ABSOLUTE FLUX CALIBRATION OF OPTICAL SPECTROPHOTOMETRIC STANDARD STARS

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Abstract

A method based on Landolt photometry in B and V is developed to correct for a wavelength independent offset of the absolute flux level of optical spectrophotometric standards. The method is based on synthetic photometry techniques in B and V and is accurate to $\sim 1\%$. The correction method is verified by Hubble Space Telescope (HST) Faint Object Spectrograph (FOS) absolute fluxes for 5 calibration stars, which agree with Landolt photometry to 0.5% in B and V.

1. INTRODUCTION

The calibration of the Hubble Space Telescope (HST) instrumentation in the optical wavelength region from 3200-9200Å is based largely on the spectrophotometry of Oke (1990), who quotes an internal uncertainty of $\sim 3\%$. Oke also recommends making all his published fluxes fainter by 0.04 mag. Calibration observations with the Faint Object Spectrograph (FOS) on HST demonstrated that the Oke spectrophotometry for BD+33D2642 has a systematic internal error of $\sim 5\%$ with respect to four of the other Oke standards.

Photometry in B and V for 28 of the 30 Oke standard stars is available from Landolt (private comm.), who quotes uncertainties of ~0.004 mag with respect to his photometric system. Since the Landolt uncertainties are smaller than those of Oke, the possibility arises of using the photometry to adjust the absolute scale of spectrophotometry in order to reduce the uncertainty in the absolute flux of the standards and consequent HST calibrations.

The accuracy of the Landolt photometry is verified by final calibrated FOS fluxes for five Oke standard stars.

The following sections detail the steps that are required to achieve these results. Section 2 describes the Oke and Landolt data. In section 3, the fundamental absolute flux distribution and Johnson B and V for Vega are presented along with the B and V for Vega in the original Landolt (1973) system. In section 4, the synthetic photometry on the more recent Landolt (1992) system for the Oke spectrophotometry is derived, since the throughput as a function of wavelength is well known. After corrections of the new Landolt photometry back to his original 1973 system, the Oke synthetic magnitudes are compared with actual Landolt photometry. The average of the B and V corrections is applied to the overall level of the Oke data for each star, separately. The rms difference of 0.012 mag between the separate B and V corrections is an indication of the expected accuracy of the corrected Oke spectrophotometry.

Checks of the results are in section 5, where the Landolt photometry is compared to a model of a pure hydrogen white dwarf. FOS photometry is also compared with the Landolt data for five HST/FOS calibration stars.

2. SPECTROPHOTOMETRY AND PHOTOMETRY OF THE STANDARDS

The sample of faint standards used in this study are from Oke (1990) and cover the 3200-9200Å spectral range. The broad band photometry is from Arlo Landolt and is mostly unpublished.

2.1 Oke's optical spectrophotometry

The complete sample consists of thirty faint spectrophotometric standards for which there are Oke's spectra over the 3200-9200Å spectral range. Coordinates and spectral type can be obtained from Turnshek et al (1990). The original spectra were obtained with a double spectrograph on the 5 m Hale telescope along with a Texas Instruments thinned back illuminated 800 x 800 pixel CCDs and slit width of $6'' - 10''$. The averaged blue and red spectra are joined at $\sim$ 4700 Å. See Oke (1990) for more details about the instrument set-up and calibration procedure.

Two of the stars in Oke's sample show close companions. BD+$28^0$4211 has a red companion, $\sim$ 5 magnitudes fainter in V and separated by $2.8''$ at PA 240^0 (Massey & Gronwall 1990). BD+$75^0$325 has a faint companion $4''$SW (Oke 1990). A third one, NGC 7293, is a planetary nebulae (see Plate 56 in Turnshek et al. 1990), These peculiarities might affect the spectroscopic and/or photometric measurements and could decrease the accuracy of the corrections obtained for these stars.

2.2 Landolt's broad-band photometry

Broad-band photometry has been carried out by Landolt (private comm.) for all of Oke's spectrophotometric standards, except HD93521 and BD+$25^0$4655. The observations were mostly done at KPNO, while a few of the standards were observed from CTIO.

Typical observations were done with a diaphragm aperture of $14''$. Landolt reports one-sigma uncertainties of a few millimag in both visual magnitude and B-V color, except for G24-9 where he quotes ± 0.012 magnitude. CCD images of the field around G24-9 shows a faint companion at just about the right distance to sometimes be in the photometer's diaphragm, and sometimes just outside, which may explain the variations evidenced in the rms error above (Landolt, private comm.).

For two of the standards (NGC 7293 and LTT 9491) KPNO and CTIO measurements exist. The discrepancy of $0.01 - 0.02$ mag between CTIO and KPNO magnitudes, are three to four times larger than the quoted one-sigma uncertainties of 0.003 to 0.005 mag (Landolt private comm.). There is no clear explanation for such a difference. However, NGC 7293 is a planetary nebulae and any small error in the positioning and centering of the target into the aperture could result in a difference in the final photometry. Also, both NGC 7293 and LTT 9491 are southern hemisphere targets (with declinations -20^0 & -17^0, respectively), implying that airmass effects could affect KPNO measurements more heavily. Consequently, CTIO magnitudes may be more reliable and will be considered here as the true magnitudes for these two standards.

3. LANDOLT'S PHOTOMETRIC SYSTEM

The use of synthetic photometry to establish absolute fluxes requires accurate characterization of the throughput and zero point of the photometer, i.e. (a) the filter band-pass, and the photomultiplier sensitivity curve of the photometer, (b) the broad-band magnitudes of a primary standard in the specific photometric system, and (c) the absolute calibrated spectrum of the primary standard over the entire spectral region of interest. Consequently, in the following sections the reconstruction of the filter plus photomultiplier set-up and the choice of Vega as the primary standard are explained.

3.1 Filter and photomultiplier transmission curves

To simulate the photometer set-up for the CTIO observations, the B and V bandpass and RCA31034A sensitivity curve are obtained from Tables 6, 7, and 11 of Landolt (1992), respectively. For the KPNO photometer configuration, information on the filter transmissions is provided by A. Landolt (private comm.), while the sensitivity curve of the specific RCA31034A photomultiplier is not known. CTIO's RCA31034A photomultiplier sensitivity curve has been used, instead. This choice is appropriate, since the average shape of several RCA 31034A photomultipliers agrees with that of CTIO (see discussion in Landolt 1992).

The characteristics of Landolt's KPNO and CTIO filters and their comparison with Johnson can be found in Table 1. The pivot wavelength λ_p is a source independent wavelength that allows an exact conversion between the broadband flux densities f_ν and f_λ, while λ_o is the more traditional mean wavelength (see Koornneef et al. 1985 for the exact definitions of these parameters). The effective wavelengths (λ_{eff}) for Vega and G191B2B, and the mean flux for Vega integrated over the bandpass are also indicated in Table 1. The corresponding parameters for Johnson's filters were obtained using Buser & Kurucz (1978) response functions.

Values for the filter transmission curves and the photomultiplier sensitivity curve are listed every 10Å and 100Å, respectively. The photomultiplier sensitivity curve is interpolated every 10Åat the wavelengths of the filter curve to produce the final KPNO and CTIO photometer sensitivity curve.

3.2 The spectrum of Vega

Over the past twenty years, there have been several spectrophotometric measurements of Vega (Oke & Schild 1970; Hayes & Latham 1975; Tüg, White & Lockwood 1977; Hayes 1985 and references) as well as detailed theoretical models (Schild, Peterson & Oke 1971; Kurucz 1979; Dreiling & Bell 1980; Castelli & Kurucz 1994). Theoretical fits to the observed spectrum experience difficulties in modeling the continuum shape around the Balmer jump and in reproducing the equivalent widths of the Balmer absorption lines

(Lange & Wing 1979, Dreiling & Bell 1980; Castelli & Kurucz 1994).

Thus, the empirical spectrum obtained by Hayes (1985) will be adopted as the absolute flux distribution of Vega. This spectrum is the weighted mean of five different spectra obtained by several authors with different telescopes at different observatories. The adopted spectrum covers the entire 3300 - 10500 Å spectral range with a uniform step of 25 Å , while the absolute flux at 5000Å is 4.65 10^{-9} erg s^{-1} cm^{-2} $Å^{-1}$.

3.3 Vega's magnitudes and zero points of the system

Vega is too bright for Landolt's telescope and photometer combination. However, Vega's magnitudes can be transferred from the original Johnson's into Landolt's original system, which use a 1P21 photomultiplier.

The V magnitude and (B-V) color of Vega in Johnson's system correspond to V= +0.030 ± 0.012 and (B-V) = 0.00 ± 0.006 (Johnson & Morgan 1953), or V= +0.040 ± 0.012 and (B-V) = 0.00 ± 0.006 according to Johnson & Harris (1954). The average V magnitude obtained from these two measurements (V= +0.035), agrees well with the average visual magnitude (V= +0.034) obtained by Kozyreva, Moshkalev, & Khaliullin (1981). Thus, Vega has a visual magnitude V= +0.035 and color (B-V)= 0.00 in Johnson's original system.

The original Landolt (1973) system is used to extend the sample of photometric standards to faint stars covering the whole sky and is tied (Landolt 1973) into the original Johnson UBV system as defined by the stars listed in Johnson (1963). The mean differences found by Landolt between his system and Johnson (Landolt minus Johnson) correspond to −0.006 ± 0.003 (m.e.) magnitudes in V, and −0.002 ± 0.002 (m.e.) magnitudes in (B-V) color (Landolt 1973). Because of uncertainties and convention a visual magnitude of V= +0.029 and color (B-V) = 0.000 is adopted for Vega in Landolt's 1P21 system. Subsequent photometry by Landolt (1983, 1992) using an RCA photomultiplier has always been tied into his original 1P21-based system (Landolt 1973) using color corrections (see §4.1 for the specifics).

4. SYNTHETIC PHOTOMETRY AND ABSOLUTE FLUX CORRECTIONS

4.1 Synthetic photometry for KPNO and CTIO observations

Our synthetic photometry uses the *calcphot* task of the synthetic photometry software (SYNPHOT) developed by the Science Software Branch at the Space Telescope Science Institute. SYNPHOT is an external package within IRAF-STSDAS. Special files with the photometer throughput for the different filter plus photomultiplier combinations (see §3.1) and with the Hayes (1985) spectrum of Vega (see §3.2) are used as input for *calcphot*. Our synthetic photometry does not take into account the effect of the transmission of the optical system over the broad bandpass of the filters. No reliable information was available for the CTIO and KPNO telescopes used during the observations. However, simulations using the Hubble Space Telescope optical transmission have been performed for stars covering a color range between −0.33 and +0.69 in B-V. Changes in the B and V magnitudes about 0.001 mag, or smaller, are measured. Also, linear changes of factors of up to 0.6 in the filter plus photomultiplier throughput over the 3000 Å range covered by the B and V filters, produce changes up to 0.016 mag in B and V for the hottest and coolest Oke standards. For a star with the colors of Vega, no differences arise in the synthetic photometry, because the zero point of B and V is determined by the Vega spectrum. Therefore, for typical throughput uncertainties of 5% over the filter bandpass, the photometric uncertainty is of the order of a few millimagnitudes. Finally, no atmospheric extinction effects are required, since the Landolt magnitudes are reduced to zero airmass.

Synthesised magnitudes in Landolt's RCA system (m_o) are obtained by the standard expression

$$m_o = m_o(\mathrm{Vega}) - 2.5 \log[F(\mathrm{star})/F(\mathrm{vega})] \quad (1)$$

where m_o(Vega) is Vega's V_o or B_o magnitude in Landolt's RCA system (see equations

2 to 6 below, where $V_S = +0.029$ and $(B-V)_S = 0.000$). F(Vega) and F(star) are the energy of Vega and of any particular star in a given band. These energies are obtained by convolving Vega's spectrum (§3.2) and Oke's original spectra (§2.1) with the V and B RCA photometer throughput (§3.1).

A last effect has to be considered in order to generate the final synthesised magnitudes B_S and V_S prior to comparison with the observations of B and V. The original Landolt (1973) photometry uses a 1P21 photomultiplier, while the most recent CTIO and KPNO observations are done with an RCA photomultiplier. As a consequence of this different set-up, a color correction is required to convert the new KPNO and CTIO RCA observations (Landolt 1983, 1992) to the original Landolt 1P21 system (1973). Consequently, to obtain the final synthesised magnitudes V_S and B_S, the magnitudes obtained from equation (1) V_o and B_o must be corrected for this effect in the same way that Landolt has converted his RCA data to the original 1P21 scale. The empirical Landolt's magnitudes can then be directly compared against B_S and V_S.

For CTIO observations, these color corrections from the RCA to the 1P21 scale are given by (Landolt 1992)

$$(B-V)_S = +0.00144 + 1.05416\ (B_o - V_o) \quad \text{if } (B_o - V_o) < +0.1 \qquad (2)$$

and

$$V_S = V_o + 0.00048 - 0.00082\ (B-V)_S \qquad (3)$$

while for KPNO, one has (Landolt, private comm.)

$$(B-V)_S = +0.00268 + 1.02847\ (B_o - V_o) \quad \text{if } (B_o - V_o) < +0.1 \qquad (4)$$

$$(B-V)_S = +0.00709 + 0.98474\ (B_o - V_o) \quad \text{if } +0.1 < (B_o - V_o) < +1.0 \qquad (5)$$

and

$$V_S = V_o - 0.00036 - 0.01444\ (B - V)_S \quad \text{if } (B_o - V_o) < +0.1 \qquad (6)$$

$$V_S = V_o - 0.00112 - 0.00271\ (B - V)_S \quad \text{if } +0.1 < (B_o - V_o) < +1.0 \qquad (7)$$

The final synthesised magnitudes V_S and B_S are compared with Landolt's photometry (Landolt, private comm.) in Table 2.

4.2 Corrections for Oke's faint spectrophotometric standards

Offsets in the absolute flux of each individual spectrophotometric standard (columns labeled as V_S- V, B_S- B and correction in Table 2) are the difference between the final V_S and B_S synthesised magnitudes and Landolt's magnitudes. The column labeled *correction* is the average of V_S- V and B_S- B. For those stars (HD93521 and BD+25^{0}4655) without Landolt photometry, an offset equal to the average value obtained for the rest of the sample is used.

The mean at the bottom of column 6 in Table 2 demonstrates that Oke's original spectrophotometry is too bright by 0.03 magnitudes in the mean. This value is close to the 0.04 mag quoted by Oke (1990) based on the comparison of his results with a few IUE fluxes near 3200Å and with Stone's spectrophotometric standards. Also, no statistically significant difference exist between the average corrections in columns 4 & 5 of Table 2, which are obtained from the V and B measurements, independently. This average correction is based on the average of 28 standards covering a luminosity range of 6 magnitudes.

However, the average B and V corrections and their scatter have similar values. Corrections for individual stars may depart from the mean by up to 2σ (see the result obtained for BD+33^{0}2642, which is one of the HST/FOS primary standards, for example). Instead of decreasing the absolute flux of all stars in the sample by the same average amount, as suggested by Oke (1990), the absolute flux of each star can be adjusted independently, with the mean offsets obtained from the average of its own V and B magnitudes. A measure of the deviation of the individual (B_S- B) and (V_S- V) corrections from their adopted average is presented in column 7 of Table 2 where $\triangle$(B−V) represents the quantity (B_S- B) − (V_S- V). The rms scatter of 0.023 mag in $\triangle$(B−V) or of 0.5$\triangle$(B−V)= 0.012 mag in the deviation from the adopted average B and V corrections is the best one-sigma estimate of the uncertainty of our correction for each star. For example, the worst case G138-3 has a 3σ difference between the B and V corrections.

5. ACCURACY OF THE ABSOLUTE FLUX CORRECTIONS

Two different tests have been performed to check the accuracy of the correction procedure outlined in previous sections: (a) a comparison of the corrected white dwarf G191B2B spectrophotometry against a pure hydrogen theoretical model, (b) a comparison of the HST/FOS spectra for the five FOS primary calibration standards with the Landolt photometry.

5.1 G191B2B's corrected spectrum versus model

Oke's original spectrum of the white dwarf G191B2B is too bright by 0.049 magnitudes, according to our calculations (see Table 2). The corrected G191B2B spectrum is obtained by decreasing the flux of the original Oke's spectrum by a factor of 1.0462 (i.e corresponding to 0.049 magnitudes fainter) over the entire 3200-9200 Å spectral range covered by Oke's observations. The theoretical model by Dr. Finley is for a pure hydrogen white dwarf with a temperature of 60000 K and a gravity of log g= 7.50 and is normalized to an isophotal flux F(5490) = 3.61 10^{-9} erg s^{-1} cm^{-2} $Å^{-1}$ for V= 0 (Finley, private comm.). To make the comparison between the empirical and theoretical spectra consistent, the spectrum provided by Dr. Finley has to be tied to Landolt's system following the steps explained in section §4.

The comparison of the synthesised magnitudes of the G191B2B model against Landolt's magnitudes, indicates that the theoretical spectrum is fainter by +0.003 and +0.007 magnitudes in B and V, respectively. The absolute flux of the model spectrum is increased by the offset measured in V, i.e by 1.00647. The reason for normalizing to V only is that the B filter covers Balmer lines which are more difficult to model precisely than the continuum.

The spectrophotometric comparison between the corrected Oke's G191B2B spectrum and normalized Finley's model shows an agreement at the 3% and 1% level over the spectral regions 3200-3850 Å and 3900-8000 Å, respectively. The somewhat worse agreement between the empirical and model spectra in the 3200-3850 Å range could reflect the observational uncertainties in this spectral region, as well as the difficulties of the theoretical modeling of the Balmer decrement and jump.

5.2 Consistency of FOS spectrophotometry

One more check of the Landolt photometry is provided by the synthetic B and V magnitudes and offsets of the HST/FOS primary standards G191B2B, BD+28^{0}4211, BD+33^{0}2642, BD+75^{0}325, and HZ44 in Table 3. Several FOS spectra are averaged for these stars (Lindler & Bohlin 1994) for an FOS calibration that is based on our corrected Oke fluxes for the 5 reference stars. Three main facts can be derived from these results: (1) the FOS spectra are brighter than the Landolt photometry by only 0.4%, in the mean; (2) the dispersion of only 0.005 mag between the FOS and Landolt photometry indicates that these 5 average FOS spectra are photometric to $\leq$ 0.5%, and (3) there is a systematic color effect in the sense that the offsets derived from the $V_S -$ V and $B_S -$ B differ by 0.010 magnitudes in the mean.

The 0.010 mag is not statistically significant to our corrected Oke data, which has 1.1% uncertainty, even though the result is an average for five stars. In terms of the ±0.005 mag photometric accuracy of the FOS, the 0.01 sytematic color difference is significant (Bohlin 1994, in preparation) but should not be applied to corrected Oke spectrophotometry.

6. SUMMARY

A general method to calculate systematic offsets on the overall absolute flux level of any sample of faint spectrophotometric standards with precise relative flux as a function of wavelength has been presented. The method, based on synthetic photometry techniques and broad-band photometry, has been applied successfully to correct Oke (1990) faint spectrophotometric standards.

Oke's spectra are too bright by 0.029 magnitudes in the mean at B and V. There is no difference (at the 0.004 level) in the mean offset obtained from the V and B magnitudes, independently.

The rms scatter in the separate B and V measurements of 0.012 mag around the mean offset is the best estimate of the uncertainty of our procedure for any individual star. For example, BD+$33^0$2642 needs a correction of 8% which is uncertain by only 1.1%, one-sigma.

New spectra for each individual star have been obtained by decreasing or increasing Oke's original flux by the amount in Table 2. The rms uncertainty in the absolute flux of the corrected Oke standards is of 1.1% over the B & V spectral range.

Digital spectra with the correction described here and the UV corrections of Bohlin (1994, in preparation) will be made available via Mosaic and the World Wide Web.

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TABLE 1: Characteristics of Landolt and Johnson filters

Parameter	B(KPNO)	B(CTIO)	B(Johnson)	V(KPNO)	V(CTIO)	V(Johnson)
λ_p^1	4348	4285	4434	5492	5418	5493
λ_o^1	4362	4295	4448	5507	5427	5505
FWHM[1]	810	681	831	938	721	827
λ_{eff}(G191B2B)[1]	4318	4264	4401	5454	5395	5463
λ_{eff}(Vega)[1]	4376	4312	4442	5479	5411	5482
F_λ(Vega)[2]	6.28	6.53	6.20	3.54	3.69	3.55

[1] expressed in Angstroms.
[2] in units of 10^{-9} erg s^{-1} cm^{-2} Å^{-1}

TABLE 2: Corrections for Oke's spectrophotometric standards

Name	V_S	B_S	$V_S - V$	$B_S - B$	Correction	$\triangle$(B-V)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
G158-100	14.854	15.543	−0.036	−0.037	−0.036	−0.001
GD50	14.053	13.796	−0.010	+0.009	−0.000	+0.019
SA95-42	15.608	15.387	+0.002	−0.004	−0.001	−0.006
HZ 4	14.493	14.599	−0.013	+0.007	−0.003	+0.020
LB227	15.338	15.386	+0.015	+0.008	+0.012	−0.007
HZ 2	13.847	13.770	−0.034	−0.019	−0.027	+0.016
G191B2B	11.728	11.410	−0.053	−0.045	−0.049	+0.008
G193-74	15.596	15.884	−0.078	−0.047	−0.063	+0.032
BD+$75^0$325	9.518	9.177	−0.030	−0.037	−0.034	−0.007
AGK+$81^0$266	11.915	11.580	−0.022	−0.017	−0.019	−0.005
GD108	13.580	13.343	+0.019	−0.003	+0.008	−0.022
Feige 34	11.135	10.769	−0.046	−0.069	−0.057	−0.024
HD93521*	6.962	6.695			−0.029	
HZ 21	14.667	14.314	−0.021	−0.047	−0.034	−0.026
Feige 66	10.426	10.142	−0.084	−0.078	−0.081	+0.005
Feige 67	11.787	11.426	−0.035	−0.053	−0.044	−0.018
G60-54	15.761	16.430	−0.047	−0.022	−0.035	+0.026
HZ 44	11.653	11.326	−0.020	−0.056	−0.038	−0.036
GRW+$70^0$5824	12.744	12.630	−0.029	−0.052	−0.040	−0.023
BD+$33^0$2642	10.747	10.568	−0.081	−0.094	−0.087	−0.013
G138-31	16.088	16.509	−0.029	+0.034	+0.002	+0.063
G24-9	15.779	16.171	+0.028	−0.005	+0.012	−0.033
LDS749B	14.659	14.585	−0.019	−0.049	−0.033	−0.015
BD+$28^0$4211	10.477	10.117	−0.032	−0.051	−0.042	−0.019
G93-48	12.726	12.710	−0.013	−0.021	−0.017	−0.007
BD+$25^0$4655*	9.656	9.351			−0.029	
NGC 7293	13.495	13.087	−0.032	−0.074	−0.053	−0.042
LTT 9491	14.085	14.122	−0.016	−0.004	−0.010	+0.012
Feige 110	11.809	11.491	−0.022	−0.036	−0.029	−0.014
GD248	15.097	15.191	−0.015	−0.015	−0.015	+0.000
Mean			−0.027	−0.031	−0.029	−0.004
Dispersion			0.027	0.031	0.027	0.023

* There is no Landolt's photometry for these stars. The tabulated correction correspond to the average value obtained for the rest of the sample. A plus sign in the correction means that the published Oke fluxes should be increased.

TABLE 3: Offsets between FOS and Landolt photometry

Name	V_S	B_S	V_S-V	B_S-B	Offset
BD+28^{0}4211	10.516	10.163	+0.007	−0.005	+0.0010
BD+33^{0}2642	10.827	10.654	−0.001	−0.008	−0.0045
BD+75^{0}325	9.543	9.198	−0.005	−0.016	−0.0105
G191B2B	11.783	11.451	+0.002	−0.004	−0.0010
HZ 44	11.680	11.372	+0.007	−0.010	−0.0015
Mean			+0.002	−0.009	−0.003
Dispersion			0.005	0.005	0.005