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Absolute Flux Calibrated Spectrum of Vega

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ABSTRACT

An absolute flux calibrated reference spectrum of Vega, the primary calibration standard in the optical, is presented. The spectrum covers the entire 0.12 to 2.6 microns wavelength. The ultraviolet spectrum is based on IUE measurements. The optical and near-infrared up to 1.05 microns consists of Hayes (1985) average spectrum. A model spectrum normalized to Hayes (1985) Johnson V flux covers the rest of the near-infrared interval up to 2.6 microns.

The uncertainty on the absolute flux of the reference spectrum over the optical and near-infrared range up to 1.05 microns is about 1.5%. For the 1.05 to 2.6 micron range the model predicts JHK fluxes 5% to 6% lower than the absolute measurements. In the ultraviolet, the uncertainty of the IUE average spectrum is about 5%.

Model spectra based on ATLAS9 and ATLAS12 Kurucz's codes and normalized to Hayes absolute scale are also presented. The model spectra agree with the optical and ultraviolet continuum measurements to 2% and 10%, respectively. Differences from 10% to 20% are obtained in the cores of the optical and near-infrared absorption lines, when the model and the observed spectra are compared.

The absolute flux calibrated spectrum of Vega presented here is used to compute the average fluxes of Vega in Johnson's UBVRI system and, subsequently, the zero-points fluxes of the photometric system. No reliable near-infrared spectrophotometric measurements of Vega exist to date. The calibrated ATLAS9 and ATLAS12 model spectra predict near-infrared JHK fluxes about 5%-6% lower than the measurements. Therefore the zero-point flux of the JHK bands cannot be determined from the flux of Vega in the same way described for the B and V bands by Colina & Bohlin (1994).

1. Introduction

The spectrum and magnitudes of Vega have been used in the past to establish the stellar photometric scale of optical photometry systems. Also, with the advent of synthetic photometry techniques, the observed absolute flux calibrated spectrum or some model spectra of Vega have been used to define the optical (see e.g. Colina & Bohlin 1994) and near-infrared magnitudes (see e.g. Megessier et al. 1995 for a detailed discussion).

Synthetic photometry packages like SYNPHOT are now implemented within the astronomical analysis software and have become a standard tool to compute magnitudes and colors using the spectrum of Vega to define the zero-point of the different systems (i.e. vegamag option in the calcphot task of SYNPHOT). However, before using synthetic photometry blindly, the accuracy of the results has to be addressed.

In general, the final accuracy of the computed synthetic magnitudes and colors depends on (1) the accuracy of the absolute flux spectrum of Vega as a function of wavelength, (2) the accuracy of the magnitude measurements of Vega in a given photometry system, and (3) the accuracy in the modeling of the photometric system used in the original measurements. As shown in this document, the uncertainty on the absolute flux of Vega's spectrum varies for different wavelength intervals, and ranges from 1.5% to 6%. Uncertainties on the modeling of the photometric system and on the magnitude of Vega in a given system could increase the final errors of the synthetic photometry by another ~ 2%, or more.

Section 2 of this document presents the absolute flux calibrated ultraviolet and optical spectra of Vega. Section 3 shows model spectra based on ATLAS9 and ATLAS12 codes while in section 4 model and observed spectra are compared. Section 5 explains how the reference spectrum has been constructed. Section 6 gives the UBVRI zero-point fluxes, and their uncertainties, as computed using synthetic photometry techniques. Section 7 indicates where to find the spectra on the web pages.

2. Absolute flux calibrated spectra of Vega

2.1 Ultraviolet spectrum

The ultraviolet 115 to 330 nm spectrum of Vega is the average of 9 and 13 spectra obtained with the short wavelength (SWP) and long wavelength (LWP) prime cameras of IUE (Bohlin et al. 1990), respectively. The average IUE spectrum has been transformed into the white dwarf absolute scale using the average IUE flux correction as explained in Bohlin (1996). IUE low dispersion mode observations are photometrically repeatable to ~2% (Bohlin et al. 1990) and for Vega, the continuity at 330 nm with Hayes (1985) flux is ~5%.

2.2 Optical spectrum

The optical 330 to 1050 nm absolute flux spectrum of Vega has been obtained by combining six independent absolute measurements covering several wavelength ranges with different resolutions (see Hayes 1985 for references). The mean flux distribution has an accuracy of 1.5% over this entire wavelength range.

2.3 Near-infrared spectrum

No near-infrared 1.05 to 2.6 microns spectrophotometric measurements of Vega are available. Only a few absolute measurements at a few wavelengths close to the standard wavelengths of the JHK bands have been obtained by Backwell et al. (1983) and Selby et al. (1983).

3. Absolute flux calibrated model spectra of Vega

Kurucz's most recent model spectrum for Vega is provided as part of his 1993 stellar atmospheres atlas (Kurucz 1993). The model spectrum is computed using the ATLAS9 code for a metallicity logZ= -0.5, effective temperature of 9550K, gravity logg= +3.95, and microturbulent velocity of 2 km s^{-1}. A second model spectrum using the ATLAS12 code with the same parameters has recently been computed by Castelli & Kurucz (1994).

Kurucz (1993) model spectrum covers the full ultraviolet to far-infrared range from 0.05 to 10 microns with a non-uniform wavelength spacing ranging from 1 nm in the ultraviolet to 10-20 nm in the near-infrared, and 40 nm in the far-infrared (beyond ~ 3 microns). On the other hand, the present version of the ATLAS12 based model spectrum (Castelli's spectrum hereafter) covers the 0.09 to 2.6 microns range with a uniform resolution of 0.1 nm. Castelli's spectrum replaces the opacity distribution functions (ODF's) adopted for computing the models and fluxes of Kurucz (1993) grids by the computation of a synthetic spectrum, in order to account for the line opacity at each 500000 resolution 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, 0.1 nm in our case.

The ATLAS9 and ATLAS12 based model spectra are converted to absolute flux units by normalizing to the average flux of the Hayes (1985) spectrum in the Johnson V filter as represented by Buser & Kurucz (1979) bandpass, i.e. to 3.55×10^{-9} erg s^{-1} cm^{-2} $Å^{-1}$.

4. Model spectrum versus empirical spectra

Castelli's spectrum departs by 5% to 10% in the ultraviolet when compared with the recent IUE spectrum of Vega on the white dwarf absolute flux scale (see Figure 1 upper panel). In the 0.4 to 0.82 microns range, the agreement between the model and Hayes (1985) spectrum is better than 2%, in the continuum (see Figure 1 lower panel). Differences from 10% to 20% are observed in the cores of the Balmer absorption lines. In the region around the Paschen discontinuity and longward, i.e. from ~0.82 to 1.05 microns, the agreement between the observed spectrum and the model is rather poor, with differences of about 5% in the continuum and from 10% to 20% in the Paschen absorption lines (see Figure 1 lower panel). Finally, longward of 1.05 microns there are no spectrophotometric measurements. However, synthetic JHK photometry using the model spectrum predicts fluxes that are 5% to 6% lower than the measurements (see section 6).

5. Absolutely Calibrated 0.12 - 2.60 microns Spectrum of Vega

To cover the wavelength range of interest to HST instruments, including STIS and NICMOS, an absolute flux spectrum for Vega is constructed by combining the empirical data with the model spectrum (see Figure 2). The ultraviolet, optical and near-infrared interval from 0.115 to 1.05 microns is covered by the IUE plus Hayes (1985) spectra on the white dwarf scale as explained in Bohlin (1996). In the near-infrared, from 1.05 to 2.6 microns, the ATLAS12 model spectrum calibrated as explained in section 3 is used.

The resolution of the spectrum is 0.1 nm for the range covered by the IUE short wavelength camera (SWP, 115 to 200 nm), 0.2 nm for the range covered by the IUE long wavelength camera (LWP, 200 nm to 330 nm), and 2.5 nm longward of 330 nm.

As already mentioned in previous sections, the uncertainty in the absolute flux of the spectrum is a function of wavelength. While in the optical interval from 0.33 to 1.05 microns the uncertainty is 1.5%, this increases to 5% - 6% in the near-infrared at wavelengths longward of 1.05 microns, and to ~5% in the ultraviolet at wavelengths shortward of 0.33 microns.

6. The Spectrum of Vega and Photometric Zero-points

Vega is the primary standard used to establish the zero-point of photometry systems in the optical and near-infrared (see Megessier 1995 and references therein). In the following, synthetic photometry techniques applied to the absolute calibrated spectrum of Vega are used to obtain the values of the zero-point of the UBVRI Johnson photometric system (see Figure 3 for a plot of Vega’s optical spectrum and filter bandpasses).

Johnson’s UBVRI original system is approximated here by the UBV passband as in Buser & Kurucz (1979) and the RI passband as in Johnson (1965). As Johnson’s two magnitudes for Vega differ by 0.01 magnitudes (Johnson, 1964, 1965), the UBVRI magnitudes of Vega considered here (see column four of Table 1) are the average values of Johnson's two measurements. The effective wavelength and width of the filters, together with the mean flux of Vega in each filter (Flux_Vega in Table 1), and the zero-points, i.e. mean flux for a A0V zero magnitude star, of the photometric system are listed in Table 1. The computed UBV zero-points fluxes agree with other published values (Lamla 1982) to better than 3%. Slight differences in the filter bandpass can account for differences at the 1% to 2% level. The RI values differ by as much as 10% to 12% as the characteristics of the RI bandpass used in the synthetic photometry here differ from those in the literature (Lamla 1982). Thus, for accurate photometric work, i.e. accuracy better than 5%, the characteristics (effective wavelength and width) of the filter's bandpass should be checked against Table 1 below.

Table 1. Vega Fluxes and Zero-points

FILTER	Effective Wavelength (Angstroms)	FWHM (Angstroms)	Vega (Magnitudes)	Flux_Vega erg s^{-1} cm^{-2} $Å^{-1}$	Zero-point erg s^{-1} cm^{-2} $Å^{-1}$
U	3735	485	0.030	4.22×10^{-9}	4.34×10^{-9}
B	4443	831	0.035	6.20×10^{-9}	6.40×10^{-9}
V	5483	827	0.035	3.55×10^{-9}	3.67×10^{-9}
R	6855	1742	0.075	1.795×10^{-9}	1.92×10^{-9}
I	8637	1970	0.095	8.60×10^{-10}	9.39×10^{-10}

In the near-infrared, JHK fluxes of the calibrated model spectrum are computed for two different set of photometry systems. The first JHK set consists of the filter bandpasses as in Bessell & Brett (1988), while the second corresponds to the Tucson sytem (M. Rieke, private communication). The effective wavelength of the filters and the mean flux of the model spectrum (Flux_Vega in Table 2) on the Bessell & Brett (J_, H_, and K_Bessell) and Tucson (J_, H_, and K_Tucson) systems are presented in Table 2. The synthetized J, H and K band fluxes of the model spectrum (see Table 2) are ~5% to 6% lower than the absolute measurements obtained using an IR furnace as calibrator (Blackwell et al. 1983, BLPM83 in Table 2; Selby et al. 1983, SMBPL83 in Table 2), or solar analog stars (Campins, Rieke & Lebofsky 1985, CRL85 in Table 2).

As discussed by Megessier (1995), Vega is an A0V star having near-infrared colors that disagree with the mean colors of A0V stars. Vega is brighter in the near-infrared than the average A0V flux distribution by 5-6%. According to Megessier (1995), this near-infrared excess could be related to the excess detected by IRAS at longer wavelengths.

Thus, if the absolute calibrated model spectrum of Vega is used to define the zero-point flux of an near-infrared photometric system, these values will be in error by 5-6%.

Table 2. Near-infrared fluxes of Vega

FILTER	Effective Wavelength (microns)	Flux_Vega erg s^{-1} cm^{-2} $Å^{-1}$	Reference
J_Bessell	1.23	3.05×10^{-10}	this work
J_Tucson	1.25	2.90×10^{-10}	this work
J	1.24	3.06×10^{-10}	BLPMS83
J	1.26	3.065×10^{-10}	CRL85
H_Bessell	1.64	1.10×10^{-10}	this work
H_Tucson	1.61	1.19×10^{-10}	this work
H	1.60	1.24×10^{-10}	CRL85
K_Bessell	2.20	3.82×10^{-11}	this work
Ks_Tucson	2.15	4.18×10^{-11}	this work
K_Tucson	2.19	3.88×10^{-11}	this work
K	2.20	3.92×10^{-11}	SMBPL83
K	2.20	4.19×10^{-11}	BLPMS83
K	2.22	3.92×10^{-11}	CRL85

7. Absolute Calibrated Spectra of Vega on the WEB

The combined IUE and Hayes spectra as mentioned in section 2 can be found on the WWW pages of the STScI Observatory Support Group. The root html address for this file is “html://www.stsci.edu/ftp/cdbs/cdbs2/calspec”, and the name of the file is alpha_lyr_004. Kurucz’s and Castelli’s models can be found in the html address “html://www.stsci.edu/ftp/cdbs/cdbs2/grid/k93models/standards” under the vega_k93 and vega_c95 names, respectively. The absolute calibrated spectrum of Vega covering the 0.12 to 2.6 micron range can be found in the same html root directory with the name vega_reference. This spectrum is formed by the observed spectra up to 1.05 microns, and by the ATLAS12-based model spectrum beyond that wavelength. All the files are in binary STSDAS table format. If needed, these tables can be converted to ASCII files using the task “tdump” within the tables. ttool IRAF package. The pedigree and references for each individual spectrum can be found in the header of the STSDAS table.

8. Summary

An absolute flux calibrated spectrum of the primary standard Vega covering the wavelength range of the STIS and NICMOS HST instruments has been constructed. The ultraviolet and optical spectral range of the spectrum, up to 1.05 microns, consists of IUE and Hayes spectra on the white dwarf flux scale. The near-infrared spectrum consists of a flux model spectrum normalized to Hayes Johnson’s V flux.

The uncertainty in the flux of the absolutely calibrated spectrum is about 1.5% in the 0.4 to 1.05 micron range; and this uncertainty increases to 5% - 6% in the ultraviolet and near-infrared.

The zero-points of the UBVRI Johnson photometric system have been computed using synthetic photometry techniques and the absolute flux spectrum of Vega. Differences of less than 3% with other published values are obtained for the UBV zero-points and are due to slight differences in the photometric systems. For the RI bands, zero-points differences of ~ 10% with respect to other published values are obtained.

Discrepancies in the zero-points are due to differences in the filter bandpasses. For accurate photometric work, i.e. accuracy better than 5%, the characteristics of a given filter’s bandpass should be checked against the values given in this document.

The synthesised JHK model spectrum fluxes give values 5% - 6% lower than the measurements of Backwell et al. (1983), Selby et al. (1983), and Clampins et al. (1985). Computation of the zero-point of a JHK near-infrared photometric system using the absolutely calibrated model spectrum of Vega will generate errors of ~5% in the fluxes and magnitudes obtained on that system.

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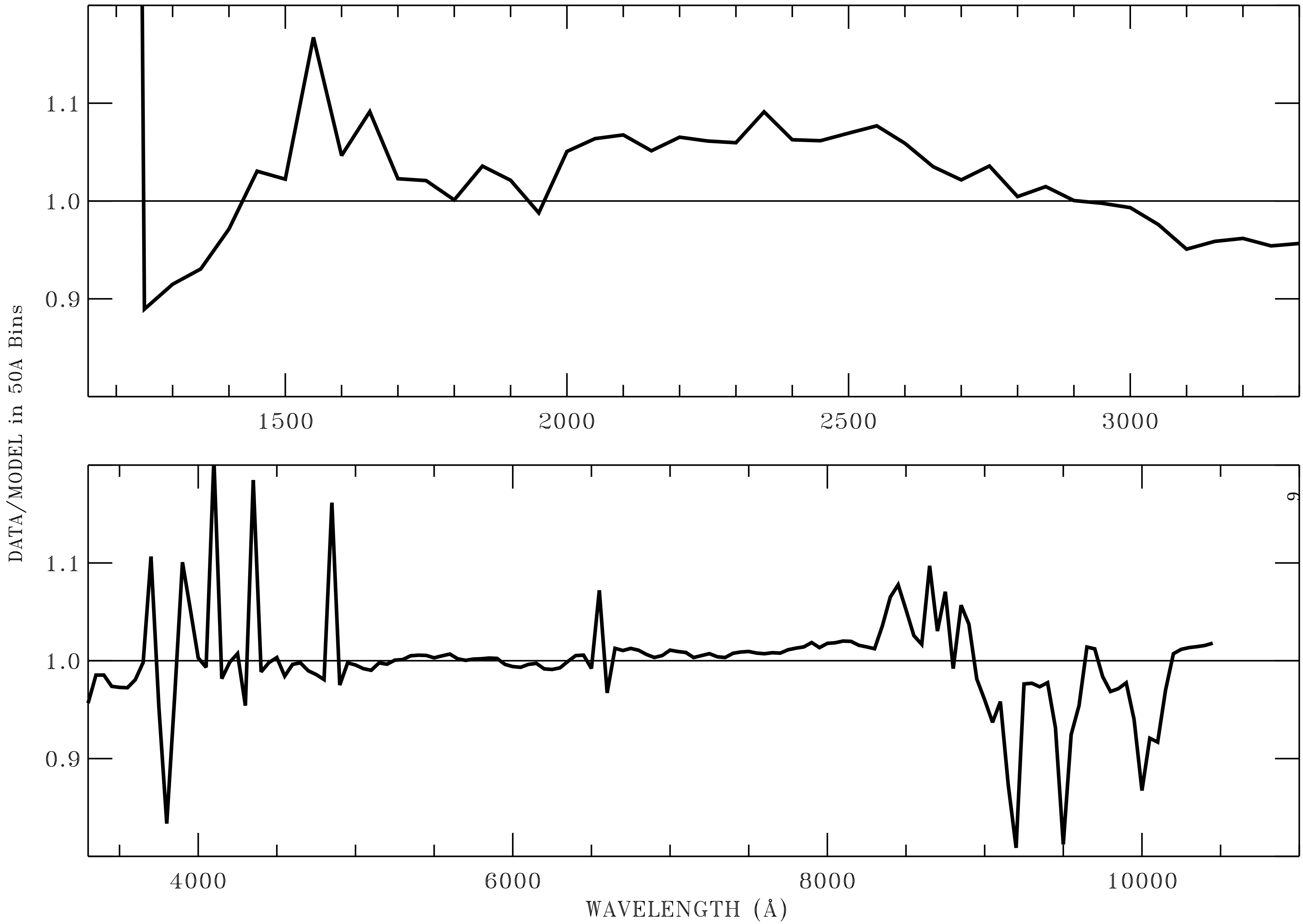
Figure 1: Ratio of the absolute flux measurements (data) to the calibrated model spectrum (model) where the measurements are the average IUE spectrum in the ultraviolet (upper panel); and the average Hayes (1985) spectrum in the optical (lower panel).

Figure 2: Absolute calibrated spectrum of Vega for the 0.12 to 1.05 microns range.

Figure 3: Hayes (1985) spectrum of Vega. Also shown are the UBV filter bandpass from Buser & Kurucz (1979) and the RI filter bandpass from Johnson (1965).



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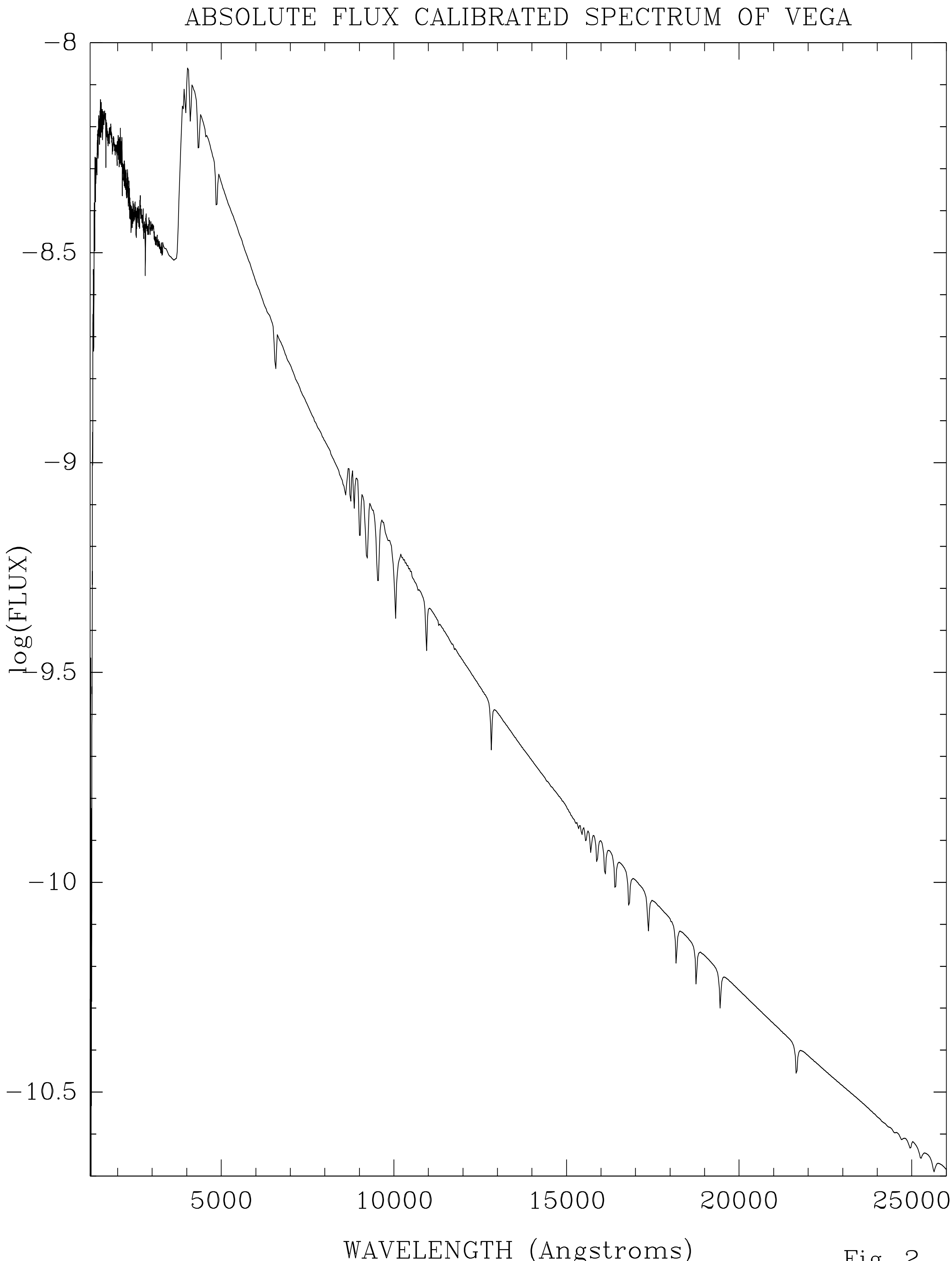
ABSOLUTE FLUX CALIBRATED SPECTRUM OF VEGA
−8
−8.5
−9
−9.5
−10
−10.5
log(FLUX)
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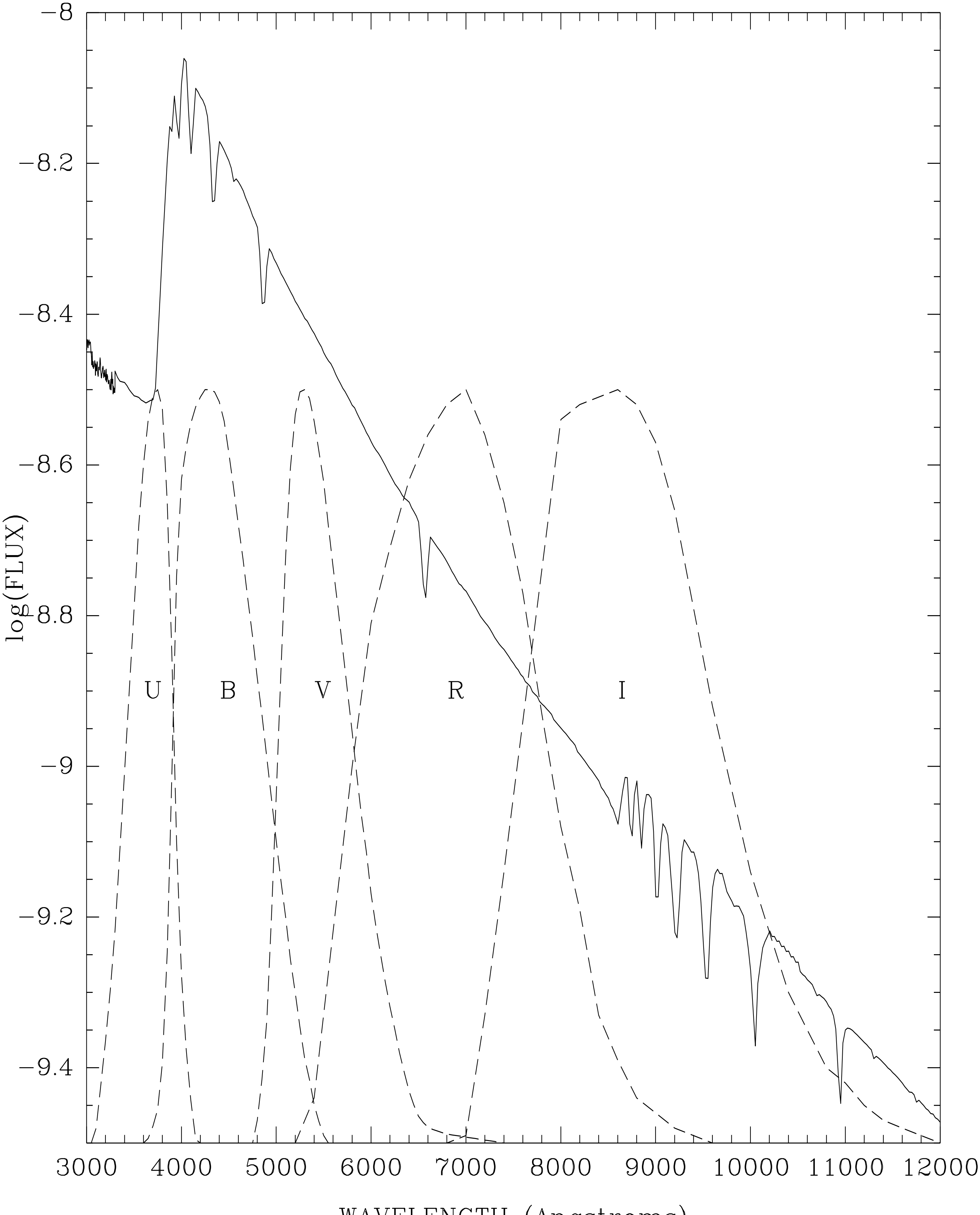
10000
15000
20000
25000
WAVELENGTH (Angstroms)
Fig. 2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−8.4
−8.6
−8.8
−9
−9.2
−9.4
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
WAVELENGTH (Angstroms)
U
B
V
R
I

Fig. 3