Comparison Between Synthetic and Photometric Magnitudes for the Sloan Standard Stars

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Received April 17, 2015; revised May 26, 2015; accepted May 28, 2015

Abstract Synthetic magnitudes derived from STIS/CALSPEC fluxes were compared to photometric magnitudes for standard stars of the Sloan system. The statistics of the magnitude differences are consistent with the stated and intended accuracies of both sources in all five Sloan bands. Close agreement in the Sloan u' band-pass extends magnitude-based verification of STIS/CALSPEC fluxes to near-ultraviolet wavelengths.

1. Introduction

The absolute calibration of spectroscopic and photometric data is critical to many astrophysical investigations. For example, accurate spectral energy distributions (SEDs) are needed for the analysis of light from red-shifted type Ia supernovae when used to study dark energy.

White dwarf stars serve as relatively stable flux standards for spectroscopic and photometric systems. Historically, SEDs of the white dwarfs were determined by Oke (1990) using the 5-meter Hale telescope. The absolute flux of the Sloan magnitude system (Smith *et al.* 2002) is tied to the SEDs from those ground-based observations performed several decades ago. Much progress has been made in the precise radiometric calibration of SEDs in recent years, though. In particular, data from the Space Telescope Imaging Spectrograph (STIS) instrument on-board Hubble are now considered to be the most accurate source of radiometrically calibrated data. The study described in this paper uses the CALSPEC database (Bohlin *et al.* 2014) of STIS SEDs to validate the magnitudes of Sloan primary stars.

Besides verifying the Sloan magnitudes, it is equally important to validate the STIS/CALSPEC SEDs themselves. Bohlin and Landolt (2015) summarize the work that has been performed using visible and near-IR Johnson-Cousins magnitudes as a comparison for CALSPEC fluxes. The present study extends that by using Sloan magnitudes for comparison and also extends it to the near-UV. Thus, this paper assesses the consistency between the absolute radiometric fluxes of the Sloan photometric system and the STIS/CALSPEC database. Since the two systems were developed independently, the comparison may be interpreted as a measure of absolute accuracy.

The methods used in selecting stars for this study and in comparing the CALSPEC fluxes with Sloan magnitudes are described in section 2. Central to this discussion is the equation used for deriving synthetic magnitudes from spectral fluxes. Section 3 lists the synthetic CALSPEC magnitudes along with their differences with respect to the Sloan magnitudes. The statistics of the differences between Sloan and CALSPEC magnitudes are next discussed and an estimate of the consistency between the two systems is given. A similar comparison based on Johnson-Cousins magnitudes (Bohlin and Landolt 2015) is described in section 4. Finally, the conclusions of this study are summarized and a suggestion for follow-up research with small telescopes is offered in section 5.

2. Methods

Stars were chosen for this study by matching the Sloan standards listed by Smith *et al.* (2002) with the CALSPEC standards listed by Bohlin *et al.* (2014). Table 1 lists the six resulting stars and shows that three of them were used as fundamental standards by Smith *et al.* The other stars are ordinary Sloan standards.

Table 1. Sloan and CALSPEC stars.

Star Name	*Type**
BD +02 3375	A5
BD +17 4708	sdF8**
BD +21 0607	F2**
BD +26 2606	A5**
BD +29 2091	F5
BD +54 1216	sdF6

** from Bohlin et al. (2014)*
*** fundamental Sloan standard*

The magnitudes used in this study were taken from Table 8 of Smith *et al.* (2002). These values are on the Sloan photometric system and they differ from those of the Sloan survey itself. The magnitudes of Smith *et al.*, which are preferred for photometry, are also available on-line at http://www-star.fnal.gov/ugriz/tab08.dat.

FITS files of CALSPEC data were retrieved from http://www.stsci.edu/hst/observatory/crds/calspec.html. The header of each file was checked to insure SEDs extending over all five Sloan band passes were from the STIS instrument. This insured that the data were of the highest possible quality.

In order to compare CALSPEC and Sloan standards, CALSPEC fluxes were transformed to Sloan magnitudes. These synthetic magnitudes were derived from SEDs by integrating the product of spectral energy multiplied by system response over each Sloan band pass. Equation 1 (Smith *et al,* 2002; Fukugita *et al.* 1996) indicates the relationship among magnitude, flux, and system response.

$$m = -2.5 \frac{\int d(\log \nu)\, f\nu\, S\nu}{\int d(\log \nu)\, S\nu} \quad (1)$$

where m is magnitude, $f\nu$ is flux, $S\nu$ is the system response, and ν is frequency. The units are ergs per square centimeter per Hertz per second. The five system response functions referenced by Smith *et al.* were retrieved from http://www-star.fnal.gov/ugriz/Filters/response.html. Their central wavelengths are u', 355.1; g', 468.6; r', 616.5; i', 748.1; and z', 893.1 nm. After solving for m, a constant of –48.60 was added to place Sloan magnitudes on the absolute AB system (Oke and Gunn 1983; Fukugita *et al.* 1996).

3. Results

The resulting synthetic magnitudes for the six stars are listed by Sloan band in Table 2. The magnitude differences for each star in the sense "synthetic magnitude minus photometric" are then listed in Table 3. Most of the differences are less than 0.01 magnitude.

Table 2. Synthetic magnitudes from STIS/CALSPEC fluxes.

Star Name	*u′*	*g′*	*r′*	*i′*	*z′*
BD +02 3375	11.027	10.132	9.816	9.702	9.672
BD +17 4708	10.569	9.643	9.358	9.269	9.254
BD +21 0607	10.284	9.391	9.117	9.034	9.024
BD +26 2606	10.756	9.884	9.605	9.515	9.496
BD +29 2091	11.356	10.471	10.118	9.997	9.965
BD +54 1216	10.783	9.886	9.589	9.498	9.486

Table 3. Synthetic magnitudes minus photometric magnitudes.

Star Name	*u′*	*g′*	*r′*	*i′*	*z′*
BD +02 3375	0.011	0.002	0.007	0.016	0.015
BD +17 4708	0.009	0.003	0.008	0.019	0.024
BD +21 0607	-0.005	-0.004	0.003	0.009	0.007
BD +26 2606	-0.005	-0.007	0.001	0.012	0.010
BD +29 2091	0.003	-0.018	-0.005	0.006	0.014
BD +54 1216	0.007	0.000	0.003	0.019	0.017

Table 4. Statistical comparison.

	u′	*g′*	*r′*	*i′*	*z′*	*All*
RMS	0.007	0.008	0.005	0.014	0.015	0.010
Mean difference	0.003	–0.004	0.003	0.014	0.014	0.006

The statistics of the differences between synthetic and photometric magnitudes from Table 3 are presented by band-pass in Table 4. The root-mean-square (RMS) values range from 0.005 to 0.015 magnitude and the mean differences range from –0.004 to +0.014. The statistical results taken across all five Sloan bands are given in the last column of the Table. The overall RMS is only 0.010 magnitude and the overall mean difference is just +0.006.

The goals for the Sloan photometric standard star system (Smith *et al.* 2002) were given in percentages ranging from 1% to 1.5%. When converted to magnitudes these values are 0.016 for u', 0.011 for g', r', and i', and 0.016 for z'. Bohlin *et al.* (2014) quote an accuracy of 1% (0.011 magnitude) from the visible to the near-IR for the STIS/CALSPEC standard stars. The combined uncertainty for STIS/CALSPEC and the Sloan photometric magnitudes considered in this study is the square root of the sum of the squares (RSS) of their separate uncertainties which follow: 0.019 for u', 0.016 for g', r', and i', and 0.019 for z'.

The RMS values in Table 4 are less than the RSS values in every band. Thus, the statistics of the observed differences between the magnitudes from the two sources are consistent with the combined uncertainties of those sources as stated therein.

The good agreement of the ultraviolet u' magnitudes (RMS, 0.007; mean, +0.003) is notable for three reasons. First, the Sloan observations were made from the ground where atmospheric extinction is very high at ultraviolet wavelengths. Second, the 1% accuracy quoted by Bohlin *et al.* applies to visible and near-IR wavelengths. Third, u' magnitudes are generally difficult to determine accurately as noted in several places, including Chonis and Gaskell (2008).

4. Comparison with Johnson-Cousins magnitudes

A study by Bohlin and Landolt (2015) is similar to that reported in this paper. However, they compared STIS/CALSPEC fluxes with magnitudes on the Johnson-Cousins photometric system. Based on data from 11 stars they found that the photometric observations and spectral fluxes agree to better than 0.010 magnitude for the B, V, R, and I bands. The central wavelengths of these bands range from 440 nm to 900 nm.

They also report that the white dwarf star BD +17 4708 varied by ~0.008 magnitude per year from 1986 through 1991. This star was included in the present study and Table 3 indicates a somewhat anomalous results in the i' and z' bands.

5. Conclusions and suggestions for future research with small telescopes

A comparison between synthetic magnitudes derived from STIS/CALSPEC fluxes and photometric magnitudes of Sloan standard stars was performed. The statistics of the differences are consistent with the stated or intended accuracies of both systems in all five Sloan bands.

The central wavelengths of those bands range from 355 to 893 nm. So, this study extends the comparison made by Bohlin and Landolt (2015) to the near-UV. It also confirms that the ground-based spectroscopy acquired by Oke (1990) was remarkably accurate.

One of the fundamental photometric standard stars was reported to be variable by Bohlin and Landolt. This star and the other white dwarfs used as standards are sufficiently bright that accurate photometry can be obtained with relatively small telescopes. Monitoring of the white dwarfs and other standard stars is suggested.

6. Acknowledgements

R. Bohlin (Space Telescope Science Institute) provided important information about the CALSPEC database. The comments of an anonymous reviewer were very helpful and improved the paper significantly.

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