Validation of "Sloan Magnitudes for the Brightest Stars" and Suggestions for Observing with Small Telescopes

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Abstract Synthetic magnitudes derived from published spectral fluxes and photometric magnitudes from CCD observations are compared to those values listed in the catalogue "Sloan Magnitudes for the Brightest Stars." The RMS differences for synthetic and observed magnitudes generally agree with the transformation-based catalogue values within the uncertainties quoted therein. These quoted values are 0.03 magnitude for the g', r', i', and z' bands, and 0.08 magnitude for the u' band. When separated according to stellar color the RMS values of the red stars are generally smaller than those of the blue stars.

1. Introduction

The catalogue "Sloan Magnitudes for the Brightest Stars" (Mallama 2014) contains 3,969 stellar objects brighter than r' ~ 7. The magnitudes of these objects, which are referred to herein as catalogue stars, were derived by transforming Johnson system magnitudes (Johnson *et al.* 1966) to the Sloan system. In this study we compare two newly determined sets of Sloan magnitudes with those of a sample of catalogue stars. One set was derived synthetically from radiometrically calibrated spectral fluxes while the other was determined by direct photometry with Sloan filters. Statistics of the differences are computed for the purpose of validating the catalogue.

We describe how synthetic magnitudes were derived from the Hubble Space Telescope library of spectral energy distributions (SEDs) and then compare the synthetic and catalogue values in section 2. The method of photometric observation and the resulting dataset are presented in section 3, and those resulting magnitudes are compared to catalogue magnitudes. Section 4 discusses the combined synthetic and photometric comparison and summarizes our conclusions. Section 5 offers a few suggestions for using the catalogue in astronomical research.

2. Synthetic magnitudes

SEDs from the Space Telescope Imaging Spectrograph (STIS) instrument on-board Hubble are considered to be the best such data available. The STIS fluxes of the CalSpec database (Bohlin *et al.* 2014) are accurate to 1% (0.01 magnitude) according to a comparison with Johnson-Cousins B, V, R, and I magnitudes of eleven stars (Bohlin and Landolt 2015). The central wavelengths of those bands range from 440 to 900 nm. Additionally, Mallama (2015) compared STIS/CalSpec fluxes to the magnitudes of six Sloan standard stars listed by Smith *et al.* (2002) in all five Sloan bands (u', g', r', i' and z') which extended the range of wavelengths down to 355 nm in the near-UV. The agreement was, again, about 0.01 magnitude. Therefore, the STIS/CalSpec data are judged to be a reliable source for validating the Sloan magnitudes in the catalogue.

Stars were chosen for the synthetic comparison by matching the catalogue objects with those in the CalSpec library. 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 verify that SEDs extending over all Sloan band-passes were obtained from the STIS instrument, thus insuring that only the most accurate SEDs were used. For HD 172167 STIS data extended to only 535 nm. However, this star is the fundamental standard, α Lyr (Vega), and the fluxes beyond 535 nm are from a carefully derived model which is considered to be highly accurate. For HD 14943 and HD 38666, the catalogue lists only the g' and r' magnitudes, so the other bands were excluded from the analysis for these stars. The seven matching stars are listed in Table 1 and it is notable that they are all hot bluish stars. This selection effect is compensated by a broader range of colors for the photometric comparison, as discussed in the next section.

Table 1. Catalogue and CalSpec stars

Catalog Name	*CalSpec Name*	*Spectral Type**	*Color g'-r'***
HD 14943	HD 14943	A5V	–0.45
HD 15318	ξ^2 Cet	B9III	–0.27
HD 34816	λ Lep	B0.5IV	–0.45
HD 38666	μ Col	0.95V	–0.50
HD 48915	α CMa (Sirius)	A1V	–0.22
HD 172167	α Lyr (Vega)	A0V	–0.23
HD 214680	10 Lac	O9V	–0.41

* *from Bohlin et al. (2014)*
** *from the catalogue*

The 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 is flux, S 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.* (2002) were retrieved from http://www-star.fnal.gov/ugriz/Filters/response.html . 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).

The synthetic magnitudes of the seven matching stars are listed in Table 2. The differences, in the sense "catalogue minus synthetic" magnitude, are listed in Table 3. The mean and the root-mean-square (RMS) of the differences in Table 3 are summarized in Table 4. These statistics will be discussed in section 4 along with those from the photometric comparison, which is described next.

Table 2. Synthetic magnitudes.

Star	*u′*	*g′*	*r′*	*i′*	*z′*
HD 14943	n/a	5.906	5.948	n/a	n/a
HD 15318	5.037	4.128	4.421	4.673	4.829
HD 34816	3.741	4.016	4.492	4.858	5.153
HD 38666	n/a	4.881	5.378	n/a	n/a
HD 48915	–0.583	–1.575	–1.310	–1.068	–0.908
HD 172167	0.987	–0.090	0.153	0.378	0.521
HD 214680	4.351	4.642	5.063	5.396	5.675

Table 3. Catalogue magnitudes minus synthetic magnitudes.

Star	*u′*	*g′*	*r′*	*i′*	*z′*
HD 14943	n/a	0.044	–0.018	n/a	n/a
HD 15318	0.103	0.032	0.009	0.007	0.031
HD 34816	0.079	0.044	0.018	0.062	0.047
HD 38666	n/a	0.039	0.042	n/a	n/a
HD 48915	0.093	0.025	–0.020	–0.022	–0.002
HD 172167	0.073	0.030	0.017	0.012	0.049
HD 214680	0.029	0.028	0.017	0.014	–0.025

Table 4. Statistics of the differences between catalogue and synthetic magnitudes.

	u′	*g′*	*r′*	*i′*	*z′*
Mean	+0.075	+0.035	+0.009	+0.015	+0.020
RMS	0.080	0.035	0.022	0.031	0.035

3. Photometric magnitudes

Nine catalogue stars were observed a total of 16 times by author BK. The magnitudes of Sloan standard stars used for reference were reported by Smith *et al.* (2002) and they are also available on-line at http://www-star.fnal.gov/ugriz/tab08.dat. The raw data were recorded using a 20-cm aperture Schmidt-Cassegrain telescope, an SBIG CCD camera containing a cooled Kodak KAF-0400 sensor, and a set of five Generation 2 Astrodon Sloan filters.

The observations from Farmington, New York, were scheduled so that they occurred when the catalogue and standard stars were within 0.15 air mass of zenith, with the average distance being 0.07. Furthermore, the delta air mass of the two stars was never greater than 0.05, with the average being 0.03. These precautions minimized uncertainties due to atmospheric extinction. Tables 7 and 8 list the air masses and delta air masses in the columns AM and ΔAM, respectively. Additionally, each catalogue star was matched with a standard star of approximately the same color to minimize transformation uncertainties.

The procedure for acquiring image data for a single Sloan magnitude in a single filter was to record two separate series of three images of the catalogue star interleaved with two such series for the standard star. The resulting magnitude for that filter represents the average of six values derived from six pairs of catalogue-and-standard CCD images. Thus, each set of five u', g', r', i', z' magnitudes derives from 60 separate images. The average exposure durations in seconds were u', 256; g', 6; r', 6; i', 14; and z', 39. Additional flat field and dark frames for image reduction were recorded at all observing sessions.

The flat field images were obtained with a light box specially constructed by author BK. A mylar sheet and a piece of milk plastic diffused the light. A Philips three-way "Reveal" bulb installed on a 10-inch reflector was used as illumination for the g', r', i', and z' filters. A blacklight was used for the u' filter and the milk plastic was removed. Flat field images obtained with the telescope aimed at the device gave practically identical results as images obtained using the twilight sky as illumination. There was almost no vignetting across the field of view and only minimal variation due to dust spots.

Early in the program we compared three different computer applications for extracting instrumental magnitudes from the CCD images. These three were AIP4WIN (Berry and Burnell 2011), the Aperture Photometry Tool (APT; California Institute of Technology 2015), and our own program called EXTRACT which we have developed over the past 25 years. EXTRACT was found to provide the best combination of accuracy and ease of use for our purposes, so we employed it for all our data reduction.

Instrumental magnitudes derived from the images were corrected for extinction and transformed to standard Sloan magnitudes. The methods originally developed by Hardie (1962) for the UBV system were adapted for the five-color Sloan system. The procedures for characterizing the color response of the hardware and of the atmospheric extinction at the observing site are also adapted from those outlined by Hardie. Color transformation coefficients were derived from observations of the primary standard stars taken at small air masses on four different nights. Atmospheric extinction coefficients were determined from time-series observations of catalogue stars as they traversed a range of about one air mass on three nights. About one hour is required for extinction stars to travel between 20 degrees elevation (2.9 air masses) and 30 degrees elevation (2.0 air masses). Figure 1 illustrates the extinction observations. The resulting coefficients are listed in Table 5.

The sixteen sets of photometric magnitudes for the nine stars listed in Table 6 are reported in Table 7. The differences, in the sense "catalogue minus photometric" magnitude, are listed in

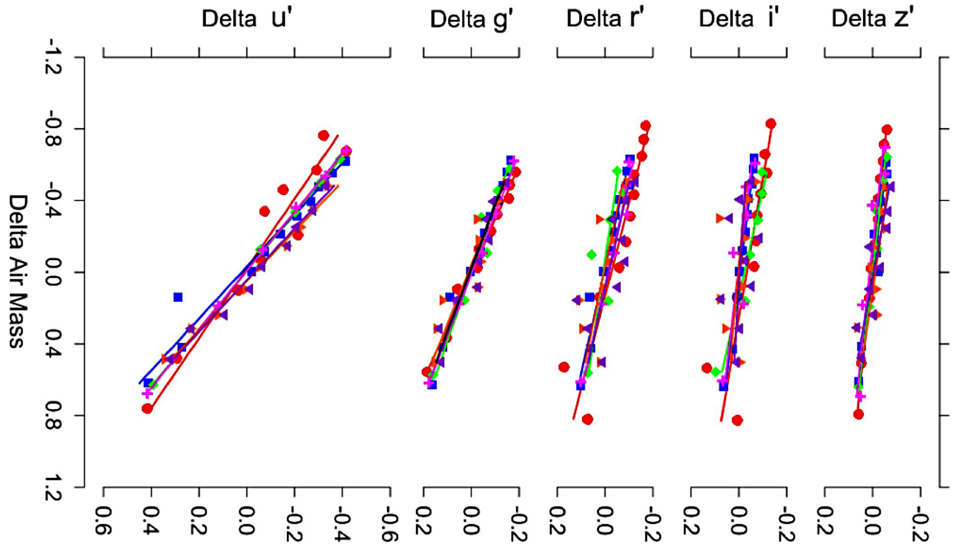

Figure 1. Magnitude changes are plotted as a function of the change in air mass. Six stars observed on three nights determined the five extinction coefficients.

Table 5. Sloan photometric calibration coefficients.

Band	*Extinction**	*Transformation***
u'	0.69	+0.102
g'	0.31	+0.064
r'	0.17	+0.019
i'	0.10	–0.072
z'	0.08	–0.017

** Magnitudes per air mass. Second order extinction was taken to be –0.02 for u' and g', and zero otherwise.*
*** Color indices corresponding to the transformation coefficients are as follows: u'–g'(u'), g'–r' (g'), g'–r' (r'), r'–i' (i'), and r'–z' (z').*

Table 6. Catalogue and photometric stars.

HD	*Spectral Type**	*Color g′-r′***
120818	A5IV	-0.11
125642	A2V	-0.17
186408	G1.5Vb	+0.42
186427	G3V	+0.42
195593	F5Ib	+0.82
206538	A2V	-0.14
207198	08.5II	+0.11
208501	B8Ib	+0.54
210702	K1III	+0.74

** from Centre de Données Astronomiques de Strasbourg*
*** from the catalogue*

Table 7. Photometric magnitudes.

HD	*JD**	*u′*	*g′*	*r′*	*i′*	*z′*	*AM*	*ΔAM*
120818	6808.65	7.770	6.598	6.700	6.869	7.008	1.06	0.02
120818	6816.64	7.836	6.662	6.727	6.900	7.016	1.07	0.02
125642	6808.63	7.360	6.247	6.401	6.590	6.733	1.04	0.05
125642	6816.63	7.399	6.288	6.420	6.613	6.756	1.04	0.04
186408	6899.63	7.589	6.246	5.798	5.675	5.657	1.05	0.04
186408	6904.61	7.640	6.234	5.787	5.675	5.641	1.05	0.05
186427	6899.63	7.879	6.512	6.048	5.926	5.885	1.05	0.04
186427	6904.61	7.871	6.507	6.041	5.919	5.882	1.05	0.05
195593	6943.58	8.707	6.690	5.834	5.436	5.177	1.08	0.02
206538	6917.59	7.068	6.015	6.156	6.327	6.439	1.04	0.05
207198	6928.54	6.305	6.080	5.898	5.909	5.998	1.08	0.02
207198	6933.54	6.332	6.005	5.880	5.889	5.976	1.07	0.01
208501	6926.59	7.191	6.143	5.547	5.263	5.089	1.05	0.03
208501	6927.55	7.182	6.143	5.559	5.247	5.078	1.06	0.01
210702	6926.66	8.584	6.346	5.643	5.382	5.310	1.15	0.00
210702	6927.63	8.586	6.344	5.658	5.414	5.321	1.12	0.01

** Add 2450000.00*

Table 8. Catalogue magnitudes minus photometric magnitudes.

HD	*JD**	*u′*	*g′*	*r′*	*i′*	*z′*	*AM*	*ΔAM*
120818	6808.65	0.080	0.022	0.030	0.041	0.052	1.06	0.02
120818	6816.64	0.014	-0.042	0.003	0.010	0.044	1.07	0.02
125642	6808.63	0.100	0.013	0.029	0.070	0.107	1.04	0.05
125642	6816.63	0.061	-0.028	0.010	0.047	0.084	1.04	0.04
186408	6899.63	0.021	-0.036	0.002	0.015	-0.007	1.05	0.04
186408	6904.61	-0.030	-0.024	0.013	0.015	0.009	1.05	0.05
186427	6899.63	0.001	-0.042	0.002	0.014	0.015	1.05	0.04
186427	6904.61	0.009	-0.037	0.009	0.021	0.018	1.05	0.05
195593	6943.58	0.063	-0.050	-0.014	-0.016	0.013	1.08	0.02
206538	6917.59	0.222	0.035	0.034	0.023	0.041	1.04	0.05
207198	6928.54	-0.025	-0.060	0.012	0.021	-0.018	1.08	0.02
207198	6933.54	-0.052	0.015	0.030	0.041	0.004	1.07	0.01
208501	6926.59	0.009	-0.043	0.013	0.017	0.041	1.05	0.03
208501	6927.55	0.018	-0.043	0.001	0.033	0.052	1.06	0.01
210702	6926.66	-0.084	0.034	-0.003	0.038	0.000	1.15	0.00
210702	6927.63	-0.086	0.036	-0.018	0.006	-0.011	1.12	0.01

** Add 2450000.00*

Table 9. Statistics of the differences between catalogue and photometric magnitudes.

	u'	*g'*	*r'*	*i'*	*z'*
Mean	+0.020	-0.016	+0.010	+0.025	+0.028
RMS	0.076	0.037	0.018	0.031	0.044

Table 10. Photometric statistics for red stars (g'-r' > 0).

	u'	*g'*	*r'*	*i'*	*z'*
Mean	-0.014	-0.023	+0.004	+0.019	+0.011
RMS	0.046	0.040	0.013	0.024	0.023

Table 11. Photometric statistics for blue stars (g'-r' < 0).

	u'	*g'*	*r'*	*i'*	*z'*
Mean	+0.095	0.000	+0.021	+0.038	+0.066
RMS	0.118	0.030	0.025	0.043	0.070

Table 12. Combined synthetic and photometric statistics for blue stars.

	u'	*g'*	*r'*	*i'*	*z'*
Mean	+0.085	+0.018	+0.015	+0.026	+0.043
RMS	0.099	+0.032	+0.024	0.037	0.052

Table 8. The mean and the RMS of the differences in Table 8 are summarized in Table 9. These statistics will be discussed in the next section along with those from the synthetic magnitude comparison.

4. Discussion and conclusions

Tables 4 and 9 listed the mean and RMS differences of catalogue minus synthetic magnitudes and of catalogue minus photometric magnitudes, respectively. The RMS values (which are necessarily larger than the means) are generally consistent with the uncertainties quoted in the catalogue, that is, 0.03 magnitude in the g', r', i', and z' band, and 0.08 in the u' band. To be more specific, the values for u' and r' are within the quoted uncertainties, the i' values come close, and those for g' and z' are somewhat greater. In the context of error estimation this level of validation is satisfactory.

The largest mean and RMS differences are those of the u' band for the synthetic magnitude comparison, 0.075 and 0.080, respectively. The similarity of their sizes implies that the most of the RMS difference is due to the mean. Such a finding is not surprising as Chonis and Gaskell (2008) and others have reported similar difficulties with the u' bandpass.

Since the stars selected for the synthetic comparison were all blue (g'–r' < 0), it is informative to separate the blue stars from the red in the photometric comparison. The red star results are shown in Table 10 while the blue results are in Table 11. Now it is apparent that the means for the u' filter of the blue photometric stars from Table 11 and those of the blue-by-default synthetic stars in Table 4 are similar at +0.095 and +0.075, respectively. Given the findings for the u' band, it is reasonable to separate the statistical results by color. Thus, the RMS values of the u', r', i' and z' bands for red photometric stars in Table 10 are all found to be within the quoted uncertainties while g' is slightly high (0.040 statistically as compared to 0.03 quoted). The synthetic and photometric results for all blue stars are averaged in Table 12. The RMS values for the g', r' and i' bands (+0.032, +0.024 and +0.037) approximate the 0.03 quoted uncertainties, while those for u' and z' (+0.099 and +0.052) both exceed the quoted values by about 0.02 magnitude.

Finally, the results for red and blue stars are plotted along with the uncertainties from the catalogue in Figure 2. The quoted uncertainties are seen to be generally consistent with the RMS values derived by comparing catalogue magnitudes with synthetic and photometric values.

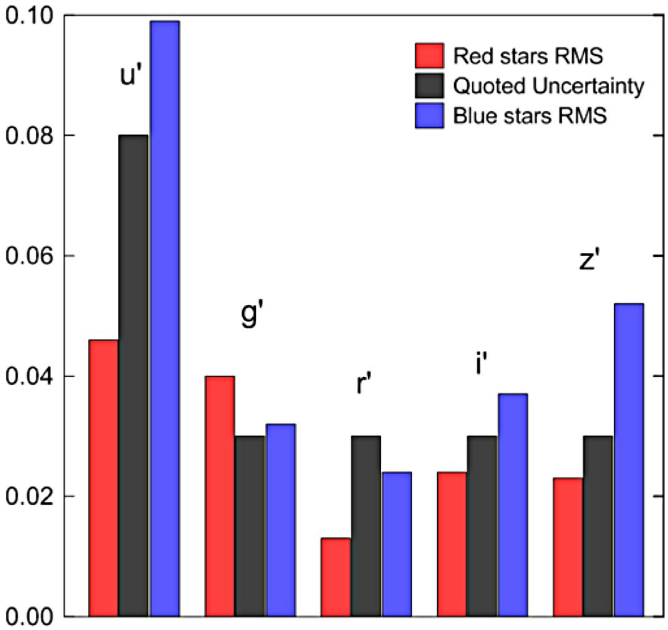

Figure 2. RMS differences for red and blue stars compared with uncertainties quoted in the catalogue.

5. Suggestions for observing with small telescopes

The measured accuracy of the catalogue "Sloan Magnitudes for the Brightest Stars" has been shown to approximate the values quoted in that paper. The uncertainties of the g', r', i', and z' magnitudes are precise enough for many useful investigations of bright objects as described later in this section. Ultraviolet (u') observations are always difficult to measure due to high atmospheric extinction and weak signals at those wavelengths, so their rather large uncertainty is not surprising. Chonis and Gaskell (2008) have commented on this. An alternative to using the u' (and other) catalogue magnitudes is to tie additional bright stars to the Sloan system by direct photometry.

Bright objects would saturate the detectors in most large observatory instrument being used today. However, the strong signals and (in some cases) the nearness of these stars to the Earth allow better spatial, photometric, and spectroscopic resolution than is possible for more distant stars. Therefore bright stars are important and the catalogue is especially well suited as a photometric reference.

One example where bright Sloan reference stars could be useful concerns novae. The magnitudes of bright novae can be accurately measured for a longer period of time than can those of faint ones. An uncertainty of 0.03 for the magnitude of the reference star is relatively small in comparison to the brightness variations of novae which may exceed 10 magnitudes. The same is true of other bright variable stars having large amplitudes.

The planets, which are all brighter than r' ~ +8, are also well suited for observing with reference stars from the catalogue. The authors of this paper, along with several other observers, have recorded and studied the brightness variations of the planets on the Johnson-Cousins system for many years. These analyses have revealed characteristics of the surface of Mercury (Mallama *et al.* 2002) and led to the detection of sulfuric acid droplets at very high altitudes in the atmosphere of Venus (Mallama *et al.* 2006), among other findings. We are now recording planetary magnitudes on the Sloan system.

Photometry of the bright satellites of Jupiter and Saturn as well as those of the large asteroids could also be pursued with small telescopes using reference magnitudes from the catalogue. Sloan magnitudes for the satellites and asteroids have not yet been determined as far as we know.

Sloan filters are now commercially available for CCD cameras and photometers. So, amateur observers can make important contributions to astronomical research by recording observations on this photometric system. The capability to report Sloan magnitudes will become more critical over time in order to maintain compatibility with the professional community. Sloan filters are being installed in most new photometric instruments being developed for large observatories and for spacecraft.

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