Rosetta-Alice calibration star reference spectra: Selection and correction

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1 Introduction

Calibration of the effective area (A_{eff}) for the Rosetta-Alice instrument requires observation of calibration stars with known FUV spectra. A number of calibration stars have been selected and observed for this purpose, and will continue to be observed in future mission phases. Calibrated spectra of the same stars from past and current FUV missions constitute the known spectra against which R-Alice instrumental spectra must be compared. This report describes the reference spectra used for each of the stars, including selection criteria, data source, corrections, uncertainties, and outstanding issues.

The optimal calibration for a far-UV spectrograph can be derived by acquiring spectra of a number of primary flux standards: white dwarf stars with well-fit theoretical models, particularly sources and models already demonstrated in calibration campaigns for other instruments. Simultaneous fitting of multiple observed spectra to these well-understood models provides reliable A_{eff} calibration. Unfortunately, these white dwarf stars are relatively faint, and would result low signal-to-noise spectra for R-Alice, even with relatively long integration times. Further complicating matters, the effective area derived from the only white dwarf star observed with R-Alice to date (WD 0501-289) is nearly a factor of two lower than A_{eff} derived using other sources. The cause of this discrepancy is unclear. Observations of the white dwarf stars G191-B2B and BD $+28^{\circ}$ 4211, which are several times brighter than WD 0501-289, are planned for observation during PC10 in the September 2009 timeframe.

Instead, for calibration of R-Alice A_{eff}, we observe a set of hot stars with fluxes more appropriate for this instrument. Reference spectra for these stars are obtained from a variety of sources, starting with the HST CALSPEC database, a collection of composite and model spectra that serve as the fundamental flux standards for HST instruments. Where it is possible to use white dwarf model spectra or STIS spectra from CALSPEC, we do so. Currently, this applies only to the STIS spectrum of Vega, at wavelengths longward of 1675 Å. For most stars and wavelength regions, where such products are not available in the HST CALSPEC database, we rely on IUE, HUT, and BEFS spectra, applying the latest available corrections. (Shorter-wavelength data in CALSPEC are typically provided by IUE spectra, scaled to match STIS calibration at longer wavelengths. However, the IUE spectra used do not reflect recent important corrections to IUE calibration. We have therefore chosen not to use the IUE-based CALSPEC data. These corrections are discussed further in Section 2.2 below.)

2 Calibration stars and archival spectra

The calibration stars observed to date with R-Alice are: Vega (α Lyr), ρ Leo, α Gru, γ Gru, HD 93521, WD 0501-289, and ζ Cas. Archival data from the International Ultraviolet Explorer (IUE, operating 1978 - 1996) exist for all of these targets, and cover the wavelength range from 1150 Å to the R-Alice long-wavelength limit near 2050 Å. Data from the Berkeley Extreme and Far-UV Spectrometer (BEFS) on the ORFEUS-SPAS II mission (flown aboard the space shuttle in 1996) provides additional coverage at short wavelengths, down to (and beyond) the 912 Å Lyman limit, for three of these stars. Spectra from the Hopkins Ultraviolet Telescope (HUT) on the Astro II mission (flown aboard the space shuttle in 1995) cover 912–1850 Å for HD 93521, and additional coverage for Vega (longward of 1675 Å) is provided by Hubble Space Telescope (HST)/Space Telescope Imaging Spectrograph (STIS) spectra. Far Ultraviolet Spectroscopic Explorer (FUSE) spectra of WD 0501-289 and HD 93521 also exist, although we do not use them. HD 93521 flux measurements by FUSE are not absolute, as the star is too bright for proper guiding, and an unknown fraction of flux appears to have been lost from the spectrograph slit. WD 0501-289 observations with R-Alice have not proven useful for A_{eff} calculations to date.

A summary of the calibration stars compiled to date, and data sources adopted for each, is given in Table 1.

In most cases, our adopted reference spectra are composites of multiple

Table 1: Calibration stars and sources of reference spectra for each.

Star	IUE	HUT	BEFS	STIS
Vega (α Lyr)	✓		✓	✓
ρ Leo	✓			✓
α Gru	✓			
γ Gru	✓			
HD 93521	✓	✓	✓	
WD 0501-289	✓		✓	
ζ Cas	✓			✓

spectra. When using multiple spectra from a single instrument and configuration (i.e. identical wavelength coverage), we combine these files by performing a weighted average of the multiple flux values at each wavelength. The errors used for weighting are those provided with the archival data. When combining spectra from different instruments or wavelength ranges, we determine a crossover wavelength, and adopt separate spectra above and below this value (rather than doing any kind of averaging in the overlap region). Where applicable, we check data quality flags in the archival spectra for indications of "bad" or "suspect" data, and treat such data points as missing flux values.

We have researched the best calibrated spectra available for the given stars only around the wavelength region of interest for R-Alice calibration. Given this limited scope, we restrict spectral coverage of this report to the 900–3000 Å region, even though some of our adopted spectra extend to longer wavelengths (e.g. STIS and IUE LWP spectra).

Two additional stars are planned for future calibration observations: G192-B2B and BD +28° 4211. Both have been observed by IUE, HUT, FUSE, BEFS, and STIS. G191-B2B also has a purely modeled spectrum in the HST CALSPEC, which will serve as the primary flux standard for this star. The primarly flux standard for BD +28° 4211 will also be the HST CALSPEC spectrum, which is based on observations by the HST Faint Object Spectrograph.

2.1 HST CALSPEC database and STIS Next Generation Spectral Library

Of the listed instruments, STIS is the most recently and most accurately calibrated. Its calibration is based on observations of a number of white dwarf primary standards, normalized to visible ground-based observations of Vega, with total uncertainties in the FUV of under 4% (*Bohlin*, 2000; *Bohlin and Gilliland*, 2004). Of the calibration stars observed by R-Alice, two are in the HST CALSPEC database: Vega and HD 93521. The CALSPEC spectra of these sources are compilations, and both contain STIS spectra, but only the Vega spectrum includes STIS data in the R-Alice wavelength band. We adopt this STIS spectrum of Vega, which extends from 1675 Å to well beyond the long-wavelength cutoff of R-Alice, as our most reliable flux standard to date. As already mentioned, and discussed in detail below, we do not adopt the remaining CALSPEC data for these standards, opting instead for corrected IUE and HUT data.

In addition to data in the CALSPEC database, we use data from the STIS Next Generation Spectral Library (NGSL). The NGSL contains spectra of some 380 stars down to a wavelength of 1675 Å, although ρ Leo is the only NGSL star used in the calibration of R-Alice. These spectra are available as a "high-level science product" from the MAST website. Calibration of the STIS NGSL at is not trivial, and at the shortest wavelengths, i.e., the region covered by R-Alice, red light contamination is a significant concern. Details of the calibration of NGSL spectra are given by *Gregg et al.* (2006). Missing, however, is a discussion of the uncertainties in the NGSL calibration, though presumably the NGSL has uncertainties comparable to the parts of the HST CALSPEC database derived from STIS observations.

2.2 IUE datasets and corrections

IUE data can be retrieved from the online MAST archive[1] hosted by the Space Telescope Science Institute. Data from two different IUE processing systems are available; we are concerned only with the data as processed with the New Spectral Image Processing System (NEWSIPS). This is the second and final processing system for IUE data, and provides better S/N and absolute calibration than its predecessor, IUESIPS.

IUE utilized two spectrographs to cover long and short wavelengths; each could send its spectra to one of two cameras, denoted primary and redundant. Because the short-wavelength redundant camera did not func-

[1] `http://archive.stsci.edu/`

tion well and was never fully calibrated, no NEWSIPS data are available for that configuration (*Massa and Fitzpatrick*, 2000). Hence the available NEWSIPS datasets fall into one of the following categories: short-wavelength primary-camera (SWP) spectra covering 1150 Å $< \lambda <$ 1975 Å; long-wavelength primary-camera (LWP) spectra covering 1910 Å $< \lambda <$ 3300 Å; and long-wavelength redundant-camera (LWR) spectra covering 1860 Å $< \lambda <$ 3300 Å. We have not used data from the LWR camera, as the necessary corrections for these files currently cannot be performed (details below).

While both of IUE's long- and short-wavelength spectrographs could acquire spectra in low-dispersion or high-dispersion modes, the high-dispersion (echelle) modes were not independently photometrically calibrated. Instead, the high-dispersion spectra for a given star have been flux-calibrated only by scaling to match the low-dispersion spectra for the same star. Furthermore, IUE could record spectra through two apertures, large and small. Only the large aperture reliably captured the full PSF of an observed star, so only large-aperture IUE spectra are photometrically reliable. Hence, we use only large-aperture, low-dispersion IUE spectra in compiling our reference spectra.

Although the NEWSIPS processing (see *Nichols and Linsky*, 1996) provides a significant improvement in data quality and absolute calibration over the previous IUESIPS processing, a later study by *Massa and Fitzpatrick* (2000, hereafter MF2000) still found significant problems with the internal consistency and absolute calibration of NEWSIPS low-dispersion, large-aperture data. The identified systematic effects include wavelength-, time-, and temperature-dependent components. The same authors developed corrections for each of these components. To improve the internal consistency, they simultaneously fit independent functions to the temporal and temperature dependencies. After removing these dependencies, they adjusted the absolute calibration by comparing IUE spectra for 3 well-observed stars to the HST/Faint Object Spectrograph (FOS) spectra for the same stars. The mean FOS:IUE ratio for these 3 stars was adopted as the IUE flux scale correction. The corrections of MF2000, implemented as IDL routines, are available for download from the MAST archive[2]. We adopt the MF2000 corrections for all SWP and LWP IUE NEWSIPS data. Currently, correc-

[2] `correct_astro.zip` is available at `http://archive.stsci.edu/iue/contrib.html`. Note that, as of the date of this report, the IDL routine `correct_astro.pro` within that archive contains a bug that prevents the temperature-dependent correction from being applied. We have confirmed this bug with Derck Massa and fixed our private copies of the routine to eliminate it.

tion attempts using the MF2000 routines fail for LWR files. This issue has been brought to the attention of Derck Massa, and we may address it in the future (particularly if available LWR data become important for any particular sources). MF2000 demonstrate that their corrections bring the IUE systematic uncertainties from 10–15% to the 3–5% range, although we find slightly larger spreads among the flux levels of corrected IUE spectra for individual sources. Also, MF2000 note that they have little data to use for calibrating IUE spectra recorded using the "pseudo-trailed" mode. Only a few of the spectra of the R-Alice calibration stars were acquired in pseudo-trailed mode[3]; we can reject these and their potential calibration errors without significantly limiting the pool of IUE reference spectra, so we do so.

In 1999-2000, the HST/FOS flux calibration (*Bohlin*, 1996) constituted the best available FUV flux standard, and therefore provided the scale to which MF2000 corrected the IUE data. The HST/FOS standard has since been superseded by the HST/STIS flux standard (*Bohlin*, 2000; *Bohlin and Gilliland*, 2004), which uses updated spectral models as well as leveraging the excellent repeatability of broadband STIS photometry to fine-tune the ground-based white dwarf photometry. In order to check the adequacy of the MF2000 corrections against this newer standard, we have compared averaged, corrected IUE spectra of Vega against the STIS spectrum of Vega from CALSPEC. We find agreement is better than 2%, so no scaling of the MF2000-corrected IUE spectra is warranted.

Although the HST CALSPEC spectrum of Vega includes scaled IUE data, the corrections and scaling applied to the raw IUE spectra are R. Bohlin's personal corrections to IUESIPS data. Because the NEWSIPS processing and MF2000 corrections both constitute significant improvements in the accuracy of the IUE calibration, we consider them more reliable than, and adopt them in preference to, the corrections and scalings of Bohlin.

IUE datasets have a "quality" flag associated with the flux value at each wavelength; a value of 0 indicates high quality data, while various values

[3]IUE low-dispersion data could be acquired in one of three pointing modes: (1) Fixed: the target was observed at a single location in the aperture; (2) Trailed: the target was allowed to drift in the cross-dispersion direction during the observation, in order to improve some aspects of S/N and calibration by exposing more detector pixels; and (3) Multiple Exposures ("pseudo-trailed"): the target was observed at 2 or 3 distinct locations in the cross-dispersion direction, to combine some of the advantages of Fixed and Trailed modes. The observing mode can be identified through the following keywords in the NEWSIPS FITS file headers: LEXPTRMD (with value X-TRAIL for Trailed mode, NO-TRAIL for Fixed and Multiple Exposure modes) and LEXPMULT (with value X-OFFSETS [or other values, e.g. Y-OFFSETS] for Multiple Exposures, NO for other modes).

< 0 indicate particular problems or ambiguities in the raw data or flux extraction. We reject IUE data points (treat them as missing data) where Quality < 0 (i.e. any data quality flags set). Individual spectra with large chunks of flagged data have been rejected in their entirety.

2.3 HUT datasets and corrections

HUT data are also available for download from the MAST archive. Of the R-Alice calibration stars, only HD 93521 was observed by HUT. However, the four available HUT spectra of this source, all taken during a single orbit in March 1995, vary widely, with up to 50% disagreement in the broadband flux levels. Paul Feldman inquired of Jeff Kruk of the HUT instrument team about these mismatches, and learned that HD 93521 was observed under different instrumental conditions. (It was used to determine the proper detector high voltage level for the mission; the settings used are listed in the FITS file headers). Only two spectra (numbers 03 and 04 of 01–04) were obtained at or near the ultimately selected HV level, and of these, one (04) appears to have had pointing issues that were not adequately corrected in postprocessing. Jeff Kruk recommended using spectrum `hd93521_032_03_a_ph.fits`, and scaling the data to match another reference spectrum of the same source (he mentioned HST/FOS in particular, but no such spectra of this source are returned by the MAST archive). Nominally, the "_a_" in the filename indicates that the recommended spectrum contains data from both dayside and nightside portions of the shuttle orbit. A file with indicator "_n_" is available for the same observation, with data only from orbital night. However, this observation was made completely during orbital night, according to both the summary on the MAST website and the file headers; the two files should contain identical data. Still, for some reason, fewer portions of the day+night spectrum are flagged with bad or dubious data quality flags, relative to the nightside-only spectrum. We adopt this higher-quality "_a_" spectrum.

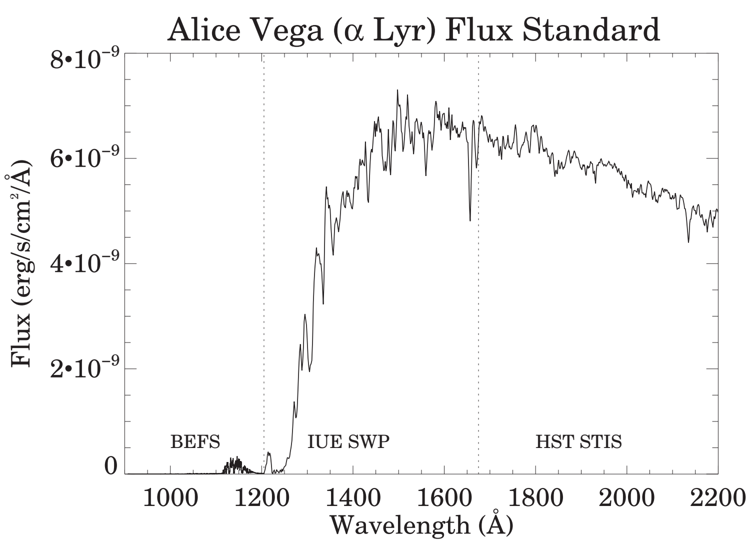
The HUT ASTRO-2 calibration was (like STIS and other UV instruments) performed by observing white dwarfs and comparing to model spectra. *Kruk et al.* (1999) claim agreement between measurements and models within 3% at all wavelengths. We have relied on the relative accuracy of the HUT spectrum of HD 93521, but—due to the particular details of this spectrum—not on its absolute scaling. Additional details are given in Section 3.5.

2.4 BEFS datasets

BEFS spectra for the R-Alice calibration sources extend from about 900 Å into the IUE waveband (which extends longward of 1150 Å). Where available, we use BEFS data (also obtained from the MAST archive) to provide coverage down the Lyman limit at 911 Å. We find good agreement between the BEFS and corrected IUE data, certainly within the $\lesssim 10\%$ level quoted for the flux calibration of BEFS (*Dixon et al.*, 2002). No scaling or correction is applied to these spectra.

3 Individual sources

3.1 Vega (α Lyr)



Summary:

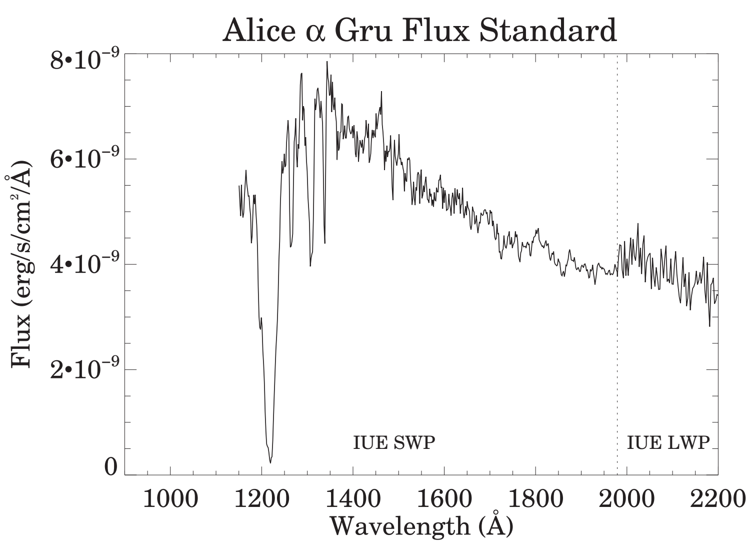
906 Å	$< \lambda <$	1205 Å:	BEFS
1205 Å	$< \lambda <$	1675 Å:	IUE
1675 Å	$< \lambda <$	3000 Å:	STIS

The STIS portion of the Vega spectrum in the current HST CALSPEC, `alpha_lyr_stis_003.fits`, extends from 1675 Å to 5300 Å and has been adopted without modification.

The IUE spectrum of Vega has been adopted from 1205 Å to 1675 Å. Of the eleven available SWP spectra, visual inspection shows that three (31155, 31156, 31157) are much noisier and have higher fluxes (by several percent) than the other spectra; they also have flagged data quality longward of about 1700 Å. Two other spectra (29866, 29867) lie about 8% low from the remaining 6 spectra. While all 5 of these apparent outlier spectra do pass a 3σ clipping based on mean flux from 1400–1700 Å, they have nevertheless been rejected based on these visual discrepancies (which are apparent both before and after correction per MF2000). The remaining 6 spectra have a net spread of only about 6%; this set has been averaged, after correction according to MF2000. There is good overall agreement in the region of overlap from 1675–1975 Å between the IUE and averaged STIS spectra. There is a discrepancy of about 2% in the immediate neighborhood of the 1675 Å crossover point, but we have opted not to make any adjustments to correct such a low-level mismatch, especially given the larger value of the spread among the IUE spectra themselves.

The single BEFS spectrum of Vega available via MAST is adopted below 1205 Å, although the model spectrum available at short wavelengths in the CALSPEC spectrum is a reasonable option as well. We prefer the BEFS spectrum, as the model spectrum has not been compared against observations in that wavelength range.

3.2 α Gru

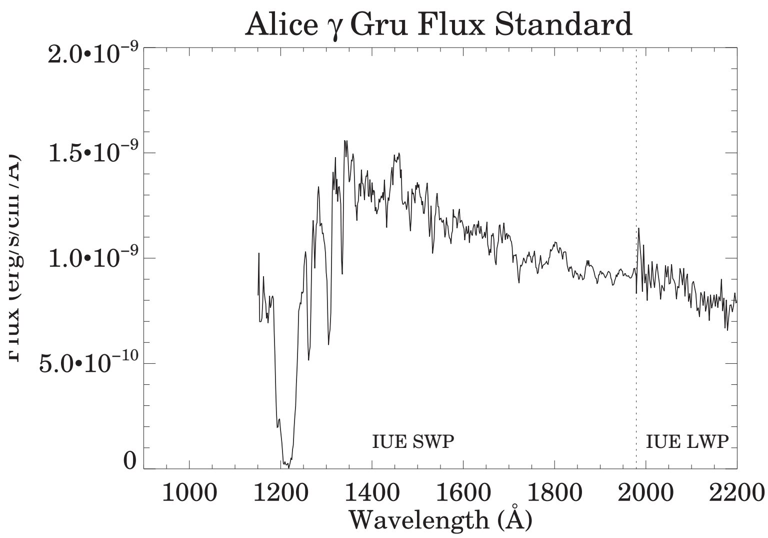


Summary:

1150 Å $< \lambda <$ 3000 Å: IUE

The only instrument with available calibrated spectra of α Gru in our wavelength regime of interest is IUE. A single SWP spectrum and a single LWP spectrum have been separately corrected according to MF2000. The spectra have been stitched together at 1979 Å.

3.3 γ Gru



Summary:

1150 Å $< \lambda <$ 3000 Å: IUE

The only instrument with available calibrated spectra of γ Gru in our wavelength regime of interest is IUE. A single SWP spectrum and a single LWP spectrum have been separately corrected according to MF2000. The spectra have been stitched together at 1979 Å.

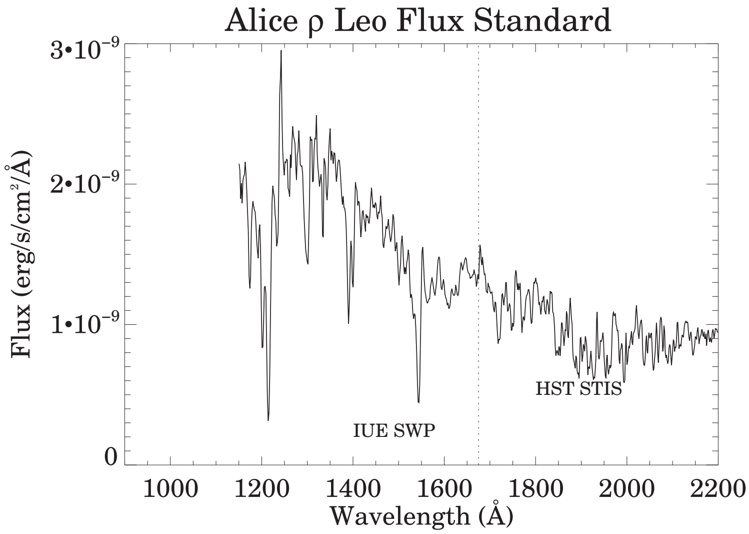
3.4 ρ Leo

Summary:

1150 Å $< \lambda <$ 1675 Å: IUE

1675 Å $< \lambda <$ 3000 Å: STIS

IUE provides the short-wavelength reference spectra for this source, and no calibrated spectra are available shortward of IUE's 1150 Å cutoff. Four SWP spectra have been corrected per MF2000 and combined as a weighted average.



The STIS NGSL spectrum of ρ Leo has been adopted longward of 1675 Å. There is excellent agreement from 1675–1950 Å between the NGSL and combined IUE spectra.

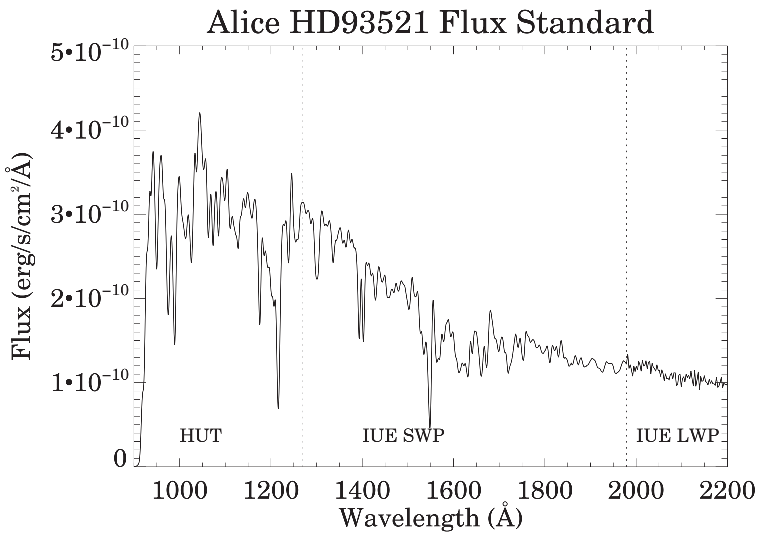
3.5 HD 93521

Summary:

814 Å	$< \lambda <$	1840 Å:	HUT
1840 Å	$< \lambda <$	3000 Å:	IUE

Longer wavelengths are adopted from a spectrum combined from the large number of available IUE spectra. Of the 232 IUE SWP spectra available, two are rejected because they are "pseudo-trailed" spectra. For the remaining spectra, average flux in the 1400–1700 Å range is computed. The mean and standard deviation of the average flux values are computed; 3σ outliers are rejected (12 spectra). The remaining 218 spectra are corrected per MF2000 and combined as a weighted average. Similarly, of 157 available LWP spectra, two pseudo-trailed spectra are rejected, as are 18 3σ outliers based on 2700–3000 Å flux. The remaining 145 spectra are corrected according to MF2000 and combined as a weighted average. The SWP and LWP composite spectra are stitched together at 1979 Å.

The single HUT spectrum used (see Section 2.3) covers the wavelength range 814–1876 Å. As the overall flux level does not agree well with the IUE spectrum for this source—and in keeping with Jeff Kruk's recommendation



to normalize the HUT spectrum against another calibrated spectrum—we have scaled the HUT spectrum by 0.792, such that mean flux in the 1700–1800 Å range matches the average IUE flux in that range. The scaled HUT spectrum is adopted at wavelengths shortward of 1840 Å, and the IUE spectrum longward of this value.

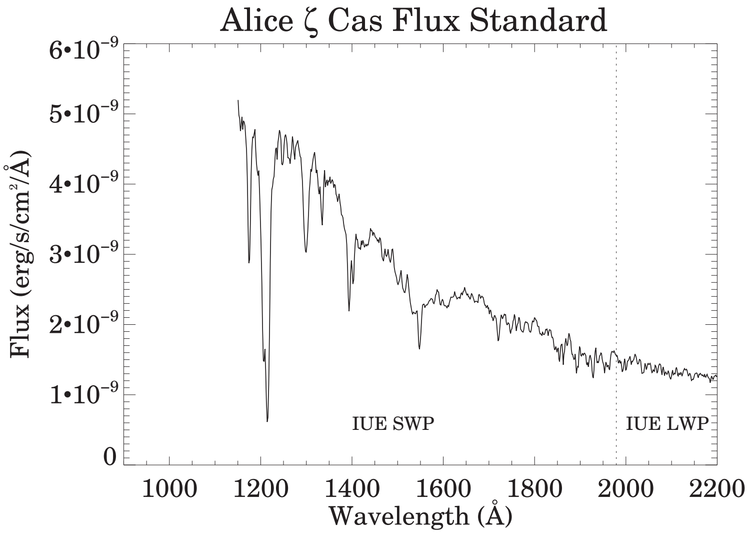
It is unclear why a scale factor significantly different from 1 is required for the HUT spectrum. Given the good agreement between a very large number of IUE spectra, the IUE flux level is not in doubt. Comparison between HUT, IUE (corrected per MF2000), and FUSE data for G191-B2B shows much better agreement than this $\sim 20\%$ disparity. It is possible that the calibration for the selected observation, which used an MCP high voltage setting of 6 instead of the setting of 7 used for the remainder of the mission after HD 93521, does not properly account for the difference in detector sensitivity.

3.6 ζ Cas

Summary:

1150 Å $< \lambda <$ 1675 Å: IUE
1675 Å $< \lambda <$ 3000 Å: IUE

IUE provides the short-wavelength reference spectra for this source, and no calibrated spectra are available shortward of IUE's 1150 Å cutoff. Of the 36 available SWP spectra, we have rejected 7 due to clear mismatches with



the flux of the remaining spectra, or due to significant chunks of flagged data. The retained spectra have been corrected according to MF2000, and combined as a weighted average.

The STIS NGSL spectrum of ζ Cas has been adopted longward of 1675 Å. There is excellent agreement from 1675–1950 Å between the NGSL and combined IUE spectra.

Note that ζ Cas was only observed by R-Alice during the PC4 observing phase in late 2006; this was the only phase to date using the reduced -3.7kV detector setting. We have not been able to reliably relate the sensitivity at that setting to the standard -3.9kV detector state, so calibration products from PC4 are of limited utility.

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