	F	
3712	168	18 α Cas	00:40:30.4	+56:32:14	2.24	K0 II-IIIvar	0	0				B	
3765			00:40:49.3	+40:11:14	7.36	K2 V	110	5957	−63.32	±0.05	0.54	F	
4128	188	16 β Cet	00:43:35.4	−17:59:12	2.04	K0 III	89	3021	+13.25	±0.04	0.41	B	
4388			00:46:27.0	+30:57:06	7.34	K3 III	145	5660	−27.40	±0.04	0.46	HF	
8779	416		01:26:27.3	−00:23:56	6.42	K0 IV	220	5982	−3.98	±0.03	0.42	F	
9138	434	98 μ Psc	01:30:11.1	+06:08:38	4.84	K4 III	41	5976	+34.37	±0.06	0.38	HF	
12029			01:58:41.9	+29:22:48	7.43	K2 III	2	1	+38.57	±0.22	0.19	HF	
12929	617	13 α Ari	02:07:10.4	+23:27:45	2.01	K2 III	46	2243	−14.48	±0.06	0.39	B	
14969			02:25:31.2	+29:52:49	7.8	K3 III	0	0				HF	Rej
18884	911	92 α Cet	03:02:16.7	+04:05:23	2.54	M2 III	73	3303	−25.57	±0.07	0.41	B	
20902	1017	33 α Per	03:24:19.4	+49:51:40	1.79	F5 Ib	0	0				B	Rej
22484	1101	10 Tau	03:36:52.4	+00:24:01	4.29	F9 V	159	6039	+27.92	±0.03	0.37	F	
23169			03:43:53.1	+25:43:32	8.50	G2 V	2	24	+14.36	±0.18	0.05	HF	
26162	1283	43 Tau	04:09:10.0	+19:36:33	5.51	K2 III	303	6042	+24.77	±0.02	0.39	F	
29139	1457	87 α Tau	04:35:55.2	+16:30:33	0.87	K5 III	99	4363	+54.15	±0.04	0.41	B	
29587			04:41:36.3	+42:07:02	7.29	G2 V	163	6074	+112.42	±0.06	0.79	F	Rej
32963			05:07:55.8	+26:19:41	7.60	G5 IV	7	3067	−62.49	±0.14	0.33	HF	
36079	1829	9 β Lep	05:28:14.7	−20:45:34	2.81	G5 II	31	3358	−13.92	±0.06	0.31	B	
35410	1787	27 Ori	05:24:28.9	−00:53:29	5.07	K0 III	26	5988	+20.76	±0.14	0.71	F	Rej
36673	1865	11 α Lep	05:32:43.8	−17:49:20	2.58	F0 Ib	0	0				B	Rej
42397			06:11:34.7	+25:00:35	7.82	G0 IV	128	1967	+37.82	±0.08	0.96	HF	Rej
44131	2275		06:19:59.6	−02:56:40	4.91	M1 III	32	6065	+48.54	±0.23	1.29	B	Rej
45348		α Car	06:23:57.1	−52:41:44	−0.62	F0 Ib	0	0				B	Rej
51250	2593	18 μ CMa	06:56:06.6	−14:02:36	5.00	B9.5 V	15	6003	+18.39	±0.10	0.26	F	
62509	2990	78 β Gem	07:45:19.0	+28:01:34	1.16	K0 IIIvar	57	2400	+3.26	±0.07	0.52	B	
65583			08:00:32.2	+29:12:45	6.97	G8 V	249	5999	+14.66	±0.04	0.57	F,COR	
65934			08:02:11.1	+26:38:16	7.70	G8 III	1	0	+36.92	±0.15	0.00	HF	
66141	3145		08:02:15.9	+02:20:04	4.39	K2 III	234	5978	+71.74	±0.03	0.41	F	
75935			08:53:49.9	+26:54:48	8.46	G8 V	0	0				HF	
80170	3694		09:16:57.1	−39:24:05	5.31	K2 III	0	0				F	
81797	3748	30 α Hya	09:27:35.2	−08:39:31	1.97	K3 III	102	4403	−4.38	±0.05	0.46	B	

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HD	HR	Name	α (J2000) δ		V	Sp	N	Span	RV	err	sd	List	Rej
84441	3873	17 ϵ Leo	09:45:51.1	+23:46:27	2.97	G0 II	0	0				B	
86801			10:01:39.4	+28:31:19	8.25	GO V	2	3779	−9.98	±0.81	1.15	HF	
89449	4054	40 Leo	10:19:44.2	+19:28:15	4.78	F6 IV	266	6211	+5.98	±0.04	0.58	F	
90861			10:29:53.7	+28:34:52	6.88	K2 III	68	5151	+37.19	±0.05	0.41	HF	
92588	4182	33 Sex	10:41:24.2	−01:44:29	6.25	K1 IV	135	5992	+42.68	±0.04	0.47	F	
102494			11:47:56.4	+27:20:26	7.48	G8 IV	243	5206	−21.97	±0.04	0.56	HF	
102870	4540	5 β Vir	11:50:41.7	+01:45:53	3.59	F8 V	75	3458	+4.38	±0.05	0.47	B,CFH	
103095	4550		11:52:58.8	+37:43:07	6.42	G8 Vp	294	5994	−98.21	±0.04	0.47	F	
107328	4695	16 Vir	12:20:21.0	+03:18:45	4.97	K1 III	95	6175	+36.53	±0.05	0.51	F	
108903	4763	γ Cru	12:31:10.0	−57:06:47	1.59	M4 III	0	0				B	
109379	4786	9 β Crv	12:34:23.2	−23:23:48	2.65	G5 II	0	0				B	
112299			12:55:28.3	+25:44:17	8.39	F8 V	168	5169	+3.76	±0.04	0.56	HF	
114762			13:12:19.7	+17:31:01	7.30	F9 V	520	5934	+49.16	±0.03	0.69	F	Rej
115521	5015	60 σ Vir	13:17:36.3	+05:28:11	4.78	M2 III	161	5999	−29.20	±0.15	1.96	F	Rej
122693			14:02:52.1	+24:33:42	8.11	F8 V	102	3640	−5.74	±0.04	0.44	HF	
123782	5300	13 Boo	14:08:17.3	+49:27:29	5.26	M2 III	33	5967	−14.12	±0.13	0.76	F	Rej
124897	5340	16 α Boo	14:15:39.7	+19:10:57	−0.05	K2 IIIp	108	3429	−5.14	±0.04	0.42	B	
126053	5384		14:23:15.3	+01:14:30	6.25	G1 V	91	6172	−19.45	±0.04	0.42	F,COR	
132737			14:59:52.4	+27:09:37	7.64	K0 III	108	5176	−23.76	±0.05	0.49	HF	
136202	5694	5 Ser	15:19:18.8	+01:45:55	5.04	F8 III-IV	238	5891	+54.35	±0.03	0.44	F	
140913			15:45:07.5	+28:28:12	8.06	G0 V	150	5111	−20.10	±0.09	1.12	HF	Rej
144579			16:04:56.8	+39:09:23	6.66	G8 V	74	5918	−59.53	±0.05	0.40	F	
145001	6008	7 κ Her	16:08:04.5	+17:02:49	5.00	G8 III	65	6219	−10.39	±0.05	0.39	F	
146051	6056	1 δ Oph	16:14:20.7	−03:41:39	2.73	M1 III	185	5767	−19.30	±0.03	0.47	B	
149803			16:35:54.3	+29:44:44	8.58	F7 V	238	5176	−7.62	±0.04	0.63	HF	
150798	6217	α TrA	16:48:39.9	−69:01:40	1.91	K2 IIb-IIIa	0	0				B	
154417	6349		17:05:16.8	+00:42:09	6.00	F9 V	140	6176	−16.89	±0.04	0.52	F,COR	
156014		64 α Her	17:14:38.9	+14:23:25	2.78	M5 IIvar	219	3639	−30.24	±0.10	1.50	B	Rej
157457	6468	κ Ara	17:26:00.1	−50:38:01	5.19	K1 III	0	0				F	
161096	6603	60 β Oph	17:43:28.4	+04:34:02	2.76	K2 III	90	3291	−12.29	±0.04	0.42	B	
168454	6859	19 δ Sgr	18:20:59.6	−29:49:42	2.72	K3 III	0	0				B	
171232			18:32:35.9	+25:29:22	7.44	G8 III	211	5773	−38.27	±0.06	0.89	HF	Rej
171391	6970		18:35:02.4	−10:58:38	5.12	G8 III	79	6028	+7.50	±0.05	0.47	F	

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HD	HR	Name	α (J2000) δ		V	Sp	N	Span	RV	err	sd	List	Rej
182572	7373	31 Aql	19:24:58.0	+11:56:40	5.17	G8 IVvar	320	6100	−100.22	±0.02	0.41	F	
		+28 3402	19:35:00.2	+29:05:13	8.88	F5 V	186	5770	−36.52	±0.05	0.66	HF	?
184467			19:31:08.0	+58:35:10	6.60	K1 V	81	6096	+10.90	±0.16	1.47	F	Rej
186791	7525	50 γ Aql	19:46:15.6	+10:36:48	2.72	K3 II	0	0				B	
187691	7560	54 o Aql	19:51:01.6	+10:24:57	5.12	F8 V	178	6217	+0.04	±0.03	0.44	F,COR	
194071			20:22:37.6	+28:14:47	7.80	G8 III	175	5768	−9.38	±0.05	0.66	HF	?
203638	8183	33 Cap	21:24:09.6	−20:51:02	5.38	K0 III	48	5848	+22.17	±0.06	0.39	F	
204867	8232	22 β Aqr	21:31:33.5	−05:34:16	2.90	G0 Ib	88	3270	+6.36	±0.06	0.56	B	
206778	8308	8 ϵ Peg	21:44:11.2	+09:52:30	2.38	K2 Ibvar	40	2243	+3.61	±0.11	0.72	B	Rej
212943	8551	35 Peg	22:27:51.5	+04:41:44	4.78	K0 III	143	6099	+54.22	±0.04	0.44	F	
213014			22:28:11.5	+17:15:48	7.45	G9 IIIcomp	328	6100	−39.68	±0.02	0.41	F	
213947			22:34:36.5	+26:35:54	6.88	K2	116	5775	+16.49	±0.06	0.69	HF	?
222368	8969	17 ι Psc	23:39:57.0	+05:37:35	4.13	F7 V	113	5679	+5.47	±0.04	0.41	B	
223094			23:46:25.5	+28:42:13	6.97	K5 III	89	5779	+19.90	±0.07	0.70	HF	Rej
223311	9014		23:48:32.5	−06:22:50	6.09	K4 III	27	5943	−20.11	±0.08	0.41	F	
223647	9032	1 γ Oct	23:52:06.5	−82:01:08	5.10	G7 III	0	0				F	

Table 2. CfA Native Velocities of Candidate G-Dwarf Radial-Velocity Standard Stars

HD	HR	Name	α (J2000)	δ	V	Sp	N	Span	RV	err	sd	List
1461	72		00:18:41.9	−08:03:11	6.47	G0 V	25	2275	−10.21	±0.11	0.56	COR
1835	88	9 Cet	00:22:51.8	−12:12:34	6.39	G3 V	32	2993	−2.61	±0.07	0.41	COR
10700	509	τ Cet	01:44:04.1	−15:56:15	3.49	G8 V	14	4117	−16.75	±0.08	0.22	CFH
16895	799	13 θ Per	02:44:12.0	+49:13:42	4.10	F7 V	25	4210	+23.97	±0.07	0.33	COR
19373	937	ι Per	03:09:04.0	+49:36:49	4.05	G0 V	17	2346	+49.37	±0.11	0.45	CFH
20630	996	κ^1 Cet	03:19:21.7	+03:22:13	4.84	G5 Vvar	49	2343	+18.84	±0.05	0.37	CFH
22879			03:40:22.1	−03:13:01	6.68	F9 V	49	3715	+120.01	±0.09	0.53	COR
31966			05:00:33.8	+14:23:02	6.75	G5 V	107	2357	−18.08	±0.05	0.55	COR
32923	1656	104 μ Tau	05:07:27.0	+18:38:42	4.91	G4 V	65	2384	+20.36	±0.06	0.47	COR
39881	2067		05:56:03.4	+13:55:30	6.60	G5 IV	55	2396	+0.14	±0.06	0.43	COR
90839	4112	36 UMa	10:30:37.6	+55:58:50	4.82	F8 V	28	2340	+8.31	±0.09	0.48	CFH
111395	4864		12:48:47.1	+24:50:25	6.29	G7 V	68	2347	−9.07	±0.06	0.52	COR
114710	4983	β Com	13:11:52.4	+27:52:42	4.23	G0 V	98	5921	+5.20	±0.05	0.54	CFH
115617	5019	61 Vir	13:18:24.3	−18:18:40	4.74	G5 V	15	2264	−7.90	±0.09	0.35	CFH
118576A			13:37:12.4	+30:05:06	9.32	G8 V	65	3339	+3.76	±0.06	0.48	COR
118576B			13:37:13.8	+30:05:14	10.64	G0	63	3338	+3.76	±0.07	0.53	COR
130948	5534		14:50:15.8	+23:54:43	5.86	G2 V	83	2416	−2.75	±0.06	0.52	COR
131156	5544	37 ξ Boo	14:51:23.4	+19:06:02	4.54	G8 V	82	2440	+1.27	±0.05	0.43	COR,CFH
140538	5853	23 ψ Ser	15:44:01.8	+02:30:55	5.86	G5 V	49	2283	+18.96	±0.06	0.39	COR
146233	6060	18 Sco	16:15:37.3	−08:22:10	5.49	G1 V	31	2440	+11.60	±0.06	0.34	COR
161797	6623	86 μ Her	17:46:27.5	+27:43:14	3.42	G5 IV	98	3707	−16.50	±0.05	0.54	COR
188512	7602	β Aql	19:55:18.8	+06:24:24	3.71	G8 IVvar	43	2410	−40.11	±0.06	0.36	CFH
190360	7670		20:03:37.4	+29:53:49	5.73	G6 IV+	75	2438	−45.31	±0.05	0.46	COR
197076	7914		20:40:45.1	+19:55:08	6.43	G5 V	81	2435	−35.38	±0.05	0.42	COR
217014	8729	51 Peg	22:57:28.0	+20:46:08	5.45	G5 V	87	2436	−33.13	±0.05	0.47	COR

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Discussion

Soderblom: Someone should put up-to-date information on standards on a web page, for access by observers atthe telescope.

Stefanik: We do plan to put it all on the IAU Commission 30 web page.

Soderblom: This is something that could occupy you forever! How do you decide on what grounds to drop objects from your list?

Stefanik: We've pretty well dropped the giants, although Willie Torres continues to take an interest in them. For solar-type stars, we've done essentially all we can; we don't expect to find any more low-mass companions.

Hearnshaw: Why do we need standard stars anyway? Most work on precise velocities of variable stars is now differential. For studies of galactic dynamics we do want absolute velocities, but instead of using standard stars, I suspect that synthetic spectra provide a better standard, as the velocity is preceisely known, and complications such as convective shifts are absent.

Stefanik: One reason is to reduce data runs, by different observers over a long period of time, to a common system. It is also desirable to have stars known to be constant, so that people searching for vary small variations in stars can check the stability of their instruments. But I do agree that the future of standard stars is not clearcut.

Udry: Concerning the systematic color effect between CfA and Coravel, you use different synthetic spectra for different stars. Are you not risking the introduction of a color effect?

Stefanik: Comparisons with others, such as Griffin, for groups such as the Hyades, show no color effect. We try to match templates to the observed stars carefully, to avoid one. The amount that remains between Coravel and CfA is still a problem.

Latham: I have experimented with our library of synthetic templates, to see what kind of velocity errors can result from template mismatch. It is not difficult to get differences as large as 1 km s^{-1} from that source, when the templates are drawn from the range of temperatures covered by our library, 3500 to 11 000 K. Rotational velocity mismatch can be even more important, especially for large $v \sin i$ values, say in the range 50 to 100 km s^{-1}. Our goal is to minimize the effects of mismatch by identifying a template that is closely similar to the observed spectrum, but it is hard to quantify how large the residual effects might be. I would be disappointed if they prove to be as large as 0.5 km s^{-1} for the cool dwarfs, as would be required to match the new proposed ELODIE velocity scale.

Gray: My comment is the flip side of John's. It seems to me that a coherent grid of radial velocities across the HR diagram is highly desirable, and if that is true, then we should be establishing what you call the absolute zero-point for all spectral types. Pinning the zero-point with the solar system is good, but not enough. Convective shifts of spectral lines vary systematically across the HR diagram, possibly from star to star, and certainly with wavelength. Do we have enough data in the world to look at things like the mean radial velocity of all

B stars, or all A stars, for example, to see if there is a net residual? Do they appear to be expanding away from us or contracting toward us? Or have we looked at cluster stars to see if we get the same velocity from groups of stars along the main sequence? There may be other such tests. Although this is probably beyond the mandate of your original project, shouldn't someone be tackling this basic problem.

Stefanik: I think that's for the future. The early standards are still in difficult shape, as Frank Fekel will soon tell us. We're stuck with the current set of stars for historical reasons; they represent an enormous amount of work, which we don't want to throw out.

Hearnshaw: In stellar photometry, however, we junked the whole sysem in the 1950's and started again.

Stefanik: We haven't done that!