AstroSat/UVIT Cluster Photometry in the Northern Disk of M31

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Abstract

The Andromeda galaxy (M31) is an object of ongoing study with the Ultraviolet Imaging Telescope (UVIT) on AstroSat. UVIT far-UV (FUV) and near-UV (NUV) photometry is carried out here for a set of 239 clusters in the NE disk and bulge of M31 that overlap with the HST/PHAT survey. Padova stellar models were applied to derive ages, masses, metallicities, and extinctions for 170 clusters. The ages show a narrow peak at $\sim$4 Myr and a broad peak around 100 Myr. $\log(Z/Z_\odot)$ values are mostly between $-0.3$ and $+0.3$. The 7 clusters in the bulge have a low metallicity and high mass. Most clusters are in the spiral arms and have metallicities in the range noted above. The youngest clusters mostly have high metallicity and are concentrated along the brightest parts of the spiral arms. The UVIT FUV and NUV data are sensitive to young stars and detect a new metal-rich peak in star formation in the disk at age $\sim$4 Myr.

Unified Astronomy Thesaurus concepts: Andromeda Galaxy (39); Star formation (1569); Photometry (1234)

Supporting material: machine-readable tables

1. Introduction

The Andromeda galaxy (M31) is our closest neighboring giant spiral galaxy and has many similarities to our galaxy. It can serve as a template for studies of parts of our galaxy that are obscured by extinction. M31 has a well-measured distance (McConnachie et al. 2005) of 785 ± 25 kpc (3.2% error). The small distance uncertainty leads to well-measured luminosities for objects in M31.

M31 has been observed extensively in optical bands. The Hubble Space Telescope has yielded the highest-resolution observations. These include the Pan-chromatic Hubble Andromeda Treasury (PHAT) survey (Williams et al. 2014). The GALEX instrument has observed M31 (Martin et al. 2005) in near- and far-ultraviolet (NUV and FUV) bands.

The optical studies have resulted in a wealth of information about M31, including its star formation history (SFH) and metal enrichment history. Dong et al. (2018) and references therein) study the SFH of the bulge of M31 and compare results from a color–magnitude diagram (CMD) analysis with a spectral energy distribution (SED) analysis. Hammer et al. (2018) and references therein) explore the merger history of M31, using simulations to explain the long-lived SFH of the 10 kpc ring in the disk. Williams et al. (2017) map the SFH across the northeast section of M31 covered by the PHAT survey ($\sim$1/3 of the whole disk), using a large number ($\sim$3300) of small regions and obtain resolved maps of the SFH and stellar mass.

More recently, M31 is part of an ongoing survey in NUV and FUV with the UltraViolet Imaging Telescope (UVIT) on AstroSat (Leahy et al. 2020). The instruments onboard AstroSat include the following: the UltraViolet Imaging Telescope (UVIT) covers the FUV and NUV, while the Soft X-ray Telescope (SXT), Large Area Proportional Counters (LAXPC), Cadmium-Zinc-Telluride Imager (CZTI), and Scanning Sky Monitor (SSM) instruments cover soft through hard X-rays (Singh et al. 2014).

UVIT has a high spatial resolution ($\sim$1″), which allows individual stellar clusters and stars in M31 to be identified. Leahy et al. (2021c) presents an analysis of the structure and stellar populations of the bulge. Leahy et al. (2021b) identify FUV-variable sources in the central 28′ of M31. Leahy et al. (2020) published the UVIT point-source catalog for M31. UVIT sources that match with Chandra sources in M31 are analyzed by Leahy & Chen (2020), and initial results of matching UVIT sources with PHAT sources are given by Leahy et al. (2021a). Leahy et al. (2018) analyzed UV-bright stars in the bulge, showing the existence of young stars in the bulge.

In this work, we analyze the stellar clusters in M31 from the PHAT Stellar Cluster Survey (Johnson et al. 2015) using combined UVIT and HST data. We use the M31 UVIT observations to obtain FUV and NUV photometry for 239 clusters, and provide the table of UVIT photometry in Section 2.1. We fit the combined UVIT and HST photometry using stellar cluster models and give the cluster model fits in Section 2.2. The model fits are presented and interpreted in Section 3, and our conclusions are summarized in Section 4.

2. Observations and Data Analysis

UVIT observed M31 galaxy in 19 fields with a diameter of 28 arcminutes, covering the NUV to FUV wavelengths (Leahy et al. 2020). Tandon et al. (2017) and Tandon et al. (2020) give a detailed description of the UVIT instrument and its filters, which are labeled by their central wavelength in nm. Four of the 19 fields overlap the region surveyed in PHAT and have measurements in the two UVIT NUV filters (Johnson et al. 2015).

The data processing is carried out using the astrometry corrections given in Postma & Leahy (2020) and data processing and calibration methods given in Leahy et al. (2020).
2.1. Cluster Selection and Photometry

The UVIT M31 survey (Table 1 and Figure 2 of Leahy et al. 2020) covers the PHAT region. In the overlap region, UVIT Fields 1, 2, 7, and 13 have both FUV and NUV observations, so we chose these four fields for our analysis. We identified the clusters in Johnson et al. (2015) that are located in these four fields, and then carried out photometry at the cluster positions in the UVIT data using CCDLAB (Postma & Leahy 2017, 2020, 2021).

We used a fitting box size of 9 pixels (∼3″/7) to correspond with previously calculated photometric conversions from Leahy et al. (2021b). As a result, we restricted our analysis to sources with an angular diameter smaller than 1″ in Johnson et al. (2015) to ensure accurate photometric measurements. This process yielded 183 clusters in Field 1, 335 clusters in Field 2, 2,618 clusters in Field 7, and 184 clusters in Field 13. For the UVIT photometry, if the magnitude calculated by CCDLAB was found at a position more than 1″ from the initial position in Johnson et al. (2015), we consider that to be a nondetection and list it as a missing value.

Of the 970 clusters, we selected 281 cluster measurements for which we have a magnitude or upper limit for every filter from Johnson et al. (2015) and a magnitude brighter than 23 for UVIT filters F148W, F172M, N219M, and N279N. Most Field 1 clusters also have an F169M magnitude. Of the cluster measurements, 84 of them are pairs of measurements from two adjacent fields. Thus, we combine these flux measurements into 42 unique cluster measurements weighted by their exposure times. This gives a total of 239 clusters. Of these, 238 have F148W, N219M, and N279N magnitudes; 239 have F172M magnitudes; and 70 have F169M magnitudes. The photometry measurements are given in Table 1 (the full table is given online).

The ranges of UVIT AB magnitudes for the 239 clusters are 17.26 to 23, mean 20.66 for F148W; 16.83 to 23, mean 20.63 for F172M; 17.26 to 23, mean 20.59 for N219M; 16.64 to 23, mean 20.10 for N279N; and 17.76 to 23, mean 20.66 for F169M. Because the errors in the N279N measurements are significantly larger than the PHAT F275W measurements and the magnitudes are consistent, we omit the N279N values from Table 1.

Systematic errors in the photometry include ∼1% calibration uncertainty (Tandon et al. 2017) and an uncertainty in the correction factor (Leahy et al. 2021b) of several percent to account for overlap in the extended wings of the UVIT point-spread function (Tandon et al. 2017). There are also systematic errors in the cluster models of a few percent (e.g., see the discussion in Williams et al. 2017). To account for these systematic errors in the photometry, we tried two cases: (i) add an error of 0.05 magnitude, and (ii) add an error of 0.1 magnitude in quadrature to the statistical error for the magnitudes.

2.2. Cluster Model Fits

To obtain cluster properties (mass, age, metallicity, and extinction), we created a Python program to model the UVIT and PHAT magnitudes with published stellar cluster models. We chose to use the Padova stellar models with a Kroupa initial mass function (Kroupa 2001), as did the work of Johnson et al. (2016).

The models were calculated using the CMD 3.4 online tool at http://stev.oapd.inaf.it/cgi-bin/cmd. Leahy et al. (2022) give a more complete description of the program. The program reads in a large grid of Padova stellar models with different metallicities (log(Z/Z⊙) = −2.616 to 0.303) and age (3.98 × 10⁶ yr to 1.5 × 10⁹ yr), then carries out a two-dimensional interpolation to obtain the multiband fluxes for any age and metallicity within these ranges. Extinction is calculated using the extinction law of Fitzpatrick & Massa (2007). The program finds the best-fit stellar cluster parameters (age, log(Z/Z⊙), mass, and extinction E(B−V)) by χ² minimization. For each cluster, we calculated fits for a grid of parameters around the best-fit parameters to determine the 1σ parameter uncertainties.

For the 239 clusters, we fit the combined HST F275W, F336W, F475W, F814W, F110W, and F160W filter photometry from Johnson et al. (2015) with the UVIT filter F148W, F172M, F169M, and N219M photometry. We chose not to fit the N279N filter because it covers essentially the same waveband as the F275W filter and has significantly larger uncertainties. We added a systematic error to the photometry, as noted above. The fits with 0.05 magnitude systematic errors...
The net result was that we obtained model fits for 170 clusters with UVIT photometry (labeled UVIT-PHAT clusters).

Using the fitting program, we obtained best-fit values of \( \log(Z/Z_{\odot}) \), \( \log(age) \), \( \log(M/M_{\odot}) \), and \( E(B-V) \) for these clusters. \( \log(Z/Z_{\odot}) \) and \( \log(age) \) were allowed to vary in the above specified ranges. \( E(B-V) \) was allowed to vary between 0 and 1, and the normalization \( (\log(M/M_{\odot})) \) was allowed to vary freely. The parameter errors were determined by calculating \( \chi^2 \) values for a finely spaced grid of parameters around the best-fit values of \( \log(age) \), \( \log(Z/Z_{\odot}) \), and \( E(B-V) \). For each set of these three parameters, the normalization \( (\log(M/M_{\odot})) \) was minimized.

Figure 1 shows an example best-fit for one of our sources. To illustrate the changes in photometry that result from the variation of single cluster parameters, Figure 1 shows six additional model curves. We renormalize each curve to match the data at 336 nm in order to emphasize the difference in shape of the different curves. Increasing age by a factor of two results in a redder spectrum (faint in FUV and NUV, bright in NIR), and decreasing age by factor two has the opposite effect. Changing the extinction, \( E(B-V) \), by \( \pm 0.08 \) has a similar effect: a redder spectrum for higher extinction, and a bluer spectrum for lower extinction. Extinction and age are only partially degenerate because they have quite different effects for the intermediate wavelengths (between 300 and 1000 nm) and the depth of the 220 nm dust absorption peak is dependent on extinction, but not age. Changing the metallicity, \( Z \), has a smaller but similar effect to age in changing the cluster model photometry. The effect of changing mass (normalization of the photometry) is not shown because it does not change the shape of the spectrum.

The parameters from the cluster model fitting are given in Table 2. The distribution of the best-fit \( \chi^2 \) values is shown in Figure 2. Table 3 shows the statistics of the \( \chi^2 \) values, the fit parameters, and their errors.

### 3. Results and Discussion

#### 3.1. Cluster Masses, Ages, Metallicities, and Extinctions

The histogram of the best-fit cluster parameters is shown in Figure 3. Fit masses range from \( \sim 60 \) to \( 2 \times 10^6 \ M_{\odot} \), with a mean error of a factor of 1.4 (0.15 error in \( \log(M/M_{\odot}) \). The mass distribution has a single broad peak at \( \sim 1000 \ M_{\odot} \). Fit ages range from \( 4 \times 10^6 \) to \( 2 \times 10^9 \) yr, with a mean error of a factor of 1.5. There is a narrow age peak at \( 4 \times 10^6 \) and a broad peak around \( 1 \times 10^8 \) yr.
Fit metallicities, \( \log \left( \frac{Z}{Z_{\odot}} \right) \), range from greatly subsolar \((-2.3)\) to supersolar \((+0.3)\), with a mean error of 0.24. There is a peak with \( \log \left( \frac{Z}{Z_{\odot}} \right) \);\(-0.3\) to \(+0.3\). Fit extinctions, \( E(B-V) \), have a fairly smooth distribution over the range from 0 to 0.6. \( E(B-V) \) mean fit errors are 0.08.

The metallicities of the clusters are shown plotted against age (top panel of Figure 4). Ninety-nine of the UVIT clusters were previously studied by Johnson et al. (2016) using a CMD analysis. They are marked in Figure 4 by the blue points. Most clusters (\( \sim 80\% \)) have \( \log \left( \frac{Z}{Z_{\odot}} \right) \) above \(-0.3\). No clear correlation of metallicity with age is seen, except that the oldest clusters (\( \log \frac{(\text{age} \text{ yr})}{\text{yr}} > 8.7 \)) are all metal poor. The plot of masses versus ages is shown in the bottom panel of Figure 4. There is a clear correlation of mass with age: older clusters are more massive.

### 3.2. Spatial Distribution of Cluster Properties

The locations of the UVIT-PHAT clusters are plotted in Figure 5 on top of the UVIT F148W mosaic image of M31 (Leahy et al. 2020). The \( \log \left( \frac{Z}{Z_{\odot}} \right) \) values are shown by the radii of the circles at the cluster positions. The majority of the clusters are located within the UV-bright spiral arms, with a small subset of about 7 clusters around the central bulge of M31 and about 10 clusters located between the arms. The clusters around the bulge all have a low metallicity, whereas the arm and interarm clusters show a wide range of metallicity.

Along the main spiral arm running diagonally across the image from NE to SW, the metallicities of the clusters are mostly positive, but about 20\% of the clusters have negative values. The inner arm has a similar metallicity pattern.

Figure 6 shows the ages of the clusters in the M31 F148W image. The youngest clusters are located along the central
bright ridges of the spiral arms. This can be seen, e.g., for the clusters near R.A. 10°55', decl. 41°12' or clusters near R.A. 11°18', decl. 41°37'. Both groups of clusters are located on the main spiral arm running diagonally from southwest to northeast across the image. Six of the seven clusters around the bulge are old (age > 3 × 10^8 yr, in magenta), and the other old clusters are not clearly correlated with the spiral arm positions. The intermediate-age clusters (in blue) are mostly near the spiral arms, and ~10 to 20% lie in the interarm or near bulge regions.

The masses of the clusters (not shown) look very similar to the ages on the M31 F148W image. The low-mass clusters are located along the spiral arms at the same positions as the low-age clusters. This is consistent with the correlation of mass and age shown in Figure 4. The seven clusters around the bulge are all massive (M > 10^5 M_\odot) and have a low metallicity (Figure 5). A few other massive and low-metallicity clusters are found in interarm regions.

The cluster extinctions, E(B−V), (not shown) have no correlation with the positions of the spiral arms or the bulge. The clusters near the bulge or the spiral arms can have high or low extinction. High-extinction clusters and low-extinction clusters often lie near each other. This is consistent with extinction caused by the line-of-sight depth into M31.

To test for variations in the cluster properties from the center of M31, assuming the clusters are concentrated in the disk of M31, we correct for the inclination of M31, which is 77°. The deprojected distance from the center in the disk plane, R in degrees, is calculated for each cluster. At the distance of M31, 0°.1 corresponds to a distance of 1.37 kpc.

The number of clusters versus R is shown in Figure 7. The two peaks in the number of clusters are from the clusters associated with the inner arm at a distance of 4.8 kpc and the clusters associated with the main spiral arm at a distance of 10 kpc from the center of M31. The main spiral arm has ~130 UVIT-PHAT clusters in it, and the inner arm has ~40 clusters. The peaks are broader than the width of each spiral arm because R of the center of the spiral arms changes with position angle.

The metallicities of the clusters with model fits are shown in Figure 8. Most disk clusters (outside of 0°.3) have log(Z/Z_\odot) between −0.3 and +0.3. In the bulge region (inside 0°.3), most clusters are metal poor. Panel (b) shows the ages of the clusters. Inside 0°.3 (4 kpc), there are only old clusters. In the dense regions of the inner and main spiral arms, there are old, intermediate, and young clusters. The few old clusters might be bulge clusters in projection on the disk. The young clusters (~10^7 yr) are smaller in number (by a factor of ~2) than the intermediate-age clusters (~10^8 yr).

Panel (c) shows the cluster masses. Inside 0°.3 (4 kpc), there are only massive (>2 × 10^5 M_\odot) clusters. In the regions of the

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2 The cluster with high metallicity at ~0°.1 appears to be located inside a few of the bulge clusters because we applied the inclination correction to the bulge clusters as well as disk clusters.
inner and main spiral arms, there are predominantly low-mass clusters. The few high-mass clusters (>10^5 \text{M}_\odot) outside 0°.3 might be bulge clusters in projection on the disk.

Extinctions of the clusters are shown in panel (d). Inside 0°.3, $E(B-V)$ values are higher (0.3–0.7), whereas from 0°.3 to 1°.2, $E(B-V)$ is nearly uniformly spread between 0 and 0.5. This is consistent with being caused by line-of-sight depth differences to different clusters.

The mean parameter values per bin are shown in Figure 8 by the points connected by dashed lines. These show that the mean cluster metallicities in the bulge are lower than for the spiral arm regions. The mean ages and masses are much younger and lower for the spiral arm regions than for the bulge (by factors of ∼100 for both). The mean extinction for the bulge is higher than for the spiral arms.

When the inner and main spiral arms are compared, the clusters have a similar metallicity distributions. However, the main arm has a significantly higher proportion of young (∼10^7 yr) clusters than the inner arm. The mass distributions are not significantly different. The lower mean mass for the main arm is caused by the higher numbers of the 10^2–10^4M_\odot clusters. The mean extinction values for the main arm and the inner arm are the same.

### 3.3. Comparison with Previous Results

#### 3.3.1. Comparison with the PHAT (Johnson et al. 2016) Cluster Analysis

Johnson et al. (2016) analyzed the subset of 1249 of the 2753 clusters from Johnson et al. (2015) with ages <300 Myr to study the cluster formation efficiency (Γ) in M31. This included photometry of resolved stars in each cluster and F475W versus F475W-F814W CMD fitting to determine age,
mass, and extinction ($A_V$). A small variation in metallicity was included ($-0.2 < \log(Z/Z_\odot) < 0.1$). Their catalog of clusters gave ages and masses, but not extinction or metallicity. They obtained maps of the star formation rate (SFR) surface density for two age bins, 10–100 Myr and 100–300 Myr, and obtained $\Gamma$ in seven spatial bins for the two age bins.

The analysis done here is significantly different. The whole-cluster photometry (UVIT and PHAT; Johnson et al. 2015) is obtained for nine wave bands from the FUV to NIR and is used to obtain age, mass, metallicity, and extinction. Larger ranges of age and metallicity are used compared to Johnson et al. (2016). Both studies use the Padova cluster models.

A subset of 99 clusters are in both studies. Figure 9 shows our results (x-axis) and the Johnson et al. (2016) results (y-axis, labeled J2016) for ages and masses. A wider range of ages and of masses is found in our study. The wider range of ages is likely caused by two factors: we include FUV and NUV bands, which are sensitive to age, and the study of Johnson et al. (2016) had a narrower range in their model age grid ($10^7$ yr to $3 \times 10^8$ yr). Their clusters near their lower or upper limits could be fit better by ages below their lower limit or above their upper limit. The change in age affects the normalization and thus the mass of each cluster, with generally lower mass required for younger age because the stars are brighter on average.

The FUV and NUV photometry of the current work should be more sensitive to extinction, which peaks near 200 nm, than previous studies. This is likely a factor in the differences in ages and masses. It can be seen from Figure 9 that the UVIT age errors are similar to and the UVIT mass errors are larger than those of Johnson et al. (2016). Nearly all of the UVIT ages are different by less than 2$\sigma$ than the Johnson et al. (2016) values. For masses, about 75% are different by less than 2$\sigma$.

Figure 10 shows the distribution of ages from our photometry analysis of the UVIT clusters (all 170 and the 99 in common with Johnson et al. 2016) and ages for the 99 clusters with CMD analysis from Johnson et al. (2016). For the 99 clusters, the UVIT/photometry age distribution (dashed magenta line) is similar to that from the CMD analysis (blue), but with a slightly larger age range. The full sample of
In summary, our method and that of Johnson et al. (2016) each have their own strengths and weaknesses. Figure 9 shows that the clusters in common have differences in ages and masses that are mostly not significant. The method of Johnson et al. (2016) works well for clusters that are diffuse enough to be dominated by resolved stars. The UVIT data have a sufficient spatial resolution (1″) to measure the whole-cluster photometry, but not that of individual stars in each cluster. The advantage of the whole-cluster photometry is that it includes light from the whole cluster, including faint and unresolved stars, whereas the advantage of CMD fitting is that it contains information for the stars that are resolved. Another advantage of the UVIT photometry for young clusters is that the stars have significant FUV and NUV emission, which is not analyzed in the F475W-F814W optical wavelength CMDs.

3.3.2. Comparison with the SFH Analysis from Starlight in the Disk and Bulge of M31

The SFH of the disk has been extensively studied using a CMD analysis on large numbers of resolved stars from PHAT (Williams et al. 2017). The main results from that study include a table of star formation (SF) rates in ~3300 spatial bins for 16 age bins from 0 to 14.1 Gyr, the metal enrichment history for three radial bins in the disk, and the history of the stellar mass buildup in the disk. Parameters derived using four different stellar evolution codes, including the Padova models, were compared. They find that most of the M31 disk stars were formed >8 Gyr, there was a widespread SF episode of age ~2 Gyr, and the 10 kpc star-forming ring (the main spiral arm in Figure 5) is visible for all ages ≲1 Gyr. Their smallest age bin is from 4 × 10⁶ to 3.2 × 10⁸ yr, which covers almost the entire age range found here for the UVIT clusters. The current study selects stars in clusters rather than fields stars, which make up most of the stellar mass. Cluster studies are biased toward the youngest stars that form in any SF episode because a higher fraction of clusters disperses for higher age (Moeckel et al. 2012)³.

Studies of the SFH of the bulge include Leahy et al. (2022), Dong et al. (2018), and Saglia et al. (2018) and references therein. They find two and possibly three episodes of SF in the bulge, with ages of 10-12 Gyr with log(Z/Z☉) ≈ 0.3 and >90% of the total stellar mass, ~600 Myr with log(Z/Z☉) ≈ 0 and ~5% of the mass, and <100 Myr (Dong et al. 2018) or ~25 Myr (Leahy et al. 2022) with log(Z/Z☉)~−0.7 and a small fraction (~10⁻⁶) of the mass. The old broad peak detected here and in Johnson et al. (2016) between ~20 and 300 Myr (Figure 10) has an age between the ages of the ~600 Myr SF peak and the youngest peak at ~25 to 100 Myr found by the studies in the bulge above. This and the different locations means that they are likely not physically related.

The youngest SF peak detected here, with an age ~5 × 10⁶ yr and a mean log(Z/Z☉) of +0.18, might be related to the detection of similarly aged stars in the bulge by the study of UV-bright stars in the bulge (Leahy et al. 2018). This youngest peak was probably not detected by Johnson et al. (2016) because of their lower age cutoff of 10⁷ yr. The FUV and NUV data from UVIT were also essential to detect these young stars here.

³ Only if SF occurs in short bursts will the clusters have the same ages as the SF episodes.

170 UVIT clusters (red) shows an additional peak at ages younger 10⁷ yr and a tail above 3 × 10⁸ yr that extends to 2 × 10⁹ yr. Thus the set of 71 UVIT clusters not in the sample of Johnson et al. (2016) contains most of the youngest and oldest clusters.

Figure 9. The UVIT-PHAT results (x-axes) for log(age) (top panel) and log(M) (bottom panel) compared to the results from Johnson et al. (2016) (x-axes) for the 99 clusters in both samples. Errors are ±1σ for both cases.

Figure 10. Distributions of age for the 134 clusters in the UVIT-PHAT sample (this work), with a cluster model lower log(age) limit of 6.6, and the Johnson et al. (2016) sample, with cluster model log(age) limits of 7.0 and 8.5.
4. Conclusions

In this study, UVIT FUV and NUV photometry was carried out for a set of 239 clusters that overlap with the HST/PHAT survey. The area covers the NE disk and bulge of M31. The FUV to NIR SEDs were constructed from our UVIT photometry and the PHAT photometry (Johnson et al. 2015) and were modeled for 170 clusters using our cluster SED fitting program with Padova stellar models to derive age, mass, metallicity, and extinction.

The best-fit models for the clusters show a range of masses from \( \sim 60 \) to \( 2 \times 10^6 \) M\(_{\odot}\). The clusters have a narrow age peak at \( 4 \times 10^6 \) yr and a broad peak around \( 1 \times 10^8 \) yr. Older clusters generally have higher masses. The metallicities (\( \log(Z/Z_\odot) \)) of the clusters are mostly in the range \( -0.3 \pm 0.3 \). The extinction, \( E(B-V) \), covers a broad range from 0 to \( \sim 0.5 \). Extinction is not correlated with position, consistent with clusters located at different line-of-sight depths, independent of sky position. The spatial distributions of the UVIT-detected clusters and their parameters show that high-metallicity/low-mass clusters are more spatially correlated with each other and are more concentrated toward the brightest parts of the spiral arms, and the low-metallicity/high-mass clusters are spread fairly uniformly.

Previous work on stellar ages and metallicities in the disk of M31 (Johnson et al. 2016) fit resolved HST CMDs of clusters in the PHAT survey. Ninety-nine of these clusters are in our UVIT sample. We find a broader range of ages and masses for the clusters, in part because we allow a wider range of ages and metallicities. However, the differences are smaller than \( 2\sigma \) for the majority of clusters. This is consistent with the studies of Olsen et al. (2021) and Johnson et al. (2013), which compared CMD and SED fitting methods.

For field stars in the disk of M31, Williams et al. (2017) carried out a CMD analysis using PHAT photometry for \( \sim 3300 \) spatial regions. They find that most stars are older than 8 Gyr, a widespread SF with an age of \( \sim 2 \) Gyr, and a weak peak with an age of \( \sim 0.6 \) to \( 1.2 \times 10^8 \) yr. The study here of clusters and the restriction to those detected in FUV and NUV means that the current work detects younger stars in contrast to their study, which detects older SF episodes.

Leahy et al. (2022) combined UVIT data with optical and IR data for the bulge of M31. The SED analysis gave results consistent with the result from HST/PHAT data (Dong et al. 2018). The M31 bulge has a dominant \( \sim 10 \) Gyr metal-rich population, a younger \( \sim 600 \) Myr population of about solar metallicity, and a small fraction of metal-poor stars with ages of \( \sim 25 \)–\( 100 \) Myr. The current study of UVIT clusters in the disk detects clusters with ages in the range of \( 10 \)–\( 100 \) Myr and a younger set of clusters with ages of \( \sim 4 \) Myr. The first set has ages similar to the youngest population in the bulge, but has a different metallicity distribution. The second UVIT set is a newly detected population, which should be followed up in more detail by new observations and analysis.

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