SPECTROPHOTOMETRIC STANDARDS FROM THE FAR-UV TO THE NEAR- IR ON THE WHITE DWARF FLUX SCALE

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ABSTRACT

The second generation instruments to be installed in 1997 on the *Hubble Space Telescope (HST)* require spectrophotometric standard stars for flux calibrations to 1.1 μm for the imaging spectrograph (STIS) and to 2.5 μm for the infrared camera (NICMOS). Calculated model atmosphere flux distributions from 0.1 to 3 μm for four pure hydrogen white dwarfs provide the fundamental basis for a new set of spectrophotometric standard stars. Precise visual photometry sets the absolute level of the model fluxes, while FOS spectrophotometry validates the relative V magnitudes to $\sim 1\%$ and the relative fluxes at other wavelengths to $\sim 2\%$. Extensive FOS observations of four more stars from 1140–8500Å expand the set of primary standards to eight stars.

These eight flux distributions are compared with IUE fluxes in the UV and with Oke spectrophotometry in the visual to define corrections as a function of wavelength. These corrections plus a wavelength independent correction to the Oke fluxes are accurate to $\sim 3\%$ and provide 18 additional standards on the WD scale from 1150–9200Å. One more standard α Lyr consists of IUE data plus the ground based spectrum of Hayes.

1. INTRODUCTION

Since about 1980, the most commonly used absolute UV fluxes of stars have come from the IUE satellite, which was originally calibrated by Bohlin *et al.* (1980), Bohlin & Holm (1980), Holm *et al.* (1982), and Bohlin & Holm (1984). A review of the derivation of the flux for the primary IUE standard η UMa appears in Bohlin (1988). In order to provide internally consistent spectrophotometry for HST calibrations, an IUE recalibration campaign produced a series of papers that culminated in paper IV by Bohlin *et al.* (1990), who noted that their IUE fluxes are low by up to 12% in comparison to a pure hydrogen model atmosphere for the white dwarf (WD) star G191B2B. Consequently, the IUE project is using a WD model for G191B2B to establish the absolute flux calibration for the NEWSIPS reprocessing of the entire archive (Nichols *et al.* 1994). The same basic WD reference fluxes are used to calibrate the Hopkins Ultraviolet Telescope spectrometer that was flown on Astro 1 and 2 (Davidsen *et al.* 1992, Kruk *et al.* 1995).

In the optical, high S/N spectrophotometry is provided by Oke (1990) for the calibration of *HST*. These optical fluxes have pedigrees traceable to α Lyr from Oke & Gunn (1983), Hayes & Latham (1975), and Hayes (1985) and agree with the WD flux scale to better than $\sim 3\%$ typically, except in the difficult region from 3200–3250Å after the corrections of Colina and Bohlin (1994) are applied; cf. also Megessier(1995).

Starting with cycle 4 in 1994 March, the absolute calibration of the *HST* instruments has been on a preliminary WD scale Bohlin (1994). The purpose of this superceeding work is to justify and document the WD basis for the reference standards, to present a set of UV-optical flux standards on the WD scale, and to provide recent extensions of WD model fluxes into the IR. These goals are achieved by the following steps:

a) Calibrate FOS by setting the absolute flux scale with pure hydrogen models, as normalized to photometry at V (section 2.1 below and Bohlin, Lindler, & Keyes 1995). These models from D. Koester (1995) for G191B2B, GD71, GD153, and HZ43 have continua from 1100 to 8200Å that are within 0.2% of the results from the earlier version of his code that is discussed in detail and verified with FOS spectrophotometry by Bohlin, Colina, & Finley (1995). The new models include the Paschen lines and extend to 3 μm to cover the STIS and NICMOS wavelength range.

b) Use the high S/N FOS UV spectra and Oke visual spectra to make standards on the WD scale for four more stars BD+28°4211, BD+75°325, BD+33°2642, and HZ44 (section 2.2 below).

c) Use these eight stars to define average corrections to the complete IUE and Oke data sets (section 3); and create a set of 27 IUE + Oke spectrophotometric flux distributions on the WD scale (section 4 and Table 2). These 27 flux distributions include the 8 stars with FOS data, α Lyr with IUE and Hayes (1985) data, and 18 stars with only IUE + Oke data.

2. FOS FLUXES ON THE WHITE DWARF SCALE

2.1. FOS Calibration

Bohlin, Lindler, & Keyes (1995) document the calibration of the Faint Object Spectrograph on the WD scale. In summary, the absolute photometric calibration is derived from observations of eight spectrophotometric standard stars, including four white dwarf (WD) stars with pure hydrogen model atmospheres (Bohlin, Colina, & Finley 1995). To get the absolute fluxes of the input reference standards, the new WD model flux distributions of Koester (1995) are normalized to the visual photometry of Landolt (1992 & private communication), while FOS relative photometry determines the absolute fluxes of the remaining four stars. The excellent photometric performance of the FOS is demonstrated by

Table 1, which tabulates the difference δV of the average FOS red-side spectrophotometry for each star integrated over the transmission function of the Landolt V filter minus the Landolt photometry. The uncertainties of the Landolt photometry are less than 1%, so the averaged FOS spectra must also be photometric to $\sim 1\%$ typically, since the 1σ RMS differences between the two data sets is $\sim 1\%$. Because of the weight of the large number of independent FOS observation of G191B2B and the normalization of the absolute scale to the V magnitudes of the WD's, the residual is nearly zero for G191B2B.

Bohlin, Colina, & Finley (1995) demonstrate that the internal consistency of the FOS high dispersion fluxes is better than 2% in the residuals of the average FOS fluxes with respect to the input flux for the four WD models. The absolute uncertainty in terms of the slope of the pure hydrogen model flux distributions is $< 1\%$ longward of 1250Å. For G191B2B, an additional 2% uncertainty exists because of line blanketing by a small amount of metals in some wavelength regions below about 2000Å. With respect to the absolute fluxes for Vega in Hayes (1985), a conservative estimate of the overall uncertainty in the broadband FOS calibration is 1–2% in the optical and increasing to 3–4% at 1200Å. See Colina and Bohlin (1994) for a discussion of the relation of the Landolt photometric system to the Hayes fluxes for Vega. In the hydrogen lines, small wavelength errors and resolution mismatches can cause residuals of several percent (Bohlin, Lindler, & Keyes 1995). At Lyα, the geocoronal emission contaminates the observations.

2.2. FOS Standard Stars

The pure hydrogen model atmospheres provide the best absolute spectrophotometric standards after normalization to precise visual photometry. However, few of these pure hydrogen WD stars exist at a V mag brighter than 15. The next best absolute flux standards are derived from FOS spectrophotometry relative to the WD stars, since Table 1 demonstrates that FOS is photometric to $\sim$ 1%. The extensive set of high dispersion FOS spectrophotometry of the four non-WD stars in Table 1 is used to manufacture four more standards, as follows. In the optical, the Oke spectra are retained, because a five meter telescope produces higher S/N spectra than FOS. To correct for the small lack of photometric precision in the ground based data, each of the four Oke spectra is bent to the broadband shape of the average FOS red-side spectrum with a smooth (15 spline node) fit to the FOS/Oke ratio from 3850 to the FOS limit at 8500Å. If the wavelength independent offsets to the Oke data are applied, as recommended by Colina & Bohlin (1994), the spline adjustments are typically 1–2% and exceed 3% only for BD+28°4211 longward of 7050Å. The large correction for BD+28°4211 is probably caused by the red companion, which is five mag fainter in V and has a separation of 2.8″ (Massey & Gronwall 1990). For HZ44, the FOS observations are few and have sufficient significance to correct the shape of the Oke spectrophotometry only to 5200Å. In addition to the broadband corrections, a detailed comparison of the Oke spectrum for G191B2B with the Koester (1995) model reveals a few 1–2% flat field features and up to 5% water vapor contamination beyond 8450Å that are removed from all of the Oke spectra, as described in section 3.2 below. This flat field correction for the Oke data is derived from a comparison of the data with the model for G191B2B only and is statistically appropriate for the other Oke spectra. In other words, this Oke flat field correction usually improves the other spectra but occasionally causes a worse blemish. The typical size of the flat field correction defines the approximate level of uncertainty of spectral features in the Oke data. Complete spectra are formed from the following best available pieces of data:

1140–2085 FOS blue side high dispersion H13 and H19 data

2085–3300 FOS red side high dispersion H19, H27, and H40 data

3300–3850 FOS blue side high dispersion H40 data. For BD+28°4211, use FOS until 3875Å to avoid an Oke data hit at 3860Å.

3850–8500 Oke data corrected with FLXCOR algorithm of section 3.2 and with FOS photometry

8500–9203 Oke data corrected with FLXCOR algorithm of section 3.2

Since the FOS has four sample points per resolution element, the FOS spectra are rebinned every four sample points to reduce noise by a factor of two and data volume by a factor of four. The result is a set of standard star spectra with a relative photometric accuracy of 1–2% with respect to the WD scale.

3. IUE AND OKE FLUX CORRECTIONS TO THE WD SCALE

Once a set of standard candles are established, any internally consistent set of photometric observations can be transformed to the flux scale of the standard, if one or more of the standards are included in the observations.

3.1. IUE

The spectroscopic observations from the low dispersion mode of IUE are photometrically repeatable to $\sim 2\%$ (Bohlin *et al.* 1990, paper IV); and seven of the standard stars in the SWP and five in the LW cameras have been well observed with at least ten IUE spectra. Figure 1 shows the average ratio for these IUE fluxes to the standard star flux, where the more recent LWP data are corrected for time variability per Garhart (1993) to the paper IV flux scale. The heavy line in Figure 1 is the adopted correction for the IUE library of standards, while the dashed line is the RMS scatter among the ratios for individual stars and is about 2%. The IUE data that define this average correction are flagged with an asterisk in Table 2.

For two sample stars, Figure 2 compares the original IUE flux with the flux corrected by the function shown in Figure 1. In addition, the higher S/N FOS spectra from column 3 of Table 2 appear at the top of Figure 2a-b, while the model for G191B2B from column 2 of Table 2 is included in Figure 2a. The connection with the Oke flux from 3200–4000Å is also shown. The corrected IUE flux is similar to the model flux distribution, as expected. In general, the continuity at 3200Å with the Oke flux corrected per section 3.2 below is sometimes as bad as $\sim 10\%$, even after both data sets are corrected to the WD scale. In the case of IUE, the sensitivity drops rapidly from 3000 to 3200Å; and noise at 3200Å can exceed 10%, except for the few massively observed IUE stars. The 3200–3300Å region has heavy atmospheric extinction and is difficult from the ground. The FOS maintains high sensitivity across the 3200Å region but has observed few candidates for standard stars.

3.2. Oke

In analogy with Figure 1, Figure 3 is the average ratio of the Oke spectrophotometry to the standard star flux for the five stars with both FOS and Oke spectrophotometry. From 3850–8500Å, the average photometric error is less than its uncertainty; and the correction has been normalized to unity overall. The small scale structure is derived from a many node spline fit to the ratio of the data/model for G191B2B only. Beyond 8500Å, the correction is again based on the data/model for G191B2B only; but the broader band photometric errors are larger and can be removed with a demonstrated improvement in spectral shape for most of the Oke spectra. The spline fit corrections shown in Figures 1 and 3 are incorporated in an IDL procedure named FLXCOR and can be obtained from the author. Figure 3 shows that the RMS scatter and uncertainty in the Oke spectrophotometry is 2–3%. Beyond 8800Å, Oke (1990) says that the second-order spectrum can cause larger errors, especially for the hottest stars. The improvements of the FLXCOR correction are demonstrated in

Figure 4 for two sample spectra.

4. THE LIBRARY OF SPECTRA ON THE WHITE DWARF FLUX SCALE

Table 2 summarizes the main set of recommended standard star spectra. More documentation on these stars is in Turnshek *et al.* (1990) and Bohlin, Colina, & Finley. The four model spectra from Koester (1995) for pure hydrogen are listed by CDBS name in column 2 and are the preferred standards, since the fluxes for every other standard are based on these four models. Since the model calculations extend to 3 μm and cover the long wavelength limits of 2.5 μm for NICMOS and 1.1 μm for STIS, these standards also provide IR calibration sources that are required after the 1997 *HST* second servicing mission. I. Hubeny computed NLTE models atmospheres for the same temperature and gravity and included the Brackett hydrogen lines, in addition to the lower line series that are in Koester's models. Below 2.5 μm, the strongest Brackett line is Bγ at 2.1655 μm with a central depth of only 4% in the coolest star GD71. If the models are all normalized at V, the largest differences in the continuum fluxes of the two independent calculations are for G191B2B, where the Hubeny flux is $\sim$ 0.5% lower below 3500Å and up to 3.5% higher in the IR at 2.5 μm.

The eight CDBS names for the second choice standard stars are listed in column 3 of Table 2 and are composed of FOS spectra in the UV and Oke spectra at the longer wavelengths. Four of these eight spectra have model flux distributions that are preferred for most purposes. However, these four observational spectra can be compared with the models; and in the case of G191B2B, there is line blanketing at the few percent level in the UV. Three of the WD stars were not observed by Oke and are the FOS spectra all the way to the FOS limit of 8500Å, where these data are noisier than the Oke data from the 5m Palomar telescope.

The names for the third choice, but largest, set of standard stars appear in column 4 of Table 2. The application of the corrections from section 3.1 to the original fluxes for IUE (Bohlin *et al.* 1990) and from section 3.2 and Colina & Bohlin (1994) for Oke (1990) produce a consistent set of spectrophotometry from 1150–9200Å. This current set of standards is composed of IUE+Oke data only, while some older versions of the *HST* standard star database have undocumented extensions to longer wavelengths that use model atmospheres. L. Colina and I are investigating new extensions that are based on more recent and better documented theoretical calculations.

The names of these composite CALSPEC files in the Calibration Data Base System (CDBS) that are listed in Table 2 can be accessed via the world wide web with the URL identifier http://www.stsci.edu/ftp/instrument_news/Observatory/astronomical_catalogs.htm l. Some additional stars in the CDBS CALOBS directory with only IUE or Oke spectra have been corrected according to algorithms discussed here and can be found by starting at the above URL. These CALOBS data have the keyword OBSMODE set to either IUE or OKE DBSP. In total, Oke supplied 30 spectra, which include five more than his 1990 publication. All CALSPEC wavelengths are in vacuum, while the Oke data and the IUE above 2000Å in CALOBS retain air wavelengths. The unit of flux in all cases is erg s^{-1} cm^{-2} $Å^{-1}$.

In summary, the WD model atmospheres for pure hydrogen stars provide the best standard spectra after normalization to Landolt photometry. For other standards, the FOS spectra are the most precise up to 3850Å; and the corrected Oke spectra extend the coverage to 9200Å. If FOS data do not exist, the IUE spectra can be used for standard flux distributions to 3200Å; and the corrected Oke spectra again extend the coverage to 9200Å.

Dr. L. Colina produced Table 1 and read a draft of this manuscript. D. J. Lindler computed the FOS calibration and prepared the final flux distributions of the spectrophotometric standard stars with support from NAS5-1630. Dr. A. Landolt provided the new photometry for GD153 and HZ43. Dr. D. Koester computed the model atmospheres for the pure hydrogen WD stars; and Dr. I. Hubeny computed NLTE models for the same temperature and gravity. This work is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract No. NAS5-26555.

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Table 1. Difference Between Landolt and FOS V mag

Star	δV	N[1]
BD+28°4211	+.006	11
BD+33°2642	–.013	2
BD+75°325	–.013	4
G191B2B	+.001	8
HZ44	+.014	2
GD71	–.011	2
GD153	+.004	3
HZ43	(+.030)[2]	3
AVG[3]	–.002	± .011

[1]Number of red side H57 FOS observation used to form the average high dispersion spectrum. Typically, the number of H40 observations is the same, while the H78 data were collected somewhat less often. For an exact tabulation, see Lindler & Bohlin (1994) and Bohlin, Lindler, & Keyes (1995).

[2]FOS photometry is used to normalize the model because of the red companion.

[3]Average δV for 7 stars and the RMS scatter about the mean.

Table 2. CDBS[1] Files of Standard Stars with Columns in Order of Preference

CDBS Name (1)	Model (2)	FOS+Oke (3)	IUE+Oke (4)	nswp (5)	nlw (6)
AGK+81D266			AGK_81D266_005	15	14
ALPHA-LYR[2]			ALPHA_LYR_004	9	13
BD+25D4655			BD_25D4655_002	3	2
BD+28D4211		BD_28D4211_FOS_002	BD_28D4211_005	233*	239*
BD+33D2642		BD_33D2642_FOS_002	BD_33D2642_004	124*	117*
BD+75D325		BD_75D325_FOS_002	BD_75D325_005	302*	263*
FEIGE110			FEIGE110_005	8	9
FEIGE34			FEIGE34_005	8	20
FEIGE66			FEIGE66_002	2	2
FEIGE67			FEIGE67_002	1	3
G191B2B	G191B2B_MOD_002	G191B2B_FOS_002	G191B2B_005	41*	41*
G93-48			G93_48_004	3	3
GD108			GD108_005	3	3
GD153	GD153_MOD_002	GD153_FOS_002[3]		11*	10*
GD50			GD50_004	5	3
GD71	GD71_MOD_002	GD71_FOS_002[3]		10*	9
GRW+70D5824			GRW_70D5824_005	9	9
HD93521			HD93521_005	199	192
HZ21			HZ21_005	12	12
HZ2			HZ2_005	5	6
HZ43	HZ43_MOD_002	HZ43_FOS_002[3]		13*	4
HZ44		HZ44_FOS_002	HZ44_005	7	5
HZ4			HZ4_004	3	4
LB227			LB227_004	5	7
LDS749B			LDS749B_005	3	4
LTT9491			LTT9491_002	2	2
NGC7293			NGC7293_005	14	11

[1]All Calibration Data Base System files have a .tab appended.

[2]Ground based data from Hayes (1985).

[3]FOS data only. Not Observed by Oke.

*Used to define the mean correction for IUE to the WD scale.

Figure 1: The correction for IUE to the WD flux scale. Seven stars in the SWP camera and five in the LW range have ten or more IUE spectra and define this average ratio. The thinner solid line is the average, while the heavy solid line is the adopted spline fit to the average. The dashed line is the RMS scatter among the individual ratios and has an offset of 0.8. IUE fluxes are low by more than 10% only in three narrow wavelength regions.

Figure 2: IUE spectra for (a) G191B2B and (b) BD+28°4211 before and after the FLXCOR correction to the WD scale. The spectra are scaled by an arbitrary power of the wavelength to flatten the flux distribution and illustrate the small features. The bottom, center, and upper sets of curves are offset by 20% for clarity, where 10% on the logarithmic scale is indicated. Bottom: Original standard star spectrum, consisting of Bohlin *et al.* (1990) IUE fluxes shortward of 3200Å and Oke (1990) fluxes beyond 3200Å. Center: Updated IUE spectrum on the original scale (dotted line) and corrected with the FLXCOR algorithm (heavy solid line). The light solid line is the corrected Oke spectrum. Top: FOS spectrum that agrees with the corrected IUE and Oke data, except for the higher S/N in the FOS spectrum. In 2a, the fundamental model for G191B2B is also displayed with an offset of 2% from the FOS data for clarity.

Figure 3: From 3200–3850Å, average ratio and fit of the Oke fluxes to the FOS standard stars on the WD scale for five stars, as in Figure 1. Beyond 3850Å, the adopted correction is based on G191B2B only. The dashed line is the RMS scatter among the individual ratios and has an offset of 0.9. These corrections exceed 3% only in narrow wavelength regions.

Figure 4: Two Oke spectra before and after the FLXCOR correction to the WD scale along with the model atmosphere for G191B2B, as in Figure 2. The corrected fluxes are forced to the shape of the WD model for G191B2B and have the largest corrections below 3850Å and beyond 8500Å. A discontinuity of $\sim 1\%$ exists where Oke joined his blue and red

spectra at ~ 4700Å in G191B2B. The large correction to the Oke spectra at 3200–3250Å removes an artifact and even reveals the HeII line at the IUE-Oke juncture in Figure 2b. The original *HST* standard spectrum at the bottom has an undocumented model extension beyond 8800Å that agrees poorly with the observed Paschen lines in BD+33°2642. The center set of spectra show a difference between the corrected (solid lines) and uncorrected (dotted lines) that is much larger in 4b than 4a because of the larger offset between Oke and the Landolt photometry for BD+33°2642 (Colina & Bohlin 1994). The top spectra are from column 3 of Table 2 and consist of FOS data below 3850Å. Longward of 3850Å, this standard star spectrum is the high S/N Oke data that has the small scale correction of the center spectrum, as well as the broadband correction to the FOS photometry with the 15 node spline fit.

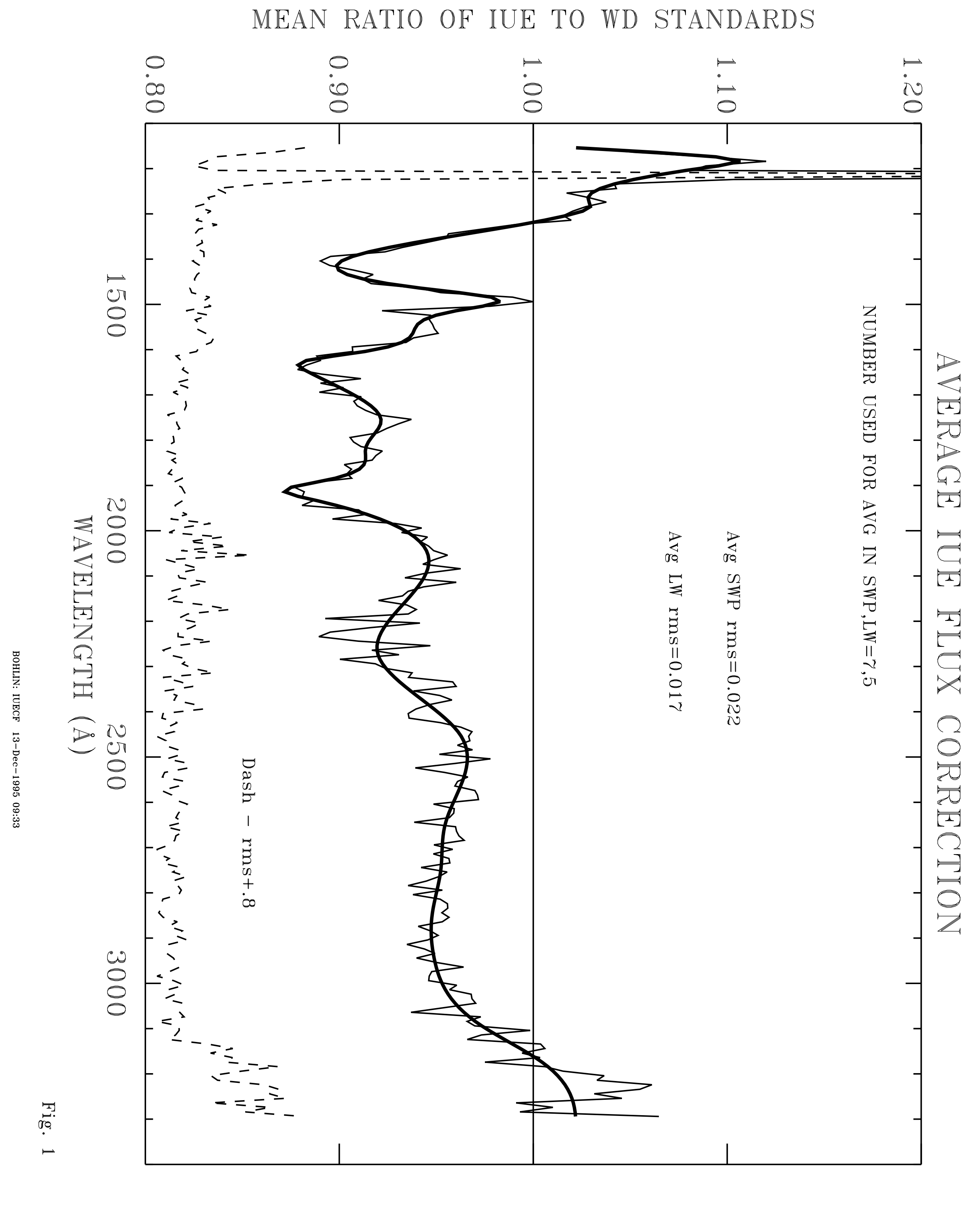
MEAN RATIO OF IUE TO WD STANDARDS
AVERAGE IUE FLUX CORRECTION
NUMBER USED FOR AVG IN SWP,LW=7,5
Avg SWP rms=0.022
Avg LW rms=0.017
Dash - rms+.8
1.20
1.10
1.00
0.90
0.80
1500
2000
2500
3000
WAVELENGTH (Å)
BOHLIN: IUECF 13-Dec-1995 09:33

Fig. 1

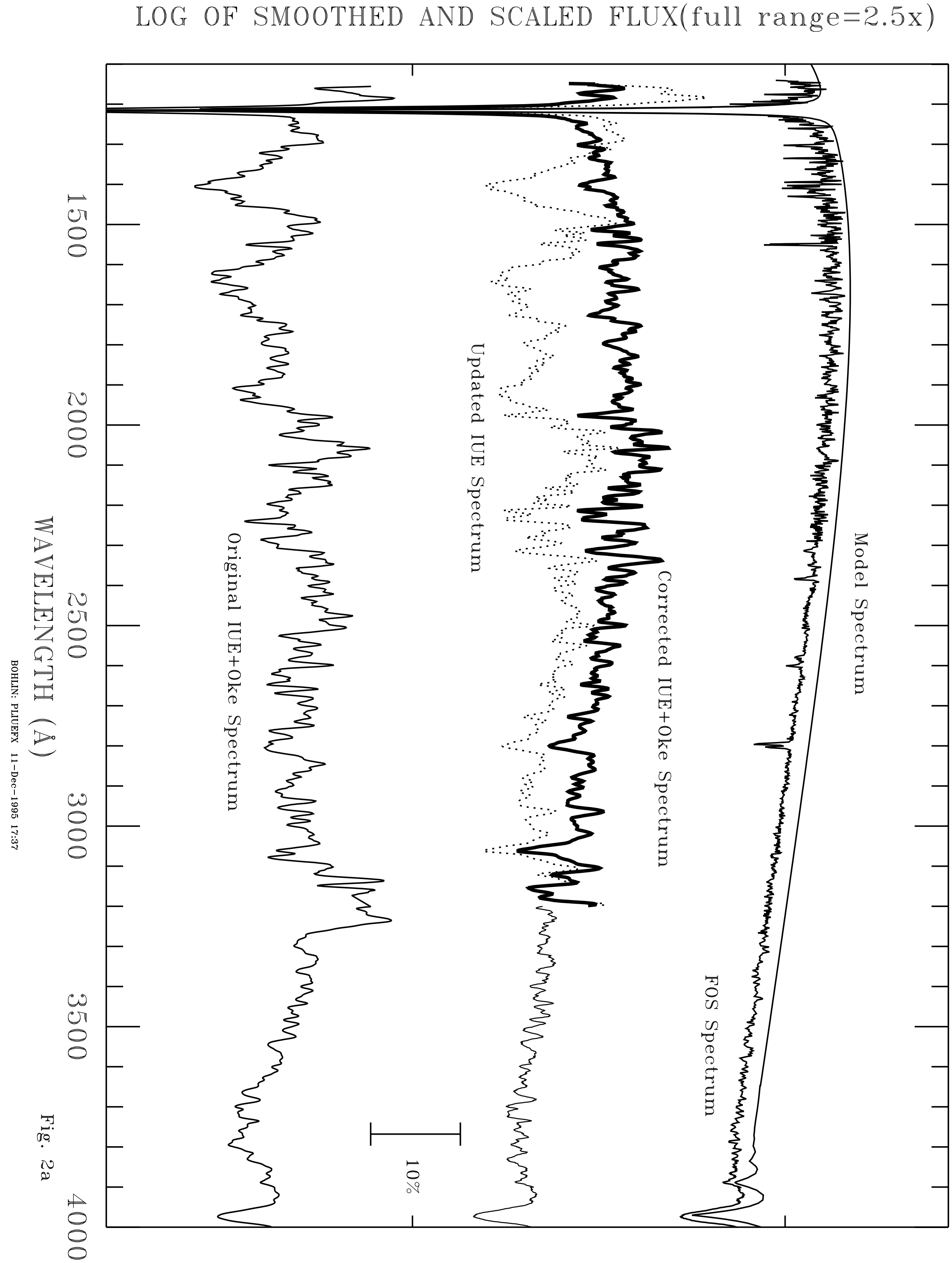
LOG OF SMOOTHED AND SCALED FLUX(full range=2.5x)
G191B2B
Model Spectrum
FOS Spectrum
Corrected IUE+Oke Spectrum
Updated IUE Spectrum
Original IUE+Oke Spectrum
10%
1500
2000
2500
3000
3500
4000
WAVELENGTH (Å)
BOHLIN: PLIUEFX 11-Dec-1995 17:37

Fig. 2a

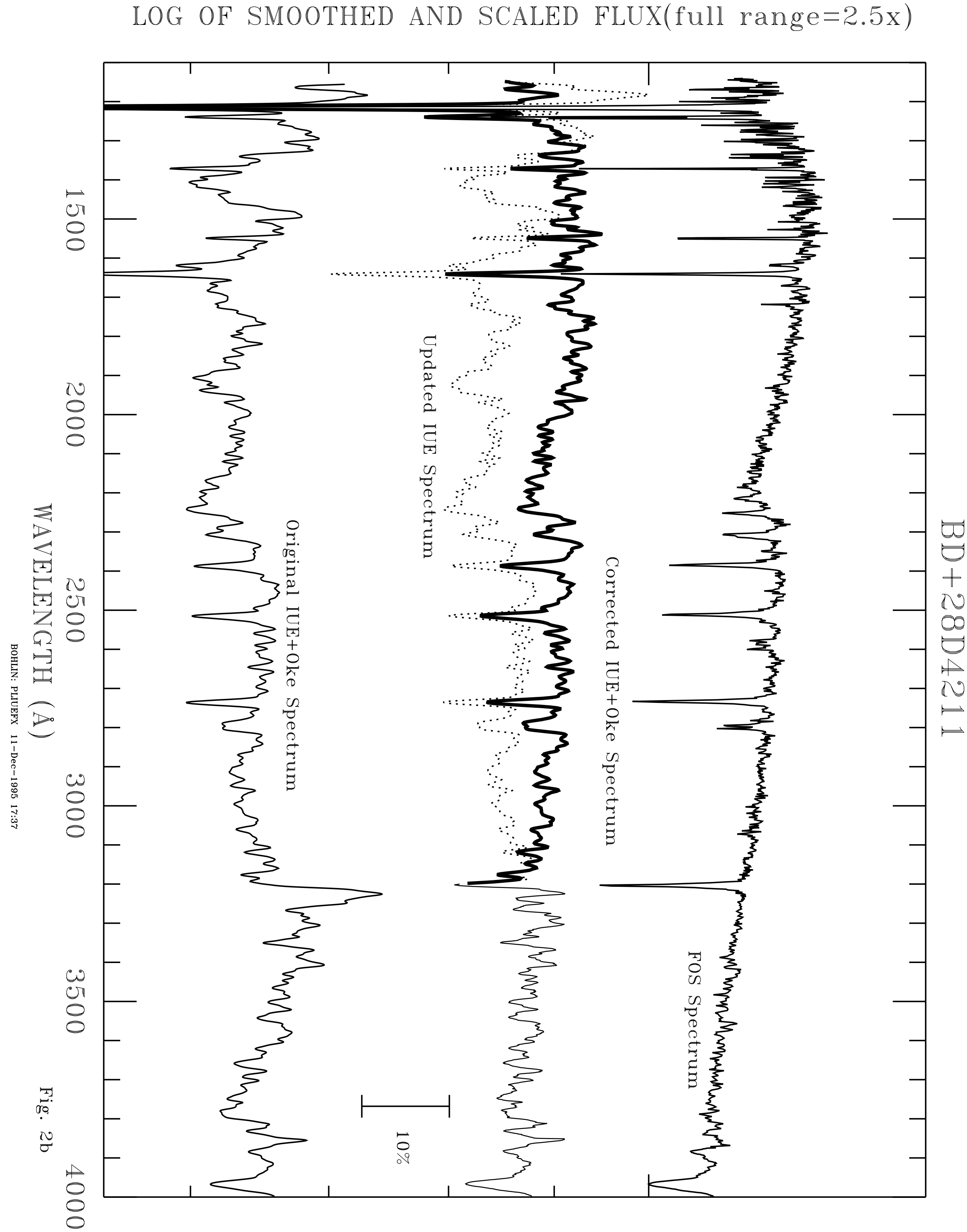
LOG OF SMOOTHED AND SCALED FLUX(full range=2.5x)
BD+28D4211
FOS Spectrum
Corrected IUE+Oke Spectrum
Updated IUE Spectrum
Original IUE+Oke Spectrum
10%
1500
2000
2500
3000
3500
4000
WAVELENGTH (Å)
BOHLIN: PLIUEFX 11-Dec-1995 17:37

Fig. 2b

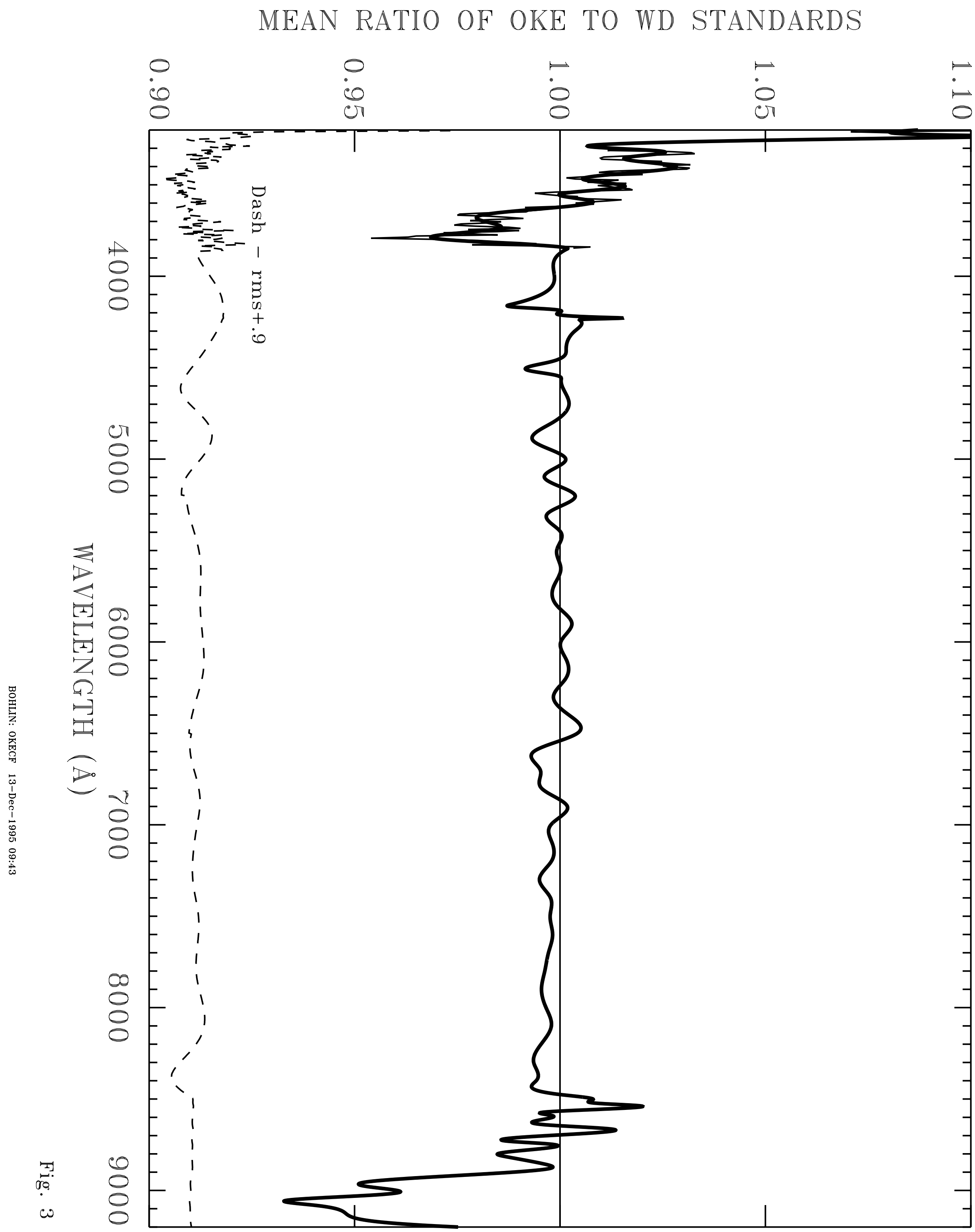
MEAN RATIO OF OKE TO WD STANDARDS
0.90
0.95
1.00
1.05
1.10
4000
5000
6000
7000
8000
9000
WAVELENGTH (Å)
Dash - rms+.9
BOHLIN: OKECF 13-Dec-1995 09:43

Fig. 3

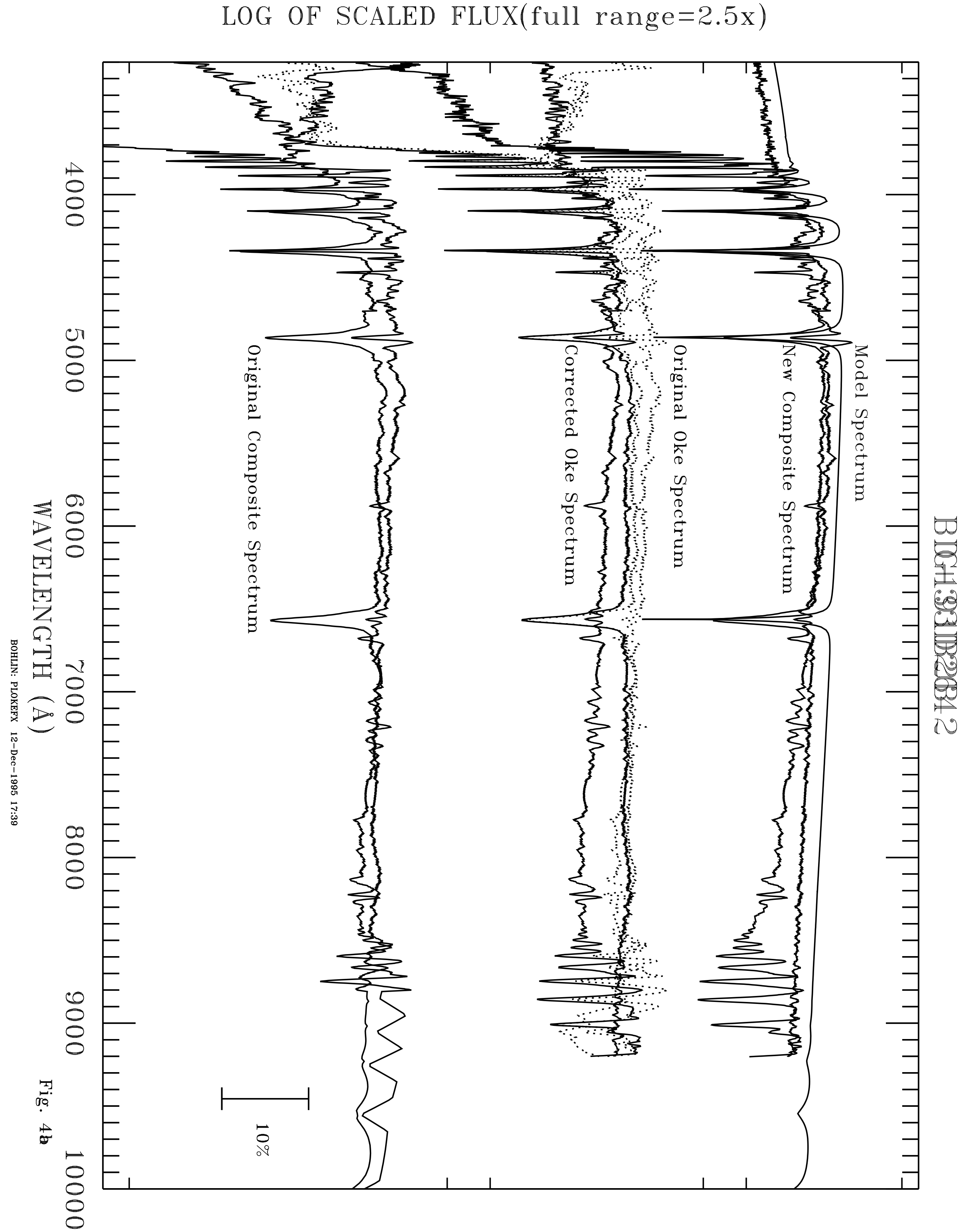
LOG OF SCALED FLUX(full range=2.5x)
BD+33D2642
Model Spectrum
New Composite Spectrum
Original Oke Spectrum
Corrected Oke Spectrum
Original Composite Spectrum
10%
4000
5000
6000
7000
8000
9000
10000
WAVELENGTH (Å)
BOHLIN: PLOKEFX 12-Dec-1995 17:39

Fig. 4b