HOW TYPICAL ARE THE LOCAL GROUP DWARF GALAXIES?*

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ABSTRACT

We compare the cumulative star formation histories (SFHs) of Local Group (LG) dwarf galaxies with those in the volume-limited ACS Nearby Galaxy Survey Treasury (ANGST) sample (D \(\lesssim\) 4 Mpc), in order to understand how typical the LG dwarf galaxies are relative to those in the nearby universe. The SFHs were derived in a uniform manner from high-quality optical color–magnitude diagrams constructed from Hubble Space Telescope imaging. We find that the mean cumulative SFHs of the LG dwarf galaxies are comparable to the mean cumulative SFHs of the ANGST sample for the three different morphological types (dwarf spheroidals/elliptical: dSph/dE; dwarf irregulars: dI; transition dwarfs: dTrans). We also discuss effects such as population gradients and systematic uncertainties in the stellar models that may influence the derived SFHs. Both the ANGST and LG dwarf galaxies show a consistent and strong morphology–density relationship, emphasizing the importance of environment in the evolution of dwarf galaxies. Specifically, we confirm that dIls are found at lower densities and higher luminosities than dSphs, within this large sample. We also find that dTrans are located in similar environments to those occupied by dwarf irregular galaxies, but have systematically lower luminosities that are more comparable to those of dwarf spheroidals. The similarity of the SFHs and morphology–density relationships of the LG and ANGST dwarf galaxies suggests that the LG dwarfs are a good representation of dwarf galaxies in the local universe.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: stellar content – Local Group

Online-only material: color figures

1. INTRODUCTION

Dwarf galaxies in the Local Group (LG) are among the most well-studied galaxies in the universe. Detailed determinations of their kinematics, metallicities, and stellar contents serve as a basis for much of what we understand about the formation and evolution of both individual and groups of galaxies (see reviews by Mateo 1998; van den Bergh 2000; Tolstoy et al. 2009). In particular, we can directly determine the history of star formation and chemical evolution for individual galaxies using Hubble Space Telescope (HST) observations of resolved stellar populations in nearby and LG galaxies (e.g., Tolstoy et al. 2009).

Although we often draw on results from LG studies to explain the evolution of galaxies in the broader universe, whether LG dwarf galaxies are representative of all dwarf galaxies remains an open question (e.g., van den Bergh 2000). The LG is a relatively dense environment with a specific history of mass accretion and interaction, which may have influenced dwarf galaxy evolution differently than nearby field or galaxy groups (e.g., the M81 Group). Because we often extrapolate results from the LG to the more distant universe, it is important to establish the degree to which the LG dwarfs represent the broader dwarf galaxy population.

The Local Volume contains a diverse set of galaxies and environments, some of which have no analogs in the LG. For example, the M81 Group is known to have undergone a recent major interaction (e.g., Yun et al. 1994; Yun 1999), which has likely influenced star formation and gas loss in the M81 Group dwarf galaxies (e.g., Weisz et al. 2008; Walter et al. 2011), and which may be responsible for the creation of new tidal dwarf galaxies (e.g., Makarova et al. 2002). At the opposite extreme in density, isolated “field” dwarf galaxies may have fewer or no interactions with more massive companions, which could result in distinctly different patterns of star formation and chemical evolution when compared to typical group members (e.g., Cole et al. 2007).

Directly comparing the stellar contents of LG dwarf galaxies to those in the nearby universe requires uniform data sets of comparable quality and size. Historically, studies of resolved stellar populations in nearby dwarf galaxies have focused on small samples or individual galaxies, and have employed a variety of analysis techniques, leading to larger systematic uncertainties when comparing different studies. Recent projects described by Holtzman et al. (2006) and Dalcanton et al. (2009) have resulted in two uniformly processed multi-color
photometric databases of the resolved stellar populations of dwarf galaxies in the LG and Local Volume, which, for the first time, allow a direct unbiased study of dwarf galaxies in a large volume, spanning a wide range of environments.

In this paper, we present a comparison of the cumulative star formation histories (SFHs) and morphology–density relationships of dwarf galaxies in the LG and the Local Volume. We have measured the SFHs from uniformly processed photometry, using the same SFH code and stellar evolution models, minimizing the effects of potential systematics for comparison of the relative SFHs. For the LG, we use the best-fit SFHs from updated analysis of the LG sample (A. E. Dolphin et al. 2010, in preparation, initially presented in Dolphin et al. 2005). SFHs for the Local Volume are taken from the measured SFHs of ACS Nearby Galaxy Survey Treasury (ANGST) dwarf galaxies (Weisz et al. 2011). We specifically address the question of whether or not the most likely cumulative SFHs of the LG dwarfs are comparable to those of the ANGST sample. In addition to comparing the mean cumulative SFHs, we also consider effects that can potentially introduce biases in the measured SFHs, such as population gradients and systematic uncertainties in the underlying stellar models.

This paper is organized as follows. In Section 2, we summarize the sample selection and data. The technique of measuring SFHs from optical color–magnitude diagrams (CMDs) is briefly reviewed in Section 3. In Section 4, we address the question of whether the SFHs of LG dwarf galaxies are consistent with those in the Local Universe, by comparing cumulative SFHs from the ANGST and LG dwarf galaxy samples. We then examine the morphology–density relationship for both LG and ANGST dwarfs, and discuss demographic differences in the samples in Section 4.2. Cosmological parameters used in this paper assume a standard WMAP-7 cosmology (Jarosik et al. 2011).

2. THE DATA

2.1. The Local Group Dwarf Galaxy Sample

For this comparison, we consider a sample of LG dwarf galaxies based on those discussed in Mateo (1998) (see Table 1). All galaxies have multi-color optical imaging taken with either the Advanced Camera for Surveys (ACS; Ford et al. 1998) or the Wide Field Planetary Camera 2 (WFPC2; Holtzman et al. 1995) aboard HST. Following the convention of Mateo (1998), we have excluded the Large Magellanic Cloud and Small Magellanic Cloud from this paper. Similarly, we have omitted NGC 3109, NGC 205, NGC 6822, and NGC 55 as these are sufficiently luminous galaxies that their status as dwarfs is ambiguous (e.g., Hodge 1971; Skillman 1996; Mateo 1998; Weisz et al. 2011). Similarly, we have excluded “ultra-faint” LG dwarf galaxies (e.g., Belokurov et al. 2006) and Andromeda companions discovered more recently than And VII (e.g., Zucker et al. 2004) from this comparison; these sets of galaxies do not yet have publicly available HST photometry that has been processed in the same way as the galaxies we consider in this paper. The resulting LG sample covers a range of $M_B$ from $-7.13$ (Ursa Minor) to $-15.57$ (IC1613).

We divide the sample into three categories, dwarf spheroidal/elliptical (dSph), dwarf irregular (dI), and transition dwarf (dTrans) galaxies according to the morphological classifications in Mateo (1998). We combine dwarf spheroidals and the two dwarf ellipticals (dE; NGC 147 and NGC 185; e.g., Mateo 1998) into a canonical gas-poor galaxy (dSph) category. Following the convention of Mateo (1998), we designate as dTrans those that have detectable amounts of H I and no significant recent star formation, as measured by Hα. We note that Mateo (1998) classifies Pegasus as a dTrans, butSkillman et al. (2003) detect significant levels of Hα, and thus we consider it to be a dI. We also exclude IC 10 due to its low galactic latitude and high foreground extinction ($A_V \sim 2.5$; Schlegel et al. 1998), making both its distance and SFH highly uncertain. In total, the LG sample has 18 dSphs, 7 dIs, and 4 dTrans (Table 1).

The SFHs used for this comparison are based on CMDs presented in Dolphin et al. (2005) and Holtzman et al. (2006) that have been remeasured and analyzed (A. E. Dolphin et al. 2010, in preparation) with updated Padova stellar evolution models (Marigo et al. 2008). These SFHs are based on photometry of HST/WFPC2 imaging that was uniformly processed using HSTPHOT (Dolphin 2000) as part of the Local Group Stellar Populations Archive11 (Holtzman et al. 2006).

Five of the LG dwarfs (Cetus, Tucana, IC 1613, Leo A, and LGS3) were more recently observed with ACS as part of the Local Cosmology with Isolated Dwarfs program (LCID; Gallart et al. 2007).

Table 1

| Galaxy Name | Main Disturber | $M_B$ | $D$ (Mpc) | $A_V$ | Type | $\Theta$ |
|-------------|----------------|-------|-----------|-------|-------|--------|
| UrsaMin     | MW             | $-7.13$ | 0.08      | 0.11  | dSph  | 3.3     |
| LGS3        | M31            | $-7.96$ | 0.61      | 0.14  | dTrans| 1.7     |
| And V       | M31            | $-8.41$ | 0.78      | 0.41  | dSph  | 2.8     |
| Draco        | MW             | $-8.74$ | 0.09      | 0.09  | dSph  | 3.0     |
| Carina      | MW             | $-8.97$ | 0.10      | 0.21  | dSph  | 2.7     |
| Leo II      | MW             | $-9.23$ | 0.20      | 0.06  | dSph  | 1.7     |
| And III     | M31            | $-9.30$ | 0.72      | 0.19  | dSph  | 3.5     |
| And II      | M31            | $-9.33$ | 0.65      | 0.21  | dSph  | 2.4     |
| Antlia      | M31            | $-9.38$ | 1.30      | 0.24  | dTrans| $-0.1$  |
| Sculptor    | MW             | $-9.77$ | 0.08      | 0.06  | dSph  | 2.8     |
| Cetus       | M31            | $-10.18$ | 0.77      | 0.10  | dSph  | 0.5     |
| Phoenix     | MW             | $-10.22$ | 0.41      | 0.05  | dTrans| 0.8     |
| And VI      | M31            | $-10.80$ | 0.83      | 0.21  | dSph  | 1.7     |
| And I       | M31            | $-10.87$ | 0.76      | 0.18  | dSph  | 3.7     |
| Leo I       | MW             | $-10.97$ | 0.25      | 0.12  | dSph  | 1.5     |
| DDO210      | M31            | $-11.09$ | 0.94      | 0.17  | dSph  | 1.6     |
| Sagittarius | MW             | $-11.47$ | 0.95      | 0.22  | dI     | 1.2     |
| SagDIG      | MW             | $-11.49$ | 1.11      | 0.40  | dI     | 0.3     |
| Fornax      | MW             | $-11.50$ | 0.14      | 0.07  | dSph  | 2.3     |
| AndVII      | M31            | $-11.67$ | 0.94      | 0.64  | dSph  | 2.0     |
| LeoA        | MW             | $-11.70$ | 0.79      | 0.07  | dI     | 0.1     |
| Sagittarius | MW             | $-12.80$ | 0.03      | 0.40  | dSph  | 4.0     |
| Tucana      | MW             | $-12.94$ | 0.86      | 0.11  | dSph  | $-0.1$  |
| Sex A       | MW             | $-13.71$ | 1.30      | 0.14  | dI     | $-0.6$  |
| Sex B       | MW             | $-13.88$ | 1.40      | 0.10  | dI     | $-0.7$  |
| WLM         | M31            | $-13.95$ | 0.93      | 0.12  | dI     | 0.3     |
| N147        | M31            | $-14.76$ | 0.61      | 0.61  | dSph/dI| 3.5     |
| N147        | M31            | $-14.79$ | 0.72      | 0.58  | dSph/dI| 3.0     |
| IC1613      | M31            | $-15.57$ | 0.74      | 0.08  | dI     | 0.9     |

Notes. Properties of the sample of LG dwarf galaxies—(1) galaxy names: the SFH data for LGS3, Cetus, IC1613, Leo A, Tucana, and IC1613 are from the LCID program (Gallart et al. 2007). The rest of the SFH data has been derived from the CMDs presented in Dolphin et al. (2005) and Holtzman et al. (2006); (2) most gravitationally influential neighbor (Karachentsev et al. 2004); (3) absolute blue magnitude; (4) distance from TRGB or horizontal branch (Dolphin et al. 2005); (5) foreground extinction (Schlegel et al. 1998); (6) morphological type (Mateo 1998); and (7) tidal index (Karachentsev et al. 2004).

11 http://astronomy.nmsu.edu/holtz/archival/html/lg.html
et al. 2007) and have significantly deeper CMDs compared to the corresponding WFPC2 photometry (e.g., Cole et al. 2007; Monelli et al. 2010a, 2010b). Photometry of ACS observations was performed with DOLPHOT, an update of HSTPHOT with an ACS specific module, which allows us to include these five SFHs without compromising uniformity.

2.2. The ANGST Dwarf Galaxy Sample

The ANGST (Dalcanton et al. 2009) sample contains dwarf galaxies located beyond the zero velocity surface of the LG (van den Bergh 2000) and within $D \sim 4$ Mpc (see Table 2). The sample contains a mixture of field and group galaxies, the latter of which are located in the M81 Group ($D_{M81} \sim 3.6$ Mpc) and in the direction of the NGC 253 clump ($D_{NGC253} \sim 3.9$ Mpc) in the Sculptor Filament (Karachentsev et al. 2003). For comparison, we have selected all dSphs, dIs, and dTrans for the ANGST dwarf sample, as defined in Weisz et al. (2011). We note that several ANGST galaxies (Antlia, GR8, Sex A, Sex B, IC 5152, and UGCA 438) are considered to be in the LG of Mateo (1998). Of these galaxies, Antlia, Sex A, and Sex B are on the periphery of the LG, and we classify them as part of the LG sample for the purposes of this study. Tip of the red giant branch (TRGB) distance determinations (e.g., Dalcanton et al. 2009) place IC 5152, GR8, and UGCA 438 clearly beyond the zero velocity surface of the LG, and we thus include them in the ANGST sample for this comparison.

The ANGST sample contains several reported dEs, all within the M81 Group: F8D1, BK5N, KDG 61, KDG 64, KK 77, FM 1, and DDO 71 (Caldwell et al. 1998; da Costa 2007). We include these in the dSph category. Although the term dSph has often been used to describe early-type dwarf galaxies outside the LG (e.g., Geha et al. 2006), here we adopt the term dSph, which has historically been used in LG studies (e.g., Mateo 1998, and references therein) as a number of the early-type ANGST dwarf galaxies have luminosities and CMDs that are similar to dSphs in the LG. We discuss potential differences between dEs and dSphs, and SFHs, have been done in a manner consistent with the LG sample, making a direct comparison possible.

The faint end of the ANGST galaxy luminosity function is likely not complete due to selection biases against identifying faint low-luminosity surface brightness galaxies. For example, the ANGST sample does not include a number of recently discovered low surface brightness M81 Group galaxies (Chiboucas et al. 2009), as they do not yet have HST imaging publicly available. The final sample of ANGST galaxies in this paper includes 12 dSphs, 25 dIs, and 11 dTrans, spanning a range in $M_B$ from $-8.49$ (KK230) to $-16.57$ (HoII).

The SFHs of the ANGST dwarf galaxies are presented in Weisz et al. (2011). Data reduction and analysis, i.e., photometry and SFHs, have been done in a manner consistent with the LG sample, making a direct comparison possible.

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12 dSphs, 25 dIs, and 11 dTrans, spanning a range in $M_B$ from $-8.49$ (KK230) to $-16.57$ (HoII).
13 http://archive.stsci.edu/prepds/angstrom/
Weisz et al.

Figure 1. Left: the cumulative SFHs of the LG and ANGST sample dwarfs galaxies with random uncertainties shown as error bars. Right: the absolute value of the difference between the mean cumulative SFHs of the ANGST and LG samples, per morphological type, with random uncertainties (black). The estimated systematic effects in each sample are plotted as colored points. These values were determined by considering the absolute value of the difference between the simulated input SFH using BASTI models and the recovered SFH using Padova models. The number and photometric depths of recovered SFHs were chosen to match to the appropriate sample (e.g., 18 and 12 SFHs with photometric depths of the LG and ANGST dSphs were used to measure the values of the red points). Because the amplitude of the systematic uncertainties increase dramatically at old ages, points in the cumulative SFHs older than $z \sim 1$ (7.6 Gyr ago) cannot be reliably compared. See Section 3 for a more detailed discussion.

(A color version of this figure is available in the online journal.)

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initial mass function (IMF), binary fraction, and allowable ranges in age, metallicity, distance, and extinction. Photometric errors and completeness are characterized by artificial star tests. From these inputs, the code generates many synthetic CMDs spanning the desired age and metallicity range. For this work, we used synthetic CMDs sampling stars with logarithmic age and metallicity spreads of 0.05 and 0.1 dex, respectively. These individual synthetic CMDs were then linearly combined along with a model foreground CMD to produce a composite synthetic CMD. The linear weights on the individual CMDs are adjusted to obtain the best fit as measured by a Poisson maximum likelihood statistic; the weights corresponding to the best fit are the most probable SFH. This process can be repeated at a variety of distance and extinction values to solve for these parameters as well.

To minimize systematic effects, we selected identical input parameters for each of the galaxies. Specifically, we chose a single power-law stellar IMF with a spectral index of $-1.30$ with mass limits of 0.1 to 120 $M_\odot$ and a binary fraction of 0.35. Due to age–metallicity degeneracies in relatively shallow CMDs (e.g., Gallart et al. 2005; Cole et al. 2005), we required that the metallicity increase as a monotonic function of time, except in the case of the LCID galaxies, where chemical evolution was well determined without this constraint (e.g., Gallart et al. 2005; Cole et al. 2007; Monelli et al. 2010a, 2010b; Hidalgo et al. 2011).

In this study, we consider the cumulative SFHs, which give the fraction of stellar mass formed prior to a given time. We prefer this presentation to the more traditional plot of star formation rate (SFR) versus time, as the cumulative SFHs allow galaxies of different masses to be directly compared, and cumulative SFH measurements are not subject to covariant SFRs in adjacent time bins (see Appendix A of Weisz et al. 2011). We specifically compute an average cumulative SFHs per morphological type for both the LG and ANGST samples, which is the unweighted mean of the individual cumulative SFHs of galaxies within each group. This scheme weights all galaxies equally, so that the resulting SFH indicates what is “typical” for a particular morphological type. The resulting mean cumulative SFHs are shown in Figure 1.

We assign uncertainties to the mean cumulative SFHs using the method of error analysis outlined in Dolphin (2002) and Weisz et al. (2011). First, we divide the total uncertainty in the derived SFH into random and systematic components. Random uncertainties are due to Poisson uncertainties of the number of stars used to derive the SFR in a given time bin. The random uncertainties include observational effects, such as photometric errors and completeness corrections, which can affect the number of stars in each model time bin. To compute the random component of the uncertainty in the mean cumulative SFH, we add the uncertainties in the SFRs per time bin from the individual SFHs in quadrature. These random uncertainties are shown as the error bars in the left panel of Figure 1. For well-populated CMDs, including most of those used to measure the SFHs considered in this paper, the amplitude of random uncertainties is typically $\lesssim 10\%$.

The second source of uncertainty we consider is systematic uncertainties. Systematics are introduced into the measured
SFHs through biases in the underlying stellar models that change as a function of photometric depth of the observed CMD. The photometric depth of a CMD determines the presence of age-sensitive features (e.g., ancient main-sequence turnoff (MSTO), horizontal branch) available for measuring an SFH (e.g., Aparicio & Hidalgo 2009; Weisz et al. 2011). For extremely deep CMDs that include the ancient MSTO, systematics are typically small, because of the reliability of MS stellar evolution models. For shallower CMDs, including the majority of those used for SFH measurements in this paper, we must rely on the evolved star populations (e.g., red giant branch and horizontal branch) to constrain the SFH. The physics of evolved stars is not yet fully understood, and consequently SFHs derived from CMDs that primarily contain evolved stars may be systematically biased (e.g., Gallart et al. 2005). Appendix B in Weisz et al. (2011) demonstrates the effect of systematic biases on SFH measurements.

For comparison of SFHs in this paper, we are interested in the differential systematic uncertainties between the LG and ANGST samples. Specifically, we wish to understand how the different typical photometric depths between the two samples affects the derived SFHs. To estimate the systematic uncertainties, we follow the procedure outlined Appendices B and C in Weisz et al. (2011).

Briefly, this technique uses the differences in SFHs derived using the BaSTI (Pietrinferni et al. 2004) and Padova stellar evolution models as an estimate of systematic errors. In the case of the LG and ANGST galaxies, we did the following exercise to gauge the systematic uncertainties in the derived SFHs. First, we simulated a CMD assuming constant SFH using the BaSTI stellar evolution models at photometric depths equivalent to those in the LG and ANGST samples. We then recovered the SFH of each simulated CMD using the Padova models. Next, we took the cumulative SFH of each realization and computed the mean of the ensemble population. For example, for each of the 18 ANGST dSphs, we simulated a CMD assuming a constant SFH to the depth of the observed CMD, using the BaSTI models, and then recovered the SFH using the Padova models. From these 18 realizations, we then computed the mean cumulative SFH for this collection of simulations. This exercise was then repeated for all the other morphological sub-groups, e.g., LG dSphs, ANGST dIs, etc.

We now want to compare the differences in the observed cumulative SFHs with the size of the systematic uncertainties. To do this, we simply take the difference of the observed cumulative SFHs and the simulated cumulative SFHs, and compare the amplitude of the difference per time bin. As a concrete example, we can consider the systematics associated with the dSphs. We first compute the difference in the mean cumulative SFHs and show them as the black points in panel (a) of Figure 1. The error bars on each point are the random uncertainties. We then compute the difference in the mean recovered SFHs of the LG and ANGST dSphs samples. This difference is plotted as the red points in panel (a) of Figure 1. In general, if the value of the red points are greater than those of the black points, the systematic uncertainties are larger than the difference in the measured SFHs. Note that this exercise is an equivalent to a single Monte Carlo realization for each ensemble, and thus provides an estimate of the systematic uncertainties.

We consider an additional source of uncertainty, which is due to the limited area sample of the LG HST observations. From studies of LG dwarfs, it has long been known that the central regions of dwarfs typically have larger numbers of young or intermediate age stars, while populations further from the center tend to have older average ages (e.g., Hodge 1973; Hunter & Gallagher 1986; Irwin & Hatzidimitriou 1995; Mateo 1998; Hidalgo et al. 2009). Because of their close proximity, LG dwarf galaxies have large angular areas relative to HST’s field of view and, in most cases, the deepest available HST observations target the central regions of dwarf galaxies (e.g., Holtzman et al. 2006). The implications for this study are that the LG SFHs derived for the central regions may not be representative of the entire galaxy. In contrast, the ANGST galaxies are distant enough that a single HST field typically covers the entire extent of a dwarf galaxy (Weisz et al. 2011). The net effect of this bias is that SFHs of the LG dwarfs are likely weighted toward somewhat younger ages. However, quantifying such an effect on SFHs must wait for wide-field CMDs that reach the ancient MSTO.

Finally, as evidenced by the amplitude of the systematic uncertainties (shown on the right-hand side of Figure 1), we cannot reliably compare SFHs prior to \( z \sim 1 \) (\( \gtrsim 7.6 \) Gyr ago). At these early epochs, only ultra-deep CMDs reaching the ancient MSTO can reliably decipher the details of the ancient SFHs, e.g., the epoch of the peak ancient SFR. Although some such CMDs are available within the LG sample, none are present for the more distance galaxies in the ANGST sample. Thus, while the two samples are generally comparable in their cumulative SFHs, studies of the detailed ancient SFHs indicate that galaxies can show wide variation in their patterns of star formation at the oldest epochs (e.g., Cole et al. 2007; Monelli et al. 2010a, 2010b). These early variations may show correlations with environment or other galaxy properties. However, we are not able to discern such differences for the vast majority of galaxies in our samples.

4. DISCUSSION

In the left panel of Figure 1, we compare the mean cumulative SFHs of the ANGST and LG samples per morphological type. The plotted error bars represent only the random uncertainties in the SFHs, i.e., the expected amplitude of systematic uncertainties are shown in the right panel.

4.1. Comparing the ANGST and LG Star Formation Histories

We first compare the mean cumulative SFHs of the ANGST and LG samples. Taken at face value, the SFHs in the left panel of Figure 1 indicate that the cumulative SFHs of dSphs and dTrans are generally comparable, for the ANGST and LG volumes. In particular, the typical dSph or dTrans galaxy in either sample formed \( \sim 70\% \) of its stars by \( z \sim 1 \) (7.6 Gyr ago), the lookback time to which the typical ANGST CMD is sensitive (Weisz et al. 2011). At more recent times, we see some differences between the cumulative SFHs of the two dSph populations. The LG dSphs appear to have formed a slightly higher percentage of stars by \( z \sim 0.2 \), but the two sample show agreement for times more recent than \( z \sim 0.1 \).

In contrast, the cumulative SFHs of LG and ANGST dIs do not generally agree within the random uncertainties. In particular, the typical LG dI has formed \( \sim 50\% \) of its stars by \( z \sim 1 \) (7.6 Gyr ago), which the typical ANGST dI has formed \( \sim 65\% \) by the same epoch, although we note that accounting for the effects of population gradients would likely increase the percentage of stellar mass formed at ancient times for the LG dIs, bringing the samples into closer agreement.

For meaningful comparison of the SFHs, we cannot take the mean SFHs at face value, and instead must consider the influence
of systematic effects on the derived SFHs. As outlined in Section 3, we have estimated the systematic effects as a function of varying numbers of galaxies observed at varying depths of photometry, and find that, overall, the differences between the LG and ANGST dwarf galaxy SFHs are typically smaller than the systematic and statistical uncertainties, suggesting that the SFHs of the two samples are likely not very different. We see that the systematic effects on the mean cumulative SFHs are largest for the dSph galaxy samples (i.e., the colored points are usually larger than the black points) for ages older than 4 Gyr. For the dTrans samples, the differences are very comparable to the systematic uncertainty estimates, and for the dIs samples, the systematic uncertainties are generally less than the observed differences in the mean cumulative SFHs. Thus, the SFHs of the dSphs and dTrans in the LG and ANGST volumes appear to be fairly similar.

Interpreting the differences in the cumulative SFHs of the LG and ANGST dls is not straightforward. On the one hand, the differences of their mean cumulative SFHs seem to exceed the estimates of the systematic uncertainties. Taken at face value, this suggests that the dls in the two samples are not consistent. However, there are two effects which convolute this interpretation. First, is the effect of population gradients, which tend to bias the ancient SFHs of LG dls to somewhat younger ages. Because we cannot quantify the size of this effect, we only note that the cumulative SFHs of the LG dls are likely lower limits. The second issue is interpreting the meaning of the systematic uncertainties. We have used the differences in SFHs recovered from two sets of stellar models as a proxy for systematic uncertainties. Yet, these models share a degree of similarity in their underlying physics, for example, nuclear reaction rate and stellar atmospheres, which may make similarities in these models larger than the similarity between any one model and observed data. Thus, in some sense, the systematics we consider in this study are also lower limits due to the inherent similarity of the underlying stellar models.

While it is not clear if the observed difference in the SFHs of the LG and ANGST dls is indicative of different modes of star formation or simply the result of several biases, we do suggest that, at minimum, these SFHs are not drastically different.

4.2. Variations among Morphological Types in the Combined Local Group and Local Volume Sample

The comparison shown in Section 4.1 suggests that the differences in the SFH between the LG and ANGST dwarfs are not pronounced. We therefore now consider the SFH and morphological properties of the combined sample of ∼80 galaxies.

From the SFH perspective, the SFHs of the entire LG and ANGST dwarf population confirm the findings of Weisz et al. (2011). Namely, we verify that the dSphs, dTrans, and dls have very similar cumulative SFHs until z ∼ 0.7. Subsequent to this time, the average dSphs formed a higher fraction of its stellar mass and appear to have little SF more recently than z ∼ 0.1. In contrast, dls formed higher fractions of their stellar mass at more recent times. dTrans straddle the middle between the dSphs and dls.

The combined LG-ANGST dwarf sample also gives us excellent dynamic range for probing the morphology–density relationship. In Figure 2, we see that the LG and ANGST samples show clear and well-matched morphology–density relationships. The dls in both samples span a broad range of predominantly negative tidal indices (Θ, a useful probe of local density; Karachentsev et al. 2004) indicating that dls are preferentially found away from dense environments. This result is consistent with previous studies of both the LG (e.g., Mateo 1998; van den Bergh 2000) and dwarf galaxies in the wider universe (e.g., Skillman et al. 2003; Geha et al. 2006). The ANGST sample has more dls with Θ < −1.5, which is due to the large field population of the sample. dSphs in the two samples typically have positive tidal indices and fainter values of MB when compared to the dls. A Kolmogorov–Smirnov (K-S) test confirms that dls and dSphs are not drawn from the same distribution in either environment or luminosity, with a less than 4 × 10−5 probability of having identical distributions.

In contrast with the sharp division in properties between dls and dSphs, dTrans have properties that are intermediate between the two classes. dTrans galaxies occupy environments that are statistically indistinguishable from those of dls, according to a K-S test. Their environments are statistically distinct from those occupied by dSphs, with only a 2 × 10−6 probability of being drawn from the same distribution of Θ. The luminosities of the dTrans galaxies have the opposite behavior. Their luminosities are statistically indistinguishable from those of dSphs, but are statistically lower luminosity than dls, with only a 10−5 probability of being drawn from the same distribution of luminosities.

To first order, the results above suggest that the majority of dTrans are consistent with being the low-mass end of the dI population. At these low masses, there are seldom more than a few HII regions per galaxy (e.g., Mateo 1998; Skillman et al. 2003) leading to a dTrans classification. However, we note that gas-rich galaxies with little Hα can form in multiple ways (e.g.,
Weisz et al. (2011), suggesting that not every dTrans has a similar evolutionary history. Those with higher tidal indices may be interacting galaxies in the process of transforming to gas-poor dSphs (e.g., Grebel et al. 2003). We refer the reader to Weisz et al. (2011) for a more detailed discussion of the nature of dTrans.

Although we have grouped all early-type dSphs and dEs together into a single “dSph” category, it is interesting to search for distinguishing characteristics between the two morphological types. Figure 2 reveals that the two dEs in the LG, $(M_B = -14.79)$ and NGC 185 $(M_B = -14.76)$, are conspicuously more luminous than other early-type dwarfs. Their intrinsic brightness is likely linked to the relatively large amount of intermediate age SF (e.g., Han et al. 1997; Mateo 1998; Butler & Martínez-Delgado 2005; Dolphin et al. 2005). In contrast, the seven dEs in the ANGST volume (F8D1, BK5N, KDG 61, KDG 64, KK 77, FM 1, and KDG 63; Caldwell et al. 1998; da Costa 2007), span a broad range of lower luminosities from FM 1 $(M_B = -10.16)$ to KDG 61 $(M_B = -12.54)$.

Examining the global SFHs of the ANGST dEs, we find that the two lowest luminosity ANGST dEs (FM 1 and BK5N) are dominated by stellar populations older than $≈10$ Gyr, while the more luminous dEs (KK 77, KDG 63, F8D1, KDG 64, and KDG 61) have larger fractions of intermediate SF, albeit at a lower absolute SFR than the two LG dEs (e.g., Weisz et al. 2011; Dolphin et al. 2005). The predominance of old stellar populations in the two low-luminosity dEs is more consistent with the LG and ANGST dSph populations, suggesting a dSph designation would be more accurate.

Interestingly, two of the most luminous ANGST dEs (F8D1 and KDG 61) have high tidal indices ($\Theta \sim 4$) that are comparable to the LG dEs. This suggests that, like NGC 147 and NGC 185 which have a history of interaction with M31 (Mateo 1998, and references therein), F8D1 and KDG 61 may have experienced interactions with their most gravitationally influential neighbor, M81. The two LG dEs may be examples of formerly gas-rich, rotationally supported dEs that are in the process of being transformed into gas-poor, pressure-supported dSphs/dEs (e.g., Geha et al. 2010). Further detailed study of the stellar kinematics of F8D1 and KDG 61 may help determine if these galaxies are undergoing a similar process, and may provide insight into the possible physical mechanisms (e.g., ram pressure and stellar mass loss; Mayer et al. 2001a, 2001b; Kazantzidis et al. 2011) driving this transformation.

5. SUMMARY

We present a comparison of the cumulative SFHs of LG and ANGST dwarf galaxies from high-quality CMDs based on HST imaging. In order to minimize systematics, the SFHs from each sample were derived using identical techniques and input parameters. The typical LG and ANGST dwarf galaxy appear to have formed the majority of their stellar mass prior to $z \sim 1$ (7.6 Gyr ago). Comparing the SFHs between the morphological types, we find that the dSphs and dTrans in the ANGST and LG samples have similar cumulative SFHs. In contrast, the LG and ANGST dls exhibit differences in their SFHs at ancient times, when taken at face value. We show that the observed differences are likely lower limits, due to the effects of population gradients, and the lower limit systematic uncertainties we have calculated.

Give that similarity of the LG and ANGST dwarf populations, we combine them into a single large sample. This combined sample exhibits a well-defined morphology–density relationship, with dls showing higher degrees of isolation than dSphs.

A K-S test reveals that dTrans occupy similar environments to dls but have luminosities comparable to dSphs. We further identify two M81 Group dEs with luminosities, tidal indices, and SFHs, which may be analogs to this rare class of galaxy in the LG. The excellent agreement between the two samples, and among the broader universe, underlines the importance of environmental factors in the evolution of dwarf galaxies.

In summary, we find that the cumulative SFHs and morphology–density relationships of the LG and ANGST samples are not drastically different. This finding suggests that the LG dwarf galaxies are reasonably representative of dwarf galaxies in the wider universe.

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