THE 0.12 – 2.5 μm ABSOLUTE FLUX DISTRIBUTION OF THE SUN FOR COMPARISON WITH SOLAR ANALOG STARS

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ABSTRACT

An absolute flux calibrated reference spectrum of the Sun covering the 0.12 to 2.5 μm wavelength range is presented. The ultraviolet and optical spectrum is based on absolute flux measurements from satellites and from the ground. The near-infrared spectrum is based on measurements using the NASA CV-990 aircraft and on a model spectrum.

The synthetic optical and near-infrared magnitudes of the absolute calibrated solar reference spectrum agree with published values to $0.01 - 0.03$ magnitudes, i.e. within the uncertainties of the measurements. The absolute flux of the reference spectrum over the optical and near-infrared 0.4 to 2.5 μm range is known with an uncertainty of 5%, or better. In the blue and ultraviolet, especially for wavelengths in the 0.12 to 0.2 μm interval, the uncertainty increases up to about 20% due to the variability of the solar energy output at these wavelengths.

The absolute flux spectrum of the Sun presented here will help to establish the absolute calibration of NICMOS, the HST near-infrared camera and Multi-object Spectrograph.

1. INTRODUCTION

The absolute calibration of current HST instruments is based primarily on the existence of absolutely calibrated spectra of a few pure hydrogen white dwarfs and hot stars accurate to $\sim 2\%$ (Colina & Bohlin 1994; Bohlin, Colina, & Finley 1995; Bohlin 1996). White dwarfs are extremely good calibrators in the ultraviolet and optical wavelength ranges, and 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 recent models of pure hydrogen white dwarfs to extrapolate the optical spectra into the near-infrared, after normalization to Landolt visual photometry (Bohlin, Colina,& Finley 1995).

An alternative method for calibrating the HST infrared camera uses the solar-analog approach. The solar-analog method has been used in the past to determine the absolute calibration of near-infrared photometry (Campins, Rieke, & Lebofsky 1985). This method consists of several steps: (i) the solar colors in the photometric system are determined by assuming that the average colors of the solar analogs are equal to those of the Sun (classified as a G2V star); (2i) the zero point of the absolute flux density in each near-infrared photometric bandpass is calculated from the photometric magnitudes for the Sun, and the absolute flux spectrum of the Sun; (3i) the absolute solar flux density in each photometric band is scaled in proportion to the magnitude of the solar analog star relative to that of the Sun. The final absolute flux accuracy achieved by the solar-analog method relies then on two basic assumptions: (1) that the absolute calibrated reference spectrum of the Sun is known with almost no uncertainty, 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. agree within the $1\%-2\%$ uncertainty in the shape of the flux distribution, at optical and infrared wavelengths.

This document presents a new absolutely calibrated low resolution reference spectrum of the Sun. Section 2 summarizes the different absolute flux distributions of the Sun available in the ultraviolet, optical and near-infrared. Section 3 presents a model spectrum based on Kurucz's ATLAS9 code. Section 4 compares the model spectral flux and the reference spectrum over the entire ultraviolet to near-infrared range. Section 5 explains the construction of the solar reference spectrum and the uncertainties in the absolute flux. Section 6 discusses the accuracy of the reference spectrum by comparing optical and near-infrared synthetic photometry with published measurements; and section 7 indicates where the different solar spectra can be found on the WEB pages. A detailed comparison between the spectra of solar analogs and the solar reference spectrum will be the subject of a future paper, as HST Faint Object Spectrograph (FOS) observations and broad-band optical and infrared photometry of NICMOS absolute standards become available.

2. EMPIRICAL CALIBRATED SPECTRA OF THE SUN

There exist several independent absolute flux measurements of the Sun. These spectra are obtained using various instruments and techniques and cover different wavelength ranges. A summary of the spectra, their pedigree, and their uncertainties follows.

2.1 Ultraviolet Spectra

The most recent measurements of the ultraviolet solar spectral irradiance [1] covering the 0.12 to 0.41 μm wavelength range have been obtained by the solar instruments onboard the Upper Atmosphere Research Satellite (UARS). UARS was flown as part of the Shuttle Atmospheric Laboratory for Applications and Science (ATLAS) missions (Woods et al. 1996). The first set of data combines observations from the UARS Solar Ultraviolet Irradiance Monitor (SUSIM) and UARS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) taken on March 29, 1992 during the ATLAS-1 mission (Table 6 of Woods et al. 1996). The second set of data combines UARS solar irradiances obtained on April

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[1] The term irradiance is used synonymously with flux, which is measured in units of erg s^{-1} cm^{-2} $Å^{-1}$.

15, 1993 during the ATLAS-2 mission (Table 7 of Woods et al. 1996).

The UARS irradiance measurements agree with the measurements obtained by previous ATLAS experiments (Woods et al. 1996). In general, these measurements agree within the 2σ uncertainty of any single independent measurement, i.e. an agreement better than 7% at wavelengths above 0.16 μm. Below 0.15 μm, there is a good agreement for the brighter emission lines at the 10% level (Woods et al. 1996).

The LOWTRAN-7 computer code includes an absolute solar-flux spectrum, the LOWTRAN spectrum (Kneizys et al. 1988). The computer code calculates atmospheric transmittance, direct solar irradiance, atmospheric background radiation, etc, and uses the LOWTRAN spectrum of the Sun as an input for the calculations. This spectrum combines several independent spectra covering different portions of the entire ultraviolet to far-infrared wavelength range (see Kneizys et al. 1988 for appropiate references). In the ultraviolet, the LOWTRAN spectrum is based on spectral irradiances obtained with SUSIM instrument onboard Spacelab 2 (van Hoosier et al. 1988).

The ratio of the spectral irradiance obtained by Woods and collaborators (average of UARS fluxes given in Table 6 and 7 of Woods et al. 1996) to the ultraviolet interval of the LOWTRAN spectrum, for wavelengths above 0.2 μm is presented in Figure 1. On average, Woods and LOWTRAN spectral irradiances agree to 10%, or better, in the 0.25 to 0.4 μm wavelength range. The ratio of the two spectra is very noisy. The photometric uncertainty of the UARS measurements is dominated by the responsivity ($\sim$2.5%; Woods et al. 1996) while the wavelength scale dominates the uncertainty of the SUSIM measurements ($\sim$3.0%; van Hoosier et al. 1988).

In the 0.33 to 0.41 μm wavelength interval, UARS spectral irradiance agrees with Neckel & Labs (1984) ground-based absolute calibrated solar spectrum to 5%, or better, although departures of up to 10% exists (see Figure 2). In summary, for wavelengths in the 0.2 to 0.4 μm range, the three independent satellite- and ground-based absolute spectral irradiances agree with each other to better than 10%, on average.

A third ultraviolet absolute calibrated solar spectrum is part of the 0.18 to 3.2 μm spectrum obtained using the SOLSPEC spectrometer onboard the ATLAS and EURECA missions (Thuillier et al. 1994). The ultraviolet interval of the SOLSPEC spectrum will be available in the near future (Thuillier, private comm.).

The solar irradiance in the 0.12 to 0.42 μm spectral interval contains radiation from the chromosphere and photosphere in both lines and continuum. Some variability of the lines and the entire 0.12 to 0.42 μm spectral interval are observed. These variations are associated with the 11 year solar activity cycle and the 27 day solar rotation period. The degree of variability decreases with increasing wavelength, except in certain strong absorption lines such as MgII (0.28 μm) and CaII (0.393 μm), where the central chromospheric emission varies more than surrounding wavelengths. Differences of 5% to 50% are measured in the 0.22 to 0.12 μm interval when different epoch observations are compared (see Woods et al. 1996 and Figure 3).

2.2 Optical Spectra

There are several absolute flux measurements of the Sun in the 0.33 to 0.90 μm range. The ground-based spectrum of Neckel & Labs (1984; NL84 hereafter) is obtained by combining absolute 20Å average fluxes with high resolution Fourier Transform Spectra obtained with the McMath Solar Telescope at Kitt Peak. The spectrum covers the 0.33 to 1.25 μm range; but due to the lack of reliable telluric line blocking values, the average radiation data for wavelengths beyond 0.87 μm represent the continuous flux rather than both continuum and line spectrum.

Additional absolutely calibrated optical spectra of the Sun include those of Arvesen, Griffin, & Douglas-Pearson (1969; AGD hereafter), Lockwood, Tüg & White (1992; LTW hereafter), and most recently Thuillier et al. (1994), and Burlov-Vasiljev et al. (1995). AGD spectrum covers the 0.3 to 2.5 μm range and was obtained using a spectroradiometer system onboard the NASA CV-990 aircraft. The uncertainty in the absolute calibration is $\sim$ 3% in the 0.4 to 1 μm range, and increases from $\sim$ 4% at 0.4 μm to 25% at 0.3 μm

(Arvesen et al. 1969).

The LTW absolute solar spectrum covers the 0.33 to 0.85 μm range; and its flux is derived from the absolute spectrophotometry of α Lyr obtained by Tüg, White & Lockwood (1977). The solar irradiance is tabulated at 4Å increments and the internal uncertainty of the measurements is less than 2%, over most of the visible spectrum (Lockwood et al. 1992). However, LTW absolute spectral irradiance shows systematic flux differences up to 10% when compared with NL84 and AGD spectra (see Figure 6 in Lockwood et al. 1992). LTW spectrum has 5% to 10% more flux than NL84 spectrum for wavelengths shorter than 0.55 μm and ~10% less flux for wavelengths above 0.6 μm. LTW spectral energy distribution agrees well with AGD in the 0.45 to 0.6 μm range, shows a dropoff for wavelengths beyond 0.6μm, and it is 5% to 10% larger than the AGD flux for wavelengths shorter than 0.45 μm (Loockwood et al. 1992).

LTW spectrum is not further considered here, since an absolutely calibrated solar reference spectrum should be independent of the uncertainties in the α Lyr absolute calibration, especially in the near-infrared where accurate spectrophotometric measurements do not exist for α Lyr (Hayes 1985).

The Burlov-Vasiljev et al. (1995) absolute measurements cover the 0.31 to 0.685 μm spectral interval with an estimated total error of ~2.5% at 0.31μm, and 2.1% at 0.68μm (Burlov-Vasiljev et al. 1995).

AGD absolute optical spectrum agrees with NL84 spectrum to 2%-3% in the 0.45 to 0.65 μm range and has 2% to 4% more flux than NL84 spectrum in the entire 0.65 to 0.80 μm interval (see Figure 6 in Lockwood et al. 1992). In the 0.33 to 0.45 μm interval, the two spectra disagree, with the NL84 spectrum low by 5% to 10% (see Fig.6 in Lockwood et al. 1992). A comparison of the recent absolute measurements by Burlov-Vasiljev et al. (1995) with the NL84 spectrum shows the same result as above, i.e. that the NL84 spectrum is low by 5% to 7% in the 0.33 to 0.42 μm interval. However, in the 0.6 to 0.7 μm range the NL84 spectrum spectral flux is 3% higher than the Burlov-Vasiljev values (see Figure 11 in Burlov-Vasiljev et al. 1995).

Although the authors of the different absolute measurements indicated above claim uncertainties in the 0.5%-2.5% range for their measurements, the relative comparison of the measurements shows that the systematic uncertainties are larger than the quoted errors by, in some cases, factors of two. Thus, a more realistic uncertainty of the optical absolute flux calibrated spectrum of the Sun would be ~4% for wavelengths shorter than 0.45 μm and longer than 0.65 μm. For the 0.45 to 0.65 μm range, the different absolute measurements agree to ~2%.

It is difficult to trace the source of systematic errors for each independent measurement as different authors have used different techniques and approaches. The errors can not only be due to difficulties due to atmospheric extinction and transmission effects in the complicated 0.32 to 0.4μm spectral range but may also arise from uncertainties in the measurement technique, and from non negligible errors (2%) in the calibration lamps and fundamental blackbodies (see Lockwood et al. 1992; Megessier 1995; Burlov-Vasiljev et al. 1995 for discussions on these topics).

An additional calibrated solar spectrum covering the optical interval with a 10Å resolution and based on SOLSPEC measurements has been obtained by Thuillier and collaborators (Thuillier et al. 1994) and will be available in the near future (Thuillier, private comm.). Finally, the ultrahigh spectral resolution National Solar Observatory spectrum of the Sun covers the 0.3 to 1.3 μm wavelength region with a resolution of 0.01Å (Kurucz et al. 1984). The individual small pieces of this spectrum are normalized to their local continuum. However, an absolutely calibrated spectrum has been obtained using the NL84 absolute calibration in the optical, and a pseudo-continuum fitted to measurements in the 0.75 to 1.3 μm range (Kurucz et al. 1984). This spectrum will not be further considered, since such ultrahigh spectral resolution is not needed for the calibration purposes for which the reference spectrum is designed, and since its optical absolute irradiance is based on NL84 absolute calibration.

2.3 Near-infrared Spectra

There is only one available absolute solar spectral irradiance in the near-infrared, which is due to Arvesen and collaborators (Arvesen et al. 1969). A second spectrum is due to Kneizys and collaborators (LOWTRAN: Kneizys et al. 1988). The LOWTRAN spectrum uses Wehrli's (1985) near-infrared spectrum, which is mostly based on Arvesen's spectrum (Smith & Gottlieb 1974; Wehrli private communication).

The Arvesen et al. (1969) solar spectrum covers the 0.9 to 2.5 μm range with flux values every 20Å to 50Å (Fig. 4), and with a claimed internal absolute flux uncertainty of 3% to 4% over the whole near-infrared spectral range (Arvesen et al. 1969). However, synthetic near-infrared photometry (see section 6 for details about filter bandpass and zero-points) on Arvesen's spectrum predict infrared colors, J−K and H−K, that are in gross disagreement with the near-infrared colors of solar analogs measured by Wamsteker (1981) or Campins et al. (1985). The synthetic photometry predicts J−K= +0.30 and +0.27, and H−K= −0.06 and −0.02 in Wamsteker's and Campin's systems, respectively. Thus, the synthesized J−K and H−K colors are bluer than the measured values by 0.07 to 0.10 magnitudes (see Table 4). The problem can be traced to the quality of the spectral irradiance in the 2.0 to 2.4 μm interval where broad strong absorption features exist (see Figure 4). A comparison of Arvesen's spectrum with the NSO ultrahigh resolution spectrum (Maiolino, private comm.) indicates that none of these absorption features seem to be real. The same conclusion is reached when Arvesen's spectrum is compared with a model spectrum (see section 4 and Figure 5) . Additional problems appear in the 1.5 to 1.7 μm interval, where a bumpy broad feature exists (see Figure 5). Thus, the near-infrared spectra obtained by Arvesen et al. (1969) or Kneizys et al. (1988) will not be used in the construction of the solar reference spectrum.

An additional absolute calibrated near-infrared spectrum based on SOLSPEC measurements (Thuillier et al. 1994) will cover the entire 0.9 to 3.2 μm range with a 0.02 μm resolution and will be available in the near future (Thuillier private communication).

Finally, the National Solar Observatory (NSO) has constructed an extension of the NSO 0.3 to 1.3 μm ultrahigh spectral resolution solar spectrum covering the 1.1 to 5.4

μm interval at a 0.05Å resolution (Livingston & Wallace 1991). However, each small spectral intervals of this spectrum is normalized to the local continuum and there is no simple way to absolutely calibrate them (Hill, private communication; Maiolino, private communication).

3. ABSOLUTE FLUX CALIBRATED MODEL SPECTRUM OF THE SUN

A solar model spectrum covering the 0.2 to 2.5 μm spectral range has been computed at 500000 resolution by using the SYNTHE code (Kurucz 1993c). The computed spectrum has then been degraded to a uniform 1Å resolution by averaging the flux in each 1Å interval.

Input data for the computed spectrum are a theoretical solar model computed with the ATLAS 9 code (Kurucz 1993b), and the atomic and molecular lines yielded by Kurucz (1993a).

The solar photospheric model is computed for 72 optical depths ranging from $\log\tau_{Ross}= -6.9$ to 2.0 and has parameters T_{eff}=5777 K, $\log g$=4.4377. The microturbulent velocity for the line opacity is 1.5 km s^{-1}, and abundances are from Anders and Grevesse (1989).

The line lists include transitions arising from both observed and predicted levels. These are the same line lists used by Kurucz to generate the opacity distribution functions (ODF's) adopted for computing the models and fluxes of the grids (Kurucz 1993b,d). For computing the fluxes of the grids, the whole wavelength range from 90Å to 100 μm is divided in 1212 intervals. ODF's are line opacity tables vs. wavelength for different temperatures and gas pressures. The size of the wavelength intervals is the resolution of the ODF's, which constrains the resolution of fluxes having ODF's as line opacity.

The solar model spectrum computed here differs from the solar flux stored on the CD-ROM (Kurucz 1993b) only in the resolution. The ODFs have been replaced by the computation of a synthetic spectrum in order to account for the line opacity at each $\triangle\lambda/\lambda$= 500000 step. This method for computing fluxes is more time consuming than the ODF approach but allows a degradation of the computed spectrum to any resolution, 1Å in our case. For comparison, the resolution of the fluxes of Kurucz's grids (Kurucz 1993b) ranges from 10Å in the ultraviolet up to 100Å − 200Å in the near-infrared.

The model spectrum is in absolute units at the surface of the Sun. When transformed to observed flux at earth for a mean distance of one astronomical unit, the computed flux in the Johnson V filter is 185.06 ergs s^{-1} cm^{-2} $Å^{-1}$. This flux agrees with Neckel & Labs absolute scale to 0.5%. However, in order to have the same scale in both measurements and models, the new model spectrum and Kurucz (1993b) solar spectrum are normalized to Neckel & Labs (1984) absolute scale. In other words, the flux of the model spectrum is normalized to the Neckel & Labs (1984) flux in the Johnson V filter, i.e. 184.2 ergs s^{-1} cm^{-2} $Å^{-1}$.

4. SOLAR MODEL SPECTRUM VERSUS EMPIRICAL SPECTRA

When the model spectrum is compared with the UARS spectrum of Woods et al. (1996) average differences of 10% − 20% are observed in the 0.2μm to 0.4μm interval, with departures of up to 40% for wavelengths shorter than 0.25 μm (Figure 5 upper panel). In the 0.4 to 0.45 μm range, these differences decrease to 4-8% while in the 0.5 to 0.87 μm interval, the calibrated model spectrum agrees with NL84 spectrum to better than 2% (see Figure 5 middle panel). In the near-infrared range (0.9 to 2.5 μm), the model spectrum departures from Arvesen et al. (1969) measurements by as much as 5%−15%, in particular in the 1.5 to 2.5 μm interval (see Figure 5 lower panel). As already mentioned in section 2.3, the spectral broad absorption features in Arvesen's spectrum are not real. Moreover, the absolute calibrated model spectrum gives the correct near-infrared magnitudes (see section 6). As a consequence, the near-infrared interval of the model spectrum will be used in the construction of the solar reference spectrum (see section 5).

5. CALIBRATED REFERENCE SPECTRUM OF THE SUN

The absolute calibrated reference spectrum of the Sun is constructed by combining the absolute calibrated solar spectral irradiances obtained using different instruments and/or models. So far, there is no single instrument able to obtain an absolute calibrated solar spectrum in the wavelength range of covered by HST.

A summary of the different spectra used in the construction of the solar reference spectrum is presented in Table 1. This absolute solar reference spectrum is plotted in Figure 6. Alternatively, the absolute calibrated model spectrum could also be used as a solar reference spectrum in the optical and near-infrared range (i.e. 0.5 to 2.5 μm; see also section 4). A brief description of the different spectra used in the construction of the solar reference spectrum follows.

5.1 Ultraviolet spectrum

The ultraviolet 0.12 to 0.33 μm solar reference spectrum is created by averaging the measurements obtained by the UARS instruments during the 1992 and 1993 campaigns (Woods et al. 1996; irradiances listed in Tables 6 and 7). As already shown in Figure 2, there is a good agreement to ($\sim$4%) between the UARS and Neckel & Labs (1984) spectra in the 0.40 to 0.41 μm region; and, therefore, there will be a smooth transition in the reference spectrum at the intersection of the violet and optical intervals, i.e. at 0.41 μm.

5.2 Optical spectrum

The solar reference spectrum uses the UARS measurements (Woods et al. 1996) for the 0.33 to 0.41 μm range, and the Neckel & Labs (1984) absolute calibrated spectrum in the 0.41 to 0.87 μm interval. As already explained in section 2.2, the NL84 spectrum is the standard reference spectrum in the optical although it shows a systematic lower flux in the violet with respect to other absolute flux measurements (see discussion in §2.2).

5.3 Near-infrared spectrum

The near-infrared reference spectrum has been divided in two separated intervals. The first interval from 0.87 to 0.96 μm uses Arvesen et al. (1969) measurements. For the second interval, covering the 0.96 to 2.5 μm range, the normalized model spectrum with flux values binned every 20Å is adopted. As mentioned in section 2.3, the available near-infrared absolute solar irradiance measurements (Arvesen et al. 1969; Kneizys et al. 1988) show broad bumps in the 1.5 to 1.75 μm range, and broad absorption features in the 2.05 to 2.4 μm range (see lower panel of Figure 5). These features would introduce errors of up to ~5—10% in the H- and K-band fluxes, if the near-infrared interval of the reference spectrum was based on Arvesen's or Kneizys' spectra (see Table 1).

6. MAGNITUDES AND COLORS OF THE SOLAR REFERENCE SPECTRUM

One use of our solar reference spectrum is to establish the absolute calibration of NICMOS broad- and narrow-band filters. To check the accuracy of the absolute flux of the solar reference spectrum, the optical and near-infrared magnitudes and colors of the reference spectrum are computed using synthetic photometry techniques. The results are then compared with published values for the Sun and solar analogs. In the following the combination of filter bandpass and zero-point fluxes only approximate the original photometric systems. Thus, discrepancies of a few percent, 2%, would be expected when comparing synthetic photometry with the original measurements.

The visual magnitude of the Sun is calculated using Buser & Kurucz (1978) filter bandpass for the Johnson V filter. Following Colina & Bohlin (1994), the Hayes (1985) optical spectrum of the primary standard α Lyr is assumed to have a visual magnitude of +0.035 in the Johnson system and the corresponding zero point flux is 3.67×10^{-9} ergs s^{-1} cm^{-2} A^{-1}. The flux of the solar reference spectrum averaged over the V filter is 184.2 ergs s^{-1} cm^{-2} A^{-1}, and corresponds to a visual magnitude of −26.75. This value is in agreement with the determinations of the apparent visual magnitude of the Sun ($V_\odot = -26.75 \pm 0.06$; Hayes 1985, and references therein).

The infrared magnitudes of the solar reference spectrum can also be computed and compared with published values (Wamsteker 1981). The filter bandpasses of Wamsteker's photometric system are not available and only the effective wavelength and bandwidth are published (Wamsteker 1981). To approximate Wamsteker's photometric system, filters with known bandpass, i.e the J Tucson filter (M. Rieke, private comm.), and the H and K filters as in Bessell & Brett (1988), are used. These filters are selected by having effective wavelengths close to that of the filters used in Wamsteker's measurements. Finally, Wamsteker's (1981) zero points are used to compute the apparent magnitudes of the Sun. The JHK synthetic magnitudes of the solar reference spectrum are within 0.01 magnitudes, or less, of the published values (see Table 2).

The optical U−B and B−V colors of the solar reference spectrum have been computed using Buser & Kurucz (1978) filter bandpass to simulate Johnson's UBV photometric system. In Johnson's system, the zero-points for the ultraviolet (U) and blue (B) magnitudes are defined here by the Hayes (1985) α Lyr spectrum and assuming U and B values for α Lyr of 0.03 and 0.035, respectively (see Megessier 1995 for a summary of Johnson's original measurements). The synthesized solar B−V color agrees to 0.01 - 0.02 magnitudes with published values of solar analogs, while the U−B color shows a 0.06 magnitude difference (see summary in Table 3). The discrepancy in the U−B color may well be related to a passband error in this very steep spectral region.

The near-infrared colors of the solar spectrum are computed in a similar way as the optical colors. Two different sets of JHK filter bandpass and zero-point fluxes are used. Wamsteker's (1981) photometric system is explained previously and the computed magnitudes (Table 2) agree to 0.01−0.02 magnitudes with Wamsteker's (1981) results.

The second set of JHK filters consists of the K bandpass as in Bessell & Brett (1988), and the Tucson J and H bandpass (M. Rieke, private comm.). 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 Hardorp class 1 solar analogs in the Tucson photometric system (Campins et al. 1985). Again, the agreement between the synthesized colors and the measurements is better than 0.03 magnitudes (Table 4). Finally, the synthesized V−K color of the reference spectrum agrees to better than 0.01 magnitudes with Wamsteker (1981) and Campins et al. (1985) average values for solar analogs.

A computation of the solar constant is a measure of the photometric accuracy of our reference spectrum integrated over all wavelengths. The 0.09 μm to 10 μm integrated flux of Kurucz (1993b) model spectrum calibrated as explained in section 3, gives a value of 1359 W m^{-2}, i.e. 1% less than the nominal 1373 ± 12 W m^{-2} value of the solar constant (Fröhlich, 1977). The integrated flux in the 0.12 to 2.5 μm range includes 97% of the solar constant, while the reference spectrum predicts the same integrated $0.12 - 2.5$ μm flux as Kurucz's model. Thus, the solar constant derived from the reference solar spectrum is $\sim$ 1% of the nominal 1373 W m^{-2} value.

In summary, the optical and infrared synthetic photometry performed on the solar reference spectrum agree with published average magnitudes and colors of solar analogs, within the uncertainties of the measurements and of the synthetic photometry. The absolute flux of the solar reference spectrum presented here gives broadband photometry that agrees with measurements to 2%−3%, over the entire optical to near-infrared range, i.e. from 0.4 to 2.5 μm.

A final remark is that the absolute flux calibrated solar reference spectrum gives the solar flux reaching the Earth for an average distance of one astronomical unit. Throughout the year a 6.6% variation in the solar apparent flux is measured due to the ellipticity of Earth's orbit (Pierce & Allen 1977).

7. CALIBRATED SOLAR SPECTRA ON THE WEB

The solar reference spectrum, absolute calibrated model spectra as well as most of the spectra mentioned in this paper can be found on the web pages of the STScI Observatory Support Group. The html direction is "html://www.stsci.edu/ftp/cdbs/cdbs2/*directory*", where *directory* is the name of the directory given in Table 5. All the files are in binary STSDAS table format. ASCII copies of all STSDAS tables are also available under the same names and wih the .ascii extension. The pedigree and references for each individual spectrum can be found on the header of the corresponding STSDAS table, or ASCII file.

6. SUMMARY

An absolute flux reference spectrum of the Sun covering the 0.12 to 2.5 μm range has been constructed. The solar reference spectrum combines measurements obtained from satellites and ground-based observatories with a model spectrum. The optical and near-infrared magnitudes of the reference spectrum agree with published values to within 0.01 to 0.03 magnitudes, i.e. uncertainties of the measurements. The predicted solar constant also agrees with the nominal value to $\sim 1\%$.

The solar reference spectrum will be used in the absolute calibration of the HST near-infared camera NICMOS. An alternative reference spectrum for the 0.4 to 2.5 μm wavelength region can be constructed using a model spectrum normalized to Neckel & Labs (1984) optical absolute calibration. This alternative spectrum differs from the reference spectrum in the 0.5 to 0.8 μm wavelength interval by 2%, at most.

Future work includes the study of the optical and near-infrared spectra of the solar analogs used as primary calibration standards for NICMOS. As spectroscopic observations and broad-band optical and near-infrared photometry of these stars become available, a direct comparison of the solar analog spectra with the solar reference spectrum will be published.

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TABLE 1: Absolute Calibrated Solar Reference Spectrum

Range	From Å	To Å	Bin Å	Reference
Ultraviolet	1195	3300	10	Woods et al. 1996
Violet	3300	4100	10	Woods et al. 1996
Optical	4100	8700	10	Neckel & Labs 1984
Near-infrared	8700	9600	20	Arvesen et al. 1969
Near-infrared	9600	25000	20	model spectrum

TABLE 2: Visual and near-infrared magnitudes of the Sun

V	J	H	K	Reference
−26.75	−27.86	−28.20	−28.22	Ref. Spectrum
−26.75	−27.86	−28.19	−28.23	Wamsteker 1981
36.7	3.18	1.18	0.417	Zero Point Flux(1)

Notes to TABLE 2

(1) The average flux over Wamsteker's (1981) JHK filter bandpass for a zero magnitude, i.e. the zero-points of the photometric system, are in units of 10^{-10} erg s^{-1} cm^{-2} $Å^{-1}$. The zero-point flux for V has been obtained as explained in section 6.

TABLE 3: Visual magnitude and optical colors of the solar spectrum

V	U−B	B−V	Reference
−26.75	0.14	0.63	Ref. Spectrum
−26.75	0.20	0.66	Wamsteker 1981(1)
−26.75	0.195	0.65	Neckel 1994
–	–	0.63	Taylor 1994

Notes to TABLE 3

(1) Assumed colors of the Sun obtained from the average colors of solar analogs in Wamsteker's (1981) photometric system.

TABLE 4: Near-infrared colors of the solar spectrum and solar analogs

V−K	J−H	J−K	H−K	Reference
1.47	0.34	0.36	0.02	Ref. Spectrum$^{(1)}$
1.48±0.02	0.33±0.02	0.37±0.02	0.04±0.02	Wamsteker 1981$^{(2)}$
1.50	0.28	0.34	0.06	Ref. Spectrum$^{(3)}$
1.49±0.03	0.31±0.01	0.37±0.02	0.06±0.02	Campins et al. 1985$^{(4)}$

Notes to TABLE 4

$^{(1)}$ Near-infrared colors of the solar reference spectrum obtained for Wamsteker (1981) photometric system. See section 6 for details.

$^{(2)}$ Assumed colors of the Sun obtained from solar analog stars in Wamsteker's (1981) photometric system.

$^{(3)}$ Near-infrared colors of the solar reference spectrum obtained for Campins et al. (1985) photometric system. See section 6 for details.

$^{(4)}$ Average colors of Hardorp class 1 solar analogs in Campins et al. (1985) photometric system.

TABLE 5: Absolute calibrated solar spectra on the Web

Filename	Directory	Description
Sun_REFERENCE	calspec	Ref. Spectrum
Sun_UV	calobs	Woods et al. 1996
Sun_NL84	calobs	Neckel & Labs 1984
Sun_LOWTRAN	calobs	Kneizys et al. 1988
Sun_ARVESEN	calobs	Arvesen et al. 1969
Sun_KURUCZ93	k93models/standards	Kurucz 1993
Sun_CASTELLI	k93models/standards	Castelli 1995

FIGURE CAPTIONS

Figure 1: Ratio of the LOWTRAN spectrum (Kneizys et al. (1988) to the UARS spectrum (Woods et al. 1996) in the ultraviolet using a bin size of 10Å.

Figure 2: Ratio of the Neckel & Labs (1984) spectrum to the UARS spectrum (Woods et al. 1996) in the $3300 - 4100$Å overlapping region, and using a bin size of 10Å.

Figure 3: Ratio of UARS independent measurements at two different epochs showing the variability of the solar spectrum in the ultraviolet (from Woods et al. 1996).

Figure 4: Arvesen et al. (1969) near-infrared spectra. Also shown are the JHK filter bandpass from Bessell & Brett (1988). Flux units are in erg s^{-1} cm^{-2} $Å^{-1}$.

Figure 5: Ratio of the absolute flux solar measurements (data) to the calibrated model spectrum (model) where the measurements are the average UARS spectra in the ultraviolet (upper panel); Neckel & Labs (1984) spectrum in the optical (middle panel), and Arvesen et al. (1969) spectrum in the near-infrared (lower panel).

Figure 6: Absolute calibrated solar reference spectrum for the 0.12 to 2.5 μm range. Flux units are in erg s^{-1} cm^{-2} $Å^{-1}$.

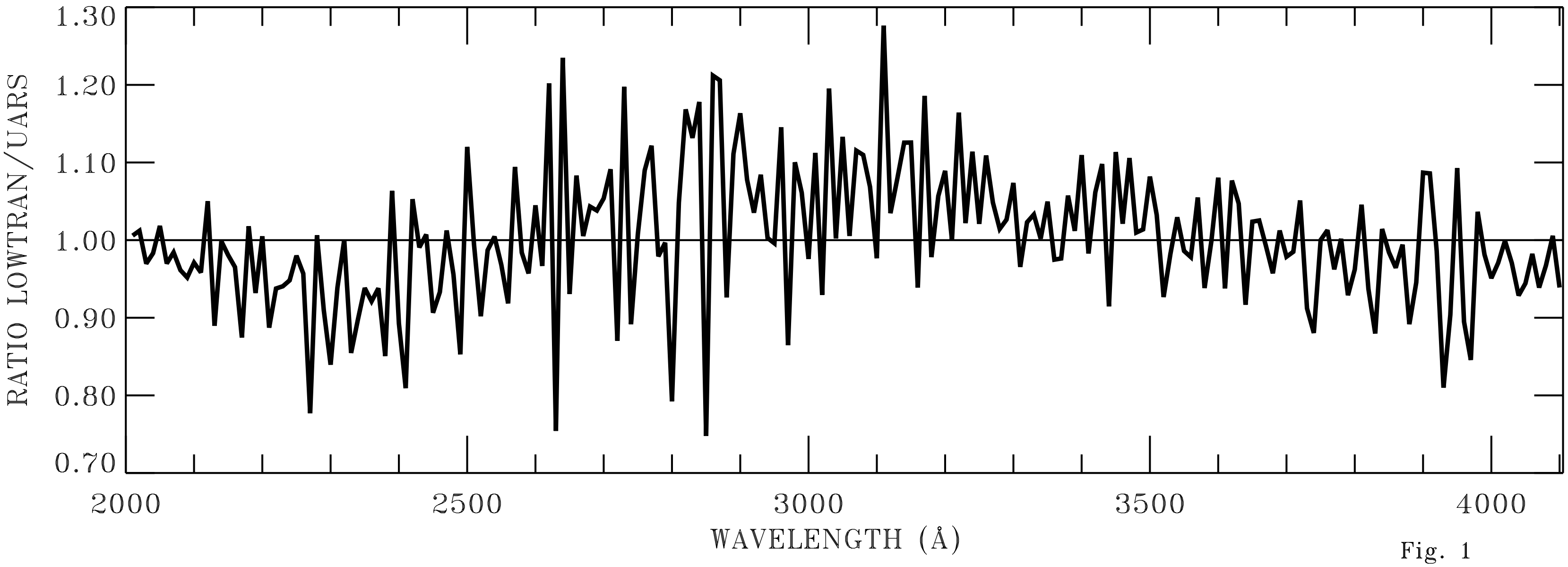


Fig. 1

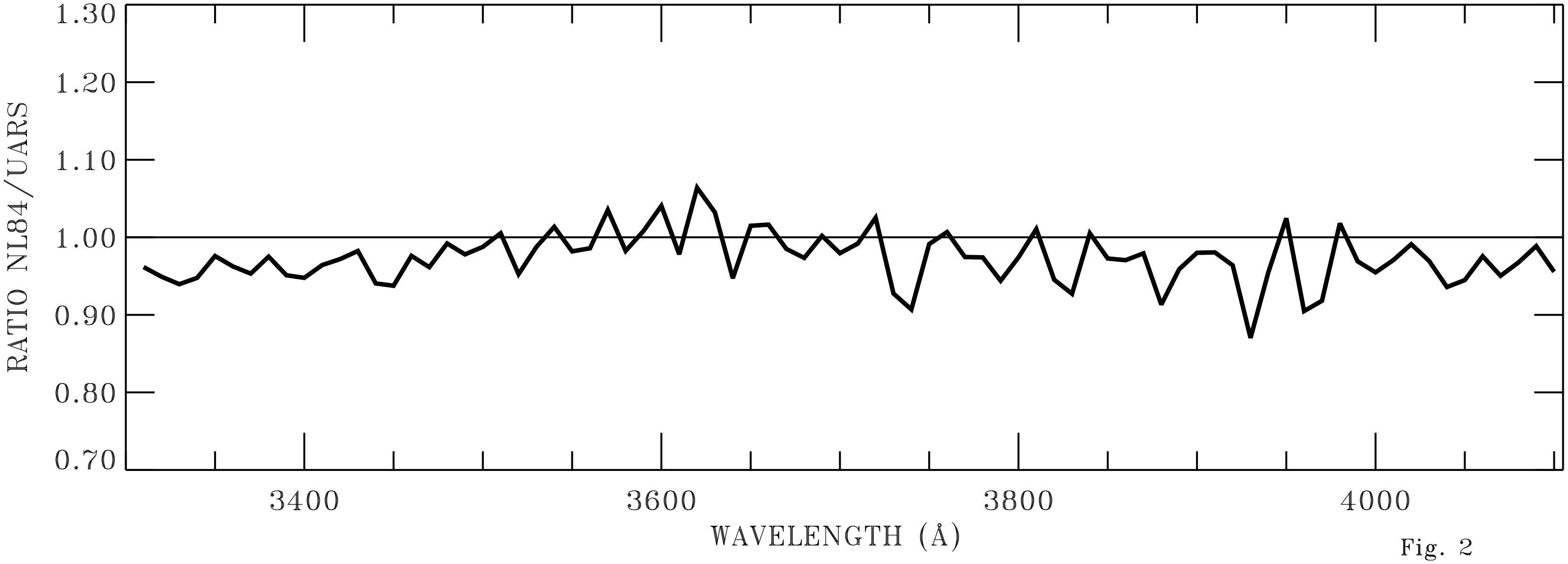
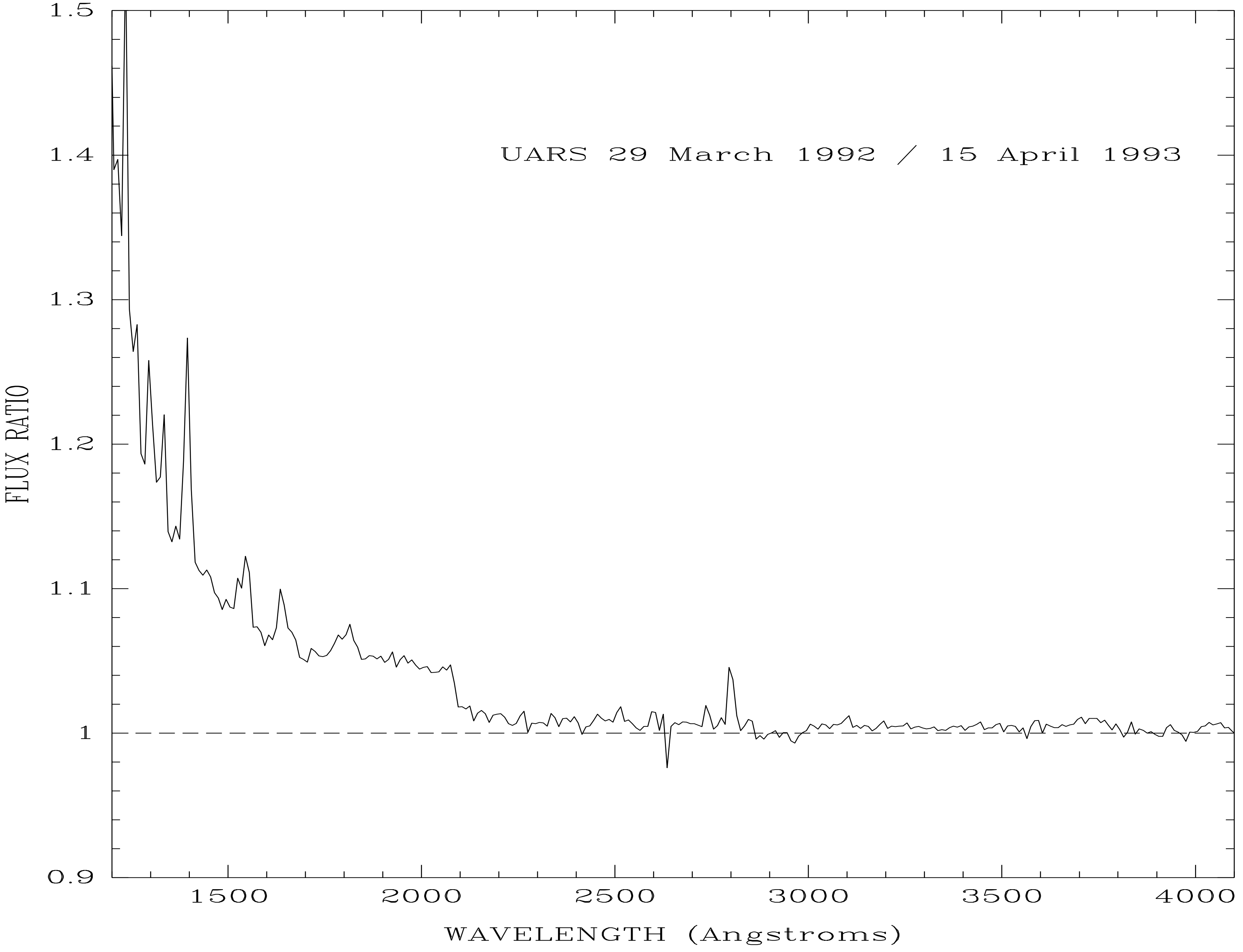
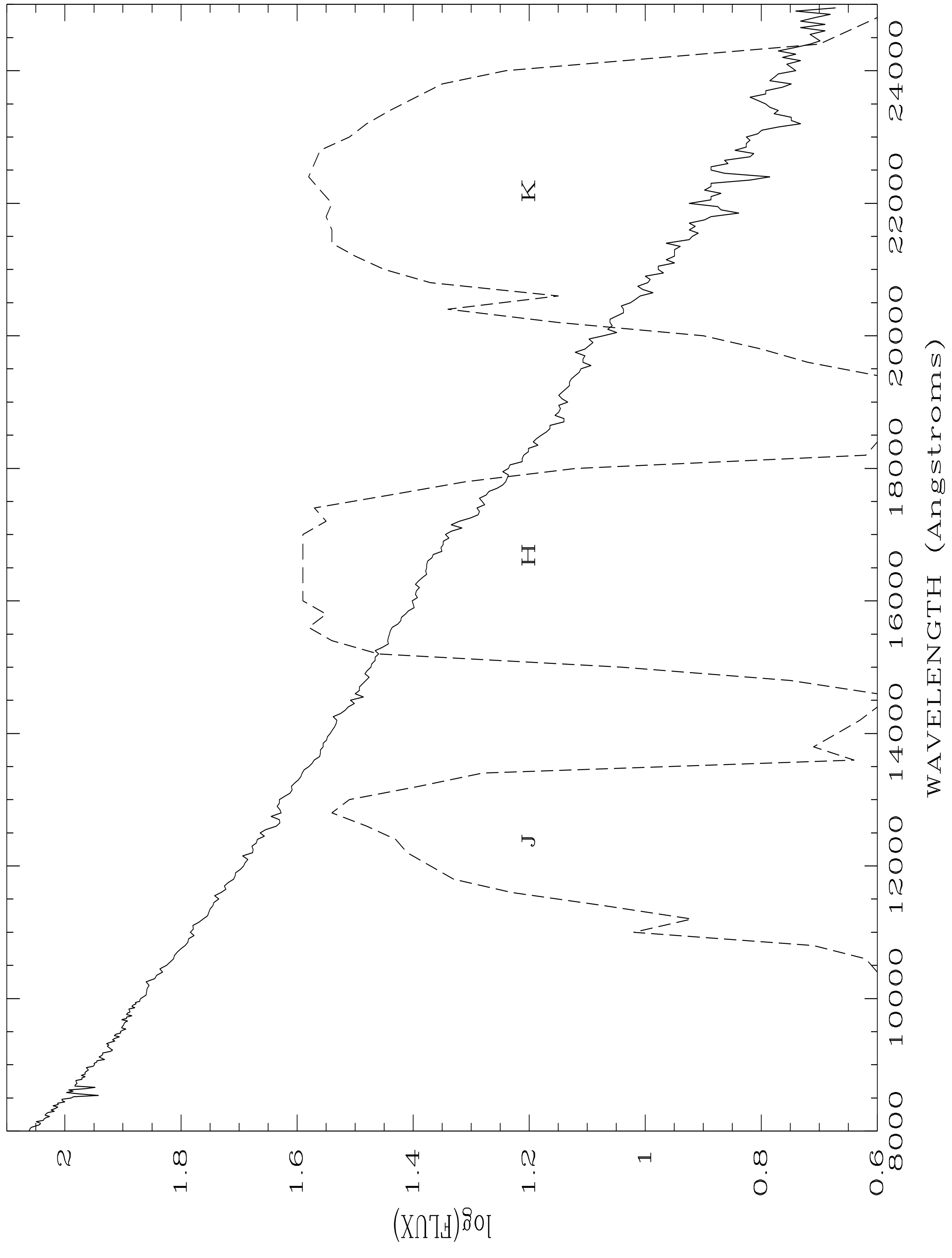
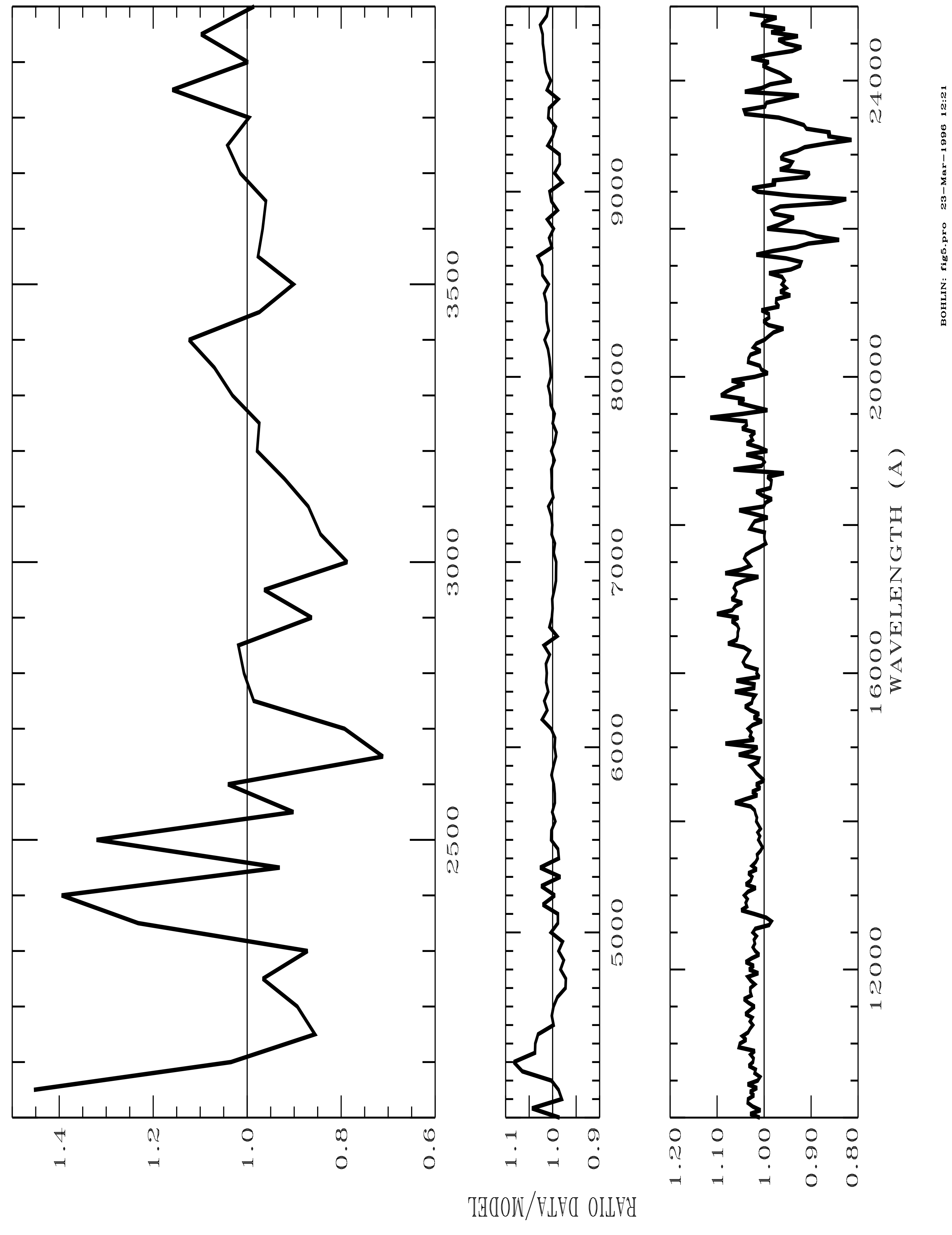


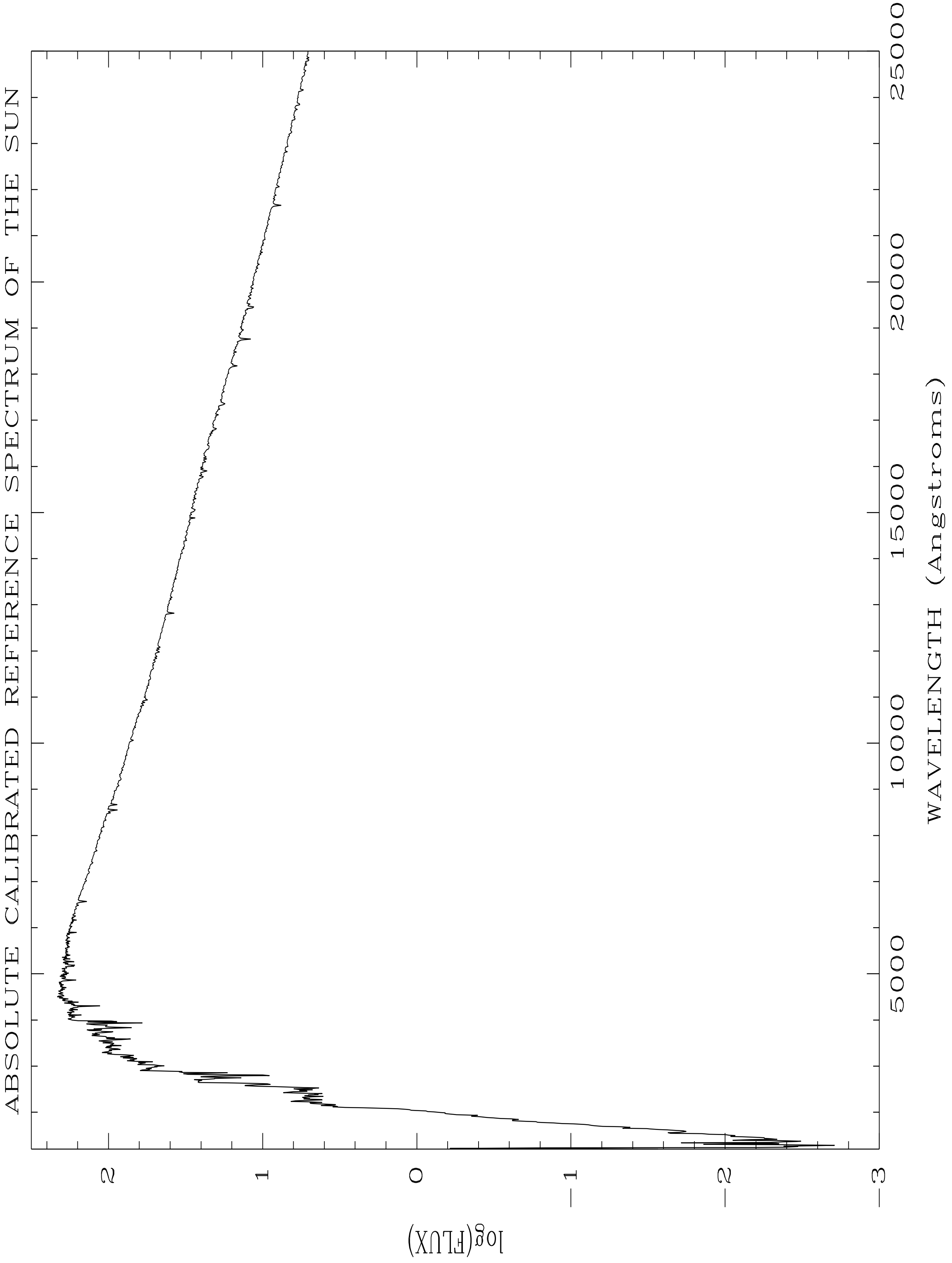
Fig. 2

BOHLIN: fig1-2.pro 25-Mar-1996 09:25


UARS 29 March 1992 / 15 April 1993
FLUX RATIO
1.5
1.4
1.3
1.2
1.1
1
0.9
1500
2000
2500
3000
3500
4000
WAVELENGTH (Angstroms)


log(FLUX)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
8000
10000
12000
14000
16000
18000
20000
22000
24000
WAVELENGTH (Angstroms)
J
H
K


RATIO DATA/MODEL
1.4
1.2
1.0
0.8
0.6
2500
3000
3500
1.1
1.0
0.9
5000
6000
7000
8000
9000
1.20
1.10
1.00
0.90
0.80
12000
16000
20000
24000
WAVELENGTH (Å)
BOHLIN: fig5.pro 23–Mar–1996 12:21


ABSOLUTE CALIBRATED REFERENCE SPECTRUM OF THE SUN
log(FLUX)
−3
−2
−1
0
1
2
WAVELENGTH (Angstroms)
5000
10000
15000
20000
25000