HST/ACS DIRECT AGES OF THE DWARF ELLIPTICAL GALAXIES NGC 147 AND NGC 185

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ABSTRACT

We present the deepest optical photometry for any dwarf elliptical (dE) galaxy based on Hubble Space Telescope Advanced Camera for Surveys (ACS) observations of the Local Group dE galaxies NGC 147 and NGC 185. Our F606W and F814W color–magnitude diagrams are the first to reach below the oldest main sequence turnoff in a dE galaxy, allowing us to determine full star formation histories in these systems. The ACS fields are located roughly ~1.5 effective radii from the galaxy center to avoid photometric crowding. While both ACS fields show unambiguous evidence for old and intermediate age stars, the mean age of NGC 147 is ~4–5 Gyr younger as compared to NGC 185. In NGC 147, only 40% of stars were in place 12.5 Gyr ago (z ~ 5), with the bulk of the remaining stellar population forming between 5 to 7 Gyr. In contrast, 70% of stars were formed in NGC 185 prior to 12.5 Gyr ago with the majority of the remaining population forming between 8 to 10 Gyr ago. Star formation has ceased in both ACS fields for at least 3 Gyr. Previous observations in the central regions of NGC 185 show evidence for star formation as recent as 100 Myr ago, and a strong metallicity gradient with radius. This implies a lack of radial mixing between the center of NGC 185 and our ACS field. The lack of radial gradients in NGC 147 suggests that our inferred SFHs are more representative of its global history. We interpret the inferred differences in star formation histories to imply an earlier infall time into the M31 environment for NGC 185 as compared to NGC 147.

Key words: galaxies: dwarf – galaxies: individual (NGC 147, NGC 185) – galaxies: stellar content

1. INTRODUCTION

Dwarf elliptical (dE) galaxies are primarily, if not exclusively, found in galaxy cluster and group environments (Binggeli et al. 1988; Ferguson & Sandage 1991; Geha et al. 2012). Environment-driven processes must play an important role in dE formation and evolution (e.g., Moore et al. 1998; Mastropietro et al. 2005; Lisker et al. 2013). However, no single process or formation mechanism can yet explain the observed diversity of dE morphologies (e.g., Lisker et al. 2009; Janz et al. 2012) or kinematics (e.g., Geha et al. 2002; van Zee et al. 2004; Toloba et al. 2014). Star formation histories are an important tool in understanding the dE galaxy class and provide insight into the assembly of galaxies in dense environments.

Stellar population studies in the nearby Virgo and Fornax galaxy clusters reveal a mixture of old to intermediate age stars in dE galaxies, and intrinsic differences in the age and/or metallicity of individual galaxies (Geha et al. 2003; Michielsen et al. 2008; Ryš et al. 2013). These studies are based on either integrated spectral line widths or narrow band imaging and cannot therefore determine the exact ratio of old to intermediate stars, nor reconstruct detailed star formation histories. The Local Group dEs share the same broad properties as galaxy cluster dEs (Bender et al. 1991), yet are sufficiently nearby that individual stars can be resolved below the main sequence turn-off, allowing for more unambiguous characterization of the stellar populations in these systems.

The Local Group contains three dE galaxies: NGC 205, NGC 147, and NGC 185, all satellites of the large spiral galaxy M31. A fourth bright satellite, M32, is far more compact and likely has a very different formation path (Monachesi et al. 2012). Of the three dEs, NGC 205 is close in projection to the M31 disk, and contamination from M31 stars complicates stellar population work in this object (Choi et al. 2002). The stellar populations of NGC 147 and NGC 185 are more amenable to study. RR Lyrae stars are detected in both NGC 147 and NGC 185 indicative of stars older than 10 Gyr (Saha & Hoessel 1990; Yang & Sarajedini 2010). AGB carbon stars are also observed in both dEs, typical of more intermediate age stars (Battinelli & Demers 2004; Davidge 2005; Sohn et al. 2006). Each of these galaxies hosts its own system of associated globular clusters (Veljanoski et al. 2013).

NGC 147 and NGC 185 share fundamental properties, such as absolute luminosity (MV ~ −16; Crnojević et al. 2014) and velocity dispersion (25 km s−1; Geha et al. 2010). However, they differ in many aspects. NGC 185 contains some gas, dust, and evidence for recent star formation confined to its inner 200 pc, while NGC 147 is devoid of gas or dust and shows no sign of recent star formation activity (Young & Lo 1997; Marleau et al. 2010). Hubble Space Telescope (HST)/WFPC2 images of both galaxies also imply the presence of intermediate-age stars, with NGC 147 having a more significant contribution than NGC 185 based on stars brighter than the main sequence (Butler & Martínez-Delgado 2005; Weisz et al. 2014). Spectroscopic metallicities show an overall more metal-rich population in NGC 147, [Fe/H] = −0.5 ± 0.1 as compared to NGC 185 of [Fe/H] = −0.9 ± 0.1 (Vargas et al. 2013).
et al. 2014). Only NGC 185 shows evidence for a metallicity gradient, becoming more metal-poor with radius (Crnojević et al. 2014; Vargas et al. 2014).

NGC 147 and NGC 185 are very close in projection on the sky (58′), leading some to argue that they may be a bound galaxy pair (van den Bergh 1998). However, kinematic evidence suggests that these may not be gravitationally bound (Geha et al. 2010; Watkins et al. 2013). Furthermore, deep photometry from the Pan-Andromeda Archaeological Survey has uncovered isophotal twisting at large radius due to the emergence of symmetric tidal tails in NGC 147, which is not seen to similar depths in NGC 185 (Crnojević et al. 2014), further suggesting these two objects have independent formation paths.

In this paper, we present deep HST Advanced Camera for Surveys (ACS) imaging for NGC 147 and NGC 185. These are the only two dE galaxies for which HST can cleanly resolve stars below the oldest main sequence turnoff region and thus directly measure their star formation histories. The paper is organized as follows. In Section 2 we discuss the HST observations and data reduction. We first compare the resulting color–magnitude diagrams (CMDs) to single stellar population models (Section 3.1), and then compute full star formation histories (Section 3.3). In Section 4, we discuss our results in the context of dE galaxy formation.

2. DATA

2.1. Image Reduction and Photometry

The HST/ACS observations were taken for NGC 147 between 2009 November–December, and for NGC 185 between 2010 January–February (HST GO-11724; PI: Geha). The ACS fields were chosen to avoid crowding while ensuring a well-populated CMD in the F606W (broad V) and F814W (I) filters, corresponding to a surface brightness of $\mu_V \sim 26$ mag arcsec$^{-2}$. The exact field locations were chosen to avoid bright foreground stars at this radius. Parallel WFC3 observations were taken as part of this program. A quick reduction of the WFC3 fields suggest a much sparser stellar density as expected, but similar stellar populations as the primary ACS fields; these data will be analyzed in a future contribution.

The ACS fields are located roughly along the major axis of each galaxy (Figure 1), at 8′6 (1.8 kpc) and 6′7 (1.2 kpc) from the galaxy center for NGC 147 and NGC 185, respectively. Using the effective radii determined by Crnojević et al. (2014) via deep Canada–France–Hawaii Telescope imaging, this corresponds to 1.3 and 2.3 effective radii from each galaxy center.

The combined ACS exposure times were 82280 s (23 hr) for NGC 147 and 62598 s (17 hr) for NGC 185. Individual exposures were well dithered to fill in the gap between the two ACS chips and improve the point-spread function (PSF). Short 30-s exposures were taken as part of the program, but were not included in our reduced image stacks as bright stars are not the focus of this paper (individual long exposures saturate brighter than $V \sim 20$). The ACS field centers and total exposure times are listed in Table 1. The location of all fields, including parallel WFC3 and archival WFPC2 pointings, are shown in Figure 1.

Our ACS images were processed through the HST archive on-the-fly reprocessing system using the most up-to-date calibration frames. The images were corrected for CCD charge transfer efficiency losses following the prescription in Anderson & Bedin (2010). We then co-added the images into a single image per field per filter using the MULTIDRIZZLE software (Fruchter & Sosey 2009), which also corrects for geometric distortion and removes bad pixels and cosmic rays. Due to the multiply dithered images, the ACS images were resampled to a final pixel size of 0′′04 (0.8 times the native plate scale).

PSF-fitting photometry was performed using the DAOPHOT/ALLSTAR II package (Stetson 1994). To create the

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**Figure 1.** Digital Sky Survey images of the Local Group dE galaxies, NGC 147 (left) and NGC 185 (right). Archival HST/WFPC2 pointings are shown in green. The ACS pointings discussed in this paper are shown in red. WFC3 pointings taken in parallel with the ACS data are shown in blue and will be analyzed in a future paper. Images are 30′ × 30′; north is up, east is to the left.
of 7° or 100 kpc is less than that from the Milky Way foregrounds and we do not account for this in the models.

The resulting HST ACS CMDs are shown for NGC 147 and NGC 185 in Figure 2. We plot one sigma errors as a function of magnitude. These represent the deepest CMDs for any dE galaxy and are the first observations of dE galaxy stars below the old main sequence turnoff.

### 2.2. Distances and Spectroscopic Metallicities

Given the extremely small photometric errors in our data, we chose to re-determine the distance of NGC 147 and NGC 185 using the HST/ACS data itself via the Tip of the Red Giant Branch (TRGB) method. The TRGB acts as a discontinuity in the stellar luminosity function, the position of which is easily measured. We measure the TRGB using the software developed by one of us (R.P.v.d.M.) and detailed in Cioni et al. (2000). The distance modulus for NGC 147 is \( (m-M)_0 = 24.30 \pm 0.05 \) (724 ± 27 kpc) and NGC 185 is \( (m-M)_0 = 24.02 \pm 0.08 \) (636 ± 26 kpc). These are slightly further, but well within the 1σ errors, of those determined by Conn et al. (2012). We assume a distance to M31 of 779 kpc from Conn et al. (2012). This places NGC 147 and NGC 185 at distances 165 and 210 kpc away from their parent galaxy M31, respectively. We adopt extinction values for NGC 147 and NGC 185 from Schlegel et al. (1998) of \( E(B-V) = 0.161 \) and 0.195.

Spectroscopic metallicities for stars in the ACS fields were obtained as part of a larger Keck/DEIMOS study of Local Group dEs (Geha et al. 2010; Vargas et al. 2014; Ho et al. 2015). We use these spectroscopic metallicities to guide our single stellar population analysis in Section 3.1. The Keck sample includes 37 member stars within our ACS field of view in NGC 147, and 30 member stars in the NGC 185 ACS field. Members are identified as having colors, magnitudes, and radial velocities consistent with each galaxy. Spectroscopic metallicities (\( [\text{Fe/H}] \)) of individual red giant branch (RGB) stars were determined using the spectral synthesis method described in Vargas et al. (2014). The mean metallicity within each ACS field is \( [\text{Fe/H}] = -0.5 \pm 0.1 \) for NGC 147 and \( [\text{Fe/H}] = -1.0 \pm 0.1 \) for NGC 185, comparable to the means of each full sample. The error on the mean is small, but there is significant internal scatter of 0.5 dex in each field. While the analysis below assumes solar alpha-abundance ratios, we note that the measured alpha-abundances are slightly enhanced at \( [\alpha/\text{Fe}] = 0.3 \pm 0.1 \) in NGC 147 and \( [\alpha/\text{Fe}] = 0.1 \pm 0.1 \) in NGC 185 (Vargas et al. 2014).

### 3. RESULTS

In Figure 2, the HST/ACS CMDs for NGC 147 and NGC 185 appear similar at first glance, yet clear differences emerge on closer inspection. Focusing first on the position of stars which have evolved off the main sequence, NGC 147 has a strong red clump (RC), while stars in the same evolutionary state in NGC 185 are instead distributed equally between the RC and a bluer horizontal branch, consistent with a lower average metallicity in NGC 185. Also seen in the CMDs of Figure 2 is the larger number of stars bluer and brighter than the oldest main sequence turnoff in NGC 147 as compared to NGC 185. While some fraction of these stars are most likely blue straggler stars (Santana...
et al. 2013), this does suggest the presence of a younger population on average in NGC 147 as compared to NGC 185. Based on this visual inspection alone, we conclude that the star formation histories of these two dEs are different.

Below, we quantify this statement via both simple comparison to single population isochrones (Section 3.1) and CMD fitting to determine the full star formation histories (Section 3.3).
3.1. Simple Constraints on the Distribution of Stellar Ages

Before modeling the inferred star formation histories from the full CMDs, we first compare the data to single stellar population isochrones to build a basic understanding of these data. We use the Padova isochrones (Girardi et al. 2002, 2010) generated in the HST ACS filters with solar abundance ratios.

We focus on the relative ages of NGC 147 and NGC 185 by comparing stars in the RC. The location of the RC is shown in Figure 2. For metallicities more metal-poor than $\sim -0.5$ dex, the F814W (roughly $I$-band) luminosity of the RC is largely dominated by age effects. In the left panel of Figure 3, we plot the F814W luminosity functions of RC stars in NGC 147 (red) and NGC 185 (blue). NGC 147’s median RC magnitude is marked by the red dotted vertical line, while the blue dashed line marks NGC 185’s RC magnitude. In the right panel of Figure 3 we compare the median RC luminosity to the values predicted for single age/metallicity stellar populations. These values were determined using the same RC boxes as the observations.

Spectroscopic abundances for NGC 147 and NGC 185 are $[\text{Fe/H}] = -0.5$ and $-1.0$, respectively (Section 2.2), thus we can use the RC to determine the relative ages of the two galaxies. The dominant RC population in NGC 147 has an age of $\sim 7$ Gyr, while NGC 185’s is $\sim 11$ Gyr old, making NGC 185 about 4 Gyr older. This is in agreement with the full SFHs discussed in Section 3.3 and serves as an independent check of those result, as the full SFHs are determined without including this region of the CMD.

In the left panels of Figure 4, we overplot onto the CMD Hess diagrams representative isochrones spanning a wide range of metallicities ($[\text{Fe/H}] = 0$ and $-2$), with one isochrone, in blue, representing the spectroscopic metallicity estimated for each galaxy (Vargas et al. 2014). For the best fitting set of isochrones which fits the RGB (blue lines for both dEs), the bulk of main sequence turnoff stars lie between the 2 and 8 Gyr tracks for NGC 147, while these stars primarily lie between the 8 to 12 Gyr tracks for NGC 185. Finally, if all of the stars bluer and brighter than the main sequence turnoff are interpreted as young stars (some fraction must be older blue straggler stars), than this population is not younger than $\sim 2$ Gyr. We explore this in more detail below.

3.2. Measuring Full Star Formation Histories

We measure the full SFHs of both galaxies using the CMD fitting package MATCH (Dolphin 2002). MATCH constructs a set of synthetic simple stellar populations which are linearly combined and added to a model foreground population from the empirical model in de Jong et al. (2010) to form a composite synthetic CMD. This CMD is then convolved with results from artificial star tests. The models and observed CMDs are compared using a Poisson likelihood statistic. The SFH that corresponds to the best matched synthetic CMD is the most likely SFH of the observed population. The fitting of these CMDs uses the Padova stellar models (Girardi et al. 2002, 2010) and follows the fitting methodology from Weisz et al. (2014). We assume a Kroupa IMF, solar-scaled isochrones and the distances/reddening stated in Section 2.2. We exclude the RC and horizontal branch regions from the fit in order to mitigate the contribution of these relatively less certain phases of stellar evolution to the SFH (Aparicio & Hidalgo 2009). The excluded region is shown above and to the left of the orange dashed lines in Figure 4. The SFH fits are performed for stars with magnitudes brighter than 28.7/28.2 for F606W/F814W in NGC 147, and 28.2/27.7 in F606W/F814W for NGC 185. This corresponds to completeness values of 60% and greater in NGC 147, and 70% and greater in NGC 185.

Uncertainties in the SFHs reflect the 68% confidence interval around the best fit SFH due to both random uncertainties (from a finite number of stars on the CMD) and systematic uncertainties (due to uncertain physics in the underlying stellar models). In both our ACS datasets, systematic errors dominate over random. We refer the reader to Dolphin (2012) for a full discussion of systematic uncertainties and Dolphin (2013) for a detailed description of random uncertainties in SFH measurements.

In panels (c) and (f) of Figure 4, we show the residual significance of each CMD fit, i.e., (data-model)/σ. The shading represents the degree of agreement between the observed and modeled CMD such that black and white regions represent the most extreme outliers (>5 sigma). The largest discrepancies between the model and observed CMDs are the horizontal branch and RC, which were not included in the CMD fit, and are therefore not expected to be well-matched to the data. The are additional low-level residuals on the RGB. We attribute these systematics to a combination of deficiencies in the stellar evolution models (e.g., the Padova models are known to have troubled matching the colors of the RGB). Despite the presence of these residuals, they are at a low-level of significance, and do not drastically affect the fidelity of the resulting SFHs.

In principle, the age–metallicity relationship can be inferred from the above star formation history fits. For ages younger than the last significant star formation event, the age–metallicity relationship is unreliable because the code tries (and fails) to fit the region contaminated in part by blue stragglers. We therefore follow Weisz et al. (2014) and fix the age–metallicity after the last significant epoch of star formation has ended ($\sim 5$ Gyr). The age–metallicity relationship for older stars shows the general trend of increasing metallicity with younger ages. We note that the resulting average metallicity of both galaxies is $\sim -0.25$ dex metal-poor than the spectroscopically observed values.

3.3. Full SFH Results

The best-fitting MATCH CMD models are compared to the observed Hess diagrams in Figure 4. The cumulative SFHs from these models and their uncertainties are shown in Figure 5. The main features of the main sequence, main sequence turnoff and upper RGBs are well fit. The cumulative SFHs of NGC 147 and NGC 185 required to achieve this agreement are significantly different from each other and are consistent with the general conclusion from Section 3.1 that NGC 185 hosts a much older stellar population as compared to NGC 147.

In NGC 147, less than half of stars (40%) were in place 12.5 Gyr ago ($z \sim 5$), with the bulk of the remaining population forming between 5 to 7 Gyr. Star formation in this ACS field appears to have been quenched roughly 5 Gyr ago. This agrees with SFHs determined from shallower HST/WFPC2 data from the more central regions of NGC 147 (Weisz et al. 2014). There are no metallicity gradients observed in this galaxy (Cnojević et al. 2014; Vargas et al. 2014), suggesting that the inferred SFH in this ACS field may be representative of
NGC 147 as a whole. Crnojević et al. (2014) has recently uncovered isophotal twisting at large radius due to the emergence of symmetric tidal tails. Our ACS field is well inside the radius at which these tidal effects are visibly observed.

The NGC 185 field, in contrast, formed 70% of stars prior to 12.5 Gyr ago, with the majority of the remaining population forming between 8 to 10 Gyr ago. Given NGC 185’s lower measured spectroscopic metallicity, an older age for NGC 185 relative to NGC 147 is in agreement with expectations from simple models of chemical evolution (e.g., Tinsley 1979). We note that the spectroscopic metallicities are not used as part of the fitting method. The presence of the smaller intermediate age (8–10 Gyr) population is independently confirmed by AGB carbon stars present in the ACS field (Battinelli & Demers 2004). A radial gradient in both carbon stars and overall stellar metallicity is observed in NGC 185 (Crnojević et al. 2014; Vargas et al. 2014), which suggests that NGC 185 has experienced little to no radial mixing. The star formation in the ACS field, which lies at 2.3 effective radius from the galaxy center (6′/7 or 1.2 kpc), is among the oldest of any Local Group dwarf galaxy (Weisz et al. 2014). This is in contrast to the inner 200 pc of NGC 185, based on HST/WFPC2 imaging, which shows evidence for very recent star formation as young as 100 Myr ago (Butler & Martínez-Delgado 2005; Weisz et al. 2014).

Figure 4. Left panels: The observed Hess diagrams for NGC 185 (top) and NGC 147 (bottom). Overplotted are Padova isochrones with [Fe/H] = −2 (green) and 0.0 dex (red) for ages of 2, 8, and 12 Gyr. Blue isochrones are the median metallicity in each galaxy ([Fe/H] = −0.5 and −0.9 for NGC 147 and NGC 185, respectively. (Middle panels) The best fitting model star formation histories as determined using MATCH. The RC and horizontal branch region above and to the left of the orange boundaries are not well modeled and are therefore excluded from the fit. (Right panels) The residual significance of each CMD fit, i.e., (data-model)/σ. The color bar represents the degree of agreement between the observed and modeled CMD in units of standard deviations.
4. FORMATION HISTORY OF NGC147 VERSUS NGC 185

Based on the star formation histories above, NGC 147 and NGC 185 built up their present-day stellar mass over very different timescales. A key question is whether these galaxies had different formation histories prior to falling into the M31 environment, or if their early histories were similar, but each fell into the M31 potential at very different times. Below we argue that a different infall time into M31 is the most plausible explanation for these different SFHs.

NGC147 and NGC 185 lie very close on the sky (58') and have been interpreted either as a bound galaxy pair or a single group that they fell into M31 (van den Bergh 1998). Kinematic evidence marginally suggests that these are not gravitational bound (Geha et al. 2010; Watkins et al. 2013). Our star formation histories, combined with the presence of a tidal tail in NGC 147 (and the lack thereof in NGC 185) suggest that these two dE galaxies are independent of each other and that their current proximity is likely a chance projection. While current data only support this conclusion indirectly, future proper motion measurements can definitively determine whether or not these two systems are on different orbits.

An outstanding issue in comparing NGC 147 to NGC 185 is the difference in gas and dust content. NGC 185 contains some gas and dust ($M_{\text{gas}} \sim 10^5 M_{\odot}$, Marleau et al. 2010), consistent with recycling from older stars. NGC 147 contains no detected gas nor dust ($M_{\text{dust}} < 45 M_{\odot}$) which has been referred to as the "missing ISM problem" (Sage et al. 1998). This issue, also seen in NGC 205, has been attributed to environmental interactions with M31 (De Looze et al. 2012). We hypothesize that NGC 147 and NGC 205 have had stronger tidal interactions due to orbits which bring them deeper into the M31 potential, stripping them of gas/dust and creating their observed tidal tails. On the other hand, we suggest that the orbit of NGC 185 has a larger comparable orbital pericenter, allowing it to maintain a small gas reservoir at its center. We interpret the very recent star formation confined to the central 200 pc of NGC 185 as having formed from this recycled material which was perhaps triggered during perigalactica.

From Figure 5, we concluded that neither our NGC 147 nor NGC 185 field have had a significant star formation event in several gigayears (we do not consider the above 100 Myr central burst in NGC 185 significant). If we assume that star formation was instantaneously quenched once it passed the M31 virial radius, we conclude infall times of 5 and 8 Gyr for NGC 147 and NGC 185, respectively. We define "quenched" as having 90% of stars in place, choosing this value (rather than 100%) due to ambiguity with blue straggler stars which are not accounted for in the models. If there is a delay time between infall and star formation quenching (e.g., Wetzel et al. 2013), then these infall times could be much earlier. Because the majority of stellar mass in NGC 185 was in place earlier than NGC 147, we conclude an earlier infall epoch for this galaxy regardless of the quenching timescale.

Finally, we compare the cumulative SFHs of NGC 147 and NGC 185 to other dwarf galaxy satellites around the Milky Way and M31 from Weisz et al. (2014). NGC 147 is typical of other luminous Local Group satellites, with evidence for a mixture of both old (12 Gyr) and more intermediate age stars. On the other hand, our NGC 185 field is more typical of the predominantly old populations seen in much lower mass systems such as Sextans and Draco. In these lower mass systems, star formation is assumed to have been suppressed due to reionization. However, NGC 185 has a factor of 100 more stellar mass than these systems and unlikely to be affected to this extent by reionization. Instead this may be further evidence for NGC 185’s early infall time into the M31 environment.

5. CONCLUSIONS

We present deep HST ACS photometry of the M31 dE satellite galaxies NGC 147 and NGC 185. These data are the first to reach below the oldest main sequence turnover in a dE galaxy and allow us to unambiguously determine their star formation histories. We find a much older population in the dE galaxy NGC 185 as compared to NGC 147: while 70% of stars were already formed in NGC 185 before 12.5 Gyr, only 40% of the present day stellar population had formed in NGC 147. We broadly interpret these results to imply a much earlier infall
time into the M31 environment for NGC 185 versus NGC 147. We further suggest that the orbit of NGC 185 has a larger perigalacticon as compared to NGC 147, allowing it to preserve radial age/metallicity gradients and maintain a small reservoir of recycled gas. These conclusions could be confirmed via future proper motion measurements of these two systems to determine their 3D orbits around M31.

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