FM12
Calibration and Standardization Issues in UV-VIS-IR Astronomy

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CALSPEC: HST Spectrophotometric Standards at 0.115 to 32 μm with a 1% Accuracy Goal

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Abstract. The flux distributions of spectrophotometric standard stars were initially derived from the comparison of stars to laboratory sources of known flux but are now based on calculated model atmospheres. For example, pure hydrogen white dwarf (WD) models provide the basis for the HST CALSPEC archive of flux standards. There is good evidence that relative fluxes from the visible to the near-IR wavelength of $\sim$2.5 μm are currently accurate to $\sim$1% for the primary reference standards.

Keywords. techniques: spectroscopic, astronomical data bases: miscellaneous, stars: fundamental parameters, (stars:) white dwarfs

1. Introduction

The measurement of precise absolute fluxes for stellar sources has been pursued with increased vigor since the discovery of the dark energy and the realization that its detailed understanding requires accurate spectral energy distributions (SEDs) of redshifted Ia supernovae in the rest frame. In addition, accurate absolute stellar fluxes as a function of wavelength are required for many astrophysical purposes. The fundamental parameters of stars, including mass, radius, metallicity, and age are inferred by matching accurate stellar atmosphere models to precisely calibrated UV spectroscopic data from which the effective temperature, surface gravity, composition, and interstellar reddening are determined for all types of stellar objects,

The Space Telescope Imaging Spectrograph (STIS), the Near Infrared Camera and Multi-Object Spectrograph (NICMOS), and the Wide Field Camera 3 (WFC3) low dispersion spectrometers on the Hubble Space Telescope (HST) have a calibration heritage that is tracable to the three unreddened, pure-hydrogen WDs, G191B2B, GD153, and GD71, which are in the effective temperature range 33590–59000 K. STIS covers the 0.115–1 μm range with 5 gratings at a resolution of R$\sim$500, while NICMOS has three grisms covering 0.8–2.5 μm at R$\sim$100. WFC3 has two bands G102 and G141 covering 1–1.7 μm at R=210 and R=130, respectively. The fluxes, i.e. spectral energy distributions (SEDs), of these primary standard stars are established using the Rauch Tübingen NLTE model atmosphere code (Rauch *et al.* 2013) to determine the relative flux vs. wavelength. Alternate NLTE Tlusty models for the same temperature and gravity differ in their relative flux distributions and are used to define the systematic uncertainties (Bohlin *et al.* 2014). The absolute normalization of the three models is from a weighted average of the absolute flux of Vega at 5556 Å and the MSX absolute flux measures of Sirius at 8–21 μm. The result of this reconciliation of the visible and mid-IR implies a flux for Vega at 5556 Å of 3.44 10^{-9} $erg\ cm^{-2}\ s^{-1}\ Å^{-1}$ ±0.5% (Bohlin 2014).

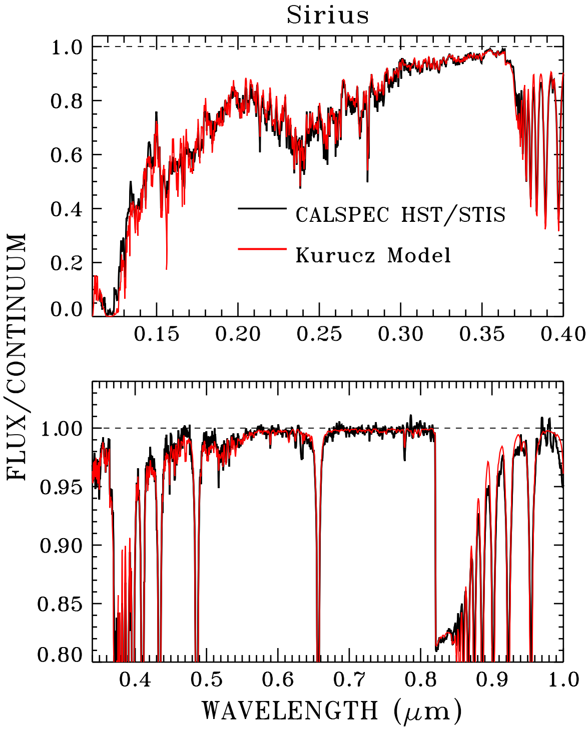

Figure 1. Comparison of STIS (black) to the Kurucz model (red) with $T_{\rm eff} = 9850\ K$, $\log g = 4.30$, and $[M/H] = +0.4$. Both the STIS SED and the model are divided by the same theoretical continuum for comparison on a magnified scale. The STIS data cover the wavelength range below 1 μm and are supplemented by IUE data below 1675 Å. The UV line-blanketing is severe, and the stellar flux goes to zero at Lα.

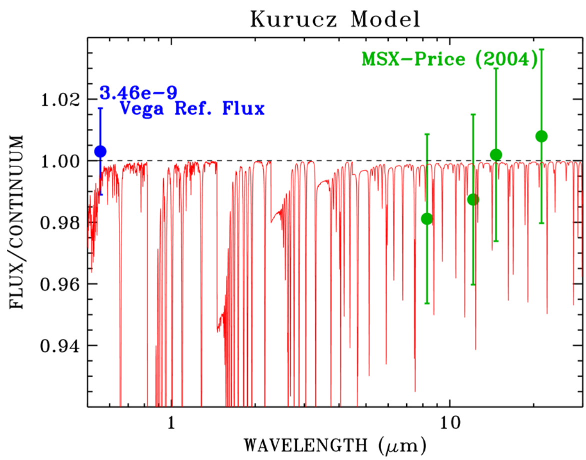

Figure 2. The green filled circles are the MSX values. The blue circle at 0.556 μm corresponds to the 3.46×10^{-9} erg cm^{-2} s^{-1} Å^{-1} value of Megessier (1995) for Vega. The adopted normalization of the model (red) is within ~0.5% of both the Megessier normalization and the average of the four MSX absolute flux measures, which implies a monochromatic best flux for Vega at 0.556 μm of 3.44×10^{-9} erg cm^{-2} s^{-1} Å^{-1}.

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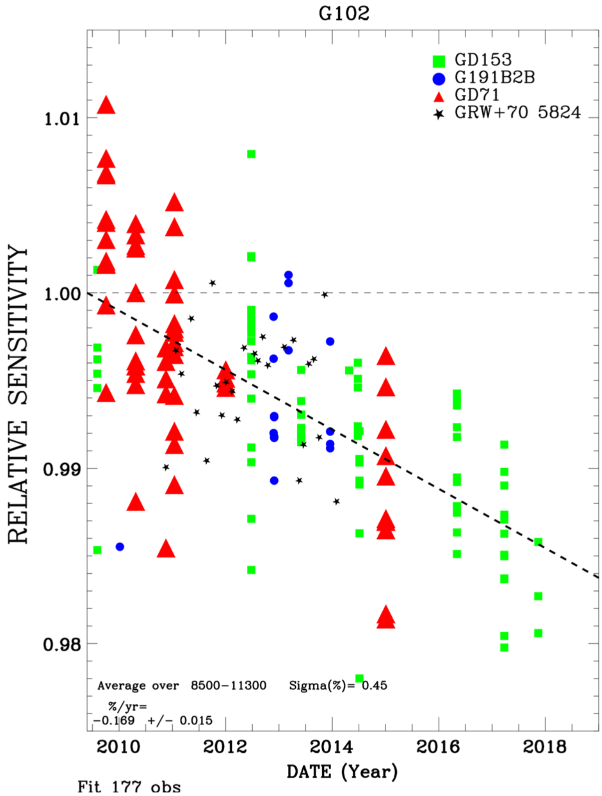

Figure 3. The change in sensitivity with time for the WFC3 G102 grism. The loss rate of 0.17 % yr^{-1} is written near the bottom of the plot.

Once calibrated using the three standard candles, the STIS and NICMOS spectrographs on HST measure the absolute flux of secondary stars from 0.115–2.5 μm with the WFC3 results replacing lower resolution NICMOS at 1–1.7 μm. The SEDs of several dozen secondaries and the three primary stars reside in the CALSPEC† database along with the covariance error matrix of uncertainties. Challenges to achieving the goal of 1% precision in the measured CALSPEC fluxes include non-linearities, changing sensitivity with time, and the high premium on HST time. However, synthetic photometry from the CALSPEC stars agrees with precision Landolt photometry to ∼1% (10 mmag) in the B, V, R, and I bands (Bohlin & Landolt 2015). Model stellar atmospheres that fit these measured SEDs to ∼1% extend the wavelength range to the James Webb Space Telescope (JWST) limit of ∼30 μm (Bohlin *et al.* 2017).

2. Sirius as the Primary IR Reference Standard

Cohen *et al.* (1992) and, more recently, Engelke *et al.* (2010) and Rieke *et al.* (in prep.) recommend the use of Sirius as the primary IR absolute flux standard, because rapid rotation and the cool debris disk of Vega complicate the modeling of its IR flux distribution. STIS has measured the flux for Sirius from 0.17–1.01 μm on the *HST* CALSPEC scale. The measured STIS flux agrees well with predictions of a special Kurucz model atmosphere† in Fig. 1, adding confidence to the modeled IR flux predictions (Bohlin 2014). This model agrees to 0.5% with both the 5556Å zeropoint for Vega (Megessier

† http://www.stsci.edu/hst/observatory/crds/calspec.html
† http://kurucz.harvard.edu/stars/SIRIUS/ and an update (Kurucz private comm. 2013)

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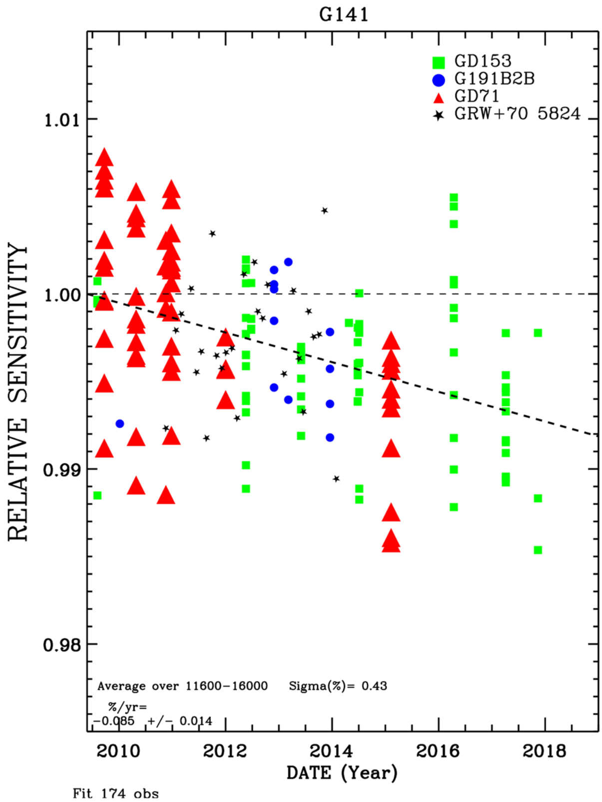

Figure 4. The change in sensitivity with time for the WFC3 G141 grism. The loss rate is 0.08 % yr^{-1}.

1995) and with the Price et al. (2004) MSX absolute flux measurements in the mid-IR at 8–21 μm, as illustrated in Fig. 2. Both the model and the STIS SED reside in CALSPEC.

3. Future CALSPEC Improvements

Old NICMOS fluxes at 1-1.7 μm will be replaced by WFC3 IR G102 and G141 IR grism SEDs, which have better wavelength accuracy, better spectral resolution, better repeatability, and, consequently, more precise flux distributions of ∼1% accuracy vs. ∼2% for NICMOS. As a first step in providing precision WFC3 SEDs, the sensitivity loss rates are found to be 0.17 and 0.08 % yr^{-1} for G102 and G141, respectively, as shown in Fig. 3 and Fig. 4. These rates are comparable to the STIS average loss rate since 2009 of 0.2 % yr^{-1} at 7900–9900 Å. Currently, only 19 CALSPEC stars have WFC3 grism data, but this sample should be expanded.

There is good evidence that the CALSPEC flux scale is correct to 1% from 0.2 to 7 μm, and there is agreement at the sub-percent level with the best absolute estimates in the visible at 0.5556 μm and at 8–21 μm. An external check against precision Landolt photometry also confirms CALSPEC flux distributions to better than 1% in the B, V, R, and I bandpasses. However, the CALSPEC SEDs all depend on the shape of theoretical WD flux distributions and on very few absolute flux measurements. To check and improve the precision of standard star SEDs, the theoretical WD model results should be tested by transferring modern laboratory flux standards to the stars.

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