White-dwarf-based evaluation of the GALEX absolute calibration

L. Camarota* and J. B. Holberg

Lunar and Planetary Laboratory, University of Arizona, Sonett Space Sciences Building, 1541 East University Boulevard, Tucson, AZ 85721-0063, USA

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ABSTRACT
This paper describes a revised photometric calibration of the Galaxy Evolution Explorer (GALEX) magnitudes, based on measurements of DA white dwarfs. The photometric magnitudes of white dwarfs measured by GALEX are compared to predicted magnitudes based on independent spectroscopic data (108 stars) and alternatively to International Ultraviolet Explorer (IUE) ultraviolet (UV) fluxes of the white dwarfs (218 stars). The results demonstrate a significant non-linear correlation and small offset between archived GALEX fluxes and observed and predicted UV fluxes for our sample. The primary source of non-linearity may be due to detector dead time corrections for brighter stars, but it should be noted that there was a predicted non-linearity in the fainter stars as well. Sample expressions are derived which ‘correct’ observed GALEX magnitudes to an absolute magnitude scale that is linear with respect, and directly related, to the Hubble Space Telescope photometric scale. These corrections should be valid for stars dimmer than magnitudes 9.3 and 10.5 in the near-UV and far-UV, respectively, and brighter than magnitude 17.5 in both.

Key words: instrumentation: detectors – telescopes – white dwarfs.

1 INTRODUCTION

1.1 GALEX mission

The Galaxy Evolution Explorer (GALEX) was a NASA Small Explorer class mission launched in 2003, whose primary objective was to conduct deep ultraviolet (UV) surveys of the sky in two broad-band bands between 1400 and 3000 Å in order to study the stellar evolution of faint external galaxies (Bianchi & GALEX Team 2000). It was operated by the California Institute of Technology with NASA support until 2012. Thereafter it was supported by Caltech with a private fund raising effort called Complete the All-sky UV Survey Extension or CAUSE. The GALEX mission was decommissioned in 2013.

GALEX operated primarily in a pointed mode, which tiled the sky with circular fields approximately 1.2 in diameter. Approximately 75 percent of the sky was observed during the GALEX mission. Areas near UV-bright sources and near the Galactic plane and other crowded regions were generally avoided by these observations. When the California Institute of Technology assumed operational control, some observation parameters were changed. GALEX started using a scanning mode to record areas that were brighter than previously permitted, including approximately 80° of the Galactic plane.

The primary mission of GALEX was to conduct observations pertaining to the spectral evolution of galaxies in the UV. The majority of GALEX observations involved four surveys. The Deep Imaging Survey (DIS) made long exposure (30 000 s) observations of regions with targets that had been extensively observed in other wavelength bands. The Medium Imaging Survey (MIS) made single orbit exposure (1500 s) observations of regions with targets observed by the Sloan Digital Sky Survey (SDSS) spectroscopic footprint, the Two Degree Field Galaxy Redshift Survey (2dFGRS) and the AAOmega (WiggleZ) project. The All sky Imaging Survey (AIS) made short exposure (100 s) observations of as much of the sky as possible. The Nearby Galaxy Survey (NGS) made single orbit exposure (1500 s) observations of nearby galaxies that have significant observations in other wavelengths. GALEX also devoted 33 percent of its observation time to guest investigators.1

The primary goal of GALEX was study of the cosmic history of star formation as evidenced in the UV fluxes from star-forming regions in distant galaxies. In addition to this goal, many other much nearer UV sources were observed with great sensitivity over a large fraction of the sky. Of particular interest here are GALEX observations of white dwarfs (WDs). WDs initially form as very hot (∼10⁷ K) dense stellar cores, and as they cool, the bulk of their luminosity shifts from the extreme and far-ultraviolet (FUV) into the near-ultraviolet (NUV) and optical bands. GALEX can detect these stars at distances of several kiloparsec.

One practical use of WDs, especially pure hydrogen DA WDs, is as flux calibration standards that span the wavelength range from the extreme ultraviolet into the near-infrared (IR; Sing, Holberg &
Dupuis 2002). Several properties of DA WDs favour their widespread use as photometric and spectrometric flux standards in the UV and optical. These are (1) their spectral energy distributions are continuum dominated; (2) the atmosphere of these stars are fully radiative and stable over a wide range of temperatures; (3) the opacities are due almost exclusively to neutral and ionized hydrogen and are thus very well determined; (4) the emergent stellar fluxes depend only on \( T_{\text{eff}} \) and \( \log g \) which can be determined spectroscopically and (5) they are relatively nearby and free from interstellar reddening. See Holberg & Bergeron (2006) for a more detailed discussion of these points.

The GALEX team originally used six WDs that had been designated by the Hubble Space Telescope (HST) as calibration standards. However, all but one of these WDs caused saturation of both GALEX’s detectors (Morrison et al. 2007). The DB WD LDS 749b was used as a primary absolute flux calibrator for GALEX. However, following the Morrison et al. (2007) results, Bohlin & Koester (2008) published a refined model of this star on the HST flux scale. Specifically, these authors included a detailed spectroscopic analysis of the He i lines to set the \( T_{\text{eff}} \) and \( \log g \) (\( T_{\text{eff}} = 13575 \pm 50 \) K and \( \log g = 8.05 \pm 0.7 \)) and evaluated the effect of possible uncertainties in these parameters as well as interstellar reddening on the UV and IR fluxes for this star. They concluded that this model now approaches the fidelity used to establish the three brighter DA WDs (GD 71, GD 153 and G191-B2B) as primary HST flux standards.

The ability to precisely relate GALEX fluxes to absolute fluxes in other bands is useful in several respects. For example, GALEX’s broad-band UV fluxes can be used to identify stars having UV excesses, due to perhaps hot WDs and/or subdwarfs (Bianchi et al. 2011). The GALEX bands are also more sensitive to low levels of interstellar extinction than other optical and near-infrared broad-band survey data, for example SDSS ugriz colours. Finally, for many objects it is useful to include GALEX fluxes as contributions to multiband spectral energy distributions. All of these objectives are enhanced if GALEX fluxes are on the same absolute flux scale as other observations.

1.2 GALEX instrumentation

The GALEX telescope employs a Ritchey–Chrétien optical design, with a 50 cm diameter primary mirror. In the focal plane light passes through an imaging window, a dispersive grism, or an opaque shutter, controlled by an optical wheel mechanism. Incoming light also passes through a dichroic beam splitter, and is directed towards the NUV (1771–2831 Å) and FUV (1344–1786 Å) detectors. The beam splitter coating is chromatically selective, with a mean transmission 83 percent in the NUV band, and a mean reflection of 61 percent in the FUV band. The transmitted light is reflected from the red blocking flat mirror to reduce the noise from zodiacal light (\( \lambda > 3000 \)), and the reflected light passes through a multilayer filter that removes short wavelength geocoronal Lyα emissions (1216 Å), as well as terrestrial \( \text{O} \) i airglow (1301–1356 Å).²

The detectors are a pair of large format microchannel plate detectors (MCP).² Each consists of a stack of three microchannel plates separating a photocathode and a delay line detecting anode. Both MCP stacks are operated at a gain on the order of \( 1 \times 10^2 \)–\( 2 \times 10^2 \), with operating voltages of 5200 and 6200 V for the NUV and FUV detectors, respectively (Jelinsky 2003). MCP detectors were selected for GALEX for their low background noise, high red rejection and lack of cooling requirement. Unfortunately, MCP detectors do have a lower quantum efficiency (around 8 percent, depending on wavelength), as well as poor field flatness as compared to the more standard CCD detectors. To mitigate local flatness variations, GALEX moves its optical axis in a 1 arcmin spiral dither pattern, at a rate of approximately 1/2 rotation min⁻¹. This spreads the image of a point source over multiple 1.5 arcsec pixels so that pixel-to-pixel variance is averaged. With dithering, the magnitude uncertainty of measured objects decreased from 0.068 and 0.125 mag in NUV and FUV to 0.027 and 0.050 mag in NUV and FUV (Morrissey et al. 2007).

1.3 GALEX data reduction and calibration

For point sources the procedures used to reduce GALEX detector counts to extracted and calibrated point source images in celestial coordinates are described in detail in Morrison et al. (2007). The GALEX data releases are referenced to the HST photometric system of Bohlin, Dickinson & Calzetti (2001) and Bohlin & Koester (2008) through the defined spectrophotometric fluxes for a limited set of HST reference standard WD stars. Because GALEX is a relatively sensitive broad-band photometric instrument, many of these HST standards are effectively too bright for GALEX, particularly in the FUV detector. The primary photometric standard for direct imaging used by GALEX is the HST standard LDS 749b. LDS 749b (WD 2129+000) is a \( V = 14.674 \) DB (pure helium) WD which has bandpass defined GALEX AB magnitudes of 14.71 and 15.57 in the NUV and FUV, respectively (Morrissey et al. 2007). The current and final GALEX data release (GR7) still basically relies on this photometric calibration. The more recent spectral model from Bohlin & Koester (2008) gives magnitudes of 14.76 and 15.6 for NUV and FUV, respectively. The published GALEX magnitudes for this star are 14.82 and 15.67 in NUV and FUV, respectively.

1.4 Objective

The primary objective of this paper is to describe a simple transformation that can be applied to observed GALEX GR7 archive NUV and FUV magnitudes that place them on the HST absolute flux scale. Although we discuss GALEX detector effects such as saturation and dead time corrections, we rely mainly on empirical correlations between observed GALEX magnitudes and synthetic magnitudes to define ‘corrected’ fluxes. Simple corrections of the type described here should be useful in directly transforming observed magnitudes to the HST absolute scale, without the need for an additional layer of analysis of detector behaviour. In Section 2 we discuss our methods of synthetic photometry. In Section 3, comparisons from synthetic photometry methods are described, and in Section 4 we describe our corrections to GALEX photometry. Our conclusions are given in Section 5.

2 PROCEDURE

2.1 Post-GR7 GALEX calibration based on white dwarf synthetic magnitudes

In this paper we follow the procedures of using synthetic photometry of DA WDs to evaluate various widely used photometric systems and to place them on the HST photometric system (Holberg & Bergeron 2006). In Holberg & Bergeron synthetic fluxes were computed

² http://www.galex.caltech.edu/researcher/techdoc-ch1.html
³ http://www.galex.caltech.edu/researcher/techdoc-ch1.html
for large samples of DA WDs which have spectroscopically determined effective temperatures and surface gravities based on the detailed fitting of observed H I Balmer lines. The resulting models’ energy distributions are then normalized to an observed flux, for example, a Johnson V or SDSS g magnitude with respect to synthetic magnitudes computed for other bands. Holberg & Bergeron also detail how this sort of synthetic DA photometry can be directly linked to the HST photometric scale. This makes possible a detailed comparison of observed magnitudes as a function of synthetic magnitudes and a natural way to define various photometric systems with respect to the HST system in terms of a consistent set of photometric zero-point fluxes. In the present paper we apply these techniques to the GALEX GR7 data set as it is currently defined. Specifically, we use a significant sample of DA WDs that have well-defined \( T_{\text{eff}} \) and \( \log g \) values, or alternately have well-determined International Ultraviolet Explorer (IUE) fluxes, to compute synthetic GALEX magnitudes and compare these to the corresponding observed GALEX fluxes. Using these techniques we can cover a wide range of GALEX magnitudes, from the brightest unsaturated WDs to stars having AB magnitudes of \( \sim 17 \). We investigate the residual linearity of GALEX GR7 fluxes as well as small systematic offsets to the basic GALEX calibration.

### 2.2 Determination of white dwarf synthetic magnitudes

Two complimentary methods were used to compare observed GALEX magnitudes with synthesized NUV and FUV magnitudes (Holberg & Bergeron 2006). The first employed model atmospheres computed from spectroscopically determined temperatures and gravities. The second directly used the IUE measured continua of WDs. In each method, synthesized GALEX magnitudes are calculated by the following:

\[
f_S = \frac{\int S(\lambda)f(\lambda) \lambda \, d\log(\lambda)}{\int S(\lambda) \lambda \, d\log(\lambda)},
\]

where \( f(\lambda) \) is the normalized model flux of the WD in erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\), \( S(\lambda) \) is the effective area of the instrument in cm\(^2\) and \( f_S \) is the integrated energy flux in erg cm\(^{-2}\) s\(^{-2}\). The integrated flux can be converted into AB magnitudes by

\[
M_{AB} = -2.5 \log(f_S) - 48.60.
\]

The GALEX photometric data of the WDs were gathered from the Mikulski Archive for Space Telescopes (MAST) public access site, using GALEX GR7 pipeline data.\(^4\) The coordinates of each of the target WDs were obtained from the Villanova Catalogue of Spectroscopically Identified White Dwarfs (McCook & Sion 1999)\(^5\) and used to locate the objects. For each WD, information on exposure time, published magnitude and Poisson magnitude uncertainty were obtained for both the NUV and FUV detectors. Where the Poisson uncertainty was less than the flat-field uncertainty (0.027 mag_{AB} in NUV and 0.050 mag_{AB} in FUV; Morrissey et al. 2007), the flat-field uncertainty was used instead.

Synthetic magnitudes were compared to the measured magnitudes. Linear, quadratic and cubic chi-squared minimizing interpolations were calculated for each set of data. In all data sets, the quadratic interpolation had significantly more predictive power than the linear interpolation, while having only marginally less predictive power than the cubic interpolation. Thus, the quadratic interpolations were ultimately used to calibrate the detectors.

### 2.3 Calibration with respect to model white dwarf atmospheres

The first step in validating the GALEX calibration using atmospheric models was to select a group of WDs whose spectra are easy to model. The WDs selected were among those from Holberg & Bergeron (2006) and Gianninas, Bergeron & Ruiz (2011) that had been observed by GALEX. The WD sample was further reduced by applying the following criteria: (1) a high enough temperature that they emit significant flux over the entire GALEX range (at least 13 000 K); (2) observed by the SDSS and SDSS photometric data consistent with model spectra of an isolated WD; (3) faint enough that they will not overwhelmingly saturate the GALEX MCP detectors (no brighter than 11 mag) and (4) near enough that interstellar reddening is not a concern.

Using the spectroscopic \( T_{\text{eff}} \) and \( \log g \) from Gianninas et al. (2011), an unnormalized model spectrum of each of the WDs was calculated. These model spectra extended from 1350 to 17 000 Å, containing both the FUV band of GALEX and the SDSS z infrared band. To normalize this spectrum, DR9 SDSS ugriz photometry was used.\(^6\) Using the technique from Holberg & Bergeron (2006), the photometric magnitudes from GALEX and SDSS were both normalized to the HST scale, and their uncertainties were calculated. A normalization factor was chosen to minimize \( \chi^2 \) error from these photometric magnitudes. When the initial model magnitudes were first compared to the measured magnitudes published by GALEX, a general trend could be seen, but there were numerous significant outliers.

One source of outliers was due stars that were too cool to have significant flux in the UV bands of GALEX, and thus were dominated by background. This lead to a practical temperature minimum cutoff of 13 000 K (i.e. spectral types of DA3.8 or earlier).

A second source of outliers came from stars that were members of known binary systems. The companions of these WDs although cooler, were luminous enough so that they had red and near-IR excesses. This excess light made normalization with respect to SDSS ugriz photometry impossible. For example, the star WD 0232+035 (Feige 24) is a known binary system consisting of a WD and an M-type star. The plot in Fig. 1 shows a calculated spectrum from its atmospheric conditions. The two points towards the left of the plot in Fig. 1 show the flux measured by the GALEX FUV and NUV detectors; the remaining points are ugriz photometric fluxes measured by the SDSS used to normalize the model spectrum. The presence of the dMe companion results in an unmodelled red excess. For comparison, star WD 1249+160 has no companion star. The plot in Fig. 2 shows the same information as the plot in Fig. 1. The ugriz photometric fluxes match the model spectra flux.

A third source of outliers was from the detector itself. The initial measurement uncertainty was based solely on Poisson counting statistics. However, the flat-field uncertainties provided a much stronger source of uncertainty for most WDs. Additionally, in 2003 the FUV detector began to exhibit an anomaly known as the ‘blob’ following a period of strong solar flares, which made some of the measurements questionable (Morrissey et al. 2007). A few WDs were removed from consideration because they had been measured
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Figure 1. Top: a model spectrum (curve) and SDSS ugriz plus GALEX photometry (points) for the well known WD+dMe binary system Feige 24 (WD 0232+035). The difficulty in normalizing SDSS photometry to the model due to the red excess of the secondary is evident in a binary system.

Figure 2. Bottom: a model spectrum (curve) and SDSS ugriz plus GALEX photometry (points) for the isolated WD (WD 1249+160). The model and photometric data are consistent for this star.

more than once with a large (>3σ) difference between the measurements. WDs that were only measured once could not be tested this way, and may result in remaining outliers. Additionally, communication with the GALEX team has suggested that there are unmodelled sensitivity corrections that affects brighter stars near the edge of the detector field. The data set that we used was insufficient to determine this correction, and it can be seen in a larger magnitude spread in the lower magnitude stars, on the order of 0.1 mag uncertainty at 15th mag.

In Fig. 3 we show the empirical correlations between observed GALEX NUV and FUV magnitudes and synthetic model fluxes. The correlations do not match the anticipated one-to-one correlations (dashed lines) as there appears to be significant magnitude-dependent curvature for both data sets. Quadratic and cubic expressions were fit to these data. Over the range of magnitudes considered, quadratic fits gave reasonable representations of the data, while cubic fits did not significantly improve the fit. We therefore have adopted the following expression to represent the best-fitting correlations between expected model magnitudes and observed GALEX data:

\[ M_{\text{GALEX}} = c_0 + c_1 M_{\text{syn}} + c_2 M_{\text{syn}}^2, \]  

where \( M_{\text{GALEX}} \) and \( M_{\text{syn}} \) are the observed GALEX and synthetic AB magnitudes, and \( c_0, c_1 \) and \( c_2 \) are the respective quadratic coefficients. The results for each band are given in Table 1, along with the chi-squared per degree of freedom for each fit.

The parameters of some of the stars used are shown in Table 2. The remaining stars are available in the web version.

![Figure](image-url)

Table 1. Quadratic fit parameters for atmospheric model.

| Property | NUV   | FUV   |
|----------|-------|-------|
| \( c_0 \) | 9.554 | 11.908|
| \( c_1 \) | -0.188| -0.529|
| \( c_2 \) | 0.038 | 0.050 |
| \( \chi^2/\text{dof} \) | 4.81  | 3.531 |
| Number of stars | 107   | 99    |
| Lower bound     | 10.5  | 10.5  |
| Upper bound     | 17.5  | 17.5  |
2.4 Calibration with respect to IUE spectra

In a second calibration procedure, GALEX WD measurements were compared to IUE low dispersion spectrum. The IUE Short-Wavelength Prime (SWP) and Long-Wavelength Prime (LWP)/Long-Wavelength Redundant (LWR) spectra camera observed 218 WD stars that were also observed by GALEX during its operational lifetime. These spectra were processed with New Spectroscopic Image Procession System (NEWSIPS) corrections and co-added where possible to produce observed UV spectral energy distributions between 1150 and 3000 Å (Holberg, Barstow & Burleigh 2003). These previously measured spectra include interstellar extinction, and do not rely on model fluxes. The downside of using the IUE spectra is that they were not as well suited for this kind of analysis. The observed spectra occasionally did not cover the entire detector passband. Finally, many of the measured spectra included had very large signal-to-noise ratios in the NUV and FUV ranges. IUE spectra used were obtained from the library of IUE low-dispersion spectra of WDs, which were processed with IUE NEWSIPS procedures and were effectively on the HST flux scale (Holberg et al. 2003).

Both the best-fitting linear and best-fitting quadratic interpolations were calculated for both the FUV and NUV detectors. For both detectors, the quadratic interpolations were significantly better than the linear interpolations, and are shown in Fig. 4. The parameters for the correlation are shown in Table 3.

The properties of some of the stars used can be seen in Table 4. The remaining stars are available in the web version.

3 COMPARISON OF SYNTHETIC MAGNITUDE METHODS

There were a total of 19 WDs that were used in both the model atmosphere method and the IUE method. All 19 WDs have synthetic FUV magnitudes from both methods, but only 11 have synthetic NUV magnitudes from available IUE data. The atmospheric model synthetic magnitudes averaged 0.168 mag$_{AB}$ higher with a standard deviation of 0.0627 mag$_{AB}$ in FUV, and 0.580 mag$_{AB}$ lower with a standard deviation of 0.356 mag$_{AB}$ in NUV. Considering all 32 measurements, the atmospheric model synthetic magnitudes averaged 0.300 mag$_{AB}$ lower with a standard deviation of 0.376 mag$_{AB}$. For the individual stars, the atmospheric model spectrum and the IUE spectrum are remarkably similar. For example, the spectrum of star WD 1658+440 (PG 1658+440) is shown in Fig. 5, along with the response functions of the detectors. For this particular star, the total difference between the atmospheric spectrum and the IUE spectrum is 2.8 per cent, with an rms of 9.8 per cent. Most of the difference in the spectrum occurs outside of the band that the detectors are sensitive to; eliminating that part, the total difference becomes just 1.5 per cent.

When looking at all 11, these results were typical. Most atmospheric model and IUE comparisons had total flux differences

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Table 2. Properties of WDs selected for model spectra calibration.

| Star WDN | Survey | Exposure time | WD properties | AB magnitudes |
|----------|--------|---------------|---------------|---------------|
|          |        | FUV | NUV | $T_{\text{eff}}$ | $T_{\text{eff}}$ err | Log | Log err | FUV | FUV err | NUV | NUV err |
| 0000+171 | AIS 172 | 172.2 | 178.2 | 21 130 | 325 | 8 | 0.05 | 14.9807 | 0.125 | 15.2681 | 0.0675 |
| 0004+330 | AIS 112 | 112 | 465 | 49 980 | 898 | 7.77 | 0.06 | 13.0285 | 0.125 | 13.0353 | 0.0675 |
| 0030−181 | AIS 126 | 126 | 126 | 14 270 | 387 | 7.94 | 0.06 | 16.9028 | 0.125 | 16.808 | 0.0675 |
| 0058−044 | AIS 208 | 208 | 208 | 17 370 | 292 | 8.1 | 0.05 | 14.8913 | 0.125 | 14.7995 | 0.0675 |
| 0127−050 | AIS 137 | 137 | 137 | 16 790 | 250 | 7.99 | 0.04 | 14.3451 | 0.125 | 14.6568 | 0.0675 |
| 0129−205 | AIS 188.05 | 188.05 | 20 | 670 | 333 | 8.01 | 0.05 | 14.3451 | 0.125 | 14.7707 | 0.0675 |
| 0155+069 | AIS 112 | 112 | 89 | 470 | 501 | 7.54 | 0.18 | 14.6068 | 0.125 | 14.8028 | 0.0675 |

Note. A machine readable version of the full table is available online.

Figure 4. The correlation between the observed GALEX NUV (top) and FUV (bottom) magnitudes and predicted IUE magnitudes are shown. The dashed lines are the expected one-to-one correlations, while the solid curves are quadratic fits to the data.

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7 http://vega.lpl.arizona.edu/newsips/low/
4.1 Corrections to GALEX GR7 magnitudes

The correlations between observed GALEX GR7 magnitudes and our model-based and IUE-based synthetic magnitudes are similar, indicating that a similar effect is being measured. We have selected the model-based synthetic magnitudes to define our empirical corrections to the GALEX AB magnitudes. This is due to the fact that our synthetic magnitudes have lower inherent dispersion with respect to the quadratic correlations (see Fig. 3) than the IUE correlations (Fig. 4).

The expressions that convert observed GALEX AB magnitudes into ‘corrected’ GALEX magnitudes as a function of observed GALEX magnitudes are basically an inversion of the correlations in Fig. 3. We have chosen explicit quadratic solutions to equations to express these relations. An alternate method that reverses the correlation plots in Fig. 3 and refits the data to observed GALEX magnitudes is also possible, but represents the data with slightly less fidelity. Our correlations to the GALEX magnitudes are

$$M_{\text{corr}} = C_0 + (C_1 M_{\text{obs}} + C_2)^{1/2}.$$  (4)

The $M_{\text{corr}}$ and $M_{\text{obs}}$ are the respective corrected and observed GALEX magnitudes, and $C_0$, $C_1$ and $C_2$ are calculated constants. These values were calculated by inverting the quadratic best-fitting lines from the synthetic magnitudes and then slightly adjusting the constant $C_0$ so that the centroid of the frequency distribution of residuals was zero. The corresponding values of these constants for the NUV and FUV corrections are given in Table 5. The magnitude ranges over which these expressions are valid are also contained in Table 5. The results of applying our recalibration corrections to the measured GALEX magnitudes are seen in Fig. 6. In the NUV, the average difference between the synthetic magnitude and the recalibrated magnitude was 0.003 mag$_{\text{AB}}$ with a variance of 0.154 mag$_{\text{AB}}$. In the FUV, the average difference between the synthetic magnitude and the calibrated magnitude was 0.002 mag$_{\text{AB}}$ with a variance of 0.134 mag$_{\text{AB}}$. In both bands, the average difference did not vary with magnitude, but the variance of the difference was largest at lower magnitudes.

One surprising result of these calibration calculations is the correction at higher magnitudes. Typically, non-linearities in measurement occur primarily in brighter stars with very high measured count rates. Figs 3 and 4 do show a non-linearity in the fainter stars. We hypothesize that this could be due to interstellar reddening, since fainter WDs tend to be farther away. However, it should be noted that there were only a few stars in this region, so corrections for stars dimmer than magnitude 16 should be treated with a little more caution.

Table 3. Quadratic fit parameters for IUE measurements.

| Property | NUV   | FUV   |
|----------|-------|-------|
| $c_0$    | 14.821| 12.498|
| $c_1$    | −0.729| −0.627|
| $c_2$    | 0.053 | 0.053 |
| $\chi^2$/dof | 16.807 | 5.989  |

Number of stars 197 218
Lower bound 9.5 10.5
Upper bound 17.5 17.5

On the order of 5 percent, with rms values on the order of 7 percent. Two stars had average flux differences greater than 10 percent, WD 0343−007 (KUV 0343−007) and WD 0939+262 (PG 0939+262). Both WDs were outliers in the IUE synthetic flux model.

4 CALIBRATION

Table 5. Inverse quadratic corrections.

| Property | NUV | FUV |
|----------|-----|-----|
| $C_0$    | 2.634 | 5.371 |
| $C_1$    | 26.316 | 20.000 |
| $C_2$    | −245.329 | −210.200 |

Number of stars used 293 298
Lower measured magnitude limit 9.321 10.509
Upper measured magnitude limit 17.5 17.5
$\chi^2$/dof 3.824 4.623

The magnitude ranges over which these expressions are valid are also contained in Table 5. The results of applying our recalibration corrections to the measured GALEX magnitudes are seen in Fig. 6. In the NUV, the average difference between the synthetic magnitude and the recalibrated magnitude was 0.003 mag$_{\text{AB}}$ with a variance of 0.154 mag$_{\text{AB}}$. In the FUV, the average difference between the synthetic magnitude and the calibrated magnitude was 0.002 mag$_{\text{AB}}$ with a variance of 0.134 mag$_{\text{AB}}$. In both bands, the average difference did not vary with magnitude, but the variance of the difference was largest at lower magnitudes.

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Table 4. Properties of WDs selected for IUE spectra calibration.

| WDN     | Survey | Exposure time | FUV | AB magnitudes |
|---------|--------|---------------|-----|---------------|
|         |        |               | NUV | FUV | FUV err | NUV | NUV err |
| 0000–170| AIS    | –             | 63.05 | – | – | 14.8972 | 0.0675 |
| 0002+729| AIS    | 208           | 208  | 15.2669 | 0.125 | 14.6308 | 0.0675 |
| 0004+330| AIS    | 122           | 465  | 13.0285 | 0.125 | 13.0353 | 0.0675 |
| 0005+511| AIS    | 219           | 219  | 12.3251 | 0.125 | 13.2181 | 0.0675 |
| 0017+136| AIS    | –             | 122  | – | – | 14.9812 | 0.0675 |
| 0022–745| AIS    | 202           | 202  | 14.0467 | 0.125 | 14.3996 | 0.0675 |
| 0037+312| AIS    | 109           | 109  | 13.2827 | 0.125 | 13.5633 | 0.0675 |
| 0041+092| AIS    | 179.05        | 179.05 | 13.1606 | 0.125 | 13.4619 | 0.0675 |

Note. A machine readable version of the full table is available online.
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Figure 6. Comparison of synthetic model magnitudes and corrected measured magnitudes for NUV (top) and FUV (bottom). The lines show the expected one-to-one correlation.

4.2 Dead time correction

The most apparent non-linearity seen in Fig. 3 corresponds to the brightest stars. This suggests effects associated with the local count rate behaviour of the detector or perhaps with the aperture extractions. Count rate related detector effects can be related to detector dead time. The GALEX images are corrected for global dead time so this effect should be negligible. On the other hand the ability of the detector to deal with high local (point source related) count rates is stated in Morrissey et al. (2007) to be less well understood and is difficult to investigate in detail. Bright point sources can locally saturate the MCP reducing gain. Morrissey et al. provide plots which measure which of this effect for both detectors. In our analysis we begin with the MAST GR7 magnitudes and empirically determine the correlation of observed magnitudes with predicted count rates. In the absence of a detailed analysis of detector behaviour this is perhaps the most effective way to estimate first-order magnitude corrections.

Although the current limiting and gain reducing aspects of local high count rates are complicated, we have attempted to use our results in Fig. 3 to interpret the effects as a standard non-paralyzable ‘dead time correction’, where the term non-paralyzable refers to time following the measurement an event the discriminator electronics are unable to register another event. The expression for a dead time correction in terms of observed count rate $C_{\text{obs}}$ and true count rate $C_{\text{true}}$ for a dead time $\tau$ is given by

$$C_{\text{true}} = \frac{C_{\text{obs}}}{1 - C_{\text{obs}} \tau}$$

GALEX magnitudes can be estimated from count rates as

$$M = -2.5 \log_{10}(C) + Z_p,$$

where $C$ is the count rate and $Z_p$ are the respective NUV and FUV zero-point magnitudes 20.02 and 18.82 (Morrissey et al. 2007). If the correlations in Fig. 3 are fit for observed GALEX magnitudes versus synthetic magnitudes and $\tau$ is found to minimize $\chi^2$ error, we find respective dead times of 578 and 1209 $\mu$s for the NUV and FUV data. When these dead time corrections were applied to the data, the results were somewhat problematic. Corrected magnitudes near the middle of the brightness range (12–14 mag) tended to be too low, while those for the brighter stars (9–11 mag) tended to be too high. This suggests that the dead time had a larger effect on brighter stars than purely non-paralyzable dead time would, which suggests that the dead time is paralyzable or semiparalyzable. Local dead time most likely comes from the decrease in MCP voltage following a discharge, also known as gain sag. In summary, a simple dead time correction model appears less than adequate.

5 CONCLUSIONS

We have conducted an empirical evaluation of the absolute calibration of GALEX fluxes with respect to DA WDs. Two independent methods were used, the first involving model atmospheres normalized to SDSS ugriz magnitudes and the second, a direct use of IUE low-dispersion spectra which were integrated with the GALEX FUV and NUV camera response curves to synthesize predicted GALEX magnitudes. We determined that GALEX fluxes possess modest magnitude-dependent departures from the expected one-to-one correlations with the predicted magnitudes.

We provide empirical quadratic magnitude-dependent corrections for observed GALEX magnitudes that place GALEX fluxes in better agreement with the AB magnitude scale. The corrections described here, strictly speaking, pertain to point sources with flat or rising spectral energy distributions. No investigations were made as to the applicability of these corrections to GALEX grism spectra or diffuse sources.

The GALEX corrections presented here have a faintness limit of approximately 17.5 mag$_{\text{AB}}$. This is primarily due to the general lack of suitable fainter DA stars having robust measurements of $T_{\text{eff}}$ and log $g$. However, it is feasible to extend our corrections to magnitudes of 19 or 20 using SDSS DA WDs. Kleinman et al. (2013) have presented a spectroscopic analysis of over 20 000 WD in the SDSS DR7 catalogue. This includes approximately 12 000 DA WDs. Use of these stars, however, will require a determination of interstellar reddening in both the SDSS bands and the GALEX bands. Holberg, Bergeron & Gianninas (2008) have shown that this is feasible to determine both distances and an interstellar reddening parameter $E(B - V)$ from the SDSS data for DA WDs. Such a project would also require determining if there are a sufficient small number of representative Galactic reddening curves that can predict interstellar extinction in the GALEX bands. Fortunately, the areal distribution of the Kleinman et al. catalogue is sufficiently dense (several stars per deg$^2$) that such a project does appear feasible.
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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 2. Properties of WDs selected for model spectra calibration.
Table 4. Properties of WDs selected for IUE spectra calibration. (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt2422/-/DC1).

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