THE ASTRONOMICAL JOURNAL VOLUME 113, NUMBER 3 MARCH 1997

ABSOLUTE FLUX DISTRIBUTIONS OF SOLAR ANALOGS FROM THE UV TO THE NEAR-IR

LUIS COLINA[1] AND RALPH BOHLIN
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218
Electronic mail: colina@stsci.edu, bohlin@stsci.edu

Received 1996 November 27; revised 1996 December 12

ABSTRACT

The 0.225–2.695 μm absolute flux distributions of the solar analogs P041C, P177D, and P330E are presented. The ultraviolet and optical wavelength range from 0.225 to 0.825 μm is based on high signal-to-noise spectra obtained with the *HST* Faint Object Spectrograph (FOS). The spectra in the near-infrared longward of 0.825 μm are scaled versions of the absolute flux calibrated reference spectrum of the Sun from Colina *et al.*, AJ, 112, 307 (1996). In the 0.400 to 0.825 μm range, the spectral energy distribution of P041C is slightly hotter than the Sun, 5900 vs 5777 K, and agrees with the shape of the solar spectrum to 5% in the optical. P177D shows evidence for interstellar absorption from the dust that corresponds to A_V=0.03 mag in the visual. The spectral energy distribution of P330E is the same as the solar reference spectrum within 2%–3%. At wavelengths shortward of 0.4 μm, the differences in the spectral energy distribution between the Sun and the solar analogs are larger, and not well understood. When normalized to the same V flux, P041C and P330E are brighter than the Sun by up to 50% below 0.25 μm, whereas P177D is as much as 10% fainter. The synthesized visual magnitudes and $B-V$ colors of the FOS absolute fluxes of P041C, P177D, and P330E agree with ground-based broad-band photometry to 0.02 mag. The flux distributions of our new solar analogs will help establish the absolute calibration of NICMOS, the *HST* near-infrared camera and multi-object spectrograph. The spectra are available via the WWW. © *1997 American Astronomical Society.* [S0004-6256(97)02603-4]

1. INTRODUCTION

The absolute calibration of current *HST* instruments in the UV and optical is based primarily on absolutely calibrated spectra of a few pure hydrogen white dwarfs with an intrinsic accuracy of ~2% (Colina & Bohlin 1994; Bohlin *et al.* 1995; Bohlin 1996). Since white dwarf model fluxes are available in the near-infrared (Bohlin 1996), the absolute calibration of near-infrared detectors like NICMOS (*HST* near-infrared camera) could be obtained by using the same models of pure hydrogen white dwarfs in the near-infrared, after normalization to Landolt visual photometry (Bohlin *et al.* 1995).

An alternative method for calibrating the *HST* infrared camera uses the solar-analog approach. The solar-analog method has been used to determine the absolute calibration of near-infrared photometry (Campins *et al.* 1985). The stellar absolute flux is calculated from the absolute solar flux and the relative magnitudes of the sun and the analog star in one photometric band. The final absolute flux accuracy achieved by the solar-analog method relies then on two basic assumptions: (1) that the absolute flux calibrated reference spectrum of the Sun is known to sufficient accuracy, and (2) that the optical-infrared spectra of the solar-analogs, used as absolute standards in the calibration, are identical to the solar spectrum, i.e., their optical and near-infrared spectral energy distributions agree within the shape of the solar flux distribution to sufficient accuracy. Colina *et al.* 1996 (CBC96) published an absolute solar reference spectrum for the ultraviolet to near-infrared spectral range, while this paper presents the absolute flux calibrated ultraviolet to near-infrared spectra of three solar analogs selected as the primary calibration standards for NICMOS.

Section 2 describes the FOS observations of the three stars. Section 3 discusses the classification of the solar analogs in the MK spectral system. A comparison between the ultraviolet and optical spectral energy distribution of the Sun and each of the stars is in Sec. 4. The ultraviolet to near-infrared absolute flux spectra of the three solar analogs are presented in Sec. 5. The accuracy of the FOS absolute spectrophotometry is assessed in Sec. 6 by comparing the results of synthetic broad-band photometry on the FOS spectra with ground-based photometry. Section 7 explains where to find the electronic versions of the spectra. Finally, Sec. 8 summarizes the results and presents guidelines for future work.

2. OBSERVATIONS OF SOLAR ANALOGS

Based on broad-band optical and near-infrared ground-based photometry, three faint solar analogs, P041C, P177D, and P330E have been selected as standards for the absolute calibration of NICMOS, the *HST* near-infrared camera and multi-object spectrograph (M. Rieke, private communication). As part of *HST* cycle 6 calibration program, the three solar analogs have been observed with the high dispersion modes of the FOS red detector, G270H, G400H, G570H, and

[1]Affiliated with the Astrophysics Division, Space Sciences Department of ESA.

TABLE 1. *HST* solar analog standards: Coordinates.

Star (1)	α(2000) (2)	δ(2000) (3)	GSC No. (4)	GS Region (5)	Plate ID (6)	Epoch (7)
P041C	14:51:58.19	+71:43:17.3	4413−304	N041	01L5	1983.29
P177D	15:59:13.59	+47:36:41.8	3493−432	N177	00T9	1982.48
P330E	16:31:33.85	+30:08:47.1	2581−2323	N330	01G4	1984.43

(2–3) J2000 coordinates from the STScI Guide Star Selection System.
(4) Guide Star Catalogue number of the standard star.
(5) Guide Star Selection System field number.
(6) Guide Star Selection System plate number.
(7) Date plate was exposed.

G780H. The aims of this specific calibration proposal are twofold: (1) to establish these stars as *HST* standards, and (2) to establish to what extend these stars are solar equivalents not only photometrically but also spectroscopically, in the spectral region covered by the FOS observations.

The coordinates and field charts for the *HST*/FOS observations of the three stars are presented in Table 1 and Figs. 1(a)–1(c), respectively. All FOS observations used the B-3 (0.86″) aperture. The journal of the observations for the calibration proposal 6925 is in Table 2.

No attempt was made to obtain the ultraviolet spectrum of the stars for wavelengths shortwards of 0.225 μm because of the faintness and probable variability of the stars.

3. MK SPECTRAL CLASSIFICATION OF THE SOLAR ANALOGS

The MK spectral classification scheme is based upon the visual comparison of intermediate resolution spectra (FWHM$\sim$2–3 Å; Keenan 1985) of the program stars with that of the MK standards in the 4000–4400 Å spectral range. The classification is determined comparing the 4000–4400 Å FOS spectra at $\sim$3 Å resolution with the corresponding spectra of MK spectroscopic G standards (Keenan & McNeil 1976), kindly provided to us by Dr. R. Gray (private communication). Based on our comparison, all three stars, P041C, P177D, and P330E, are MK spectral type G0 V. The Sun is classified as a G2 V star in the MK system (Keenan & McNeil 1976).

4. COMPARISONS WITH THE SOLAR REFERENCE SPECTRUM

The FOS spectrum of each of the solar analogs in the 0.225–0.825 μm spectral range is compared with the absolute flux calibrated solar reference spectrum (CBC96), after normalizing to the same *V* band flux. The absolute fluxes and the ratios to the Sun are presented in Figs. 2(a)–2(c) for P041C, P177D, and P330E, respectively.

The solar ultraviolet spectrum contains radiation from the chromosphere and photosphere both in lines and continuum. Variability of the strong 0.28 μm Mg II absorption line ($\sim$5%) and ultraviolet continuum ($\sim$5% to 50% shortwards of 0.22 μm) has been observed (see CBC96, and references therein). However, when normalized to the same visual flux, the spectral energy distribution of the solar analogs deviate from that of the Sun by more than the known solar variability in the 0.22–0.40 μm spectral range. P177D is on average about 5% fainter than the Sun, whereas P041C is brighter than the Sun by a few to several percent ($\sim$4% to 20%). P330E shows the largest discrepancies of up to 50% brighter than the Sun at wavelengths shortwards of 0.28 μm. The absolute flux solar spectral energy distribution in the ultraviolet is known with a $\sim$10% uncertainty (see CBC96 and references), and therefore the observed differences are real. These differences are however not well understood and could be due to a combination of several factors, including small amounts of interstellar extinction (P177D, see below), effective temperatures hotter than that of the Sun (P041C, see below), or differences in gravity or in the energy output from the chromosphere. Since even detailed physical models of the Sun predict an ultraviolet spectral energy distribution that deviates from the observed spectrum by $\sim$ 10% to 40% (CBC96), the attention will be focussed into the optical part of the spectra in the rest of the analysis.

In the 0.4–0.825 μm range, the broadband slope of the continua of the P177D and P330E agree with that of the Sun to 3% (see Figs. 2(a) and 2(b)), whereas discrepancies of about ±5% are measured in the spectrum of P041C. In addition, there is a local 6% deep absorption feature at 0.64 μm. This absorption is a detector artifact caused by a temporal change in the flat field used to correct the observed FOS spectra. In the following, the differences between the optical spectra of the solar analogs and that of the Sun are addressed in more detail.

4.1 P041C

P041C is the brightest of the three solar analogs. The ratio of P041C to the solar flux decreases from 1.05 at 0.4 μm to 0.96 at 0.8 μm, when the flux ratio is normalized to 1.0 at 0.55 μm. This trend in the flux ratio as a function of wavelength can be a temperature effect, if P041C is hotter than the Sun. To derive the temperature of P041C, the modeled spectral energy distribution for the Sun ($T_{\rm eff}$=5777 K) and for G type stars with the same metallicity and gravity as the Sun and covering a range of temperatures were computed (F. Castelli, private communication). The ratios of the hotter models to the solar model energy distribution are compared with the ratio of P041C to the observed solar energy distribution. Over the 0.45–0.825 μm range, a G star with an effective temperature of 5900±20 K gives the best fit to the observed P041C to Sun flux ratio (see Fig. 3). Therefore, P041C is a solar analog with an effective temperature of 5900 K.

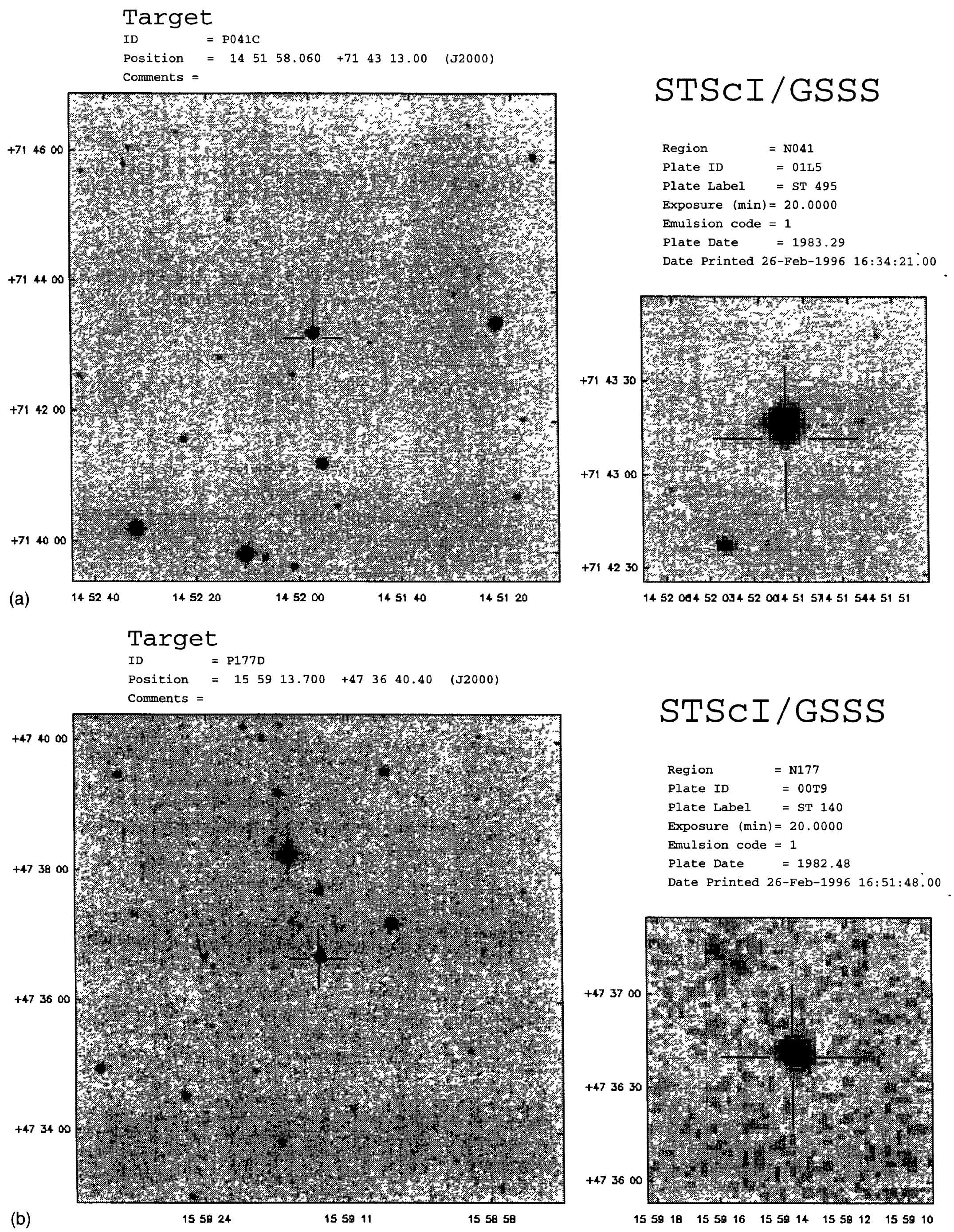


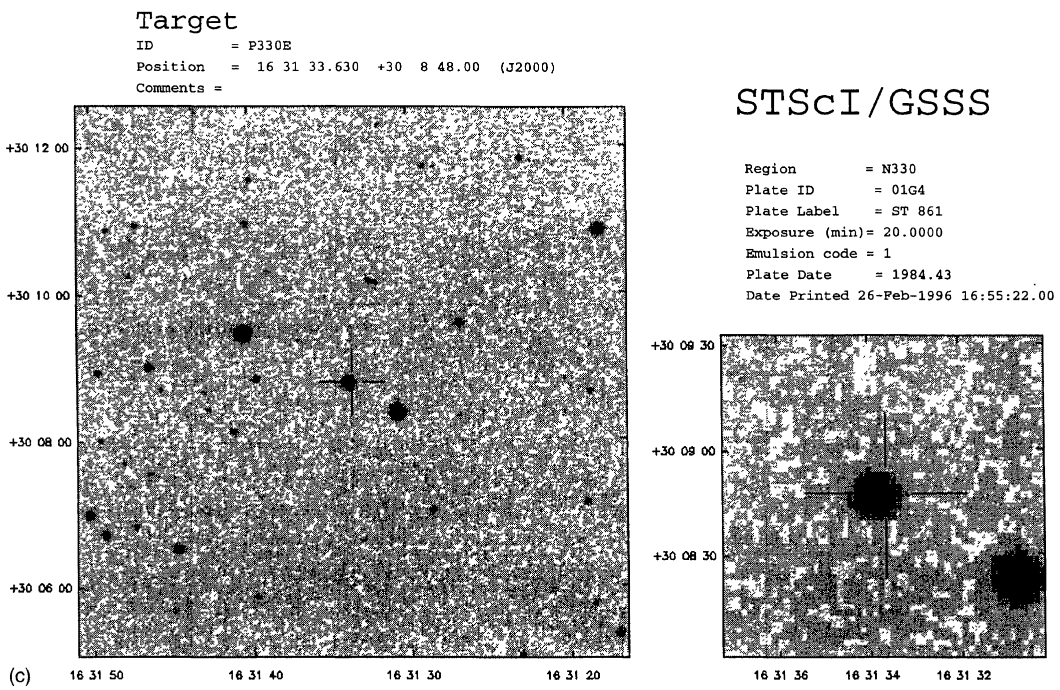
FIG. 1. STScI Guide Star System finding charts for: (a) P041C, (b) P177D, and (c) P330E. The field frame is 7.15 arcmin square, and the magnified frame is 85 arcsec square.

4.2 P177D

The ratio of the observed P177D flux to the solar flux shows a trend such that the ratio increases from ~0.95 to ~1.03 as the wavelength increases from ~0.37 to ~0.82 μm. A small amount of interstellar extinction can contribute in part to produce such a trend. When corrected for an extinction equivalent to A_V=0.031 mag, the P177D to solar flux ratio flattens out to a value of 1.0 for the entire 0.4–0.825 μm spectral range (see Fig. 4) whereas moves to about 0.96 in the 0.25–0.35 μm range.

4.3 P330E

Judging only from the optical portion of the FOS spectra from 0.4 to 0.825 μm, P330E is the best of the three solar



(c)

FIG. 1. (continued)

analogs. The ratio of P330E to the solar energy distribution is flat with an average value of 1.0 and deviations of no more than 3% in the continuum, i.e., the differences are within the intrinsic uncertainties in the spectral energy distribution of the FOS and solar reference spectra.

5. THE SOLAR ANALOG REFERENCE SPECTRA

The absolute flux distributions for the three solar analogs combine the FOS spectra for wavelengths shortward of 0.825 μm with scaled versions of the absolute flux calibrated solar reference spectrum (CBC96) for wavelengths beyond 0.825 μm. The procedure used to determine the spectra longward of 0.825 μm is slightly different in each case.

As explained in Sec. *4.1*, the optical spectrum of P041C indicates that this star is a solar analog with a temperature slightly hotter than the Sun (5900 vs 5777 K). Therefore, the near-infrared spectrum of P041C is the solar reference spectrum normalized to the flux of P041C in the *V* band and multiplied by the ratio of the modeled 5900 to 5777 K spectral energy distributions.

As mentioned before (see Sec. *4.2*), the optical spectrum of P177D is reddened by a small amount of interstellar extinction. The near-infrared spectrum of this star is obtained by reddening the solar reference spectrum by the average galactic extinction curve of Savage & Mathis (1979) for $E(B-V)=0.01$ and then normalizing to the *V* flux of the P177D FOS spectrum.

The optical spectrum of P330E does not deviate from the solar reference spectrum. The near-infrared spectrum of this star is just the rescaling of the solar reference flux to the P330E FOS spectrum in the *V* band.

TABLE 2. *HST* solar analog standards. FOS observing log.

Star	Instrument	Aperture	Grating	Date	Exp. Time (sec.)
P041C	FOS/RD	B-3	G270H	Sept. 12, 1996	2630
			G400H	and	100
			G570H	Nov. 21, 1996	60
			G780H		1800
P177D	FOS/RD	B-3	G270H	July 10, 1996	3000
			G400H	and	180
			G570H	July 12, 1996	120
			G780H		1500
P330E	FOS/RD	B-3	G270H	July 27, 1996	2750
			G400H	and	160
			G570H	Sept. 2, 1996	100
			G780H		1550

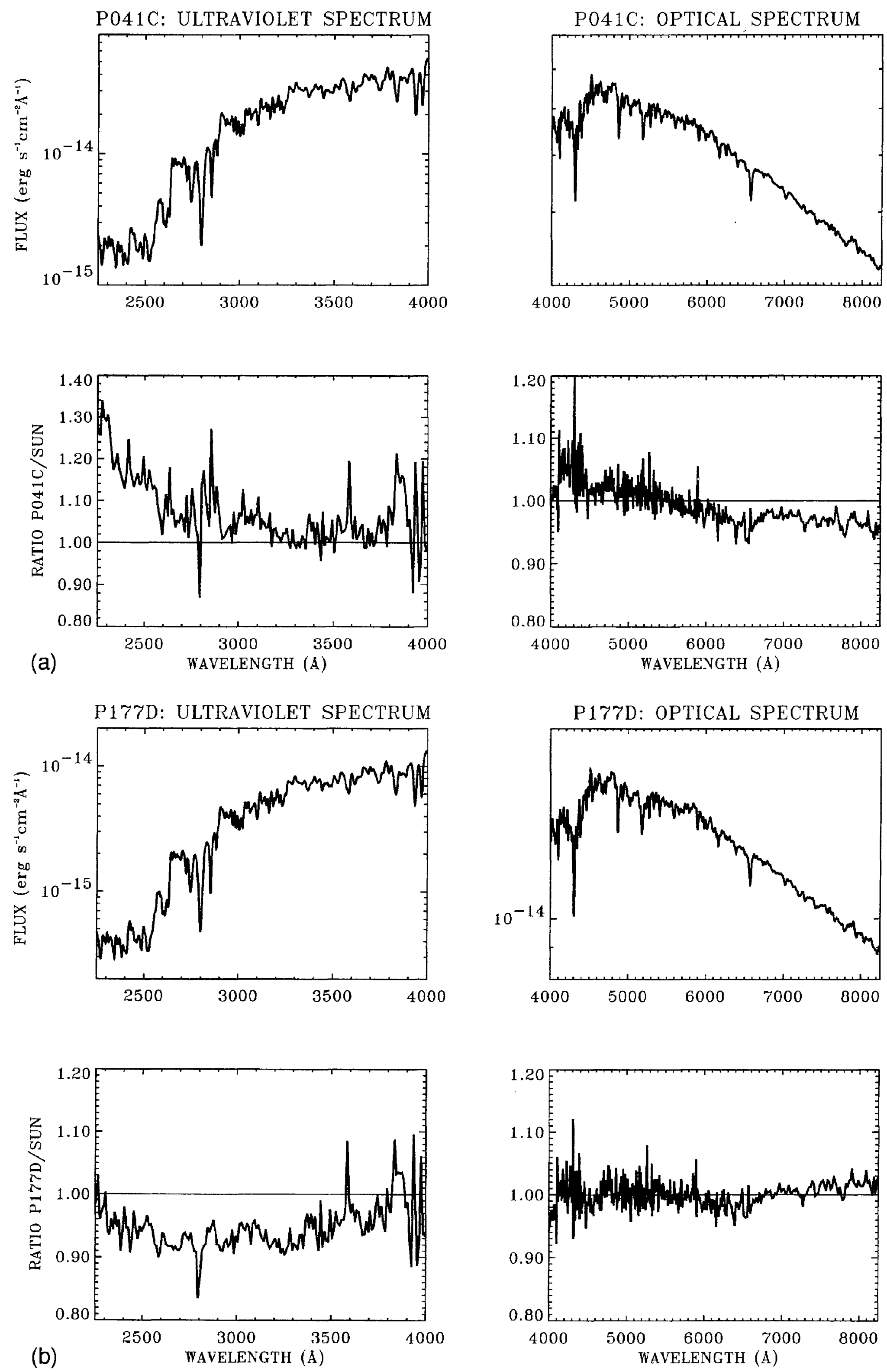


FIG. 2. Absolute ultraviolet and optical energy distributions for: (a) P041C, (b) P177D, and (c) P330E (top panels). After normalization of the two spectra in the visual, the ratios of the FOS fluxes to the spectral energy distribution of the Sun are in the bottom panels.

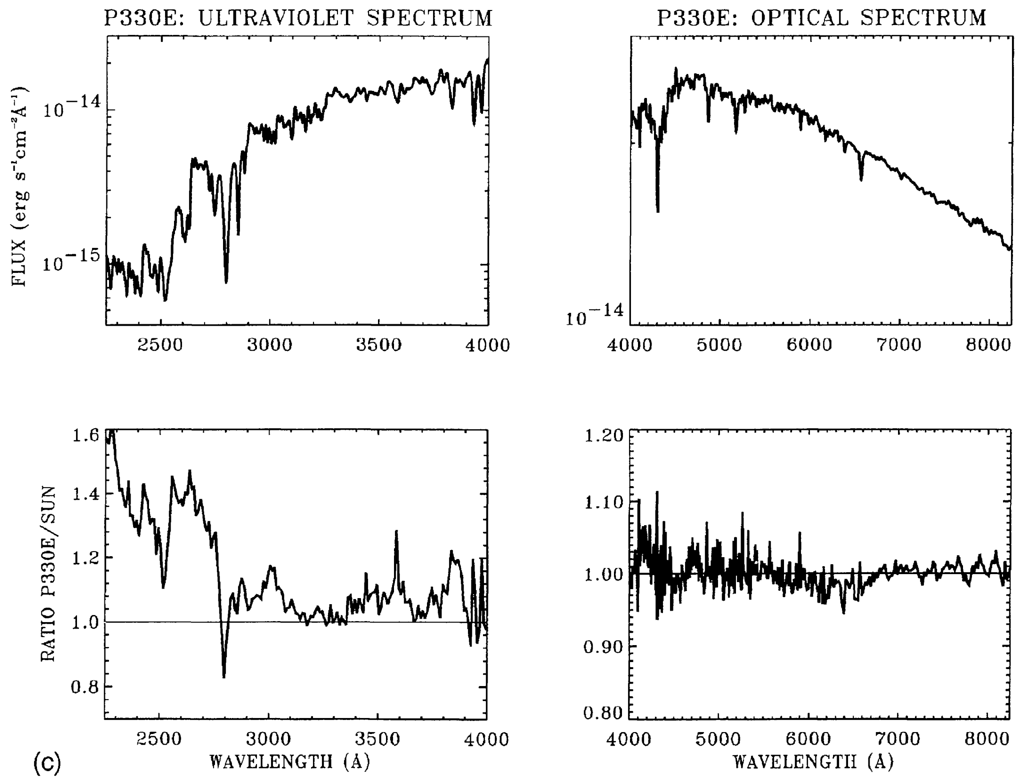


FIG. 2. (continued)

6. MAGNITUDES AND COLORS OF THE SOLAR ANALOGS

The absolute flux calibration of the solar analog FOS spectra is based on the *HST* white dwarf scale (Bohlin *et al.* 1995; Bohlin 1996). The FOS absolute flux of the three white dwarfs that are the primary calibration standards in the ultraviolet and optical agree with Landolt's photometry to better than 1% on average, in *B* and *V* (Bohlin *et al.* 1995). The accuracy in the absolute flux of the FOS spectra for the solar analogs can be assessed in a similar way by computing the synthetic photometry for the FOS spectra and comparing the results with the ground-based photometry. The visual and blue magnitudes of the solar analogs are calculated using Buser & Kurucz (1976) filter bandpass for the Johnson *V* and *B* filters. Following Colina & Bohlin (1994), the Hayes (1985) optical spectrum of the primary standard αLyr is assumed to have a visual magnitude of +0.035 and a color $B-V$=0.000 in the Johnson system. The computed *V* and *B* synthetic broad-band photometry (Table 3) agrees with ground-based measurements (M. Rieke, private communication) to better than 2%, on average.

The near-infrared magnitudes and colors of the solar analog spectra have also been computed. As explained in CBC96, the selected *JHK* set of filters consists of the *K*

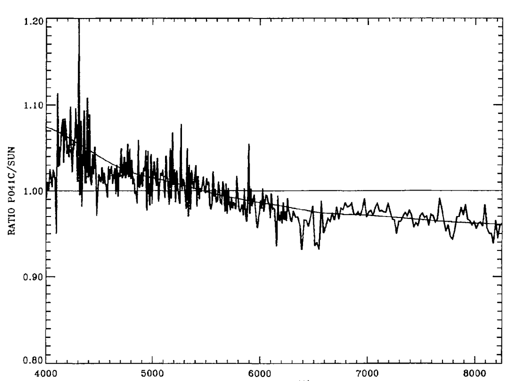


FIG. 3. Ratio of P041C to the solar spectral energy distributions in the optical range (thick line). The corresponding ratio for the 5900 to 5777 K model spectral energy distributions (thin line) is also plotted for comparison.

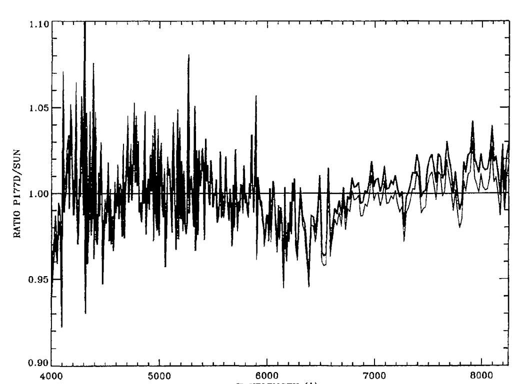


FIG. 4. Ratio of the optical FOS spectrum of P177D to the solar reference spectrum without extinction correction (thick line), and with an extinction correction equivalent to $E(B-V)=0.01$ (thin line).

TABLE 3. *HST* solar analog standards. Synthetic photometry.

Star	V	$B-V$	H	$V-K$	$J-H$	$J-K$	$H-K$
P041C	12.01	0.60	10.65	1.42	0.26	0.32	0.06
P177D	13.48	0.63	12.01	1.54	0.28	0.35	0.07
P330E	13.01	0.62	11.57	1.50	0.28	0.34	0.06
SUN$^{(1)}$	−26.75	0.63	−28.20	1.50	0.28	0.34	0.06
Hardorp-1$^{(2)}$	–	–	–	1.49	0.31	0.37	0.06

(1) Synthetic photometry from CBC96.
(2) Hardorp class 1 solar analogs from Campins *et al.* (1985)

bandpass as in Bessell & Brett (1988), and the Tucson J and H bandpass (M. Rieke, private communication). These filters bandpass are used in conjunction with Campins *et al.* (1985) zero points to approximate the Tucson photometric system. The results of the synthetic *JHK* photometry are compared with the near-infrared colors of the solar reference spectrum (CBC96), and Hardorp class 1 solar analogs in the Tucson photometric system (see Table 3 for a summary of the results). The computed colors for P041C show the largest departures of all three stars, when compared with the colors of the Sun and Hardorp class 1 solar analogs. As already discussed in Sec. *4.1*, P041C is hotter than the Sun by about a hundred degrees, which explains the differences in the colors. P177D is a little redder in the $V-K$ color as a consequence of the extinction of E$(B-V)$=0.01.

7. PUBLIC ACCESS TO THE DIGITAL SPECTRA OF THE SOLAR ANALOGS

The absolute fluxes of the three solar analogs, covering the complete 0.22 to 2.7 μm range, can be found in UNIX SDAS binary table format on the World Wide Web with the URL identifier http://www.stsci.edu/ftp/cdbs2/calspec. Filename is *_001.tab. The * indicates the name of the star (i.e., P041C, P177D, or P330E). Any future updates to the flux distributions will have the same root name, except that the 001 will be incremented. To convert the SDAS tables into ASCII files, use the task *tdump* within IRAF. On the VMS STScI science cluster, the same data can be found in disk$calibration:[cdbsdata.refer.calspec]. Additional information on all *HST* calibration standards can be found in the web page http://www.stsci.edu/ftp/instrument_news/Observatory/calspec.html

8. SUMMARY

Absolute ultraviolet to near-infrared reference spectra for P041C, P177D, and P330E are presented. The ultraviolet and optical wavelength range, 0.225–0.825 μm, is based on high signal-to-noise spectra obtained with the *HST* Faint Object Spectrograph (FOS). The spectra in the near-infrared wavelength range, 0.825–2.695 μm, are obtained by appropriate rescaling of the absolute flux of the Sun.

The stars are classified as G0 V in the MK spectral classification system where the Sun, by definition, is a G2 V star. The violet and ultraviolet (0.225–0.400 μm) portion of the solar analog spectra departs from that of the Sun. In the optical, the departures in the spectral energy distribution of P041C and P177D with respect to that of the Sun may be due to a slight interstellar extinction (P177D) or a slightly higher effective temperature (P041C).

The synthesized visual magnitudes and $B-V$ colors of the FOS absolutely calibrated spectra of P041C, P177D, and P330E agree with ground-based broad-band photometry to better than 0.02 mag, i.e., within the uncertainties of the measurements. This result also confirms the accuracy of the FOS spectrophotometry, already demonstrated for O, B, and white dwarfs standards (Colina & Bohlin 1994; Bohlin *et al.* 1995).

Spectra of the three solar analog calibration standards are available electronically. The absolute flux spectra of these solar analogs will help establish the absolute flux calibration of NICMOS, the *HST* near-infrared camera and multi-object spectrograph.

HST STIS and NICMOS low resolution observations (R $\sim$ 500–1000) of the three solar analogs should be part of future *HST* calibration programs.

We thank Drs. R. Garrison and R. Gray for kindly providing us with digital spectra of MK spectroscopic standards and for patiently answering our questions regarding the spectral classification of G-type stars. Dr. F. Castelli provided us detailed physical model spectra for solar analog stars.

REFERENCES

Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Bohlin, R. C. 1996, AJ, 111, 1743
Buser, R., & Kurucz, R. L. 1978, A&A, 70, 555
Campins, H., Rieke, G. H., & Lebofsky, M. J. 1985, AJ, 90, 896
Bohlin, R. C., Colina, L., & Finley, D. S. 1995, AJ, 110, 1316
Colina, L., & Bohlin, R. C. 1994, AJ, 108, 1931
Colina, L., Bohlin, R. C., & Castelli, F. 1996, AJ, 112, 307 (CBC96)
Hayes, D. S. 1985, in Calibration of Fundamental Quantities, Proceedings of IAU Symposium No. 111, edited by D. S. Hayes, L. E. Pasinetti, and A. G. Davis Phillip (Reidel, Dordrecht), p. 225
Keenan, P. C. 1985, in Calibration of Fundamental Stellar Quantities, IAU Symposium 111, edited by D. S. Hayes, L. E. Pasinetti, and A. G. Davis Philip (Reidel, Dordrecht), p. 121
Keenan, P. C., & McNeil, R. C. 1976, Atlas of Spectra of the Cooler Stars. Types G, K., M, S, and C (Ohio State University Press, Ohio)
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73