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SECONDARY STANDARD STARS FOR ABSOLUTE SPECTROPHOTOMETRY

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ABSTRACT

Based on an adopted absolute spectral energy distribution for the primary standard star α Lyrae, absolute fluxes are given for four very metal-deficient F type subdwarfs HD 19445, HD 84937, BD +26°2606, and BD +17°4708. Somewhat inferior data are also given for HD 140283. The data are given for 40 Å bands and cover the wavelength range from 3080 Å to 12000 Å. The four stars, all near magnitude 9 and distributed around the sky, are intended as secondary standards for absolute spectrophotometry.

Subject headings: spectrophotometry — stars: subdwarfs — stars: weak-line

I. INTRODUCTION

When the Multichannel Spectrophotometer was put into operation in 1969 on the Hale 5.08 m telescope, it was necessary to set up a series of spectrophotometric standard stars around the sky for calibration purposes. Since the instrument covered the range from 3200 Å to 11000 Å and measured at all wavelengths, it was desirable to have standards with moderately flat spectra with as weak features as possible. Since F type subdwarfs of very low metallicity matched these requirements very well, the standards chosen were a set of four such stars at about visual magnitude 9. The standards were HD 19445, HD 84937, HD 140283, and BD +17°4708. In 1978 BD +26°2606 was introduced as an additional standard and HD 140283, which is at a declination of −11°, was gradually phased out. The absolute calibration for these stars, called AB_{69}, was based on limited comparisons with α Lyrae and other A type secondary standards (Oke 1964) and was intended to be preliminary only. It was realized that small color and magnitude errors would be present and that the calibration near the Balmer lines and in the 3700–4100 Å region would be quite uncertain because A stars are not calibrated in these wavelength regions.

Four years ago a program was carried out to improve the absolute calibrations of these stars. The process used and the results, called AB_{79}, are described in this paper.

II. CALIBRATION PROCEDURE

The process of recalibrating the five stars was done in the following steps. (1) A choice was made for the absolute calibration of the primary standard α Lyrae. (2) The adopted calibration of α Lyrae was transferred directly to BD +17°4708 using a nearby intermediate magnitude star. This is possible since all the stars are in the same part of the sky. (3) The calibration for each star was corrected in the 3700–4100 Å region and near the Balmer lines using data from very hot nearby line-free subdwarfs. (4) The other standard stars were calibrated by intercomparing them among themselves and with BD +17°4708 on many photometric nights.

Extinction is calculated as a_λ sec z where the table of coefficients a_λ was derived using the recipe recommended by Hayes and Latham (1975). The quality of the night is judged by comparing the instrumental sensitivity derived from different standards observed at different air masses at different times during the night. On the nights used for the comparisons below, these differences amounted to at most 0.02 mag over the whole range of observed wavelengths and for values of sec z less than 2.

Below we discuss each of these steps in detail.

1. *The absolute calibration of α Lyrae*. Two absolute calibrations of α Lyrae were available, one by Hayes (1970) and one by Oke and Schild (1970). Hayes and Latham (1975) have compared the two calibrations and adopted a mean calibration which is given in their Table 7. We have adopted this mean absolute calibration except in the very far red where it has been smoothed slightly using an interpolated $T_e = 9700$ K, $\log g = 4.0$ model atmosphere based on models by Kurucz, Peytremann, and Avrett (1974). The model is used only to smooth points, not to alter the slope in any way. The points at 7550 Å and 7780 Å in Table 7 of

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TABLE 1

ABSOLUTE SPECTRAL ENERGY DISTRIBUTIONS FOR α LYRAE AND SUBDWARF STANDARDS

		AB	AB$_{79}$				
λ	$1/\lambda$	α Lyr	19445	84937	+26°2606	+17°4708	140283
3080	3.247	...	9.476	9.677	11.155	10.955	9.05
3160	3.165	...	9.391	9.610	11.072	10.872	8.82
3240	3.086	1.220	9.310	9.542	10.998	10.798	8.63
3320	3.012	1.193	9.232	9.480	10.935	10.718	8.52
3400	2.941	1.168	9.168	9.422	10.866	10.663	8.43
3480	2.874	1.142	9.103	9.370	10.806	10.601	8.36
3560	2.809	1.120	9.039	9.310	10.750	10.536	8.30
3640	2.747	1.096	8.979	9.269	10.698	10.487	8.23
3680	2.717	1.085	8.945	9.243	10.670	10.452	8.20
3720	2.688	...	8.919	9.205	10.651	10.426	8.16
3760	2.660	...	8.849	9.099	10.540	10.307	8.05
3800	2.632	...	8.731	8.937	10.394	10.163	7.93
3840	2.604	...	8.744	8.910	10.393	10.157	7.91
3880	2.577	...	8.702	8.873	10.356	10.118	7.88
3920	2.551	...	8.702	8.815	10.292	10.121	7.85
3960	2.525	...	8.690	8.843	10.318	10.120	7.84
3980	2.513	...	8.681	8.841	10.317	10.091	7.84
4000	2.500	...	8.500	8.667	10.144	9.890	7.68
4020	2.488	...	8.483	8.642	10.116	9.866	7.68
4060	2.463	...	8.479	8.640	10.104	9.873	7.68
4100	2.439	...	8.527	8.726	10.184	9.941	7.74
4140	2.415	...	8.403	8.572	10.060	9.790	7.59
4200	2.381	-0.235	8.385	8.548	10.021	9.765	7.56
4240	2.358	-0.228	8.373	8.543	10.005	9.758	7.55
4260	2.347	-0.223	8.378	8.547	10.008	9.760	7.55
4300	2.326	...	8.434	8.602	10.060	9.830	7.56
4340	2.304	...	8.483	8.691	10.139	9.869	7.67
4380	2.283	...	8.296	8.522	9.971	9.714	7.49
4400	2.273	-0.197	8.293	8.496	9.955	9.690	7.47
4560	2.193	-0.160	8.235	8.448	9.908	9.637	7.42
4760	2.101	-0.120	8.180	8.400	9.843	9.573	7.34
4800	2.083	-0.110	8.157	8.400	9.824	9.558	7.33
4820	2.075	...	8.166	8.398	9.822	9.574	7.32
4860	2.058	...	8.250	8.522	9.930	9.679	7.42
4900	2.041	...	8.136	8.393	9.804	9.535	7.30

		AB	AB$_{79}$				
λ	$1/\lambda$	α Lyr	19445	84937	+26°2606	+17°4708	140283
4920	2.033	-0.084	8.134	8.383	9.800	9.533	7.30
4960	2.016	-0.075	8.130	8.359	9.782	9.531	7.27
5000	2.000	-0.066	8.118	8.351	9.768	9.520	7.26
5120	1.951	-0.040	8.081	8.332	9.741	9.491	7.23
5240	1.908	-0.015	8.048	8.315	9.719	9.465	7.21
5400	1.852	+0.018	8.014	8.290	9.693	9.434	7.17
5560	1.799	+0.045	7.982	8.266	9.660	9.405	7.12
5760	1.736	+0.087	7.948	8.237	9.630	9.374	7.08
6020	1.661	+0.135	7.908	8.202	9.594	9.337	7.04
6420	1.558	+0.203	7.862	8.174	9.552	9.294	6.97
6460	1.548	+0.212	7.858	8.171	9.548	9.289	6.96
6500	1.538	+0.220	7.854	8.178	9.550	9.290	6.95
6540	1.529	...	7.890	8.245	9.590	9.348	6.98
6560	1.524	...	7.948	8.313	9.637	9.406	7.02
6580	1.520	...	7.907	8.244	9.597	9.344	6.98
6620	1.511	+0.237	7.845	8.176	9.545	9.282	6.93
6660	1.502	+0.242	7.843	8.166	9.539	9.274	6.93
6700	1.493	+0.250	7.840	8.162	9.535	9.270	6.93
6740	1.484	+0.255	7.839	8.161	9.532	9.267	6.93
6780	1.475	+0.262	7.837	8.150	9.527	9.262	6.93
7100	1.408	+0.313	7.812	8.133	9.502	9.233	6.89
7460	1.340	+0.372	7.790	8.125	9.485	9.216	6.86
7780	1.285	+0.422	7.776	8.123	9.474	9.211	6.84
8100	1.235	+0.470	7.760	8.112	9.463	9.200	6.83
8380	1.193	...	7.759	8.111	9.457	9.194	6.81
8780	1.139	...	7.755	8.115	9.457	9.194	6.80
9300	1.075	...	7.752	8.119	9.458	9.195	6.81
9700	1.031	+0.525	7.752	8.123	9.458	9.195	6.84
9940	1.006	+0.565	7.752	8.130	9.461	9.198	6.86
10260	0.975	+0.610	7.752	8.137	9.462	9.199	6.88
10820	0.924	+0.690	7.760	8.150	9.468	9.205	...
11140	0.898	(+0.740)	7.760	8.160	9.473	9.210	...
12000	0.833	(+0.853)	7.763	8.180	9.488	9.225	...

Hayes and Latham have been raised by 1.5% while the point at 4465 Å has been decreased by 1.5%. It should be noted that this calibration of α Lyrae has no points near the Paschen jump from 8300 Å to 9500 Å and near the Balmer jump between 3700 Å and 4032 Å. There is also no calibration near Hα, Hβ, Hγ, and Hδ. The absolute calibration adopted for α Lyrae is given in Table 1. The gaps reflect the omitted regions above. We have also adopted the Oke and Schild (1970) absolute flux measurement at 5480 Å and an apparent visual magnitude for α Lyrae of $V = +0.03$. On this basis we define a monochromatic magnitude

$$AB = -2.5 \log f_\nu + 48.60,$$

where f_ν is the flux in ergs cm^{-2} s^{-1} Hz^{-1}. The constant is chosen such that $AB = V$ for an object with a flat spectrum; practically, $AB = V$ at 5480 Å for objects with relatively smooth spectra.

2. *Transfer of the calibration for α Lyrae to BD +17°4708*. This transfer was carried out with the Multichannel Spectrophotometer on the Hale telescope on two nights using the intermediate magnitude A3 V star HD 196180, which has $V = 4.64$ and $B - V = 0.10$. The transfer from α Lyrae to HD 196180 was done with the telescope diaphragmed to 2.5 m (actually one-eighth of the total mirror area) and with a neutral density $D = 2$ glass filter which gives an effective mirror diameter of 18 cm. HD 196180 was then compared with BD +17°4708 again with the telescope diaphragmed to 2.5 m, but with no neutral density filter. This procedure guaranteed that pulse counting rates would be within very safe limits and the telescope and spectrometer optics identical for each comparison. The comparisons were made over a very short interval of time and at a nearly constant air mass. If one omits wavelength bands where spectral features occur, it is found empirically that the magnitude differences AB (17°4708) − AB(α Lyrae) define three linear relations for each of the Paschen (9500–10500 Å), Balmer (4000–8300 Å), and Lyman (3180–3700 Å) continuum regions. Using these linear relations to smooth measuring errors which may be as large as 0.03 mag in the far-violet and far-red, we obtain the new energy distribution AB_{79} for BD +17°4708 from 3180 to 10500 Å but with the wavelength gaps from α Lyrae still present. To extrapolate the energy distribution redward of 10500 Å and to estimate the fluxes in the Paschen jump 8300–9500 Å region for BD +17°4708, a model atmosphere interpolated among unpublished line-free models similar to those described by Mihalas (1965) was fitted to the observed fluxes between 5000 and 10500 Å. The model was used to generate smooth fluxes between 8300 Å and 9500 Å and to add far-infrared points at 10800 Å, 11100 Å, and 12000 Å. The model also indicated that the measured flux at 10400 Å should be brightened by 1.5%.

3. *Calibration near Balmer lines and the Balmer limit*. As has already been noted, α Lyrae cannot provide any absolute calibration near Balmer lines or near the Balmer series limit. The new cool extreme subdwarf standards have much weaker Balmer lines than α Lyrae and also only very weak metal lines, so they can be used for calibrating these spectral regions in unknown stars if they themselves can be calibrated. Calibration of the subdwarfs in these spectral regions can be done only by interpolation using stars which are known to have no spectral features and at the same time smooth continua. A group of very hot subdwarfs, BD +28°4211, Feige 34, and Feige 67, which almost fulfill these requirements, was used for this purpose. These stars have very weak Balmer and He II lines in their spectra. Errors of several percent would have been made by ignoring the features in our 40 Å bands. They were therefore measured on calibrated photographic spectra kindly lent to us by Dr. J. L. Greenstein. Intercomparison of results from several plates of BD +28°4211 and Feige 67 indicates that typical accuracies of 5% in the equivalent widths are achieved; this translates into uncertainties in the fluxes of less than 1% in our bands. By insisting that the hot subdwarfs have smooth continua, apart from the faint line features, it is possible to generate an energy distribution for BD +17°4708 on a point-by-point basis over limited wavelength intervals. This process when applied and added to the limited calibration in step (2) above yields a complete absolute calibration for BD +17°4708 in all wavelength bands. The difference between this new calibration and the older one, AB_{69}, is shown in Figure 1 in two parts. Figure 1*a* shows the smooth difference which is caused by the adopted change in the absolute calibration of α Lyrae and by any slight color errors in the observations, while Figure 1*b* shows the point-by-point corrections produced from the hot subdwarf data. The old AB_{69} calibration corrected by using the hot stars will be referred to as AB_{77}. AB_{77} numbers were also generated for HD 19445, HD 84937, and HD 140283. The corrections are similar but different in detail from those shown in Figure 1*b*.

4. *Calibration of the remaining standard stars*. The final step is to generate AB_{79} calibrations for the remaining standards. Observations made with the Multichannel Spectrophotometer on excellent nights were used to measure the difference AB(BD +17°4708) − AB(19445), etc., at selected wavelengths where there are no spectral features. One difference is shown in Figure 1*c*. These smooth differences were used to convert AB_{77} to AB_{79} numbers for HD 19445, HD 84937, and HD 140283 standards. Model atmospheres were used to smooth the calibration between 3160 Å and 3720 Å where only very weak lines should exist. These corrections are typically 0.01–0.02 mag except for two points in HD 84937 which have 0.04 and 0.05 mag corrections near 3200 Å. In the case of HD 140283, fewer data are

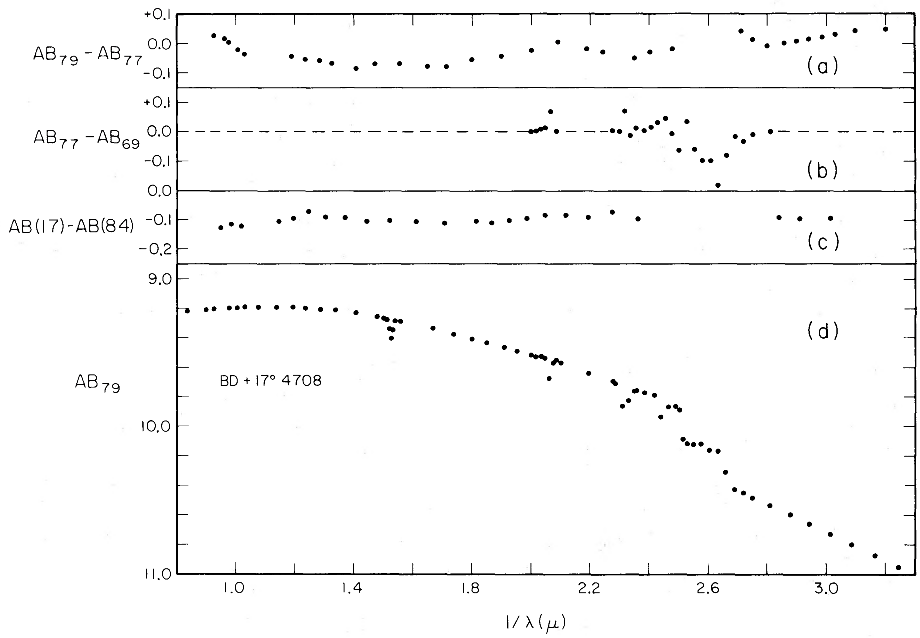

FIG. 1.—(a) The difference between AB_{79} and AB_{77} for BD +17°4708. This reflects primarily the change in the adopted calibration of α Lyrae. (b) Corrections to the AB_{69} calibration of BD +17°4708 based on the hot subdwarf star observations. (c) The difference in fluxes between BD +17°4708 and HD 84937 at selected continuum wavelengths. (d) The adopted AB_{79} absolute spectral energy distribution for BD +17°4708.

TABLE 2

$AB_{79} - AB_{69}$ FOR SUBDWARF STANDARDS

λ	19445	84937	+17°4708	+26°2606	140283	λ	19445	84937	+17°4708	+26°2606	140283
3080	0.08	0.16	0.06	0.06	0.03	5120	0.01	+0.07	-0.04	0.02	-0.04
3160	0.08	0.13	0.05	0.06	0.02	5240	0.00	0.07	-0.04	0.03	-0.04
3240	0.06	0.09	0.04	0.09	0.01	5400	-0.02	0.06	-0.05	0.02	-0.04
3320	0.05	0.08	0.03	0.10	0.00	5560	-0.03	0.05	-0.06	0.01	-0.06
3400	0.05	0.09	0.02	0.10	-0.01	5760	-0.05	0.04	-0.07	0.00	-0.06
3480	0.06	0.10	0.01	0.09	-0.02	6020	-0.06	0.03	-0.08	-0.02	-0.06
3560	0.04	0.10	-0.01	0.09	-0.03	6420	-0.06	0.03	-0.07	-0.03	-0.07
3640	0.04	0.13	0.01	0.10	-0.02	6460	-0.06	0.03	-0.07	-0.03	-0.07
3680	0.03	0.14	0.01	0.10	0.00	6500	-0.06	0.03	-0.07	-0.02	-0.08
3720	0.03	0.14	0.02	0.11	0.00	6540	-0.06	0.03	-0.07	-0.03	-0.07
3760	-0.01	0.10	-0.05	+0.05	-0.06	6580	-0.06	0.03	-0.07	-0.02	-0.08
3800	-0.09	0.07	-0.03	-0.03	-0.12	6620	-0.06	0.03	-0.07	-0.02	-0.08
3840	-0.05	0.16	-0.09	+0.04	-0.07	6660	-0.06	0.03	-0.07	-0.01	-0.07
3880	-0.06	0.07	-0.09	+0.04	-0.06	6700	-0.06	0.03	-0.07	-0.01	-0.07
3920	-0.01	0.00	-0.06	-0.01	-0.08	6740	-0.06	0.03	-0.07	-0.01	-0.07
3960	0.06	0.04	0.03	0.06	-0.04	6780	-0.06	0.02	-0.07	-0.01	-0.06
4000	-0.05	-0.05	-0.07	-0.04	-0.09	7100	-0.07	0.02	-0.08	-0.02	-0.07
4040	0.00	0.07	-0.03	-0.01	-0.03	7460	-0.07	0.02	-0.08	-0.02	-0.07
4080	0.04	0.05	0.02	0.02	-0.03	7780	-0.05	0.02	-0.06	-0.02	-0.07
4120	0.03	0.08	0.00	0.06	-0.03	8100	-0.04	0.03	-0.05	0.00	-0.05
4160	0.00	0.03	-0.02	0.00	-0.06	8380	-0.03	0.05	-0.04	0.02	-0.06
4200	0.00	0.04	-0.04	0.01	-0.05	8780	-0.03	0.06	-0.04	0.05	-0.06
4240	-0.01	0.05	-0.04	0.01	-0.05	9300	-0.03	0.06	-0.04	0.05	-0.02
4280	-0.01	0.04	-0.06	0.00	-0.04	9700	-0.02	0.07	-0.04	0.05	0.02
4320	0.05	0.02	0.02	0.04	-0.01	9940	-0.01	0.09	-0.02	0.07	0.05
4360	-0.02	0.03	-0.05	0.01	-0.07	10260	0.00	+0.11	-0.01	+0.06	0.09
4400	-0.02	0.06	-0.04	0.00	-0.05	10820	0.00	0.12	0.00	0.07	...
4560	0.01	0.07	-0.02	0.05	-0.03						
4760	0.03	0.07	+0.01	0.04	-0.03						
4800	0.04	0.08	0.00	0.03	-0.03						
4840	0.08	0.10	0.06	0.07	-0.02						
4880	0.03	0.13	0.00	0.07	-0.03						
4920	0.02	0.09	-0.01	0.02	-0.02						
4960	0.02	0.07	-0.02	0.02	-0.04						
5000	0.02	0.07	-0.02	0.01	-0.04						

available to carry out the above procedures since the star is no longer being used as a standard. AB_{79} for this star is included here mainly to permit older data to be corrected; the calibration is inferior to that of the other standards.

The standard BD +26°2606 must be treated separately since it was added as a standard only in 1978. Detailed differences between BD +26°2606 and BD +17°4708 were generated at every measured wavelength on six excellent nights when the objects were observed at sec $z \lesssim 1.06$. These differences can then be used directly to generate an AB_{79} calibration for BD +26°2606. Points have been smoothed slightly where the spectrum is known to be smooth. Model atmospheres were again used to correct six points by 0.005 ~ 0.015 mag.

III. RESULTS

The original calibrations used 40 Å bands which split Hα, Hβ, and Hγ in the middle, i.e., the bands near Hα were 6520–6560 Å and 6560–6600 Å. These points, when used for calibration, can cause errors if there are small wavelength errors. Additional points, centered on the Balmer lines, are therefore inserted in the table. They have been derived using higher resolution Double Spectrograph data.

The final AB_{79} calibrations are given in Table 1. Very recent work indicates that at 3800 Å the entries for 19445, +26°2606, and 17°4708 should be, respectively, 8.780, 10.420, and 10.230. The fluxes are for 40 Å bands centered at the tabulated wavelength; this is true even when the bands are less than 40 Å apart. Where gaps occur values of AB can be interpolated linearly. The actual energy distribution for BD +17°4708 is shown in Figure 1*d*.

For continuum points the relative uncertainty between the standards, based on multichannel observations, is approximately 0.01 mag. Within lines and near the Balmer limit the uncertainties are larger because the numbers are obtained by using hot subdwarfs and assuming smoothness. The absolute flux accuracy is the same as that of α Lyrae itself. Over the range for 3200 Å to 10000 Å, it is probably not in error by more than 5% in the color over that baseline.

Since the AB_{69} fluxes have been used extensively by many observers, the difference $AB_{79} - AB_{69}$ is listed in Table 2. Note that the wavelength entries are not identical in Tables 1 and 2.

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REFERENCES

Hayes, D. S. 1970, *Ap. J.*, **159**, 165.
Hayes, D. S., and Latham, D. W. 1975, *Ap. J.*, **197**, 593.
Kurucz, R. L., Peytremann, E., and Avrett, E. H. 1974, *Blanketed Model Atmospheres for Early-Type Stars* (Washington, D.C.: Smithsonian Institution).
Mihalas, D. 1965, *Ap. J. Suppl.*, **9**, 321.
Oke, J. B. 1964, *Ap. J.*, **140**, 689.
Oke, J. B., and Schild, R. E. 1970, *Ap. J.*, **161**, 1015.

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