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Faint NUV/FUV Standards from Swift/UVOT, GALEX and SDSS Photometry

Michael H. Siegel¹, Erik A. Hoversten¹, Peter W. A. Roming¹, Wayne B. Landsman², Carlos Allende Prieto^{3,4}, Alice A. Breeveld³, Peter Brown^{1,5}, Stephen T. Holland², N. P. M. Kuin³, Mathew J. Page³, Daniel E. Vanden Berk⁶

ABSTRACT

At present, the precision of deep ultraviolet photometry is somewhat limited by the dearth of faint ultraviolet standard stars. In an effort to improve this situation, we present a uniform catalog of eleven new faint ($u \sim 17$) ultraviolet standard stars. High-precision photometry of these stars has been taken from the Sloan Digital Sky Survey and *Galaxy Evolution Explorer* and combined with new data from the *Swift* Ultraviolet Optical Telescope to provide precise photometric measures extending from the Near Infrared to the Far Ultraviolet. These stars were chosen because they are known to be hot ($20,000 < T_{eff} < 50,000K$) DA white dwarfs with published Sloan spectra that should be photometrically stable. This careful selection allows us to compare the combined photometry and Sloan spectroscopy to models of pure hydrogen atmospheres to both constrain the underlying properties of the white dwarfs and test the ability of white dwarf models to predict the photometric measures. We find that the photometry provides good constraint on white dwarf temperatures, which demonstrates the

¹Pennsylvania State University, Department of Astronomy, 525 Davey Laboratory, University Park, PA, 16802 (siegel@astro.psu.edu, hoversten@astro.psu.edu, roming@astro.psu.edu, brown@astro.psu.edu)

²NASA/Goddard Space Flight Center, Astrophysics Science Division, Code 661, Greenbelt, MD 20771 (wayne.b.landsman@nasa.gov, Stephen.T.Holland@nasa.gov)

³Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT (cap@mssl.ucl.ac.uk, aab@mssl.ucl.ac.uk, npmk@mssl.ucl.ac.uk, mjp@mssl.ucl.ac.uk)

⁴Current address: Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain

⁵Current address: Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112

⁶Physics Department, St. Vincent College, Latrobe, PA 15650 (daniel.vandenberk@email.stvincent.edu)

ability of Swift/UVOT to investigate the properties of hot luminous stars. We further find that the models reproduce the photometric measures in all eleven passbands to within their systematic uncertainties. Within the limits of our photometry, we find the standard stars to be photometrically stable. This success indicates that the models can be used to calibrate additional filters to our standard system, permitting easier comparison of photometry from heterogeneous sources. The largest source of uncertainty in the model fitting is the uncertainty in the foreground reddening curve, a problem that is especially acute in the UV.

Subject headings: white dwarfs; techniques: photometric; ultraviolet: general; ultraviolet: stars

1. Introduction

The last three decades have witnessed the advent of numerous space-based ultraviolet-sensitive instruments. Programs such as the *Hubble Space Telescope* Faint Object Spectrograph (FOS), Space Telescope Imaging Spectrograph (STIS), and Advanced Camera for Surveys (ACS), *International Ultraviolet Explorer*, *Far Ultraviolet Spectroscopic Explorer*, *Galex Evolution Explorer* and *Hopkins Ultraviolet Telescope* have created an infusion of scientific discovery, particularly in hot or high-energy environments.

The expansion of ultraviolet astronomy, however, has run into a problem of calibration. The primary set of UV calibration standards for the above missions consists of four hot white dwarf stars – G 191-B2B, GD 153, GD 71, and HZ 43 (Bohlin 1996, 2000, 2007; Bohlin et al. 2001; Bohlin & Gilliland 2004; Nichols & Linsky 1996; Kruk et al. 1999). All four, however, are brighter than $m_V = 13.4$ (Holberg and Bergeron 2006). While such bright standards were excellent for previous generations of instruments, they are too bright for the latest generation of telescopes. The Bohlin standards would quickly saturate CCD cameras on large telescopes (or, in the case of the Cosmic Origins Spectrograph, potentially damage the detector) and short exposure times bring shutter resolution into play. Observations with photon-counting instruments – such as the *Swift* Ultraviolet Optical Telescope (UVOT), ASTROSAT’s Ultraviolet Imaging Telescope or the Tel Aviv University UV Explorer – are compromised by coincidence loss. Coincidence loss occurs when two or more photons from an astronomical source arrive within a single detector read time and are therefore read as a single photon (Fordham, Moorhead, & Galbraith 2000). The brighter the source, the greater the coincidence loss. Coincidence loss can not be ameliorated by shorter exposure times. Beyond a certain range (with UVOT, about 100 ph sec^{-1}) coincidence loss becomes so great as to make measured brightnesses unreliable (see Poole et al. 2008, hereafter P08,

their figure 6).

Recent calibration efforts using faint UV standards have been made by the *Swift*/UVOT team (P08). However, even UVOT is only calibrated to three objects – WD 1657+343, WD 1121+145 and WD 1026+453 – in the UV passbands. These hot white dwarfs have U magnitudes of 14.8-15.4 and were observed as part of an HST faint extension calibration program (10094). However, the HST program was unable to proceed after 2003 owing to the failure of STIS and a fourth faint standard (WD 0947+857) was suspected to have a composite UV-optical spectrum (Lajoie & Bergeron, 2007). The need for a larger number of faint UV standards remains critical.

A recent study by Allende Prieto et al. (2009, hereafter AP09) has taken the first step in this direction. Using data from the Sloan Digital Sky Survey (SDSS), they identify nine hot faint DA white dwarfs as potential spectrophotometric standards. Hot DA white dwarfs are suitable as UV standard candles because of their high UV luminosity, blue colors and the paucity of spectral lines that makes them easy to model. In turn, because the UV passbands are sensitive to the properties of white dwarfs (see Figure 1), studying white dwarf standards can provide a reciprocal test on the white dwarf models themselves and provide additional constraint on the properties of white dwarfs.

Our study complements the AP09 study by using *Swift*/UVOT to observe eleven faint hot DA white dwarfs selected not only from the SDSS but also from the *Galaxy Evolution Explorer* (GALEX) catalog. We use the combined data, covering the spectral range from the NIR to the FUV, to provide tight constraints on the temperatures of the white dwarf stars. Moreover, we test the ability of pure hydrogen models of white dwarfs to reproduce the measured photometry. The result is a group of stars with calibrated observations in eleven passbands, published SDSS spectra and well-constrained model spectra that can be used to calibrate existing or future instruments that may use different filters.

2. Observations and Data

2.1. Sample Selection

The first step in constructing the catalog of faint UV standards was to select good candidate stars. DA white dwarf stars are ideal targets for a number of reasons. First, while some may suffer from metal pollution, they are expected to manifest mostly hydrogen absorption

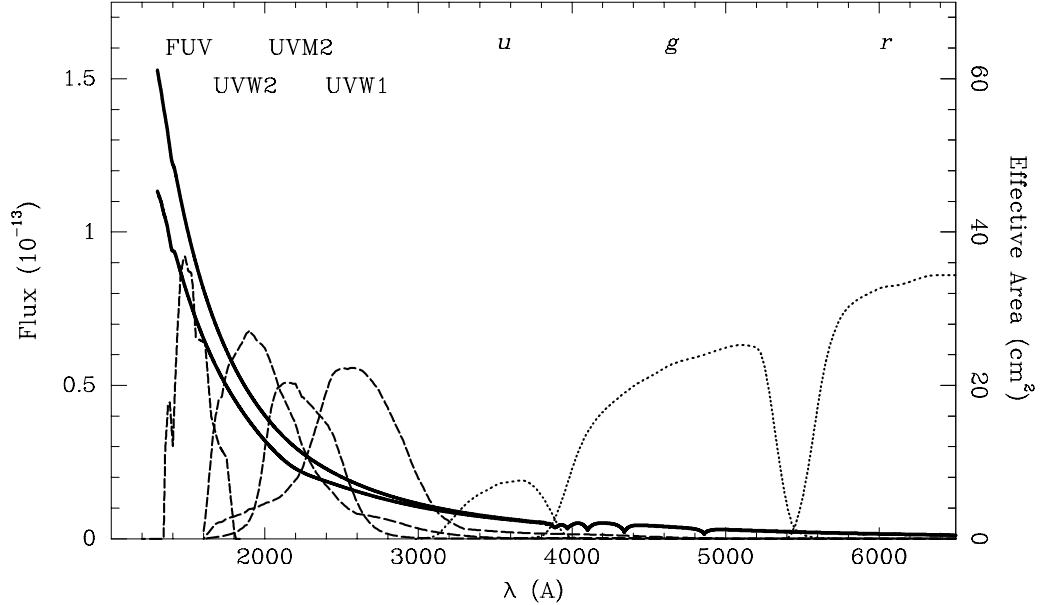


Fig. 1.— The sensitivity of the NUV and FUV passbands to the properties of white dwarfs. The thick lines are two of our fitted white dwarf models. The upper line is SDSS J150050.71+040430.0; the lower line is SDSS J173020.12+613937.5. Note that the flux is dominated by the UV emission, where the *GALEX* and *Swift*/UVOT filters (dashed lines) are centered. Note also the lack of distinct spectral lines in the UV passbands. The SDSS filters are shown in dotted lines and arbitrarily scaled down to provide a comparison to the NUV and FUV filters.

lines, none of which would be in the 1700–3000 Å wavelength range of UVOT’s UV filters. This simplifies the modeling. Second, white dwarfs have been successfully modeled at the 1% level over the temperature range of $20,000 \text{ K} < T_{eff} < 90,000 \text{ K}$, allowing confident comparison between theoretical models and empirical magnitudes (Holberg & Bergeron 2006). Third, trigonometric parallaxes have confirmed the utility of photometric parallaxes (Holberg et al. 2008). Fourth, outside of the known instability strip, DA white dwarf luminosity variations are driven by radiative cooling over long timescales and they are therefore expected to show little photometric variability. Finally, large catalogs of spectroscopically confirmed

white dwarf stars have already been compiled (e.g., McCook & Sion 1999; Eisenstein et al. 2006).

We began our selection with the catalog of 9316 spectroscopically confirmed white dwarfs from the SDSS fourth data release (Eisenstein, et al. 2006). The advantage of the Eisenstein, et al. (2006) catalog is that it contains uniform, high quality photometry in five filters ranging from roughly 3500 to 10000 Å as well as uniform spectroscopy at $R \simeq 1800$ covering a wavelength range of 3800 to 9200 Å (Stoughton et al. 2002). Eisenstein, et al. (2006) provide spectral classifications for each object as well as a homogenous set of effective temperatures and surface gravities. The primary drawback of the SDSS catalog is that the survey footprint primarily covers declinations above zero that are accessible from Apache Point and avoids the Galactic plane. These limitations preclude a uniform sky distribution of standard stars.

We selected white dwarfs from the SDSS catalog that were spectroscopically classified as DA white dwarfs. To ensure their suitability for simple modeling, we further restricted the sample to stars that lack K or M star companions, strong magnetic contributions, or evidence of helium, carbon, or other metal lines. Additionally, to minimize the effects of coincidence loss, we required that the flux in each filter be less than 5 counts s^{-1} , which corresponds to a magnitude range of $uvw2 < 15$, with UVOT magnitudes estimated from the SDSS u -band magnitude and the effective temperatures of Eisenstein, et al. (2006). At count rates of 5 counts s^{-1} or below, the coincidence loss is less than 3% and is corrected by the formulation given in P08 to better than 1%.

We selected stars with stellar temperatures of $20,000 \text{ K} < T_{eff} < 50,000 \text{ K}$. Previous investigations (e.g., Holberg & Bergeron, 2006) have shown DA white dwarfs in this temperature range to be modellable to better than 1% precision. The lower temperature bound also avoids the instability strip that white dwarfs cross as they undergo radiative cooling and become DAV variable stars (e.g. Mukadam, et al. 2004; Mullally, et al. 2005). We also removed stars that either had large uncertainties in effective temperature or surface gravity ($>1000 \text{ K}$ and 0.3 dex, respectively) or where the dust maps of Schlegel, Finkbeiner, & Davis (1998) indicate a reddening of $E(B - V) > 0.05$. The latter cut is especially critical in the ultraviolet, where extinction is much higher and more uncertain than in the optical (e.g. see Pei 1992, for dust models from the Milky Way and Magellanic Clouds), significantly multiplying the impact of any uncertainty in the foreground extinction. Moreover, the extinction law itself may vary from $R_V \sim 3.1$ over a range of 2.2-5.8, depending on the line of sight through the Galaxy (Fitzpatrick 1999).

All of these cuts reduced our sample to 136 candidate stars (1.5% of the sample). We then imposed the additional requirement that data for each star be available from the

GALEX mission (Martin et al. 2005; Morrissey et al. 2007). GALEX has a near-UV filter with an effective wavelength of 2267 Å, which overlaps the UVOT filters. More importantly, it has a far-UV filter with an effective wavelength of 1516 Å, bluer than the Swift filters, which allows for even more rigorous constraint of T_{eff} . While GALEX’s All-Sky Imaging Survey covers most of the sky with an exposure time of at least 100 seconds, the Medium Imaging Survey (MIS) covers 1000 square degrees in the SDSS footprint with exposure times greater than 1500 seconds. We selected only stars that were covered by MIS where the GALEX photometry error is dominated by systematics. The MIS requirement eliminated most remaining candidate stars because the MIS only covers one sixth of DR4’s 6670 square degree footprint (Adelman-McCarthy, et al. 2006).¹

From the remaining candidates, we selected 12 stars that were as equally spaced across the sky as possible, given the constraint of the SDSS/MIS footprint, had no other sources within 15” and no bright stars within the 17’ UVOT field of view (FOV). Eleven of these were subsequently observed by Swift/UVOT and these eleven comprise our new catalog of standards. The final list of target stars and observations is shown in Table 1. We list the SDSS identification, coordinates and SDSS u magnitude as well as the number of *Swift* observations and total UVOT exposure time as detailed in the next subsection. We also list the reddening values derived from the maps of Schlegel, Finkbeiner, & Davis (1998). SDSS and GALEX photometry are listed in Tables 2 and 3, respectively. In all cases, we have listed, in the top row, the uncertainty in the photometric zero points specified by Ivezić et al. 2004 (SDSS), Morrissey et al. 2007 (GALEX) and P08 (Swift/UVOT). These uncertainties are added to the random photometric uncertainties for our analysis.

Our selection was made prior to the publication of AP09 and has only one target in common (J134430.11+032423.2). However, AP09 had a brighter magnitude limit, which would have excluded all but four of our target stars. They further refined the sample based on the quality of agreement between observations and models. Their final selection of nine stars, against which we have no overlap, is based on expected uncertainties in photometry. Our selection, by contrast, was aimed at finding stars that would produce high-quality UVOT data and had extant GALEX photometry. However, Swift/UVOT observation of the AP09 standards is highly recommended.

¹The list of targets was created in early 2008 before the release of GALEX DR5, so this requirement would be less stringent today.

2.2. Photometry

We supplemented the existing GALEX and SDSS photometry for the DA white dwarfs with a new epoch of photometry from the UVOT instrument aboard the *Swift* Gamma Ray Burst Mission (Gehrels et al. 2004). UVOT is a modified Richey-Chretien 30 cm telescope that has a wide ($17' \times 17'$) field of view and a microchannel plate intensified CCD operating in photon counting mode (see details in Roming et al. 2005). It is designed to catch the early optical/ultraviolet afterglows of gamma ray bursts. However, as a wide field instrument sensitive over the wavelength range of 1700-8000 Å that observes simultaneously with *Swift's* X-Ray Telescope (XRT; Burrows et al. 2005), it fills a unique niche beyond gamma ray bursts, allowing multi-wavelength investigations into a wide range of astrophysical phenomena.

The instrument is equipped with a filter wheel that includes a clear white filter, u , b and v optical filters, $uvw1$, $uvm2$ and $uvw2$ ultraviolet filters, a magnifier, two grisms and a blocked filter. The UV filters are narrower than those of GALEX. This narrowness limits the overall spectral range but significantly improves the spectral resolution. For the purpose of our faint UV standard catalog, the UVOT data allow a potent extension into the UV, providing keener sensitivity to the properties of our white dwarf standard stars, particularly their temperatures.

Eleven of our twelve target stars were observed as fill-in targets during the 2008-9 *Swift* AO4 observing cycle. Data were taken in the u , $uvw1$, $uvm2$ and $uvw2$ filters between June 2008 and February 2009. A handful of stars were re-observed in June 2009 for additional calibration. Exposure times and sequencing varied depending on observing windows, XRT temperature concerns and interrupting gamma ray bursts or targets of opportunity. Multiple epochs were obtained to both improve photometric precision and allow a check on the variability of our standard stars.

Photometry was generated and calibrated through the standard pipeline described in P08 and Marshall et al. (in preparation). The P08 photometric system has been shown to be consistent at the 1-3% level, a performance we check in §2.3. The latest pipeline also accounts for the 1% per year decline in UVOT's sensitivity (Breeveld et al. 2010a).

In addition to the standard photometric transformation, we performed additional corrections which will soon be incorporated in the UVOT calibration. The first was a slight correction to the zero points of P08 and revision of the $uvw1$ response curve based on observations of numerous reference stars. This reflects a new UVOT calibration that supersedes

Table 1. Swift/GALEX/SDSS UV Standard Stars

Target	RA	DEC	E (B-V) _{SFD}	<i>u</i>	<i>N</i> ^a _{obs,Swift}	Exp Time (ks)
SDSS J002806.49+010112.2	7.0271	1.0200	0.021	17.5	3 (70)	12.7
SDSS J083421.23+533615.6	128.5883	53.6042	0.039	16.5	3 (120)	19.8
SDSS J092404.84+593128.8	141.0200	59.5247	0.025	17.5	3 (80)	18.5
SDSS J103906.00+654555.5	159.7750	65.7653	0.018	17.7	2 (71)	13.5
SDSS J134430.11+032423.2	206.1254	3.4064	0.026	16.5	1 (36)	4.5
SDSS J140641.95+031940.5	211.6750	3.3278	0.035	17.9	2 (64)	11.2
SDSS J144108.43+011020.0	220.2850	1.1722	0.040	16.7	2 (48)	4.4
SDSS J150050.71+040430.0	225.2113	4.0750	0.044	17.7	2 (45)	8.9
SDSS J173020.12+613937.5	262.5838	61.6603	0.040	17.8	4 (134)	17.3
SDSS J231731.36-001604.9	349.3808	-0.2681	0.040	16.4	3 (104)	15.3
SDSS J235825.80-103413.4	359.6075	-10.5703	0.032	17.3	3 (56)	11.1

^aNumber of Swift epochs (Total Number of UVOT images)

Table 2. SDSS Photometry of Faint UV Standards

Name	<i>u</i>	<i>g</i>	<i>r</i>	<i>i</i>	<i>z</i>
Systematic Uncertainty	±.03	±.01	±.01	±.01	±.02
SDSS J002806.49+010112.2	17.457 ± 0.021	17.559 ± 0.019	17.938 ± 0.017	18.227 ± 0.020	18.528 ± 0.041
SDSS J083421.23+533615.6	16.496 ± 0.029	16.685 ± 0.015	17.088 ± 0.020	17.422 ± 0.022	17.789 ± 0.031
SDSS J092404.84+593128.8	17.524 ± 0.015	17.542 ± 0.032	17.942 ± 0.014	18.276 ± 0.023	18.578 ± 0.033
SDSS J103906.00+654555.5	17.729 ± 0.015	17.883 ± 0.021	18.281 ± 0.018	18.588 ± 0.018	18.870 ± 0.055
SDSS J134430.11+032423.2	16.482 ± 0.015	16.603 ± 0.018	17.005 ± 0.016	17.323 ± 0.016	17.613 ± 0.025
SDSS J140641.95+031940.5	17.896 ± 0.024	17.900 ± 0.014	18.300 ± 0.019	18.576 ± 0.020	18.916 ± 0.051
SDSS J144108.43+011020.0	16.669 ± 0.015	16.870 ± 0.020	17.299 ± 0.016	17.604 ± 0.023	17.879 ± 0.026
SDSS J150050.71+040430.0	17.744 ± 0.015	17.880 ± 0.018	18.259 ± 0.014	18.561 ± 0.014	18.793 ± 0.044
SDSS J173020.12+613937.5	17.830 ± 0.021	17.837 ± 0.017	18.147 ± 0.018	18.451 ± 0.019	18.756 ± 0.043
SDSS J231731.36-001604.9	16.401 ± 0.020	16.485 ± 0.025	16.834 ± 0.021	17.142 ± 0.017	17.441 ± 0.023
SDSS J235825.80-103413.4	17.247 ± 0.029	17.220 ± 0.029	17.640 ± 0.020	17.880 ± 0.015	18.263 ± 0.034

Table 3. *Swift* UVOT and GALEX Photometry of Faint UV Standards (AB mags)

Name	FUV	NUV	<i>uvw2</i>	<i>uvm2</i>	<i>uvw1</i>	<i>u</i>	Var
Systematic Uncertainty	±.05	±.03	±.03	±.03	±.03	±.02	
SDSS J002806.49+010112.2	16.446 ± 0.004	16.801 ± 0.004	16.694 ± 0.007	16.834 ± 0.010	16.977 ± 0.010	17.290 ± 0.009	0.55
SDSS J083421.23+533615.6	15.429 ± 0.006	15.893 ± 0.004	15.761 ± 0.004	15.908 ± 0.005	16.070 ± 0.005	16.431 ± 0.005	1.57
SDSS J092404.84+593128.8	16.716 ± 0.007	17.041 ± 0.006	16.979 ± 0.007	17.099 ± 0.010	17.216 ± 0.009	17.455 ± 0.008	2.45
SDSS J103906.00+654555.5	16.859 ± 0.012	17.206 ± 0.008	17.072 ± 0.007	17.197 ± 0.010	17.363 ± 0.010	17.672 ± 0.010	0.55
SDSS J134430.11+032423.2	15.434 ± 0.007	15.880 ± 0.003	15.784 ± 0.007	15.948 ± 0.010	16.118 ± 0.010	16.390 ± 0.009	0.38
SDSS J140641.95+031940.5	16.994 ± 0.012	17.433 ± 0.009	17.356 ± 0.009	17.474 ± 0.013	17.602 ± 0.012	17.819 ± 0.013	2.87
SDSS J144108.43+011020.0	15.487 ± 0.007	16.015 ± 0.005	15.882 ± 0.008	16.023 ± 0.010	16.221 ± 0.012	16.562 ± 0.010	2.02
SDSS J150050.71+040430.0	16.779 ± 0.011	17.162 ± 0.007	17.056 ± 0.008	17.223 ± 0.015	17.331 ± 0.016	17.629 ± 0.011	1.90
SDSS J173020.12+613937.5	17.069 ± 0.010	17.408 ± 0.005	17.312 ± 0.007	17.381 ± 0.010	17.486 ± 0.010	17.724 ± 0.010	1.60
SDSS J231731.36-001604.9	15.499 ± 0.003	15.893 ± 0.002	15.796 ± 0.005	15.930 ± 0.006	16.065 ± 0.006	16.314 ± 0.005	2.35
SDSS J235825.80-103413.4	16.416 ± 0.005	16.722 ± 0.004	16.662 ± 0.008	16.752 ± 0.011	16.885 ± 0.010	17.101 ± 0.009	0.79

P08 and will soon be described in Breeveld et al. (2010b, in prep). The second was a transformation to the ABmag system. For the P08 calibration, we transformed the Vega magnitudes to the AB system by using the Vega spectrum of Bohlin & Gilliland (2004) to calculate the magnitude of Vega in the Swift filters, essentially reversing the Vegamag transformation of P08.² For the revised calibration, we used the February 2010 CALSPEC spectrum³. The AB magnitude corrections, for both the P08 and revised calibrations, are given in Table 4.

2.3. Photometric Stability

The photometric uncertainty of any particular standard star’s photometric measures is the combination of the Poisson noise of the observation⁴, the uncertainty in the photometric zero points and, in the case of aperture photometry, any variation in the PSF. As a photon-counting instrument, UVOT’s read noise is irrelevant to the error budget. In the case of UVOT, the first two sources of uncertainty are quantified by our photometry pipeline and P08, respectively, and included in Table 3. The third – variation of the PSF – has been quantified by B10, along with other small instrumental effects. However, it can be independently checked from our standard star data.

The observations of our standard stars consist of 1-3 epochs of UVOT data. Each of these epochs is, in turn, comprised of many (mean of 30) independent UVOT exposures

²The P08 zero point uncertainties quoted in Table 3 include a $\sim 1\%$ uncertainty arising from the ABmag to Vegamag conversion. By effectively removing this conversion, our actual zero point uncertainties are marginally but not significantly smaller than those given P08.

³Available at <http://www.stsci.edu/hst/observatory/cdbs/calspec.html>

⁴With a small correction in the UVOT arising from the finite number of CCD frames in an observation (Kuin & Rosen 2008), which can be neglected for our sources.

Table 4. Correction from Swift Vegamag to ABmag System

Filter	P08 Calibration	New Calibration
<i>u</i>	1.02	1.02
<i>uvw1</i>	1.48	1.51
<i>wm2</i>	1.71	1.69
<i>uvw2</i>	1.72	1.73

taken over multiple orbits of the *Swift* satellite. The photometric measures in Table 3 are taken from deep images produced by combining all the extant data. However, the 10-45 independent UVOT exposures that comprise each stacked image allow us to check for any photometric zero point residuals in the data. More importantly, the independent images allow a check on the photometric stability of the standard stars themselves.

We photometered the individual UVOT exposures using the APPHOT package in IRAF, with apertures set to the $5''.0$ optimal apertures specified in P08. The raw photometry was corrected for coincidence loss using the formulation of P08 and calibrated using the transformations of P08 and iterative matrix inversion techniques described in Siegel et al. (2002). The iteration process derives and corrects for exposure-to-exposure zero point residuals within each photometric passband, with residuals measured from the mean zero point.

Figure 2 shows a typical result of our investigation – the distribution of exposure-to-exposure photometric zero point residuals for SDSS J002806.49+010112.2. The distribution is roughly Gaussian with a typical zero point dispersion of 0.02-0.04 magnitudes. This dispersion is comparable to the scale of the instrumental effects quantified in B10.

The individual UVOT exposures, however, are shallow and have few stars with which to make comparisons (2-60, with a median of 7). With such small numbers of comparison stars, a single bad measure could dramatically alter the measured residuals. To improve the statistics, we combined the UVOT images from each epoch separately and photometered them using the techniques described above. In this case, exposure time was no longer constant across the stacked image owing to the roll and pointing uncertainty of the spacecraft, but was easily corrected from the exposure maps produced by the UVOT reduction pipeline. The dispersion of these epoch-to-epoch photometric residuals was calculated from a much deeper sample of 10-163 (median 30) common stars and shows a much clearer Gaussian pattern with a dispersion of .01-.02 magnitudes (Figure 3). The reduction in the residual dispersion is consistent with having averaged out by subsampling some of the PSF variability in the combination. We expect that further improvement of the UVOT pipeline or attention to the systematics quantified by B10 will further reduce or eliminate these residual effects.

Removing these small zero point residuals using the aforementioned iterative calibration allows a more precise check on the variability of our new UV standards. Figure 4 shows

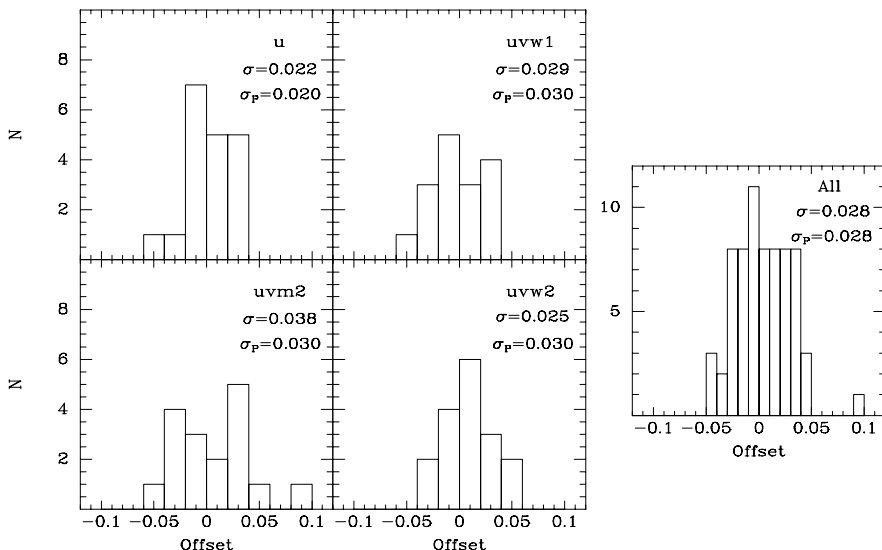


Fig. 2.— The distribution of zero point offsets from the mean frame for each individual UVOT image of SDSS J002806.49+010112.2. The data are broken down by filter and then combined in the right-hand panel. The distribution of the offsets is roughly Gaussian with typical σ measures of 0.02-0.04 magnitudes, similar in scale to the calibration uncertainty given in P08 (listed as σ_P).

the ratio of measured photometric scatter to measurement uncertainty as a function of magnitude, after the correction for the zero point residuals. This measure is, essentially, the χ^2 of a constant magnitude fit to the data. While a few stars have high variability measures, the majority are clumped at low values, with a mean variability index of 1.41 and a 90% interval between 0.4 and 3.1. This would be consistent with some residual zero point systematic error in the photometric measures inflating the ratio over its expected value of 1.0. The white dwarf stars have a mean variability index of 1.55 with a maximum of 2.87, well within the bulk of field star distribution. The variability indices are listed in the final column of Table 3.

Within the limits measured by our UVOT program, our standard stars appear to be photometrically stable. Further monitoring, to measure any potential variation over year-long timescales, is recommended.

As a further check on the photometric stability of the stars, we have examined the

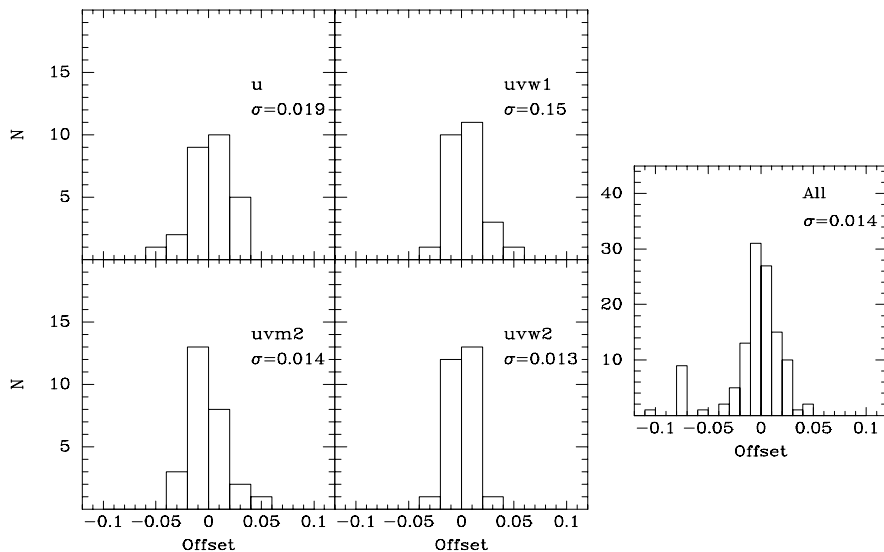


Fig. 3.— The distribution of zero point offsets of the combined UVOT epochs from the mean for all eleven of our new standards. The data are broken down by filter and then combined in the right-hand panel. The distribution of the offsets is roughly Gaussian with typical σ measures of 0.01-0.02 magnitudes

SDSS photometry of two stars which fall within the SDSS Southern Stripe (Stripe 82), a section of the DR4 which has been repeatedly observed, yielding data of 1% precision, half the more typical 2% precision of SDSS data (Ivezić et al. 2007). We confined our analysis to data taken before MJD 53400 (12:00 pm January 29, 2005 UT). Beyond that date, the photometric measures are more dense but include many data taken under non-photometric conditions.

Figure 5 shows the measured photometry and no variability is seen. The variability indices are all significantly less than 1.0, indicating excellent photometric stability over the 5-6 year time scale of the observational set. We note that SDSS J231731.36-001604.9, which has a variability index in the Swift data of 2.35, shows miniscule variability in the more extensive Sloan data.

As a final check, we took advantage of the simultaneous X-ray observations of our targets produced by the XRT. While our white dwarf stars are too faint and cold to produce noticeable X-ray flux, an X-ray signal could be produced in the (unlikely) event that one

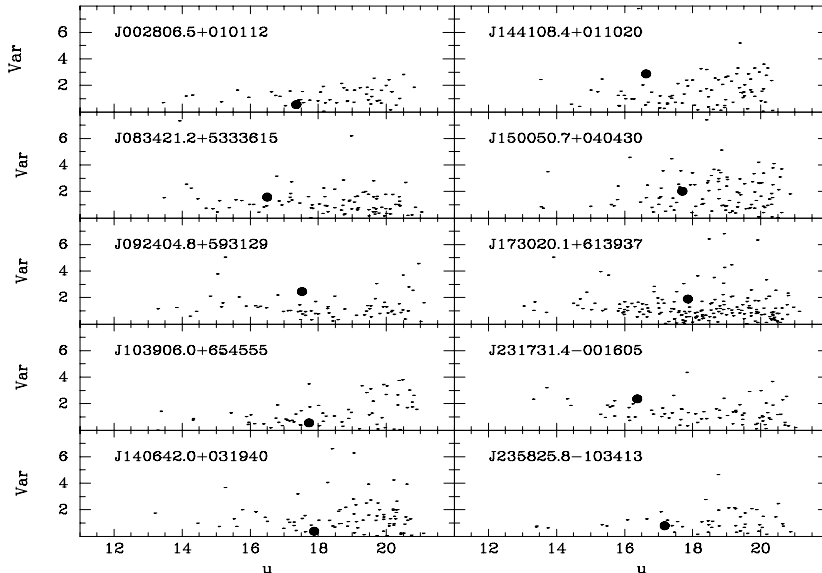


Fig. 4.— The ratio of observed scatter to measurement uncertainty of stars in the UV standard fields. Large points are our new UV standards. The measures clump close to 1.0 with some notable variable stars at high ratios. None of our white dwarfs show significant long-term variability over the months-long timescale of the UVOT observations. SDSS J134430.11+032423.2 is not plotted since it had a single epoch of observation.

were an accreting X-ray binary. After running the automated analysis of Evans et al. (2009), however, we find no X-ray source at the position of any of our standard stars.

3. Comparison to Spectral Models

With the suitability and photometric stability of our standards assured, we can now constrain the underlying white dwarf spectral model and test the ability of the models to reproduce the observed photometry. A reliable model spectrum could be used for calibrating other UV telescopes regardless of whether their filter response curves resemble those of UVOT or GALEX. While Eisenstein et al. and AP09 have fit SDSS white dwarf parameters from optical and near-infrared spectra, our UV photometry provides additional leverage on the effective temperatures of the white dwarfs because the UV samples a much more sensitive portion of the white dwarf spectrum.

The complexity of modeling the photometry is greatly reduced by our limiting of the candidate list to DA stars without evidence of magnetic fields, metal lines or companions.

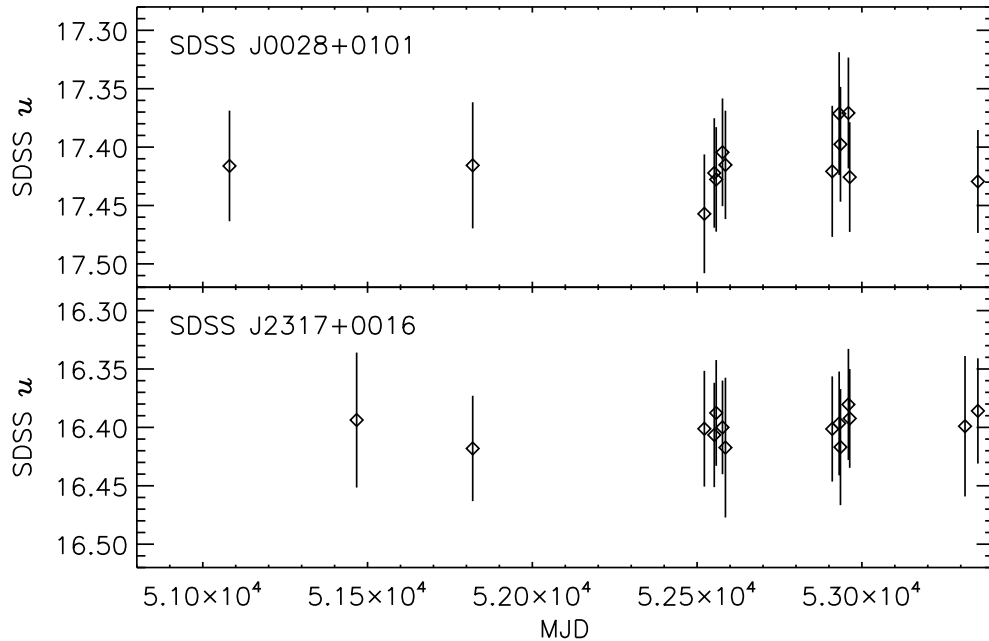


Fig. 5.— Photometric measures of two standard stars in the SDSS Southern Stripe over 5-6 years.

The key parameters of the models are T_{eff} , $\log g$ and A_V , the V -band foreground extinction.

As a preliminary step, we refit the continuum-corrected SDSS spectra using the methods outlined in AP09. This was done primarily to better constrain $\log g$, which our photometry proved to be relatively insensitive to. The parameters of the purely spectral fits are given in Table 5 and the continuum-corrected fits are shown in Figure 6. They are similar to those of Eisenstein et al. with the notable exception of SDSS J092404.84+593128.8, for which we find a lower gravity. In all cases, the χ^2 of the fit is less than 1.0.

Before fitting the photometry, we corrected the models for extinction by simply taking the V -band extinction values (A_V) from the reddening maps of Schlegel, Finkbeiner, & Davis (1998) listed in Table 1 and applying the extinction curve give in Pei (1992) to the model spectra. This technique is essentially an inversion of the "extinction without standards" method outlined in Fitzpatrick & Massa (2005), which combines photometry with spectral models to derive a UV extinction curve. In this case, we used photometry and an assumed extinction curve to constrain the spectral models.

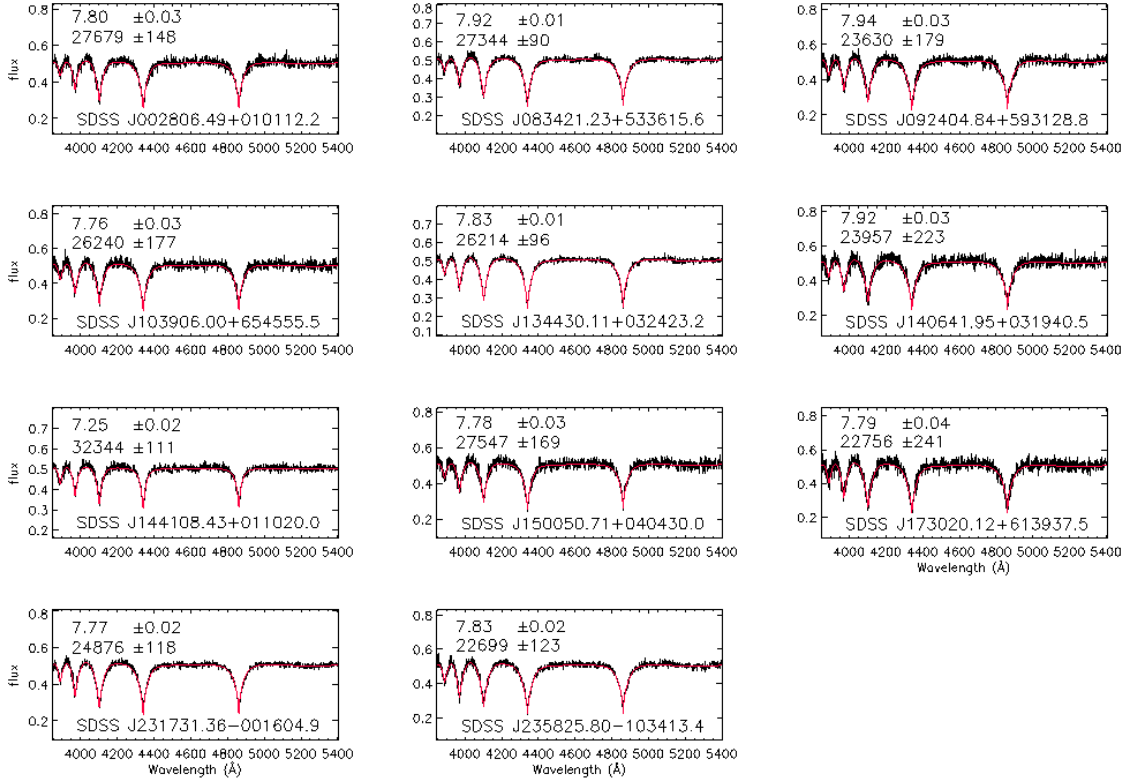


Fig. 6.— Model fits to the continuums-subtracted SDSS spectra, following the prescription of AP09. As in AP09, the parameters of the fits given in Table 5 differ slightly from those shown in the figure.

Attempts were made to fit A_V directly from the photometric measures by producing multiple families of models with different foreground extinction values and UV extinction laws. However, we found the fitted A_V values to be both imprecise (typical fitting uncertainty was 0.1 magnitudes – an uncertainty larger than the total Schlegel, Finkbeiner, & Davis (1998) measures) and co-variant with the fitted T_{eff} .

It is possible that using the full Schlegel, Finkbeiner, & Davis (1998) values over-corrects the models for extinction. The Schlegel, Finkbeiner, & Davis (1998) values are for the full dust column and have been shown to be possibly over-estimated (see, e.g., Cambresy et al. 2005). However, our white dwarfs are typically at distances of 150-250 pc. Given an exponential dust scale height of 134 pc (Marshall et al. 2006), it is likely that we are viewing the white dwarfs through 70-85% of the total dust along the line of sight. The difference between this and the full Schlegel, Finkbeiner, & Davis (1998) values is less than 0.01 magnitudes.

The significance of a 0.01 magnitude uncertainty in the foreground extinction is small. Analysis of our models indicates that changing the assumed reddening by 0.02 magnitude would alter the derived temperatures by, on average, 100 degrees, with over-estimates of reddening producing over-estimates of temperature and under-estimates being similarly covariant. Thus, the effect of reddening uncertainty on our model fitting is expected to be less than that of the photometric uncertainties.

With revised $\log g$ values and A_V values, we turned to constraining the white dwarf temperatures based purely on the photometry. We calculated a grid of pure hydrogen non-LTE models using Version 204 of TLUSTY (Lanz & Hubeny, 1995), including the quasi-molecular satellites of Lyman α and Lyman β . These models do not include the new Stark broadening calculations of Tremblay & Bergeron (2009), which could shift the derived T_{eff} by as much as +1500 K.

A grid of model spectra was calculated for $T_{eff} = 20000, 22500, 25000, 27500, 30000$ K and $\log g = 7.0, 7.5, 8.0, 8.5$ and 9.0 . We linearly interpolated these spectra to a resolution of 100 K and 0.05 in $\log g$. We then reddened the models based on the foreground reddening and Pei dust curve. At each temperature and gravity combination, synthetic magnitudes were then calculated by convolving the synthetic spectrum with the most recent filter response curves for UVOT, GALEX and SDSS using the formulation:

$$m = -2.5 \log \left(\frac{\int d(\log \lambda) \lambda^2 f_\lambda S_\lambda}{\int d(\log \lambda) S_\lambda} \right) + C \quad (1)$$

where f_λ is the model spectrum flux and S_λ is the system throughput per unit wavelength. C is the zero point magnitude.

Observed magnitudes were compared to model magnitudes using

$$\chi^2 = \sum_i \frac{(m_i - m_{model,i} + c)^2}{\sigma_i^2} \quad (2)$$

where m_i is the observed magnitude, $m_{model,i}$ is the model magnitude, and σ_i is the photometric error for in the i th filter. The summation is over all 11 filters shown in Tables 2 and 3 and described in §2.2.

The value c is a normalization constant which matches the observed and model spectra to the same level. The optimal value of c can be analytically determined by setting $\partial \chi^2 / \partial c = 0$.

Solving for c yields

$$c = \frac{\left(\sum_i \frac{m_{model,i}}{\sigma_i^2} - \sum_i \frac{m_i}{\sigma_i^2} \right)}{\sum_i 1/\sigma_i^2} \quad (3)$$

The value of c was calculated independently for each combination of observed and model magnitudes and use to calculate and minimize χ^2 .

To quantify the non-linear effect of photometric uncertainty upon our model fits, we performed a Monte Carlo simulation on the data. The photometric measures were perturbed by the photometric errors and T_{eff} was refit using Equation 2. A general description of the Monte Carlo technique can be found in Press et al. (1992). Given the relative brightness of our candidate stars, the photometric errors were dominated by systematic zero point errors and not the random Poisson errors for all stars in all bands. Zero point errors were modeled as uniformly distributed with end points set the photometric uncertainties. For each star, this process was repeated for 10000 Monte Carlo realizations. The resulting distributions of T_{eff} was used to determine the best values from the median and 90% error bars.

The best-fit model parameters are given in Table 6. The model fits and Monte Carlo error simulations are shown in figures 7-10. For all of our dwarf stars, we find a favored T_{eff} that accurately reproduces the observed photometric measures across all eleven passbands. No stars has a reduced χ^2 greater than 1.51 and the mean χ^2 is 0.92, indicating that the residuals are within the photometric uncertainties.

Figures 11 and 12 show the photometric residuals ($\Delta_m = m_{model} - m_{data}$) for all of our stars in each filter while Table 7 list the mean, median and dispersion of the residuals in comparison to the systematic uncertainties in the photometric zero points (σ_{sys}) for each filter. In almost all cases, the mean and median Δ_m are within one or two σ_{sys} of zero, indicating that our models agree with the measured photometry within the zero point uncertainties compiled in Tables 2 and 3. The mean $\frac{|\langle \Delta_m \rangle|}{\sigma_{sys}}$ is 0.99, indicating excellent agreement between the models and data. This confirms that the spectra can be used by future investigations to extrapolate predicted magnitudes in other passbands. It also confirms the quality and consistency of the most recent UVOT calibration.

Figure 13 compares the Eisenstein et al. (2006) effective temperatures against those derived in our model fitting. While the values roughly track each other, we find our temperatures average slightly lower than those given in Eisenstein et al. A similar result was found in AP09, who found the Eisenstein et al. temperatures to be a few percent lower than theirs up to 30,000 degrees and slightly warmer at higher temperatures.

The fitted spectral models are included in the electronic version of the *Astrophysical Journal* (Table 8). These can be compared to measured spectra or convolved with filter functions using the procedure outlined above to predict standard stellar magnitudes in non-UVOT passbands. However, given uncertainties in any model fitting and the likelihood of future updates to the TLUSTY code, it may be advisable for future calibrations to use our published photometry and fit parameters as a starting point for a refined exploration of these new standard stars.

4. Conclusions

We have created a catalog of 11 faint DA white dwarf ultraviolet standards for use with space-based UV detectors. Our stars have been carefully chosen for simple modeling, low extinction, a lack of nearby stellar companions, even distribution across the sky and faintness that will avert problems of saturation or coincidence loss. In combination with SDSS and GALEX, we provide precise photometry for these stars from the NIR to the FUV. Checks from both UVOT and SDSS data show that our white dwarf stars are photometrically stable. When combined with recent sample of spectrophotometric standards recommended by AP09, up to 20 new UV standard stars are now potentially available to the community, all of which

Table 5. Spectral Fits to Continuum-Corrected SDSS Spectra

Name	T_{eff}	$\log g$	χ^2
SDSS J002806.49+010112.2	27679 (148)	7.804 (0.025)	0.63
SDSS J083421.23+533615.6	27344 (90)	7.916 (0.015)	0.73
SDSS J092404.84+593128.8	23630 (179)	7.943 (0.025)	0.62
SDSS J103906.00+654555.5	26240 (177)	7.762 (0.026)	0.68
SDSS J134430.11+032423.2	26214 (96)	7.828 (0.014)	0.51
SDSS J140641.95+031940.5	23957 (223)	7.924 (0.030)	0.72
SDSS J144108.43+011020.0	32344 (111)	7.254 (0.024)	0.56
SDSS J150050.71+040430.0	27547 (169)	7.777 (0.028)	0.65
SDSS J173020.12+613937.5	22756 (241)	7.791 (0.035)	0.68
SDSS J231731.36-001604.9	24876 (118)	7.768 (0.016)	0.58
SDSS J235825.80-103413.4	22699 (123)	7.833 (0.018)	0.67

Table 6. Best Fit Effective Temperatures of UV Standards

Name	T_{eff} 90% Lower Bound	T_{eff} Best Fit	T_{eff} 90% Upper Bound	χ^2_{red}
SDSS J002806.49+010112.2	25200	26100	26400	1.51
SDSS J083421.23+533615.6	28000	28500	29500	0.45
SDSS J092404.84+593128.8	22500	22500	22900	0.72
SDSS J103906.00+654555.5	24800	24800	25200	0.78
SDSS J134430.11+032423.2	25600	25600	26100	0.97
SDSS J140641.95+031940.5	22700	22700	23100	0.58
SDSS J144108.43+011020.0	30800	30800	31800	1.01
SDSS J150050.71+040430.0	23300	23300	24100	1.28
SDSS J173020.12+613937.5	22300	22300	22700	0.68
SDSS J231731.36-001604.9	24300	24300	24900	0.71
SDSS J235825.80-103413.4	23000	23000	23200	1.44

Table 7. Residuals of Fits to Photometry

Filter	$\langle \Delta_m \rangle$	median (Δ_m)	σ_{Δ_m}	σ_{sys}
FUV	-0.054	-0.055	0.047	0.05
NUV	0.044	0.047	0.013	0.03
<i>uvw2</i>	-0.014	-0.011	0.011	0.03
<i>uvm2</i>	0.010	0.014	0.026	0.03
<i>uvw1</i>	-0.038	-0.034	0.022	0.03
<i>u</i> (UVOT)	0.029	0.031	0.019	0.02
<i>u</i> (SDSS)	-0.032	-0.026	0.029	0.03
<i>g</i>	-0.008	-0.016	0.025	0.01
<i>r</i>	-0.013	-0.015	0.015	0.01
<i>i</i>	0.002	-0.001	0.014	0.01
<i>z</i>	0.029	0.023	0.047	0.02

Table 8. Model Flux^a for WD Standards

Wavelength (Å)	J002806.49+010112.2	J083421.23+533615.6	J092404.84+593128.8	J103906.00+654555.5	J134430.11+032423.2	J140641.95+0319
1300.0	2.0081E-13	4.7217E-13	1.4265E-13	1.3793E-13	4.6467E-13	1.0135E-13
1300.5	2.0057E-13	4.7166E-13	1.4253E-13	1.3776E-13	4.6414E-13	1.0126E-13
1301.0	2.0037E-13	4.7121E-13	1.4243E-13	1.3763E-13	4.6369E-13	1.0119E-13
1301.5	2.0017E-13	4.7067E-13	1.4233E-13	1.3750E-13	4.6323E-13	1.0112E-13
1302.0	1.9997E-13	4.7021E-13	1.4223E-13	1.3737E-13	4.6278E-13	1.0105E-13
1302.5	1.9980E-13	4.6976E-13	1.4213E-13	1.3727E-13	4.6239E-13	1.0098E-13
1303.0	1.9968E-13	4.6939E-13	1.4214E-13	1.3717E-13	4.6211E-13	1.0097E-13
1303.5	1.9948E-13	4.6894E-13	1.4204E-13	1.3704E-13	4.6166E-13	1.0090E-13
1304.0	1.9933E-13	4.6848E-13	1.4204E-13	1.3695E-13	4.6134E-13	1.0090E-13
1304.5	1.9913E-13	4.6803E-13	1.4194E-13	1.3681E-13	4.6089E-13	1.0083E-13

^aFlux in $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$

have published SDSS photometry and eleven of which now have published NUV and FUV photometry.

We have fit both the SDSS spectra and measured photometry of our standard stars with relatively simple white dwarf stellar atmospheric models. We find that these models provide strong and consistent constraints on the properties of the white dwarf stars, reproducing the photometric measures to within the 1-5% uncertainty of their photometric zero points. This indicates outstanding suitability of our standard stars for calibration of future missions that may not share the filter set of UVOT and GALEX through the use of simple white dwarf atmospheric models.

Of our eleven stars, we do not find any that are of poor or limited quality. The mean reduced χ^2 of the model fits to spectra and photometry are 0.64 and 0.92, respectively, indicating excellent agreement between models and data. Measurement of stellar variability shows some stars to have moderately elevated photometric scatter. However, this scatter is within the distribution of stable field stars and does not appear in the more extensive SDSS Stripe 82 data. We do, however, recommend further monitoring to ensure that the stars are photometrically stable.

The two most significant uncertainties in our standard stars are (1) the systematic uncertainty in the photometric zero points of GALEX and UVOT, which limit the models to reproducing the photometry within the 1-5% uncertainty of the zero points; (2) the previously known uncertainty in the UV extinction law. These systematic uncertainties dominate over our random errors. We are engaged in effort to better understand the UV extinction curve in Galactic dust. We also recommend further investigation to improve the calibration of both GALEX and UVOT. In combination, these two endeavors – dust properties and calibration – would enhance the precision of our faint UV standard to better than 1%, which would both improve the capabilities of UVOT and help other missions to explore the ultraviolet range of the spectrum.

The good agreement between model, spectra and photometry is indicative of the outstanding suitability of DA White Dwarfs as UV standard stars. As the models and especially our understanding of the UV properties of the dust improve, our ability to characterize the white dwarf properties will also improve. This will allow further investigation into more distant and/or more reddened white dwarfs to improve our understanding of these stellar relics.

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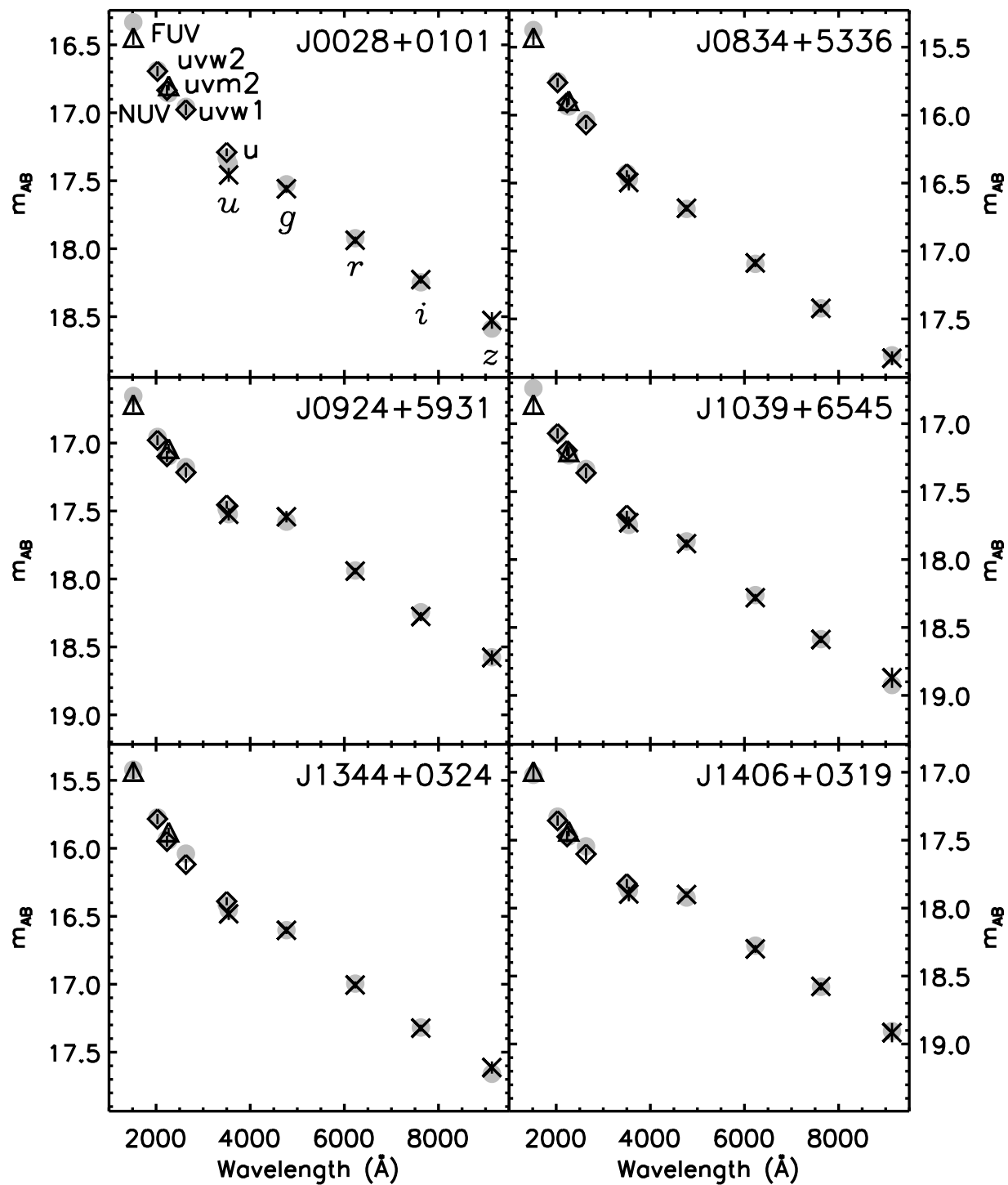


Fig. 7.— Comparison of the white dwarf photometry to the predicted magnitudes of the model atmospheres. The grey dots represent the model; X's, diamonds and triangles represent SDSS, UVOT and GALEX photometry, respectively. Individual filters are labeled in the first panel.

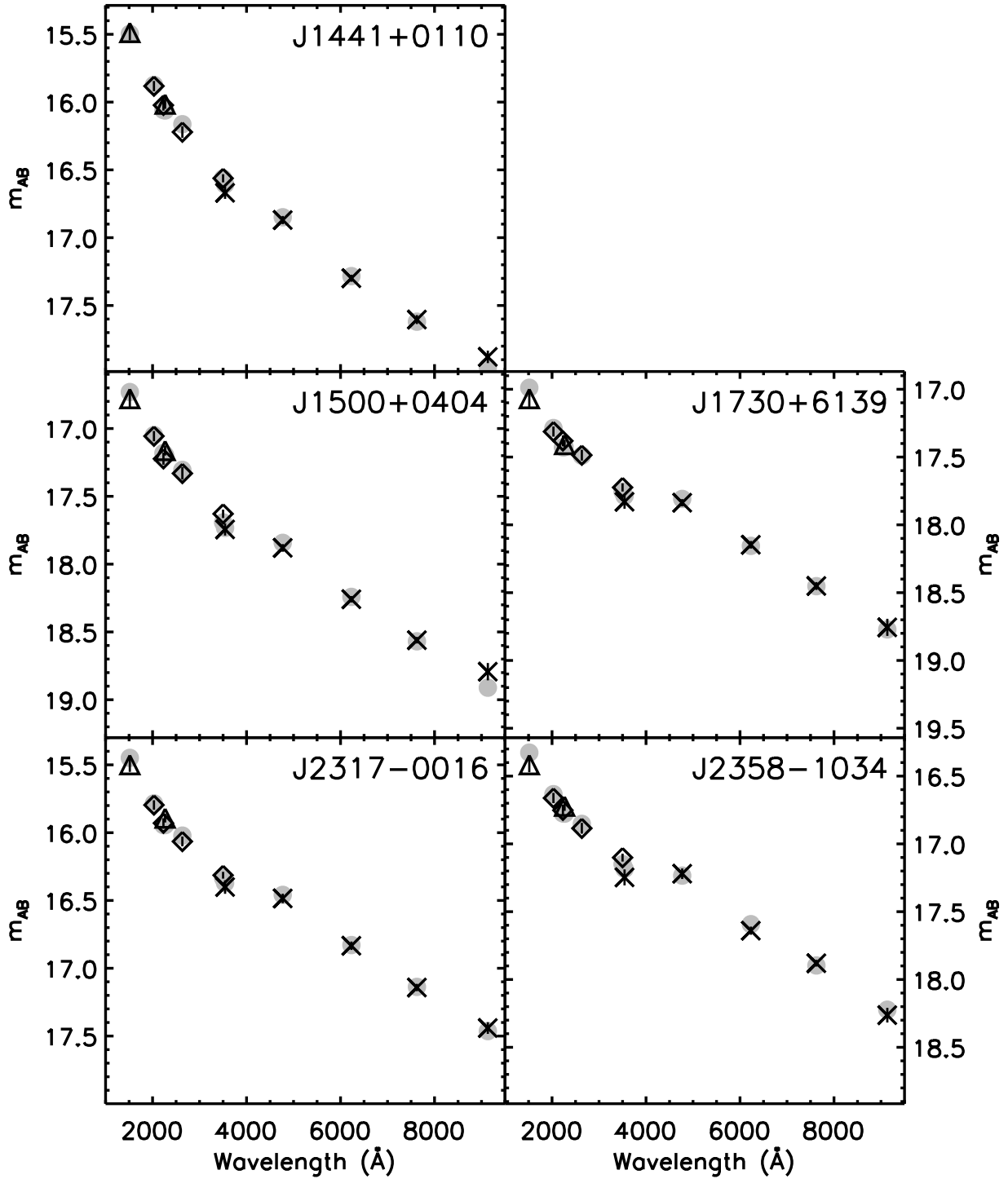


Fig. 8.— Comparison of the white dwarf photometry to the predicted magnitudes of the model atmospheres. The grey dots represent the model; X's, diamonds and triangles represent SDSS, UVOT and GALEX photometry, respectively.

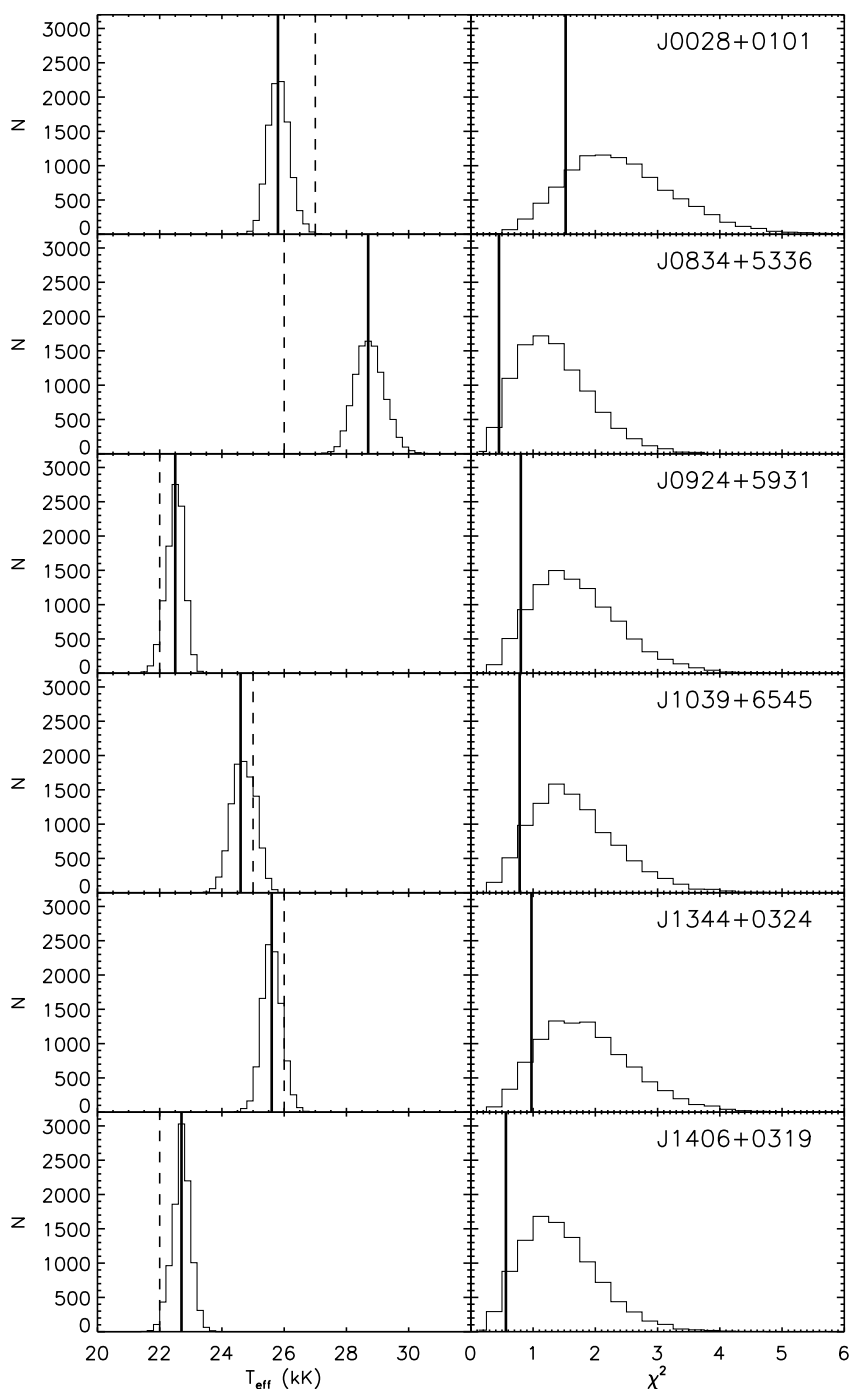


Fig. 9.— Monte Carlo simulation of white dwarf parameters for our UV standards. The histogram indicates the distribution of model fits after perturbing the photometry with zero point offsets drawn from a uniform distribution set to the stated random and systematic uncertainties in the photometric measures. The dashed line represents the T_{eff} reported in Eisenstein et al.; the solid lines represent our best fit from the photometry.

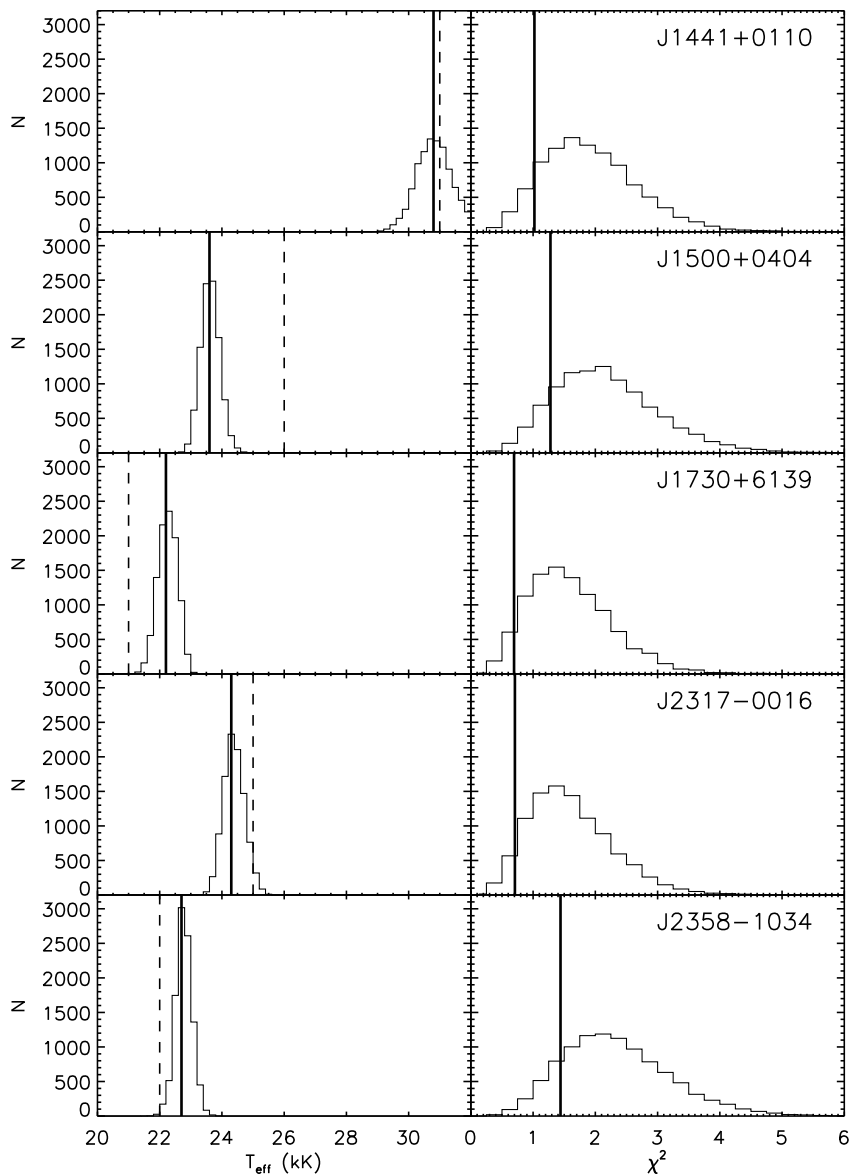


Fig. 10.— Monte Carlo simulation of white dwarf parameters for our UV standards. The histogram indicates the distribution of model fits after perturbing the photometry with zero point offsets drawn from a uniform distribution set to the stated random and systematic uncertainties in the photometric measures. The dashed line represents the T_{eff} reported in Eisenstein et al.; the solid lines represent our best fit from the photometry.

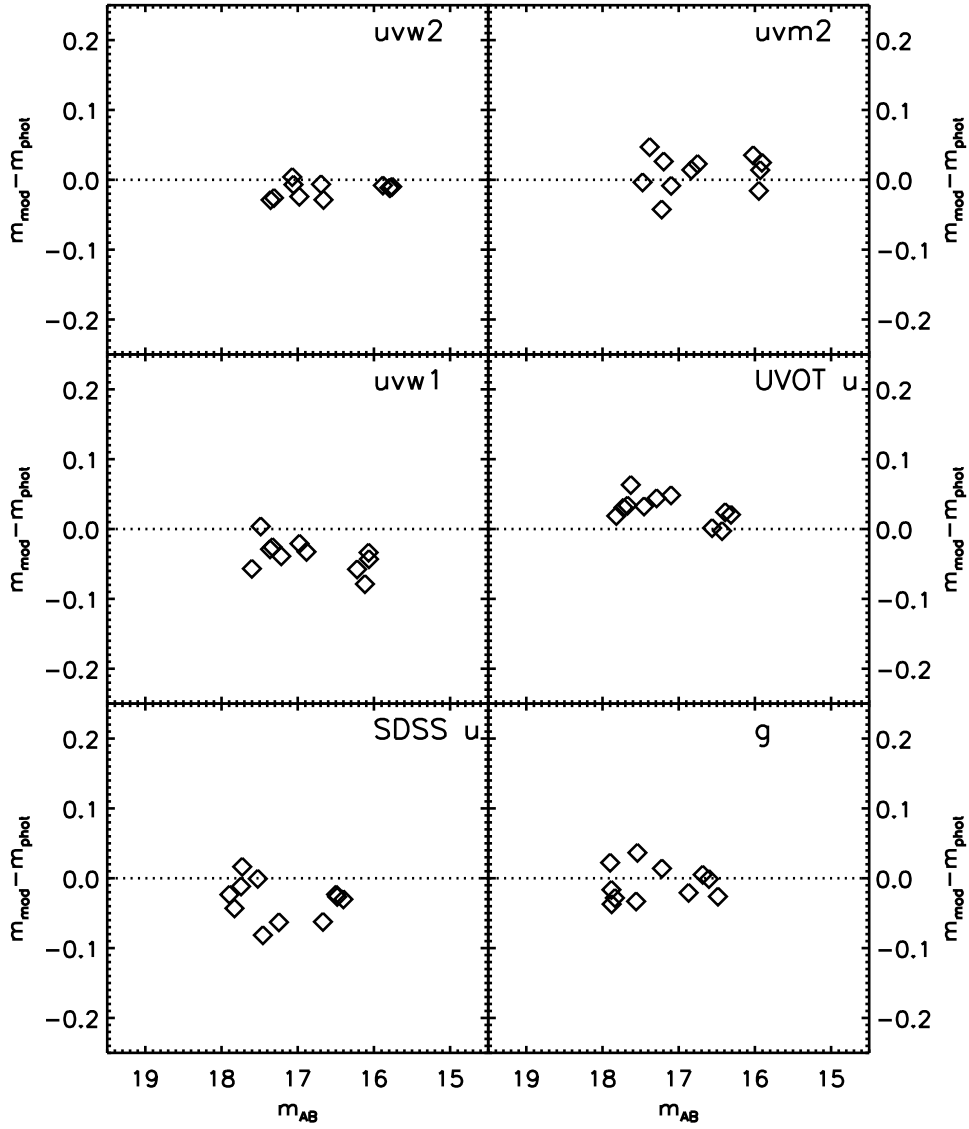


Fig. 11.— The photometric residuals of fitted white dwarf models to measured photometry broken down by filter.

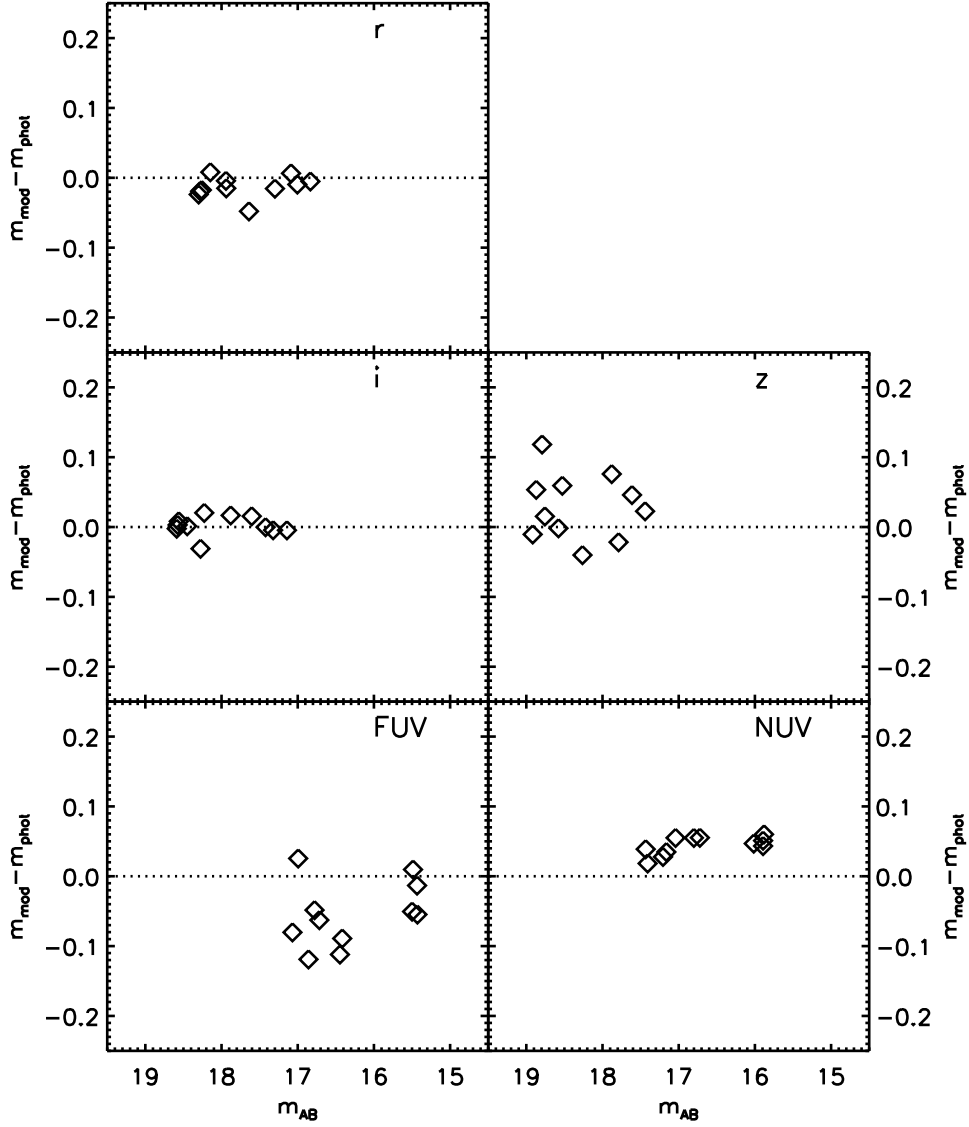


Fig. 12.— The photometric residuals of fitted white dwarf models to measured photometry broken down by filter.

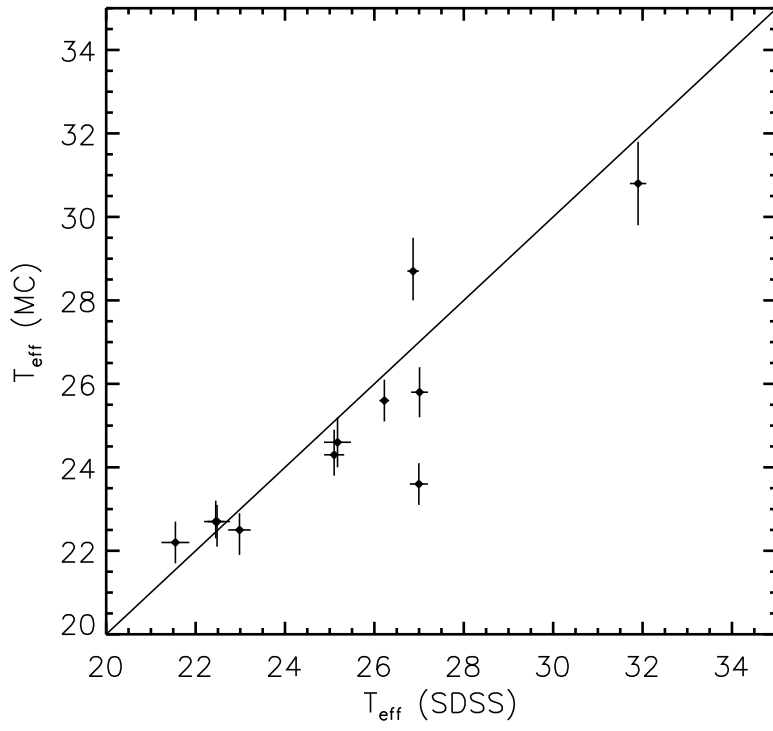


Fig. 13.— A comparison of the SDSS effective temperatures from Eisenstein et al. against those derived from our spectral fitting. The solid line indicates unity.