GALEX Catalog of UV Point Sources in M33

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1 INTRODUCTION

M33, also known as the Triangulum Galaxy, was "officially" discovered by Messier [1781], although it might have been noted more than a century earlier by Hodiernus [1654]. There is a wide range of calculated distances for this Local Group galaxy, ranging from 700-1100 kpc, and we adopt a distance of d = 964 kpc [Bonanos et al. 2006]. Being so close, it is a well-studied galaxy indeed: as of June 2014, ADS reveals >1,200 refereed articles with “M33” in the abstract. M33 has been studied across many wavelengths (e.g., Helfer et al. 2003; Massey et al. 2006; Warner et al. 1973; Pietsch et al. 2004; Long et al. 2010; Thompson et al. 2009; Massey et al. 1996) and across time (e.g., Hubble 1926; Hubble & Sandage 1953; Freedman et al. 1997; Maeri et al. 2001; Hartman et al. 2006). Perhaps surprisingly, there have been relatively few studies of M33 in UV wavelengths (e.g., Massey et al. 1996; Thilker et al. 2005), and no catalog of points sources based on GALEX images of M33 has been published, a situation which we rectify in this paper.

The Galaxy Evolution Explorer (GALEX) was launched in 2003. It was designed as a UV all-sky survey, with 5 smaller surveys making up the first portion of the mission. The goal of the telescope was to gain a better understanding of galaxy evolution by studying local star formation, star formation histories, extinction, and UV galaxy morphology (Martin & GALEX Science Team 2003). The instrument consisted of a 50 cm telescope connected to two sealed tube detectors and microchannel plates with a peak quantum efficiency of about 10%. The dichroic splitter allowed for simultaneous observation in both the near and far UV filters spanning from 1750 to 2800Å, and effective wavelengths of 2267Å and 1516Å, respectively. The instrument has a 1.2° diameter field of view centered on the galaxy, and the full-width half-maximum (FWHM) of the exposure time of 3334 seconds. The simultaneous near-UV (NUV) and far-UV (FUV) images have passbands 1750-2800Å and 1350-1750Å and effective wavelengths of 2267Å and 1516Å, respectively. The instrument has a 1.2° diameter field of view centered on the galaxy, and the full-width half-maximum (FWHM) of the NUV and FUV detectors are 4''2 and 5''3, respectively, sampled with 1''5/pixel.

The d_{25}, the diameter at which the surface brightness drops to 25 mag/arcsec², for M33 is 1.2° (de Vaucouleurs et al. 1991), which corresponds well to the GALEX field of view. We began construction of our point source catalog with the total counts images from the GALEX pipeline, corrected for effective exposure times, by performing PSF photometry with a combination of the DAOPHOT and ALLSTAR programs (Stetson 1987). In our reduction, sources are required to have at least a 5σ detection, and we begin by fitting a purely analytic PSF for our baseline, a step that is strongly suggested for crowded sources as is the case with M33. A

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We begin by discussing the methods used for the construction of our catalog and matching against the GALEX pipeline, UIT, and optical catalogs of M33 in §2. In §3 we discuss the most interesting sources and aspects of our final product and then conclude.

2 DATA AND METHODS

2.1 UV Photometry

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1 We retrieved these images from the Barbara A. Mikulski Archive for Space Telescopes (MAST).
subset of the brightest and relatively isolated sources found under these conditions were then re-run through the reduction after subtracting out their nearest neighbors to iteratively improve the PSF model empirically. This refined PSF became the basis for our final source extraction. We then derived the necessary aperture correction on the brightest few hundred sources, separately for the two bands, by using successively larger apertures (after subtracting out all other detected sources) and measuring the magnitude offsets between these and those measured in the original reduction. For our aperture corrections, we found values of 0.03 magnitudes for the FUV and 0.06 magnitudes for the NUV. We next converted our instrumental magnitudes back to counts per second, which have been calibrated into both fluxes and AB magnitudes (Hayes & Latham 1975) by the GALEX Team (Morrissey et al. 2007). The AB magnitude system, in wavelength, is defined as

\[ m_v = -2.5 \log \left( \frac{F_\lambda}{c} \right) - 48.60, \]

where flux \( F_\lambda \) is given in erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\).

After applying the respective aperture corrections to the NUV and FUV catalogs and converting all sources to the AB system, we sought to match the FUV and NUV source catalogs. To do so while minimizing false matches, we began by matching using a 3 pixel maximum radius, or approximately 4.5\,″. As there were fewer sources in the FUV, we then kept only those sources with only one NUV match to a given FUV source within this radius. With this stringent cut of relatively large matching radius combined with only a single match, this list would contain a high concentration of correct source pairings. From these matches, we found the average offset between the NUV and FUV sources’ magnitudes (i.e. colors) and positions, along with the dispersion around these two values. These were then used to do a second round of matching the NUV to the FUV source list, keeping sources with more than a single counterpart in the NUV this time, based on minimizing the distance between objects in position-magnitude space with a maximum allowed physical separation of 2 pixels, or \( \sim 3'' \). This resulted in a catalog of 27901 distinct GALEX FUV sources with NUV matches.

As a sanity check, we compared our results to the GALEXPipeline-provided catalog for M33\(^2\). These were found using the Source Extractor program (Bertin & Arnouts 1996) and are provided alongside the images in the MAST archive. The GALEX catalog, combined between NUV and FUV, has a total of 8843 sources. Individually, the NUV catalog has 6740 sources while the FUV catalog is comprised of 4129 sources. The GALEX pipeline did not require a source to be detected in both bands to be reported. The NUV sources in the GALEX catalog run the range of 11.0-28.1, while the FUV runs the range of 10.5-24.9. Our catalog is quite different, however, with the NUV spanning the range of 14.4-23.8 mag and the FUV going from 14.9-23.4. This is largely due to the fact that the ~20000 sources that are fainter than our limits but are present in the GALEX catalog are NUV-only sources, which would not pass the criteria necessary to be included in our catalog.

The average magnitude offset between our sources and their matching counterparts in the GALEX-provided catalog in the NUV was 0.01 mag. For the FUV, this offset was 0.06. In both of these cases, this difference is in the direction that our sources are slightly brighter than the corresponding ones in the GALEX catalogs.

We then compared our catalog to the existing UV catalog of M33 sources compiled in Massey et al. (1996). This catalog was made using the Ultraviolet Imaging Telescope (UIT), an instrument aboard the Astro-1 Mission (Stecher et al. 1992). UIT used photographic plates with the B1 and A1 filters roughly corresponding to the FUV and NUV filters of GALEX, having central wavelengths of \( \sim 1500\,\text{Å} \) and \( 2400\,\text{Å} \), respectively. It should be noted, however, that the A1 filter is significantly broader than the NUV filter on GALEX, reaching several hundred angstroms to the red end of its GALEX counterpart. The field of view of UIT is also circular but has a smaller radius of 18′, which can be seen within the GALEX field of view in Figure 1. The FWHM of UIT is comparable to that of GALEX, at 4′′ and 5′′/2 in the NUV and FUV filters, respectively. GALEX, however, reaps the reward of technological advancement over time in its implementation of more efficient microchannel plates instead of UIT’s photographic ones. For more information on UIT and its detector’s properties, see Stecher et al. (1992) and Landsman et al. (1992).

Similar to the analysis route we adopted, Massey et al. (1996) only keep sources for which there are both NUV and FUV detections, and they supplement these with \( U, B, \) and \( V \) ground-based data as well. Their final catalog has 356 sources (note that the catalog naming scheme goes as high as 374 as certain numbers are skipped), which they judge to be complete to an FUV AB magnitude of \( \sim 18.5 \), corresponding to a specific flux of \( F_{1500\,\text{Å}} = 2.5 \times 10^{-15} \,\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1} \), and its faintest source has an FUV magnitude of 19.7, corresponding to a specific flux of \( F_{1500\,\text{Å}} = 6.4 \times 10^{-16} \,\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1} \). The GALEX observations are much more sensitive, and over 20,000 of our sources are fainter than this, a difference that is highlighted in Figure 2. The faintest source in our final catalog has an FUV magnitude of 23.3, corresponding to a specific flux of \( F_{1500\,\text{Å}} = 2.3 \times 10^{-17} \,\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1} \).

Looking at the astrometry solution for GALEX, we found there were some slight distortions in the two images, especially near the edges of the galaxy. We use the astrometry.net world coordinate system (WCS) solution for our field (Lang et al. 2012).
to correct this. As the FUV image image does not have enough sources outside the galaxy to find a solution, we apply the solution for the NUV image to the FUV one as well. Similar to the procedure followed for matching our NUV and FUV sources internally, we matched to the UIT catalog, this time with a radius of 3′′2 to complement our previous maximum radius, cut to those sources for which there was only a single UIT star within this radius, and then found the average and standard deviation for the magnitude and position offsets between the two catalogs. After this, we rematched based on magnitude and position once again. The distribution of matches by separation is shown in Figure 4. From this, we decided to stick with a maximum radial separation of 3′′2 as before. The remaining sources making this cut had a right ascension and declination offsets (UIT - GALEX) of 0′′17 and 0′′08, respectively. Both of these are quite small compared to the size of the PSF.

This final catalog had 348 sources in common with the original UIT catalog of M33, which contained 356 sources. The average difference between NUV magnitudes (UIT - our catalog) is 0.73 mag with a spread of 0.38. For the FUV filters, the same calculation gives an offset of ∼0.04 mag and a dispersion of 0.60. These offsets as a function of magnitude in both NUV and FUV are shown in Figure 4. While the NUV has a large offset, it does not appear to have any structure in it, whereas the FUV shows a trend of the GALEX photometry of faint sources being systematically fainter than in the original catalog. Looking at the eight sources that we did not recover, seven of them were in crowded regions separated into sources by our PSF photometry differently than UIT such that the UIT object had several potential GALEX matches surrounding it, but none were within the matching radius. The final source, [MBH96] 167, is in a more diffuse, fainter region and it is surprising that it does not appear in our catalog given that GALEX has a higher sensitivity than UIT. We investigate our raw photometry and the images themselves and found this object appears in both of the images and in the initial far-UV photometry but was not selected as a near-UV source and hence did not make it into our catalog.

After that, we inspected by eye many of the sources with the largest discrepancies in magnitude (Δ mag>1) in either band between the UIT and our catalog. The largest offsets in the FUV were typically sources that were in crowded regions that were split into several sources in GALEX and tended to be brighter in UIT, as one might expect. The largest offsets in the NUV, however, were all brighter in our catalog. Most of these were in more diffuse or isolated regions compared to the more clustered FUV-discrepant sources. There were a total of 65, 30 sources differing by more than a magnitude in the NUV and FUV, respectively.

To test for any systematic separation between our magnitudes and those from [Massey et al. 1996] due to differences in the filter shapes of UIT and GALEX, we applied the four filter curves (UIT A1, B1 and GALEX FUV, NUV) to various temperature black bodies to estimate what the magnitude separation would be between UIT and GALEX. The FUV filters for the two instruments are quite similar, and, as such, the magnitude difference for a 40,000 K black body (UIT - GALEX), a temperature equivalent to a warm O star,
Figure 3. AB magnitude difference between UIT [Massey et al. 1996] and our GALEX catalog as a function of GALEX NUV (left) and FUV (right) magnitude.

was -0.02, which is quite close to the average offset we reported above. For the NUV, however, the 40,000 K black body has a magnitude difference (again, UIT - GALEX) of 0.17, which does not fully account for the average NUV offset we find.

The UIT catalog, with both the original and newly-derived GALEX parameter values (when available), is presented in Table 2.
| UIT  | \( \alpha_U \)   | \( \delta_U \)   | \( \alpha_G \)   | \( \delta_G \)   | FUV\(_U\) | NUV\(_U\)  | FUV\(_G\) | NUV\(_G\)  | FUV\(_U-G\) | NUV\(_U-G\) | Sep(\(''\)) |
|------|------------------|------------------|------------------|------------------|-----------|-----------|-----------|-----------|-------------|-------------|------------|
| 2    | 23.13300         | 30.58275         | 23.13335         | 30.58262         | 18.19     | 18.31     | 18.03±0.06 | 17.62±0.03 | 0.09        | 0.69        | 1.18       |
| 3    | 23.15708         | 30.66825         | 23.15577         | 30.66829         | 17.44     | 17.35     | 17.59±0.08 | 16.86±0.02 | 0.01        | 0.49        | 0.97       |
| 4    | 23.15854         | 30.66797         | 23.15813         | 30.66810         | 17.70     | 18.31     | 17.69±0.06 | 17.48±0.03 | -0.94       | 0.83        | 1.35       |
| 5    | 23.17871         | 30.64644         | 23.17855         | 30.64642         | 18.15     | 17.84     | 18.26±0.15 | 16.96±0.01 | 1.37        | 0.88        | 0.50       |
| 6    | 23.18583         | 30.58325         | 23.18597         | 30.58333         | 17.67     | 17.93     | 17.80±0.09 | 17.40±0.08 | -0.35       | 0.53        | 0.52       |

**Table 1:** UIT sources that were recovered using GALEX data. Here, 'Matches' refers to the number of GALEX objects we find that are within 5\(''\) and compatible with the given UIT source. The subscript 'U' stands for UIT, whereas the subscript 'G' stands for GALEX. The first five sources are given to show the formatting. The full version of this table is available in the online version.
Having completed our first goal of updating the UIT catalog of known M33 UV sources with GALEX photometry, we next set out to expand on this with our additional $\sim 25,000$ sources. To this end, we combine our UV sources with optical counterparts found in a similar-depth study of M33 in U, B, V, R, and I from the Local Group Galaxies Survey (LGGS; Massey et al. 2006).

First, we matched our catalog to the LGGS one with our previous matching radius of $3''2$. As before, to get an idea of what physical matches look like, we investigated those sources that only had a single optical counterpart within the matching radius. This informed us of the true sky separations and colors we might expect from all real matches, since these sources are relatively isolated and there will be little confusion in any matching for them. These single matches are shown in Figure 5. Of special note is the blue vertical line in the figure. This represents approximately the bluest color a blackbody can have (NUV - V = -2.5), assuming both the NUV and V data lie on the Rayleigh-Jeans tail on the red side of the Wien’s Law peak. Stars can, of course, get around this via emission and absorption, but it is illustrative to know what fraction of our sources are “unphysically” blue. In this subsample, we find that only 0.1% of our pairs are bluer than this line. The average color (NUV-V) of all our singly-matched sources is -0.09, but the dispersion is not surprisingly high, given the wealth of different stars we are probing, at 0.82.

Enlightened by our clean, 1:1 sample, we then iteratively redefined our matching algorithm, i.e. combinations of colors and positional offsets, to determine our final matches. We expected that a successfully matched paired catalog would have similar properties to that shown in Figure 5. The full matched CMD is shown in Figure 6. We note that it is bluer on average than the clean sample at -0.42 mag with a median of -0.45 mag, has slightly lower dispersion, and the same fraction of “too blue” stars.

Investigating some of the brightest of these “too blue” sources, a pattern emerges. The brightest of these are all surrounding bright foreground objects and are thus likely being affected by image processing artifacts and their proximity to these extremely bright stars. The rest appear to cluster in a single dense region of the galaxy.

Our final catalog, with data spanning 1516-7980Å for most stars, is provided in Table 2.2 and has a total of 24738 sources. Note that the catalog has been constructed in such a way that each detected FUV source appears only once, but that each optical source has the freedom to match to more than one FUV source. When this happens, we report all the separate UV sources that have each given optical star as its best match. The average number of optical matches to a given UV source is 2.75 with a maximum of 20. The average positional offset between UV and V coordinates is 1''25 with a standard deviation of 0''74. These are both smaller than the FWHM of the GALEX detector. We also calculate approximate luminosities in each band by using the effective wavelengths of each filter, the GALEX calibrations for the near- and far-ultraviolet flux zeropoints and optical zeropoints taken from Bessell et al. (1998), and the distance to M33 adopted from Bonanos et al. (2006).
### Full Catalog

| Name                  | $\alpha_{\text{UV}}$ | $\delta_{\text{UV}}$ | $\alpha_{\text{Opt}}$ | $\delta_{\text{Opt}}$ | FUV     | NUV     | V           | B-V       | U-B     | V-R     | R-I       | Sep(") | Matches |
|-----------------------|-----------------------|-----------------------|------------------------|------------------------|---------|---------|-------------|-----------|---------|---------|-----------|---------|---------|
| J013146.73+303118.0   | 22.94532              | 30.52193              | 22.94471               | 30.52167               | 22.564±0.207 | 22.184±0.097 | 22.110   | 1.256    | 99.999 | 0.710  | 0.805     | 2.111   | 1       |
| J013148.03+303031.2   | 22.95054              | 30.50867              | 22.95012               | 30.50867               | 21.097±0.138 | 20.301±0.099 | 21.547   | 0.237    | -0.647 | 0.520  | 0.064     | 1.303   | 1       |
| J013148.46+303030.3   | 22.95151              | 30.50780              | 22.95192               | 30.50842               | 21.126±0.144 | 20.248±0.134 | 20.129   | -1.476   | 2.557  | 0.908  | -0.262    | 2.569   | 3       |
| J013148.46+303030.3   | 22.95214              | 30.50871              | 22.95192               | 30.50842               | 20.810±0.090 | 19.984±0.057 | 20.129   | -1.476   | 2.557  | 0.908  | -0.262    | 1.247   | 3       |
| J013148.58+303037.7   | 22.95223              | 30.51031              | 22.95242               | 30.51047               | 20.701±0.129 | 20.227±0.076 | 21.000   | 0.182    | 0.008  | 0.211  | 0.274     | 0.824   | 3       |

Table 2: Our UV sources that had optical counterparts from the LGGS. Note that the FUV and NUV magnitudes are in the AB system whereas the $U$, $B$, $V$, $R$, and $I$ data are all in the Vega system. Here, 'Matches' refers to the number of optical objects we find that are within 3" of the GALEX source. Note that 'Sep' refers to the absolute separation between the object's position in the UV and optical catalogs. The full version of this table is available in the online version.
DISCUSSION

With our UV/optical catalog in hand, we next investigate a selection of the more well-known stars in M33 that are likely also UV bright. First, we look at a selection of Wolf-Rayet stars (WR), thought to be massive (>20M\(_\odot\)) stars that have blown off their envelopes and have become essentially hot, exposed stellar cores. With effective temperatures typically in excess of 30,000 K and occasionally reaching well over 100,000 K, these stars should peak at a wavelength blueward of even GALEX’s FUV filter. As such, ignoring any absorption or extinction, we expect these stars to have the highest luminosity in the FUV from the bandpasses presented here. In Figure 7, the sources [MBH96] 16, Romano’s Star (Romano 1978), and [MBH96] 77, presented in the top and middle rows, are a selection of the most well-known WR stars in the galaxy. [MBH96] 16, as can be seen from the figure, has three separate UV matches to its optical counterpart in our data. Two of these peak in the NUV, whereas one continues to rise in the FUV. Since it is a WR star, the most likely true match is this hottest UV source. Romano’s Star, [MBH96] 77, LGGS J013358.69+303526.5, and LGGS J013406.80+304727.0 also exhibit this behavior, albeit with somewhat different slopes. Comparing our sources to a catalog of known WR stars in M33 (Neugent & Massey 2011), we recover 114 out of a total 206.

Another star we investigate is a detached eclipsing binary used by the DIRECT Project (Bonanos et al. 2006) to measure the distance to M33 itself, whose SED is presented in Figure 8. The two stars in this binary have derived temperatures in excess of 35,000 K. Our best matches, however, peak in the near-UV rather than the FUV, as one might expect. Next, we look at M33 X-7 (e.g. Long et al. 1981, 2010), a high mass X-ray binary. From Figure 8 we see that it is quite luminous in the UV bands, as might be predicted due to the presence of both an accreting compact object and a hot stellar companion. We also have a number of well-studied blue supergiants in our sample, including Hubble-Sandage Variable B (Hubble & Sandage 1953) and 2MASS J01332895+3047441 (Kunchev & Ivanov 1986; Ivanov et al. 1993; Skrutskie et al. 2003). These stars, although blue, are much cooler than WR stars and we anticipate them to peak at longer wavelengths. Both matches to 2MASS J01332895+3047441 peak in the NUV. This star has been classified as a B-type supergiant (Massey et al. 2006), which can indeed be warm enough to peak blueward of the optical range.

After searching the catalog for known interesting sources, an obvious next step is to look at the luminous stars in the catalog. We present the 6 most luminous sources in Figure 9 where “most luminous” here is defined as the summation of fluxes from all available bands. Immediately a trend appears. All of these stars have most of their flux in the optical bandpasses and the UV data contributes minimally to their total bolometric luminosity. The brightest stars in the catalog, then, are likely all relatively common and cooler red supergiants, though there may be also some of the rarer yet more intrinsically luminous yellow supergiants, as well as a few foreground sources.

For which stars does the UV data significantly change their inferred bolometric luminosities? To answer this question, we present the six stars with the highest luminosity in GALEX’s FUV bandpass in Figure 10. Three of these were found in the UIT catalog of M33, but three are new UV sources. All of these tend to have near and far-UV luminosities of around 10^6L\(_\odot\). This is a factor of six down from the peak bandpass luminosity in Figure 9 but it is of the same order of magnitude as in those stars. The difference is that the UV bright stars are bright solely in the UV, often dropping by at least a factor of two in flux between the near-UV and V bands. And this is not unexpected of extremely hot stars which will emit significantly in the UV but have their flux fall continually in redder bands.

With this work, we seek to update and expand the existing UV catalog of M33 using archival GALEX data. Using FSP photometry to better manage crowded fields, we find tens of thousands of more sources than in the pipeline product. We match these to the UIT catalog (Massey et al. 1996) and recover all but eight of these sources. Next, we match to an optical catalog from the LGGS (Massey et al. 2008) to create a final table of 24738 sources, with many of these spanning seven filters from the far-UV to near-IR. We then investigate the properties of our catalog and find that the most overall luminous sources are typically brightest in the optical bands (and hence likely evolved stars), but there are still many sources that are continuing to rise in the UV range, indicating high effective temperatures.

A useful future endeavor would be to perform a similar analysis with the Swift UV data of M33 (Immler & Swift Satellite Team 2008). Swift covers 3 UV filters with high spatial resolution, which would further assist in lessening the obvious crowding issue that is persistent in both the GALEX and UIT data.

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Figure 7. A selection of some of the UV-brightest and most well-studied Wolf-Rayet stars in M33 that are in the final catalog. **First Row**: [MBH96] 16 (left) and Romano’s Star (right). **Second Row**: [MBH96] 77 (left) and J013432.60+304705.9 (right). **Third Row**: LGGS J013358.69+303526.5 (left) and J013406.80+304727.0 (right). In the top-right corner of each panel, the value “N” corresponds to the number of optical sources that were within 3″ of the UV source and is provided as a measure of crowding, which tended to be most severe for the few hundred brightest of the UV sources. In the cases where there are multiple UV sources with a given optical star as its best match, the value given for “N” is the average amongst these sources. For a description of the matching process, see §2.2.
Figure 8. Same as Figure 7 but for other, non WR sources in M33. First Row: MBH96 196, a detached eclipsing binary that has been used to measure the distance to M33, and M33 X-7 (HMXB). Second Row: Hubble-Sandage Variable B (left) and 2MASS J01332895+3047441, both blue supergiants.
Figure 9. Same as Figure 7 but for the six most luminous stars in the catalog (combination of all bands). We note that the UV brightest stars also tend to be the most crowded, as is evident from the large values of “N”.

GALEX Catalog of UV Point Sources in M33
Figure 10. Same as Figure 7 but for the six stars with the highest UV luminosity in the catalog.