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SCIENCE RESULTS

Potential UV standards for UVIT filter system

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Abstract. We propose a set of eleven faint UV white dwarf stars as potential UV standards for the UVIT filter system on-board AstroSat mission. Synthetic photometry of these stars has been carried out using the in-orbit filter curves of UVIT, GALEX, UVOT and model spectra in the literature. The synthetic photometry of GALEX and UVOT is well correlated with their respective observations. The synthetic UVIT photometry is found to be strongly correlated with that of GALEX. The UV extinction A_λ for these stars has been computed using CCM-89 extinction model and its value for the λ_{mean} of each UVIT filter band has been listed. These results motivate us to recommend this set of stars as additional UVIT flux calibrators.

Keywords. UVIT—synthetic photometry—UV colors—potential standards.

1. Introduction

AstroSat, the first Indian astronomy satellite designed for simultaneous multi-wavelength astronomy was launched in september 2015 (Tandon 2017a). The Ultra-Voilet Imaging Telescope (UVIT), one of the five instruments on board AstroSat is equipped with multiple broad and narrow band filters in far-UV, near-UV and visual regions of the electro-magnetic spectrum to carry out imaging observations. In-orbit calibrations of the UVIT have been carried out by Tandon (2017b) and Rahna (2017). The science goals of UVIT include studies of a variety of astrophysical objects both stellar and non-stellar. The successful operation and performance of the mission and in particular UVIT has resulted in a large number of scientific journal papers (e.g. Subramaniam 2016, 2017; Rao 2018a, b, 2020), and several other investigators). Additional in-flight calibrations have also been presented recently (Tandon 2020).

While typical astronomical observations span a range in spectral and luminosity classes, the available flux standards in UV are limited in number, sky coverage, brightness range and spectral type. The contemporary UV missions HST, GALEX, Swift/UVOT use 1 to 4 primary standards as flux calibrators and these are brighter than $V \sim 14$. One of the aims of any space based observatory should be to expand the list of flux calibrators. This can be achieved by identifying the suitable candidate stars, carrying out their repeated observations and calibration until arriving at reliable photometry to establish their candidature. This process should continue until the space-craft remains in the orbit. Bhargavi and Pati (2009) had commenced a compilation of an all-sky catalog of stellar sources which would be suitable as standards for UVIT. As a first step, the magnitude scales and UV colours for UVIT filters were examined for standard stars with known Spectral Energy Distributions (SED) and later being extended to suitable stars (particularly those with UV observations) from the existing catalogs in order to span a range of spectral type and colour.

As an extension and expansion to all-sky secondary standards for UVIT program here, I present a detailed analysis for a set of faint UV stars which could be potential UVIT standards. In the following section, we describe the methodology followed in computing the synthetic photometry, details of the filter sets and stellar libraries used. In Section 3, we have examined

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the UV magnitudes and colours of a catalog of faint UV White dwarfs that could be potential standards for UVIT and also computed UV extinctions for these set of stars. Discussion and conclusions are presented in Section 4.

2. Synthetic photometry

In Bhargavi and Pati (2009), calculations of instrumental magnitudes for a set of HST's primary standard stars were carried out through pre-flight filter curves of UVIT, assuming unit collecting area for all telescopes, unit efficiency in the reflectivity of mirrors and unit detector response in all filter bands since actual detector and other telescope characteristics were not available at that time. The instrumental UV magnitudes and colours computed for the filter systems of UVIT, Tauvex, GALEX as well as optical were inter-compared. The Color–Magnitude Diagrams (CMD) and Color–Color (C–C) plots showed that the proposed UVIT filters provide a large spread of colours and thus will be able to offer better discrimination with temperature. In the subsequent run we took into account the actual measured parameters such as mirror reflectivity, detector response etc., and studied the UV colour distribution for a larger sample of stars spanning a range in luminosity and spectral classes across the H-R diagram.

2.1 *Methodology*

The methodology to compute the synthetic photometry of stellar sources with known absolute Spectral Energy Distribution (SED) through the bandpasses of UVIT is detailed below. In the discussion following, the words 'filter or bandpass' refers to the over all sensitivity of the photometric system, which includes the effects of filters, detector as well as telescope optics and mirror, expressed in units of Effective Area (EA) (cm^2). The details of filter sets and SEDs used in this work are detailed in the next section.

To compute the photometric magnitudes, we obtained effective flux $F^{\rm eff}$ by integrating the stellar flux (F_λ) of each star through the filter sensitivity (S_λ) normalized to unit filter area as given in Equation (1) below. In order to achieve uniform wavelength grids for both SED and bandpass we interpolated the functions using a cubic spline function. Typically, grid width of $\delta\lambda \sim 3-5$ Å was used to achieve a good fit. The 'SPLINE' and 'SPLINT' tasks of Press (1992) were used for interpolation and integration.

$$F^{\rm eff} = \frac{\int \lambda S_\lambda F_\lambda {\rm d}\lambda}{\int \lambda S_\lambda {\rm d}\lambda}. \tag{1}$$

Here, F_λ is in units of erg/s/cm^2/Å. Effective fluxes thus obtained were then converted into magnitudes in Vega system as follows:

$$m_\lambda = ({\rm ZP})_{\rm Vega} - 2.5 \times \log_{10}(F^{\rm eff}). \tag{2}$$

The Zero Point (ZP) of the magnitude scale in Vega system, $({\rm ZP})_{\rm Vega} = 21.175$. It is the magnitude corresponding to the monochromatic flux $F_{0,\lambda} = 3.39 \times 10^{-9}$ erg/s/cm^2/Å of Vega star outside the Earth's atmosphere at all wavelengths. The AB magnitudes can be obtained using Equation (3) below:

$$m_{\rm AB} = ({\rm ZP})_{\rm AB} - 2.5 \times \log_{10}(F_\nu). \tag{3}$$

Here, F_ν is computed using the relation:

$$F_\nu = F^{\rm eff} \times \frac{(\lambda_{\rm eff})^2}{c}. \tag{4}$$

Here, c is velocity of light and $\lambda_{\rm eff}$ is effective wavelength given by

$$\lambda_{\rm eff} = \frac{\int \lambda S_\lambda F_\lambda {\rm d}\lambda}{\int S_\lambda F_\lambda {\rm d}\lambda}. \tag{5}$$

The zero point of the magnitude scale in AB system is $({\rm ZP})_{\rm AB} = -48.6$ and it corresponds to the flux $F_{0,\nu} = 3.5 \times 10^{-20}$ erg/s/cm^2/Hz in all bands. While the traditional Vega system is preferred, it was decided to compute AB as well, due to its popularity among modern surveys.

2.2 *Filter sets*

We have used the following filter sets to compute the synthetic photometry.

Table 1 contains filter abbreviations adopted by Tandon (2017a) followed by the filter names (in brackets) in column 2. The mean wavelengths $\lambda_{\rm mean}$ in column 3 are computed using Equation (6). We have used the latest in-orbit filter curves available at the UVIT page[1]. The filter curves S_λ (i.e., plots of wavelength vs. EA) of UVIT are not shown here instead, the reader is referred to UVIT page or Tandon (2017b). Effective areas of GALEX bandpasses are obtained from GALEX home page[2] and those of

[1] http://uvit.iiap.res.in/Instruments/Filters.

[2] See http://www.GALEX.caltech.edu.

Table 1. Filter sets.

	Filter Abbr. (Name)	λ_{mean} (Å)
UVIT-FUV	F148W (Caf2-1)	1520.12
	F148Wa (Caf2-2)	1524.56
	F154W (Baf2)	1555.81
	F169M (Sapphire)	1602.36
	F172M (Silica)	1718.03
UVIT-NUV	N219M (NUV-B15)	2211.20
	N245M (NUV-B13)	2448.38
	N263M (NUV-B4)	2625.39
	N279N (NUV-N2)	2792.37
	N242W (NUV-Silica)	2421.47
GALEX	G-FUV	1538.62
	G-NUV	2315.66
UVOT	NUV-W2	2139.53
	NUV-M2	2271.85
	NUV-W1	2677.44

UVOT from Swift home page[3]. The effective wavelengths computed using Equation (5) for UVIT filters are presented in Table A1 in Appendix.

2.3 *Spectral Energy Distributions (SEDs) of stars*

In the following, we list the various sources of SEDs used in this work. The SEDs we obtained from published atlasses and catalogs are calibrated, absolute fluxes. Where ever necessary FITS files were converted into ascii using the tool MRDFITS of IDL package or Fortran programs we wrote.

(i) *SEDs of HST fundamental standard stars*: The reference spectra used in the calibration of the HST instruments are available to the public for the absolute calibration of ground-based or satellite data. This database known as CALSPEC[4] contains composite ultraviolet and optical absolute calibrated stellar spectra of the HST standard stars. We obtained SEDs of 29 standards to calibrate the UVIT filter system. The spectra span a wavelength range of 1050–10000 Å compiled from various sources Calspec stores the spectra in multiple extension .FITS table format. Tasks to convert to ASCII table and also to plot the spectra are available in IRAF v2.11.2 onwards as well as in IDL graphic package[5].

[3]See https://swift.gsfc.nasa.gov/.

[4]See www.stsci.edu and MAST

[5]idlastro.gsfc.nasa.gov

Table 2. UV faint stars.

Sl. No.	Star Id	A_v (mag)
1	J002806.49+010112.2	0.067
2	J083421.23+533615.6	0.122
3	J092404.84+593128.8	0.079
4	J103906.00+654555.5	0.058
5	J134430.11+032423.2	0.082
6	J140641.95+031940.5	0.108
7	J144108.43+011020.0	0.127
8	J150050.71+040430.0	0.014
9	J173020.12+613937.5	0.126
10	J231731.36−001604.9	0.126
11	J235825.80−103413.4	0.101

(ii) *Faint UV white dwarfs*: Model spectra presented by Siegel (2010) of eleven faint UV white dwarf stars previously identified as standards for GALEX and Swift/UVOT.

3. Examining the suitability of faint UV stars as potential standards for UVIT filter system

About a dozen faint ($U \sim 17$) DA White dwarf stars observed by GALEX, Swift/UVOT and SDSS have been identified as faint UV secondary standards (see Table 2). The basic parameters of these stars along with Swift/UVOT and GALEX photometry are available in Tables 1 and 2 in Siegel (2010). The

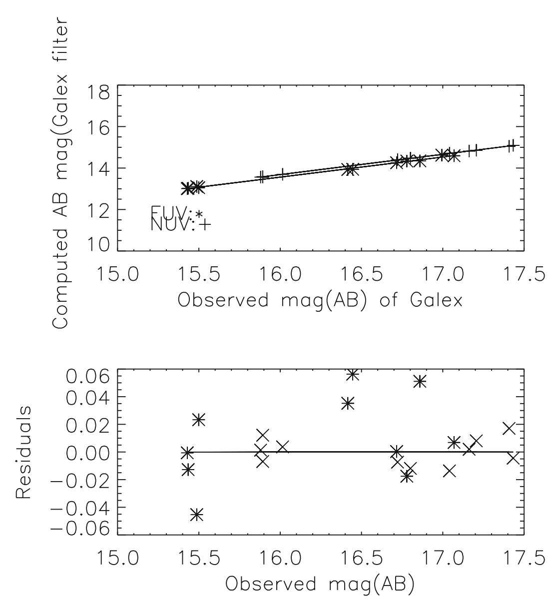

Figure 1. *Top panel*: Observed vs. synthetic AB magnitudes of UV faint standards. Points marked (*) are for GALEX FUV filters and (+) for GALEX NUV filters. *Bottom panel*: Residuals of the fit.

Table 3. GALEX magnitudes of UV faint stars.

Star#	FUV	NUV	FUV	NUV	FUV	NUV
1	2	3	4	5	6	7
1	13.938	14.480	14.116	14.658	16.446	16.801
2	13.008	13.585	13.332	13.908	15.429	15.893
3	14.256	14.717	14.466	14.926	16.716	17.041
4	14.344	14.857	14.498	15.011	16.859	17.206
5	13.025	13.564	13.243	13.782	15.434	15.880
6	14.623	15.092	14.910	15.378	16.994	17.433
7	13.109	13.694	13.447	14.031	15.487	16.015
8	14.335	14.820	14.372	14.857	16.779	17.162
9	14.592	15.046	14.926	15.379	17.069	17.408
10	13.052	13.566	13.387	13.899	15.499	15.893
11	13.930	14.398	14.198	14.665	16.416	16.722

Column 1: Star IDs as in Table 2; Column 2, 3 synthetic mags; Columns 4, 5: synthetic, reddened mags; Columns 6, 7: GALEX observations (Siegel 2010).

model fluxes are in Table 8 of online version. Here we use their photometric data and model spectra to examine their suitability to UVIT as secondary standards. The model spectra are convolved through GALEX, UVOT and in-flight filter curves of UVIT to obtain synthetic magnitudes.

In the top panel of Fig. 1, the observed GALEX magnitudes are plotted against those we synthesized for GALEX filters. The FUV and NUV points are marked by '*' and '+' respectively. A simple linear fit of the form $Y = mX + c$ gives slope $m = 0.972 \pm 0.02$ and $c = -1.96 \pm 0.35$ for FUV and for NUV the slope is $m = 0.98 \pm 0.005$ and $c = -1.99 \pm 0.08$. The residuals of the fit are shown in the bottom panel of Fig. 1 and are within 1% error ($\bar{x} = 0.58\%, 0.91\%$ for FUV and NUV respectively). We repeated these computations for swift/UVOT filters and also obtained less than 1% errors of residuals.

Table 4. Synthetic UVIT (AB) magnitudes.

Star#	F148W	F148Wa	F154W	F169M	F172M	N219M	N245M	N263M	N279N	N242W
1	13.927	13.930	13.952	13.986	14.075	14.457	14.544	14.606	14.671	14.533
2	12.997	13.000	13.022	13.055	13.146	13.575	13.651	13.707	13.771	13.641
3	14.250	14.253	14.269	14.296	14.372	14.699	14.766	14.814	14.866	14.760
4	14.333	14.336	14.358	14.391	14.478	14.826	14.919	14.984	15.050	14.908
5	13.014	13.017	13.039	13.073	13.161	13.541	13.627	13.689	13.753	13.617
6	14.617	14.619	14.635	14.661	14.736	15.086	15.138	15.177	15.224	15.135
7	13.098	13.102	13.123	13.157	13.247	13.684	13.762	13.819	13.886	13.752
8	14.323	14.327	14.349	14.382	14.467	14.773	14.884	14.961	15.032	14.871
9	14.587	14.590	14.604	14.627	14.698	15.048	15.086	15.116	15.156	15.085
10	13.044	13.047	13.065	13.094	13.176	13.564	13.617	13.657	13.707	13.612
11	13.924	13.927	13.943	13.969	14.044	14.389	14.445	14.486	14.534	14.440

See Table 2 for star IDs.

Table 5. Computed UV extinction.

Filter	λ_{mean} Å	Star 1	Star 2	Star 3	Star 4	Star 5	Star 6	Star 7	Star 8	Star 9	Star 10	Star 11
F148W	1520.12	0.176	0.322	0.208	0.153	0.216	0.285	0.335	0.0369	0.332	0.332	0.266
G-FUV	1538.62	0.175	0.319	0.207	0.152	0.214	0.282	0.332	0.0366	0.329	0.329	0.264
F154W	1555.81	0.174	0.317	0.205	0.151	0.213	0.281	0.330	0.0363	0.327	0.327	0.262
F169M	1602.36	0.171	0.312	0.202	0.148	0.210	0.276	0.325	0.0358	0.322	0.322	0.258
F172M	1718.03	0.168	0.306	0.198	0.145	0.205	0.271	0.318	0.0351	0.316	0.316	0.253
N219M	2211.20	0.209	0.381	0.247	0.181	0.256	0.338	0.397	0.0438	0.394	0.394	0.316
G-NUV	2315.50	0.188	0.342	0.222	0.163	0.230	0.303	0.356	0.0393	0.354	0.354	0.284
N242W	2421.47	0.166	0.304	0.197	0.144	0.204	0.269	0.316	0.0348	0.314	0.314	0.251
N245M	2448.38	0.162	0.295	0.191	0.141	0.199	0.262	0.308	0.0339	0.305	0.305	0.245
N263M	2625.39	0.142	0.258	0.167	0.123	0.173	0.228	0.269	0.0297	0.267	0.267	0.214
N279N	2792.37	0.130	0.238	0.154	0.113	0.160	0.211	0.248	0.0273	0.246	0.246	0.197

See Table 2 for star ID.

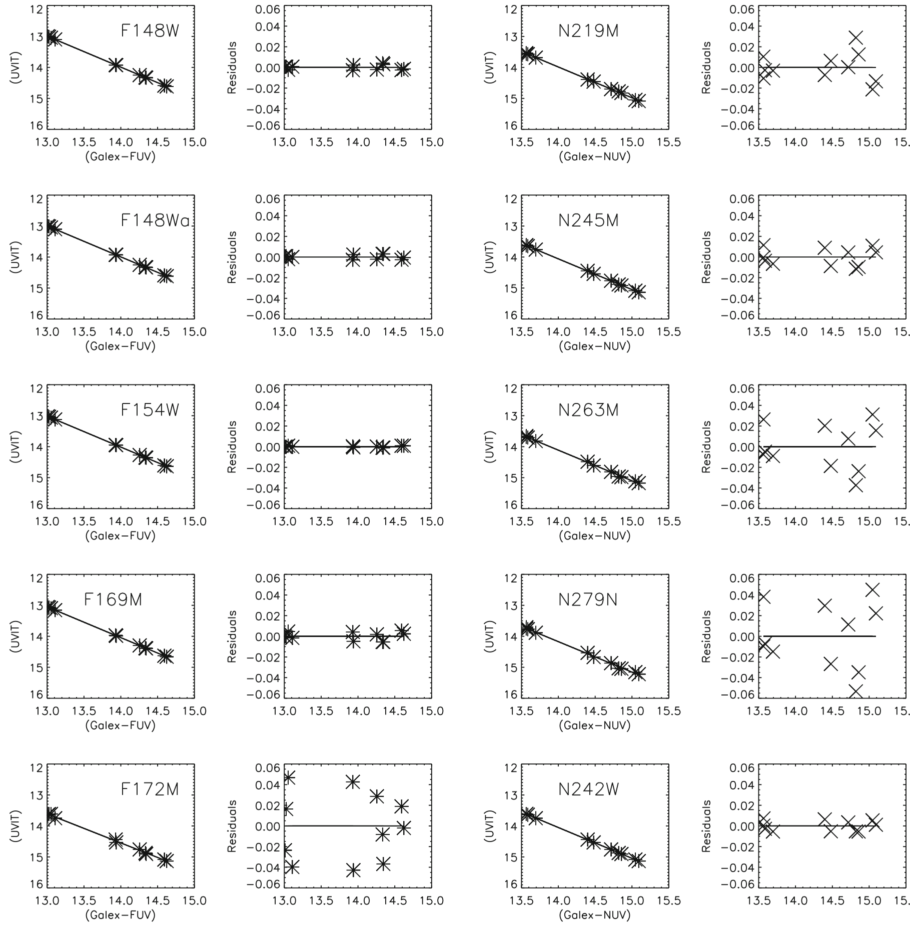

Figure 2. Synthetic AB magnitudes: GALEX-FUV vs. UVIT far-UV (column 1); corresponding residuals (column 2); GALEX-NUV vs. UVIT near-UV (column 3); corresponding residuals (column 4).

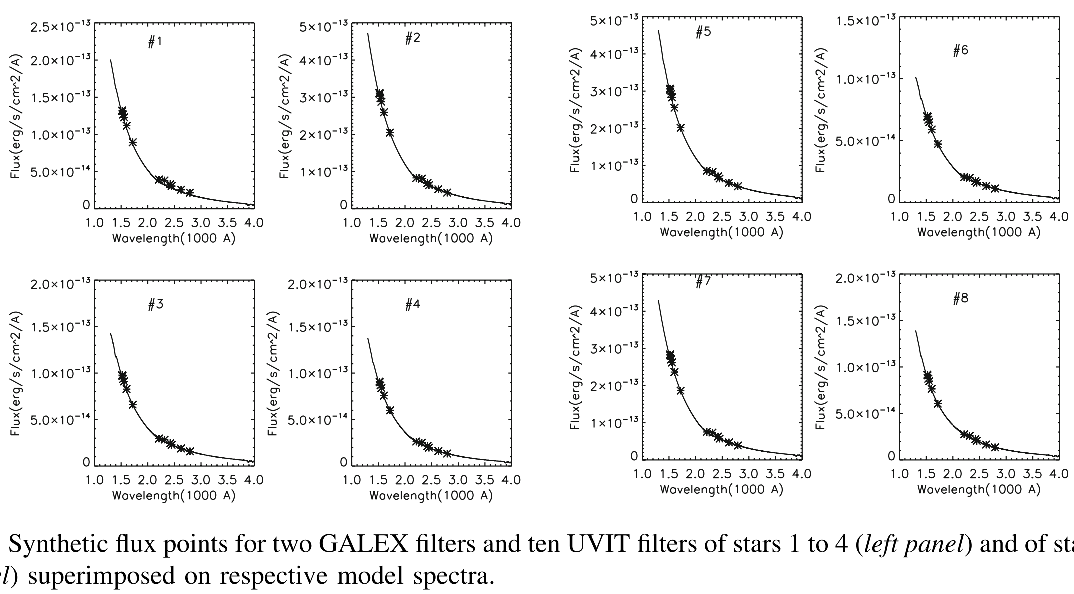

Figure 3. Synthetic flux points for two GALEX filters and ten UVIT filters of stars 1 to 4 (*left panel*) and of stars 5 to 8 in (*right panel*) superimposed on respective model spectra.

As an additional test, we reddened the model spectra of each star and repeated the run to compute the magnitudes through GALEX filters. To do this, UV extinctions (A_λ) are computed adopting A_v values from Siegel (2010) and using the CCM-89 model as detailed in the next section. The right panel of Fig. 4 shows UV extinction curves for eleven faint stars.

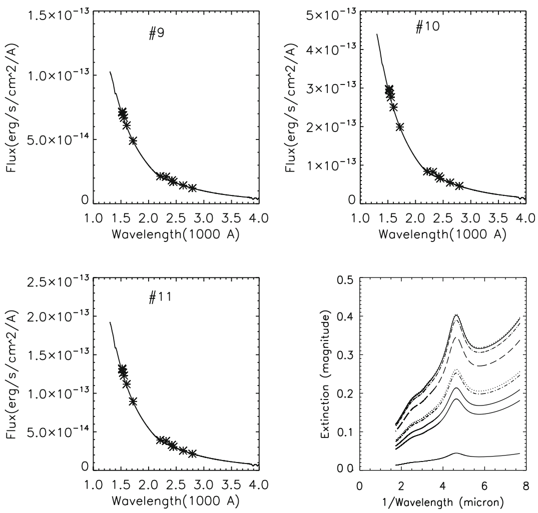

Figure 4. *Left panel*: Synthetic flux points for two GALEX filters and ten UVIT filters of stars 9 to 11 superimposed on respective model spectra. *Right panel*: UV extinction curves for eleven UV faint stars using CCM-89 model.

In Table 3, the columns 2 (FUV) and 3 (NUV) give unreddened synthetic magnitudes, the columns 4 (FUV) and 5 (NUV) give reddened synthetic magnitudes computed for GALEX FUV and NUV filters respectivly. The columns 6 (FUV) and 7 (NUV) are actual GALEX observations from Siegel (2010). The reddened magnitudes when corrected by the fit coefficients match the observed GALEX magnitudes within the errors.

Next, we performed the synthetic photometry of UV faint standards for UVIT filters. Table 4 gives the synthetic UV magnitues in columns 1 to 10. We have listed the AB magnitudes although magnitudes have been computed for both Vega and AB systems. In Fig. 3 and left panel of Fig. 4 the synthetic fluxes are superimposed on the corresponding model spectra. To obtain the expected magnitudes from UVIT observations we need to apply the fit coefficients and extinction (see next section). Figure 2 demonstarates strong GALEX vs. UVIT correlation of synthetic magnitudes. The column 1 is plots of GALEX-FUV vs. UVIT far-UV and column 3 is plots of GALEX NUV vs. UVIT near-UV. Filter names can be seen within the panels. The corresponding residuals are plotted on the right side panels (columns 2 and 4). The slopes of linear fit for various UVIT filters are as follows: F148W: 1.0018 ± 0.001, F148Wa: 1.0016 ± 0.001, F154W: 0.999 ± 0.0003, F169M: 0.996 ± 0.002, F172M: 0.938 ± 0.016, N219M: 0.995 ± 0.007, N245M: 0.992 ± 0.004, N263M: 0.989 ± 0.011, N279N: 0.983 ± 0.016, N242W: 0.993 ± 0.003. The residuals are within ± 0.06. Note that the residuals are higher for narrow band filters (F172M, N279N and N219M) than the broader bands. Such GALEX-UVIT correlation have been used for the in-flight photometric calibration of UVIT by Rahna (2017). In conclusion, given this detailed analysis including the UV extinctions, and the resulting strong correlations between (i) (synthetic vs. observed) quantities of GALEX as well as UVOT and (ii) synthetic photometry of (UVIT vs. GALEX) filter systems, it is strongly recommended that these faint stars be observed and included as UVIT flux standards.

3.1 *UV extinction*

Study of UV extinction is interesting due to its variation as a function of wavelength as well as along different sight lines. Several authors in literature have modelled UV extinction of which we prefer the model of (Cardelli et al. 1989; CCM-89). This model provides A_λ/A_v, the extinction normalized by visual extinction A_v. The values of visual extinction for each star were adopted from the Siegel's model parameters. The UV faint stars studied here are located at high Galactic lattitudes and extinctions are small. However it is necessary to account for the extinction in precise photometry and particularly for candidate standards. The extinction curves we computed for the faint stars are presented in th right panel of Fig. 4. In Table 5, we have tabulated the extinction (A_λ) at the mean wavelength $\lambda_{\rm mean}$ of each filter. The mean wavelengths $\lambda_{\rm mean}$ given in column 2 are computed using the equation below:

$$\lambda_{\rm mean} = \frac{\int \lambda S_\lambda {\rm d}\lambda}{\int S_\lambda {\rm d}\lambda}. \qquad (6)$$

4. Discussion and conclusions

We propose a set of 11 faint UV white dwarf stars as potential UV standards for UVIT. A detailed analysis of these stars using synthetic photometry has been carried out.

The set of 11 UV faint stars analysed here satisfy following selection criteria for all-sky secondary standards for UVIT:

(i) Stars known to be photometrically stable and single.
(ii) Location to be ~ 30 degree above or below the galactic lattitude.

Table A1. Effective wavelengths.

Star#	F148W	F148Wa	F154W	F169M	F172M	N219M	N245M	N263M	N279N	N242W
1	1488.76	1493.33	1530.48	1587.21	1714.71	2206.81	2438.91	2617.24	2791.37	2344.90
2	1488.88	1493.45	1530.49	1587.19	1714.65	2206.97	2439.39	2617.33	2791.36	2345.53
3	1491.03	1495.60	1532.11	1587.96	1714.89	2207.05	2439.55	2617.76	2791.43	2349.64
4	1488.91	1493.49	1530.66	1587.34	1714.77	2206.72	2438.64	2617.20	2791.38	2344.70
5	1488.84	1493.42	1530.53	1587.23	1714.72	2206.82	2438.94	2617.27	2791.37	2345.12
6	1491.28	1495.84	1532.26	1588.02	1714.88	2207.25	2440.12	2618.01	2791.45	2351.66
7	1488.94	1493.51	1530.54	1587.24	1714.65	2206.96	2439.35	2617.25	2791.35	2344.95
8	1488.83	1493.41	1530.68	1587.39	1714.82	2206.47	2437.89	2616.91	2791.36	2342.53
9	1492.02	1496.58	1532.79	1588.29	1714.92	2207.43	2440.63	2618.29	2791.48	2354.13
10	1490.24	1494.81	1531.51	1587.69	1714.78	2207.25	2440.15	2617.92	2791.43	2350.63
11	1491.14	1495.71	1532.19	1588.01	1714.88	2207.20	2439.98	2617.95	2791.45	2351.15

See Table 2 for star IDs.

(iii) Absence of any other bright source in the FoV for the safety of the on-orbit detectors.
(iv) The FoV to be uncrowded.
(v) Extinctions to be low in the line of sight.
(vi) Availability of UV observations or SEDs.

DA white dwarfs are ideal candidates for flux calibration. They have pure hydrogen atmospheres and hence lack spectral features in UV regime making it simpler to compute the model spectra. Siegel (2010) constructed the model spectra for 11 UV faint stars using the spectroscopic data of Sloan survey as well as photometry from GALEX and UVOT. Their models could reproduce the photometric measurements from GALEX and UVOT. We used these model spectra to compute synthetic photometry for UVIT, GALEX and UVOT filter systems and compared the results. The fact that (i) these stars were identified as standards for GALEX and UVOT, (ii) the correlation between synthetic vs. observed photometry with GALEX as well as UVOT filter system and (iii) the strong correlation between synthetic UVIT vs. GALEX filter systems makes them potential UV standards for UVIT. Finally, having a common network of standard stars across many UV missions allows photometric transformation and intercomparison easier and reliable.

Acknowledgements

This work has made use of MAST, SIMBAD and vizier data bases. IDL graphic package and Fortran 77 are used to write own codes. The work presented here is carried out at home without any institutional support. The software programs used here are advanced versions of preliminary programs developed during the tenure at Indian Institute of Astrophysics (IIA), Bangalore. I wish to acknowledge that the investigations presented here basically began from the initial discussions with Professor A. K. Pati (IIA) to compile 'An All-Sky catalog of secondary standards for UVIT' and then were developed further. The UVIT is built in collaboration between IIA, IUCAA, TIFR, ISRO and CSA. This publication uses the data from the AstroSat mission of the Indian Space Research Organisation (ISRO), archived at the Indian Space Science Data Centre (ISSDC).

Appendix

The effective wavelengths are given in Table A1.

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