FAINT NEAR-ULTRAVIOLET/FAR-ULTRAVIOLET STANDARDS FROM SWIFT/UVOT, GALEX, AND SDSS PHOTOMETRY

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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 11 new faint (μ ~ 17) ultraviolet standard stars. High-precision photometry of these stars has been taken from the Sloan Digital Sky Survey and Galaxy Evolution Explorer archives 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 < 50,000 K) 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 constraints on white dwarf temperatures, which demonstrates the ability of Swift/UVOT to investigate the properties of hot luminous stars. We further find that the models reproduce the photometric measures in all 11 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.

Key words: techniques: photometric – ultraviolet: general – ultraviolet: stars – white dwarfs

Online-only material: color figure, machine-readable table

1. INTRODUCTION

The last three decades have witnessed the advent of numerous space-based ultraviolet-sensitive instruments. Programs such as the Hubble Space Telescope (HST) Faint Object Spectrograph, Space Telescope Imaging Spectrograph (STIS), and Advanced Camera for Surveys, International Ultraviolet Explorer, Far-ultraviolet Spectroscopic Explorer, Galaxy Evolution Explorer (GALEX), and Hopkins Ultraviolet Telescope have created an infusion of scientific discovery, particularly in hot and 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 191-2B2, 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 μ_v = 13.4 (Holberg & 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 et al. 2000). The brighter the source, the greater the coincidence loss. Coincidence loss cannot be ameliorated by shorter exposure times. Beyond a certain range (with UVOT, about 100 photon s^{-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.

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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 dwarf DA white dwarfs as potential spectrophotometric standards. Hot DA white dwarfs are suitable as UV standard candles because of their high UV luminosities, 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 constraints on the properties of white dwarfs.

Our study complements the AP09 study by using Swift/UVOT to observe 11 faint hot DA white dwarfs selected not only from the SDSS but also from the GALEX catalog. We use the combined data, covering the spectral range from the near-IR (NIR) to the far-UV (FUV), to provide 1% 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 11 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 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 to be modelable 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 K and 0.3 dex, respectively) or where the dust maps of Schlegel et al. (1998) indicate a reddening of 

\[ A_V > 0.05 \]  

The latter cut is especially critical in the UV, 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 

\[ T_{\text{eff}} \]  

While GALEX’s All-Sky Imaging Survey covers most of the sky with an exposure time of at least 100 s, the Medium Imaging Survey (MIS) covers 1000 deg² with exposure times greater than 1500 s. 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 deg² footprint (Adelman-McCarthy et al. 2006).7

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 11 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 et al. (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.

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

### 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′ × 17′) FOV 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 a 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, $uvw1$, $uvw2$, and $uw2$ ultraviolet filters, a magnifier, two grisms, and a blocked

| Name   | FUV | NUV | $uvw2$ | $uvw2$ | $uvw1$ | $u$ | $Var$ |
|--------|-----|-----|--------|--------|--------|-----|-------|
| 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+01020.0 | 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 | 15.496 ± 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 |
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 12 target stars were observed as fill-in targets during the 2008–2009 Swift AO4 observing cycle. Data were taken in the $u$, $uvw1$, $uvw2$, and $uw2$ filters between 2008 June and 2009 February. A handful of stars were re-observed in 2009 June 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 F. E. Marshall et al. (2011, in preparation). The P08 photometric system has been shown to be consistent at the $1\%$–$3\%$ level, a performance we check in Section 2.3. The latest pipeline also accounts for the $1\%$ per year decline in UVOT’s sensitivity (Breeveld et al. 2010).

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 P08 and will soon be described in A. A. Breeveld et al. (2011, in preparation). 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. For the revised calibration, we used the 2010 February CALSPEC spectrum.

The AB magnitude corrections, for both the P08 and revised calibrations, are given in Table 4.

### Table 4

| Filter | P08 Calibration | New Calibration |
|--------|-----------------|-----------------|
| $u$    | 1.02            | 1.02            |
| $uvw1$ | 1.48            | 1.51            |
| $uvw2$ | 1.71            | 1.69            |
| $uw2$  | 1.72            | 1.73            |

2.3. Photometric Stability

The photometric uncertainty of any particular standard star’s photometric measures is the combination of the Poisson noise of the observation, 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 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 APHOT package in IRAF, with apertures set to the 5% 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 mag. 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 0.01–0.02 mag (Figure 3).

Figure 1. 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 J150507.1+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.
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 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 $\chi^2$ 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 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 53,400 (12:00 pm 2005 January 29 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 minuscule variability in the more extensive Sloan data.
Figure 4. 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 shows 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.

Figure 5. Photometric measures of two standard stars in the SDSS Southern Stripe over 5–6 years.

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

As a preliminary step, we re-fitted 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 \( \chi^2 \) 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 et al. (1998) listed in Table 1 and applying the extinction curve given 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.

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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 mag—an uncertainty larger than the total Schlegel et al. 1998 measures) and co-variant with the fitted $T_{\text{eff}}$.

It is possible that using the full Schlegel et al. (1998) values over-corrects the models for extinction. The Schlegel et al. 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 et al. values is less than 0.01 mag.

The significance of a 0.01 mag uncertainty in the foreground extinction is small. Analysis of our models indicates that changing the assumed reddening by 0.02 mag would alter the derived temperatures by, on average, 100°, with overestimates of reddening producing overestimates of temperature and underestimates 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 Ly$\alpha$ and Ly$\beta$. These models do not include the new Stark broadening calculations of Tremblay & Bergeron (2009), which could shift the derived $T_{\text{eff}}$ by as much as +1500 K.

A grid of model spectra was calculated for $T_{\text{eff}} = 20,000, 22,500, 25,000, 27,500, 30,000, 32,500$ and 35,000 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:

$$m = -2.5 \log \left( \frac{\int d(log \lambda) S_{\lambda}}{\int d(log \lambda) S_{\lambda}} \right) + C,$$

where $f_{\lambda}$ is the model spectrum flux and $S_{\lambda}$ is the system throughput per unit wavelength. $C$ is the zero-point magnitude.

Observed magnitudes were compared to model magnitudes using

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

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

The value of $c$ 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

$$c = \left( \frac{\sum_i (m_{\text{model},i} - m_{\text{obs},i})}{\sum_i 1/\sigma^2_i} \right).$$

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

To quantify the nonlinear 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 $T_{\text{eff}}$ 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 10,000 Monte Carlo realizations. The resulting distributions of $T_{\text{eff}}$ were 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 $T_{\text{eff}}$ that accurately reproduces the observed photometric measures across all 11 passbands. No star has a reduced $\chi^2$ of zero, 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

Table 6

| Name                      | $T_{\text{eff}}$ 90% Lower Bound | $T_{\text{eff}}$ Best Fit | $T_{\text{eff}}$ 90% Upper Bound | $\chi^2_{\text{red}}$ |
|---------------------------|----------------------------------|---------------------------|----------------------------------|-----------------------|
| 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                            | 22900                     | 22900                            | 0.72                  |
| SDSS J103906.00+654555.5   | 24800                            | 24800                     | 25200                            | 0.78                  |
| SDSS J134340.11+023223.2   | 25600                            | 25600                     | 26100                            | 0.97                  |
| SDSS J140641.95+013940.5   | 22700                            | 22700                     | 23100                            | 0.58                  |
| SDSS J144108.43+010102.0   | 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

| Filter | $\langle \Delta m \rangle$ | Median $\langle \Delta m \rangle$ | $\sigma_{\Delta m}$ | $\sigma_{\text{sys}}$ |
|--------|-----------------------------|-----------------------------------|---------------------|----------------------|
| FUV    | −0.054                      | −0.055                            | 0.047               | 0.05                 |
| NUV    | 0.044                       | 0.047                             | 0.013               | 0.03                 |
| u     | −0.014                      | −0.011                            | 0.011               | 0.03                 |
| u     | 0.010                       | 0.014                             | 0.026               | 0.03                 |
| u     | −0.038                      | −0.034                            | 0.022               | 0.03                 |
| u     | 0.029                       | 0.031                             | 0.019               | 0.02                 |
| u     | −0.032                      | −0.026                            | 0.029               | 0.03                 |
| g     | −0.008                      | −0.016                            | 0.025               | 0.01                 |
| r     | −0.013                      | −0.015                            | 0.015               | 0.01                 |
| i     | 0.002                       | −0.001                            | 0.014               | 0.01                 |
| z     | 0.029                       | 0.023                             | 0.047               | 0.02                 |

Figure 7. Comparison of the white dwarf photometry to the predicted magnitudes of the model atmospheres. The gray dots represent the model; crosses, diamonds, and triangles represent SDSS, UVOT, and GALEX photometry, respectively. Individual filters are labeled in the first panel.
Table 8

| Wavelength (Å) | J002806.49+010112.2 | J083421.23+533615.6 | J092404.84+593128.8 |
|----------------|---------------------|---------------------|---------------------|
| 1300.0         | 2.0081E−13          | 4.7217E−13          | 1.4265E−13          |
| 1300.5         | 2.0057E−13          | 4.7166E−13          | 1.4253E−13          |
| 1301.0         | 2.0037E−13          | 4.7121E−13          | 1.4243E−13          |
| 1301.5         | 2.0017E−13          | 4.7067E−13          | 1.4233E−13          |
| 1302.0         | 1.9997E−13          | 4.7021E−13          | 1.4223E−13          |
| 1302.5         | 1.9980E−13          | 4.6976E−13          | 1.4213E−13          |
| 1303.0         | 1.9968E−13          | 4.6939E−13          | 1.4214E−13          |
| 1303.5         | 1.9948E−13          | 4.6894E−13          | 1.4204E−13          |
| 1304.0         | 1.9933E−13          | 4.6848E−13          | 1.4204E−13          |
| 1304.5         | 1.9913E−13          | 4.6803E−13          | 1.4194E−13          |

Notes.

* Flux in erg cm−2 s−1 Å−1.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 8. Comparison of the white dwarf photometry to the predicted magnitudes of the model atmospheres. The gray dots represent the model; crosses, diamonds, and triangles represent SDSS, UVOT, and GALEX photometry, respectively.

the values roughly track each other, we find that 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° and slightly warmer at higher temperatures.

The fitted spectral models are included in the online version of the 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...
Figure 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 $T_{\text{eff}}$ reported in Eisenstein et al.; the solid lines represent our best fit from the photometry.

Figure 11. Photometric residuals of fitted white dwarf models to measured photometry broken down by filter.

Figure 12. Photometric residuals of fitted white dwarf models to measured photometry broken down by filter.

Figure 13. Comparison of the SDSS effective temperatures from Eisenstein et al. against those derived from our spectral fitting. The solid line indicates unity.

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 the 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 have published SDSS photometry and 11 of which now have published NUV and FUV photometry.

We have fitted 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 11 stars, we do not find any that are of poor or limited quality. The mean reduced χ² of the model fits to spectra and photometry is 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 and (2) the previously known uncertainty in the UV extinction law. These systematic uncertainties dominate over our random errors. We are engaged in an 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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