THE ASTROPHYSICAL JOURNAL, 358:344–349, 1990 July 20

THE KITT PEAK SPECTROPHOTOMETRIC STANDARDS: EXTENSION TO 1 MICRON

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Received 1989 October 10; accepted 1990 January 18

ABSTRACT

We extend the wavelength coverage of 11 of the KPNO spectrophotometric standard stars out past 1 μm. The internal agreement is better than a few percent, while the external error at longer wavelengths appears to be 5% or better. We note that the well-known standard star BD +28°4211 has a faint red companion.

Subject headings: infrared: spectra — spectrophotometry

I. INTRODUCTION

In a previous paper (Massey *et al.* 1988, hereafter Paper I) we presented spectrophotometry for 25 stars intended to be used as standards. These stars were chosen from the PG survey (Green, Schmidt, and Liebert 1986) and from spectrophotometric standard star lists (e.g., the "IIDS list" compiled by K. Strom from studies by Oke [1974] and Stone [1974, 1977]) and were selected for having nearly featureless spectra. The need for these new standard observations arose due to the proliferation of linear detectors, particularly CCDs, on spectrographs, making spectrophotometry a common by-product of most spectroscopic observations. However, the coarse spacing of the Hayes and Latham (1975) flux points made the use of the "IIDS" standard stars difficult with CCDs due to the small wavelength coverage usually obtained. The 25 spectrophotometric standard stars presented in Paper I were calibrated at 50 Å intervals and covered the wavelength range $\lambda\lambda$3200–8200.

However, another consequence of the "CCD revolution" is that observations in the far red (i.e., out to 1 μm) are now readily obtainable by mere mortals and are no longer in the exclusive province of the infrared astronomer. The original calibration of Vega and other bright *primary* standards by Hayes (1970) had in fact extended to λ10870. These stars, however are all much too bright ($V = 0$–5.6) to be used with even modest-sized apertures and modern detectors, and the flux points are very coarsely spaced in the red. The excellent *secondary* standards calibrated by Stone (1977), which serve as the basis for Paper I, extend only to λ8370. The Oke (1974) stars are both faint enough and the observations extend far enough to the red for these to be used as *tertiary* standards, and they have proved a valuable resource. However, the conversion of the Oke (1974) fluxes to the Hayes and Latham (1975) system (essentially identical to the Palomar AB79 system of Oke and Gunn 1983) is not straightforward, as discussed in Paper I.

In this paper, we extend the wavelength coverage of 11 of the brighter stars given in Paper 1 out to 1 μm, using the Hayes (1970) standards as a reference. The star identifications are given in Table 1; finding charts and other information can be obtained from Paper I.

[1] NOAO is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

II. OBSERVATIONS AND REDUCTIONS

Our data were collected on 18 nights with the CCD spectrometer ("GoldCam") on the 2.1 m telescope on Kitt Peak. The observing took place between 1988 February and December. In Table 2, we list the total number of observations of each star and, in parentheses, the number of these observations which were photometric. The number of observations is approximately equivalent to the number of different nights on which a star was observed. Occasionally, a star was observed more than once on a given night.

The observations were made using a 158 lines mm^{-1} silvered grating in first order; the grating blaze was at λ6750. The observations covered the range $\lambda\lambda$6600–10300. A slit width of 800 μm (10″) was used to permit most of the light to go down the slit at the cost of spectral resolution (approximately 15 Å). An OG550 filter was used to block second-order blue. The long-slit capability of GoldCam allowed for accurate sky subtraction, which is important in this wavelength region due to the presence of OH emission lines from the night sky.

The data were reduced using the Image Reduction Analysis Facility (IRAF). For each night of data, the following steps were performed. Additive instrumental effects were removed by subtracting the electronic pedestal level and the preflash level from each frame. Dividing each frame by a flat-field exposure removed multiplicative gain and illumination variations across the chip. The one-dimensional spectra for each observation were then extracted from the two-dimensional image by summing the pixels within the aperture at each point along the dispersion axis and subtracting out the sky background. Nightly exposures of a He-Ne-Ar lamp were used to define a wavelength solution for each spectra.

In treating atmospheric extinction, we adopted a mean extinction curve. There is little error introduced by this procedure, since the observations were restricted to small air masses (< 1.5), and since the extinction this far in the red is small in any event. For calibration, we used five *primary* spectrophotometric standards (58 Aql, 29 Psc, ξ^2 Cet, η Hya, and θ Crt) observed by Hayes (1970). There has been a recent attempt to recalibrate these stars by Taylor (1984); for consistency with our earlier work in Paper I, we have used the Hayes (1970) numbers after applying the Hayes and Latham (1975) corrections, as this was the basis of Stone's (1979) observations, upon which the fluxes in Paper I are based. Since these stars are relatively bright, they were observed with a 2.5 mag filter. For each observation of a Hayes standard, the data were summed within the Hayes (1970) bandpasses, although we note that the

TABLE 1

KPNO Spectrophotometric Standards With Coverage to 1 μm

Star	α_{1950}	δ_{1950}	Spectral Type	V	$B-V$	$m_{\lambda 5556}$
G191B2B	05h01m31.5s	+52°45′52″	dAwk	11.80	−0.32	11.85
Hiltner 600	06 42 37.2	+02 11 25	B1V	10.45	+0.18	10.42
PG 0823+546	08 23 01.0	+54 37 58	sdOC	...	...	14.36
Feige 34	10 36 41.2	+43 21 50	sdO	11.23	−0.30	11.25
GD 140	11 34 27.5	+30 04 27	DA2	12.50	−0.06	12.50
Feige 66	12 34 54.7	+25 20 31	sdO	...	...	10.54
Feige 67	12 39 18.9	+17 47 24	sdO	11.82	−0.32	11.89
HZ 44	13 21 19.0	+36 23 39	sdO	11.68	−0.29	11.74
Wolf 1346	20 32 12.9	+24 53 32	DA	11.54	−0.07	11.59
BD +28°4211	21 48 57.1	+28 37 48	sdOp	10.53	−0.34	10.56
Feige 110	23 17 23.5	−05 26 22	sdO	11.50	−0.32	11.88

calibration is relatively insensitive to the bandpass used. In determining the sensitivity function, we found it necessary to correct the nominal exposure times by −0.24 s, a value we determined by several series of exposures of varying lengths of bright stars near the zenith. The brightest stars from Paper I (Hilter 600, Feige 34, Feige 66, HD 192281, HD 217086, and BD +28°4211) were observed both with and without the 2.5 mag filter. The fluxes determined from the calibrated 2.5 mag observations were then used to calibrate the observations of these stars observed without the filter. Finally, the sensitivity functions determined from these observations were used to then calibrate the remaining program stars. Poor agreement between the new observations of HD 192281 and HD 217086 with our earlier work (as described below) caused us to drop these two stars from the present program.

III. ANALYSIS

In calculating the final magnitudes, we decided to use 50 Å bandpasses centered every 50 Å, avoiding regions with known atmospheric absorption lines. The nonphotometric observations were combined with the photometric observations by first combining the photometric observations with no adjustments in level and then applying appropriate gray shifts to the nonphotometric data. Magnitudes were calculated by averaging magnitudes from the photometric and adjusted nonphotometric observations. The average (over all wavelengths) standard deviation and standard deviation of the mean of the magnitude calculations for each star are given in Table 2. The standard deviation shows how well each observation agrees with the mean, while the standard deviation of the mean provides a measure of the internal precision of our observations. We see that the average precision of our data is ~0.01 mag and never worse than ~0.03 mag. Figure 1 shows the individual agreement of our six photometric observations of Feige 110. Note that the regions showing discrepancies are regions of atmospheric absorption which we avoided when calculating final magnitudes. The individual final spectra of the 11 program stars are shown in Figure 2, and the magnitudes are given in Table 3.

Below we give individual comments on specific stars from Paper I.

BD +28°4211.—This star is a well-known standard and is one of the primary *IUE* calibration stars (Bohlin 1986). It was one of the two standards which defined the system of Paper I. During the course of the observations presented here, our alert telescope operator John Booth noted from the acquisition TV monitor that the star appears to have a faint companion. CCD frames obtained by Booth, George Jacoby, Robin Ciardullo, and Taft Armandroff with the 4 m telescope confirms that BD

TABLE 2

Number of Observations and Internal Photometric Agreement

Star	Number of Observations	Photometric Error σ	Photometric Error σ_μ
G191B2B	12(4)	0.037	0.011
Hiltner 600	5(2)	0.041	0.023
PG 0823+546	4(2)	0.059	0.034
Feige 34	11(3)	0.046	0.015
GD 140	8(3)	0.028	0.011
Feige 66	10(3)	0.034	0.011
Feige 67	9(3)	0.037	0.013
HZ 44	7(3)	0.039	0.016
Wolf 1346	15(8)	0.030	0.008
BD +28°4211	20(12)	0.031	0.007
Feige 110	11(6)	0.023	0.007

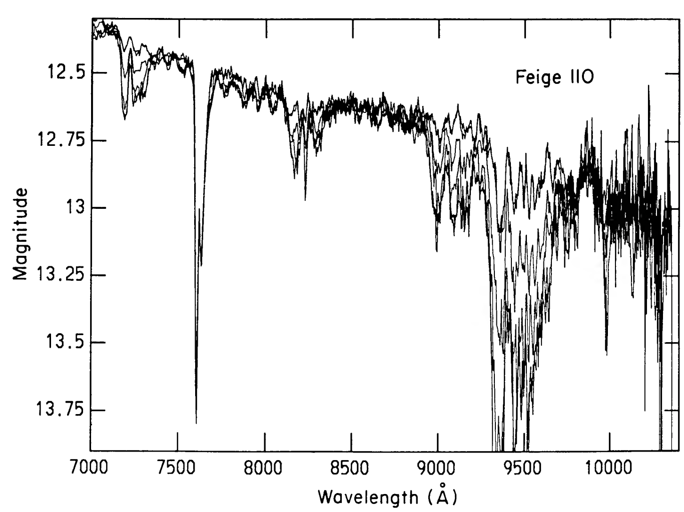

Fig. 1.—The six photometric observations of Feige 110 are shown superposed.

TABLE 3

MAGNITUDES OF STANDARD STARS AT 50 Å INTERVALS

λ	G191B2B	Hiltner 600	PG 0823 +546	Feige 34	GD 140	Feige 66	Feige 67	HZ 44	Wolf 1346	BD +28° 4211	Feige 110
7350.....	12.43	10.57	14.80	11.79	13.04	11.13	12.46	12.30	12.06	11.14	12.45
7400.....	12.42	10.56	14.80	11.79	13.03	11.13	12.46	12.29	12.05	11.13	12.44
7450.....	12.44	10.56	14.82	11.81	13.05	11.14	12.48	12.31	12.07	11.15	12.45
7500.....	12.45	10.56	14.82	11.81	13.06	11.15	12.48	12.32	12.08	11.16	12.46
7750.....	12.51	10.58	14.86	11.86	13.09	11.19	12.53	12.37	12.13	11.22	12.53
7800.....	12.53	10.60	14.89	11.89	13.13	11.23	12.56	12.41	12.15	11.23	12.53
7850.....	12.53	10.57	14.86	11.88	13.12	11.22	12.56	12.40	12.15	11.24	12.55
7900.....	12.55	10.60	14.88	11.88	13.11	11.22	12.57	12.41	12.16	11.26	12.57
7950.....	12.57	10.60	14.91	11.91	13.15	11.25	12.59	12.44	12.18	11.28	12.58
8000.....	12.56	10.59	14.88	11.88	13.12	11.23	12.57	12.41	12.16	11.26	12.57
8050.....	12.59	10.62	14.92	11.91	13.15	11.26	12.61	12.45	12.19	11.30	12.61
8600.....	12.63	10.58	14.94	11.94	13.18	11.29	12.64	12.49	12.22	11.33	12.64
8650.....	12.62	10.57	14.90	11.94	13.18	11.29	12.65	12.49	12.22	11.34	12.65
8700.....	12.63	10.51	14.91	11.93	13.18	11.30	12.63	12.48	12.22	11.33	12.64
8750.....	12.64	10.57	14.88	11.93	13.17	11.29	12.64	12.48	12.23	11.35	12.66
8800.....	12.64	10.51	14.88	11.94	13.17	11.30	12.65	12.49	12.23	11.35	12.67
8850.....	12.65	10.55	14.89	11.93	13.16	11.30	12.63	12.48	12.23	11.35	12.68
8900.....	12.66	10.52	14.94	11.95	13.18	11.30	12.65	12.49	12.24	11.36	12.68
9700.....	12.93	10.68	15.18	12.14	13.41	11.53	12.90	12.75	12.45	11.62	12.94
9750.....	12.95	10.66	15.44	12.14	13.41	11.53	12.92	12.73	12.47	11.63	12.99
9800.....	12.95	10.67	15.19	12.18	13.42	11.57	12.94	12.76	12.47	11.63	12.95
9850.....	12.87	10.61	14.91	12.12	13.40	11.54	12.89	12.73	12.42	11.59	12.86
9900.....	12.88	10.58	15.10	12.17	13.48	11.59	12.94	12.78	12.45	11.57	12.86
9950.....	13.00	10.61	15.86	12.23	13.60	11.64	13.02	12.84	12.58	11.63	13.00
10000.....	12.99	10.61	15.96	12.27	13.71	11.66	13.06	12.93	12.63	11.64	13.02
10050.....	12.98	10.69	15.22	12.28	13.68	11.77	13.08	12.95	12.69	11.71	13.01
10100.....	12.98	10.63	15.11	12.31	13.68	11.78	13.10	12.98	12.65	11.75	12.98
10150.....	12.96	10.59	15.19	12.29	13.65	11.74	12.12	12.95	12.61	11.73	13.00
10200.....	12.95	10.53	15.08	12.29	13.73	11.77	13.15	12.97	12.63	11.74	13.01

+28°4211 has a red companion, about 5 mag fainter at V. The separation is 2".8, with the faint companion having a position angle of 240°. Inspection of older CCD frames confirms that the companion was similarly present 5 yr ago as well. Subsequent to his discovery, Booth made careful note of spectroscopic observations and found instances of variable emission at Hα. While we believe that this star is still well suited as a standard in the blue, where the contribution of the companion is negligible, we do not recommend its use in the red.

EG 81.—This star is clearly double, with a separation of a few arcseconds. Observations in Paper I were made using a large aperture that included both components. We dropped this star from the present program, and we do not recommend using this star as a standard.

HD 192281 and HD 217086.—The new observations of these two stars had excellent internal agreement, but in each case they differed by nearly 0.1 mag from observations obtained in Paper I. The shape of the spectral energy distribution measured for these two stars by Whiteoak (1966) agree with Paper I and not with the new observations. We do not understand the source of the present discrepancy, but we suspect that it is somehow related to a poorly understood color effect, since these are by far the reddest stars in our original program. Since these stars are red due to interstellar reddening, possibly polarization plays a role in compromising the data obtained as part of the present project. We do not include the fluxes of these two stars in the present paper.

What is the external accuracy of these data? In Table 4 we

TABLE 4

COMPARISON WITH STONE (1977)

	Hiltner 600		Feige 34		BD +28°4211		Feige 110	
λ	Difference	σ_μ	Difference	σ_μ	Difference	σ_μ	Difference	σ_μ
7100.....	0.01	0.01	−0.02	0.01	0.01	0.00	0.03	0.00
7550.....	0.03	0.01	0.02	0.01	0.09	0.01	0.04	0.00
7780.....	0.01	0.02	0.04	0.01	0.07	.0.00	0.03	0.00
8090.....	0.01	0.01	−0.03	0.01	0.09	0.00	0.08	0.00
8370.....	−0.06	0.01	0.00	0.01	0.06	0.00	0.05	0.00

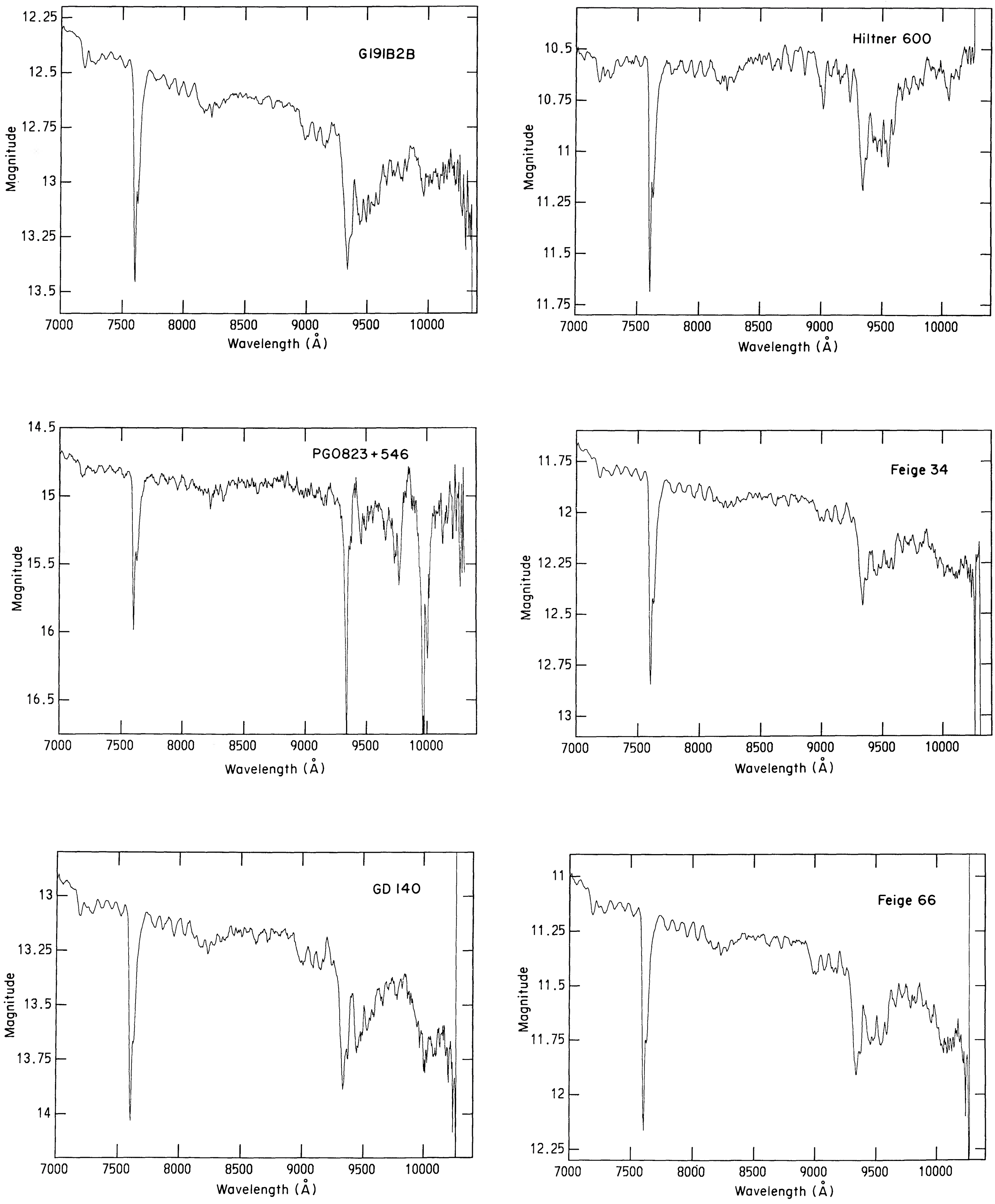

FIG. 2.—The flux distributions of the 11 program stars are shown here

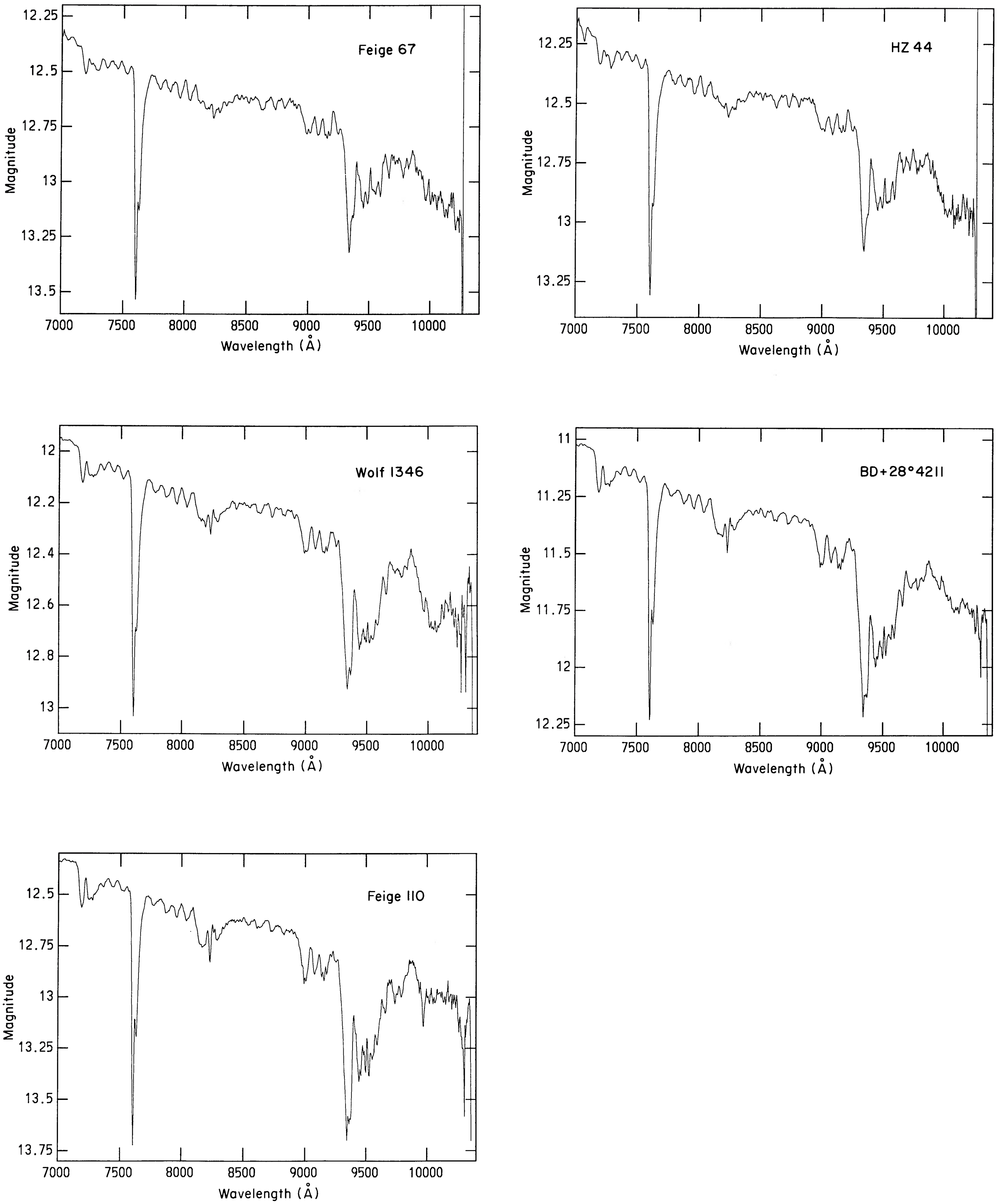

FIG. 2—*continued*

TABLE 5

COMPARISON WITH MASSEY *et al.* (1986)

STAR	λ 7350	7400	7450	7500
G191B2B:				
Difference	0.02	0.02	0.02	0.04
σ_μ	0.00	0.00	0.00	0.00
Hiltner 600:				
Difference	0.00	0.01	−0.01	0.00
σ_μ	0.01	0.01	0.02	0.01
PG 0823+546:				
Difference	0.01	−0.12	0.00	−0.04
σ_μ	0.02	0.01	0.01	0.01
Feige 34:				
Difference	−0.01	0.00	0.01	0.00
σ_μ	0.00	0.01	0.01	0.01
GD 140:				
Difference	0.00	−0.05	−0.04	−0.02
σ_μ	0.01	0.01	0.01	0.00
Feige 66:				
Difference	0.03	0.01	0.02	0.02
σ_μ	0.01	0.01	0.01	0.00
Feige 67:				
Difference	−0.02	−0.01	−0.05	−0.03
σ_μ	0.00	0.01	0.01	0.01
HZ 44:				
Difference	−0.04	−0.05	−0.03	−0.02
σ_μ	0.01	0.01	0.01	0.01
Wolf 1346:				
Difference	−0.02	−0.03	−0.01	0.00
σ_μ	0.00	0.00	0.00	0.00
BD +28°4211:				
Difference	0.00	−0.01	0.00	0.01
σ_μ	0.00	0.00	0.00	0.00
Feige 110:				
Difference	0.05	0.00	0.03	0.01
σ_μ	0.00	0.00	0.00	0.00

compare our data to the magnitudes of Stone (1977) for the four stars in common, where we have used our flux data to compute magnitudes in the same bandpasses as used by Stone. The agreement is fairly good for Hiltner 600, Feige 34, and Feige 110, and somewhat worse for BD +28°4211. Possibly the companion discussed above has varied between the time of Stone (1977) and our work. In Table 5 we compared our data to that of Paper I, where we have used the data in 50 Å bandpasses. The agreement is again reassuring, typically much better than 5%. In the case of greater discrepancies, we recommend the current values, given the better sensitivity on the red of GoldCam compared to the instruments used in Paper I. We note that Taylor's (1979, 1984) data indicate that there is a systematic difference of 7%–9% between the "winter" and "summer" Hayes (1970) standards at longer wavelengths (e.g., from the λ9834 flux point and redder). We looked for this effect in our data but were unable to answer the question one way or another; until a fundamental recalibration of all the bright *primary* standards is attempted in this wavelength region, it is perhaps fair to expect that the external errors will be larger than in the traditional optical range (e.g., <8100 Å). It is worth recalling Hayes's (1985) characterization of the fundamental calibration of Vega as "mature" in the optical, but "immature" at longer wavelengths.

We wish to thank John Booth for his expert assistance at the telescope, and Ed Anderson for his aid in obtaining some of the observations. Frank Valdez kindly provided modifications to standard IRAF routines to handle noninteger integration times; Jeannette Barnes and Rob Seaman gave much useful reduction advice. C. G. was supported by the NSF Research Experiences for Undergraduates program.

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