THE STAR FORMATION HISTORIES OF LOCAL GROUP DWARF GALAXIES. III. CHARACTERIZING QUENCHING IN LOW-MASS GALAXIES*

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ABSTRACT

We explore the quenching of low-mass galaxies ($10^4 \lesssim M_* \lesssim 10^8 M_\odot$) as a function of lookback time using the star formation histories (SFHs) of 38 Local Group dwarf galaxies. The SFHs were derived by analyzing color–magnitude diagrams of resolved stellar populations in archival Hubble Space Telescope/Wide Field Planetary Camera 2 imaging. We find: (1) lower-mass galaxies quench earlier than higher-mass galaxies; (2) inside of $R_{\text{vir}}$ there is no correlation between a satellite’s current proximity to a massive host and its quenching epoch; and (3) there are hints of systematic differences in the quenching times of M31 and Milky Way (MW) satellites, although the sample size and uncertainties in the SFHs of M31 dwarfs prohibit definitive conclusions. Combined with results from the literature, we qualitatively consider the redshift evolution ($z = 0–1$) of the quenched galaxy fraction over $\sim 7$ dex in stellar mass ($10^4 \lesssim M_* \lesssim 10^{11.5} M_\odot$). The quenched fraction of all galaxies generally increases toward the present, with both the lowest and highest-mass systems exhibiting the largest quenched fractions at all redshifts. In contrast, galaxies between $M_* \sim 10^8–10^{10} M_\odot$ have the lowest quenched fractions. We suggest that such intermediate-mass galaxies are the least efficient at quenching. Finally, we compare our quenching times with predictions for infall times for low-mass galaxies associated with the MW. We find that some of the lowest-mass satellites (e.g., CVn II, Leo IV) may have been quenched before infall, while higher-mass satellites (e.g., Leo I, Fornax) typically quench $\sim 1–4$ Gyr after infall.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: stellar content – Hertzsprung–Russell and C–M diagrams – Local Group

1. INTRODUCTION

Environment is believed to play an important role in the evolution of low-mass galaxies. Their shallow potentials make them vulnerable to a variety of internal (e.g., galactic winds, supernovae feedback) and external (e.g., tidal effects, ram pressure stripping) processes that can reshape and remove their baryons. The central role of the environment is observationally borne out by the dwarf “morphology–density” relationship, which shows that red, gas-poor, non-star-forming dwarf galaxies are predominantly found in close proximity to a massive host, while blue, gas-rich, star-forming dwarfs are preferentially located in lower density environments (e.g., Hodge 1971; Einasto et al. 1974; van den Bergh 1994, 2000; Mateo 1998; Greivich & Putman 2009; Tolstoy et al. 2009; Weisz et al. 2011; Geha et al. 2012; McConnachie 2012; Spekkens et al. 2014). This powerful observational constraint favors models in which quenching (i.e., the complete cessation of star formation)3 is induced by environmental mechanisms (e.g., Mayer et al. 2001, 2006) as opposed to purely internal processes (e.g., Dekel & Silk 1986).

Despite the clear importance of environment for gas removal and quenching in low-mass galaxies, our knowledge of the responsible mechanisms is limited. Tidal effects and ram pressure are believed to be the primary mechanisms for shutting down star formation (e.g., Gunn & Gott 1972; Einasto et al. 1974; Faber & Lin 1983). However, their relative effectiveness is modulated by a number of factors including halo mass and accretion history, infall time, proximity to a host, stellar feedback (which can induce outflows and weaken the effective potential), and the heating of gas from cosmic reionization in the lowest-mass systems (e.g., Dekel & Silk 1986; Thoul & Weinberg 1996; Gnedin 2000; Mayer et al. 2001; Busha et al. 2010; Governato et al. 2010; Zolotov et al. 2012; Lu et al. 2014; Wetzel et al. 2015). Because the complex interplay between each of these processes can vary with time, the morphology–density relationship at $z = 0$ cannot strongly discriminate between various scenarios for creating environmentally dependent quenching in dwarf galaxies.

Orthogonal constraints on quenching mechanisms come from star formation histories (SFHs). By tracing star formation over cosmic time, it is possible to determine exactly when and how quickly a dwarf galaxy quenched, providing insights into the physical mechanisms responsible for shutting down star formation. SFHs for galaxies located within a few Mpc can be reconstructed in detail by analyzing their resolved star color–magnitude diagrams (CMDs; e.g., Tosi et al. 1989; Harris & Zaritsky 2001; Dolphin 2002; Aparicio & Hidalgo 2009). The power of SFHs for constraining quenching was recently illustrated by Sohn et al. (2013) in their analysis of the Milky

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3 We define quenched galaxies as those without cold gas and without evidence of recent star formation (e.g., as traced by H\alpha and ultraviolet flux). In these systems, the reignition of a star formation is unlikely without significant gas accretion. We view such quenched systems as qualitatively different from post-starburst galaxies, despite the use of similar “quenching” terminology in the literature. Generally, post-starburst galaxies have had recent but no current star formation (i.e., ultraviolet flux but no detectable H\alpha), and typically have large gas reservoirs, suggesting that they may be capable of restarting star formation in the future.
Way (MW) satellite Leo I. The reconstructed orbital history has revealed that Leo I entered the virial radius of the MW 2 Gyr ago and made a pericentric passage ~1 Gyr ago at a distance of 90 kpc. The SFH shows an enhancement followed by a complete cessation of star formation over the same timescale, suggestive of a rapid quenching scenario likely due to ram pressure stripping, as its pericentric distance seems too large for tidal effects to be significant.

Despite the clear utility of SFHs for quenching studies, there have been few efforts to systematically characterize and analyze quenching in nearby dwarfs. The majority of relevant studies largely focus on quantifying the effects of early reionization on the lowest mass ($M_\star \lesssim 10^6 M_\odot$) MW satellites (e.g., Sand et al. 2009, 2010; Brown et al. 2012, 2014; Okamoto et al. 2012). Outside of the MW sub-group, there is only a small sample of quenched, low-mass galaxies with well-constrained SFHs (Cetus, Tucana, Andromeda II, Andromeda XVI; Monelli et al. 2010a, 2010b; Weisz et al. 2014c), making it challenging to explore broad quenching trends in low-mass systems. At the same time, several studies have compared N-body simulations to $z = 0$ properties of low-mass galaxies to constrain quenching timescales (e.g., Slater & Bell 2013, 2014; Phillips et al. 2014, 2015; Wheeler et al. 2014), but combining SFHs with the simulations is still an emerging field (e.g., Rocha et al. 2012).

In this paper, we use the SFHs of 38 LG dwarf galaxies to systematically measure the quenching epochs and timescales in low-mass systems ($M_\star \lesssim 10^6 M_\odot$). The SFHs are taken from the Weisz et al. (2014a) uniform analysis of optical CMDs based on archival imaging taken with the Hubble Space Telescope/Wide Field Planetary Camera 2 (HST/WFPC2; Holtzman et al. 1995). Using these SFHs, we investigate empirical trends in quenching epochs and timescales as functions of basic galaxy properties (e.g., stellar mass, proximity to a host), place the LG into the context of broader studies of quenching, and compare our data with select models of satellite infall in the LG. We have previously used this data set to examine the observational evidence for reionization as a quenching mechanism in the lowest-mass systems, and refer readers to Weisz et al. (2014b) for a more detailed discussion of this specific quenching mechanism.

This paper is organized as follows. We summarize the sample selection, photometry, and SFH measurement technique in Section 2. In Section 3, we explore empirical trends in a fraction of quenched galaxies as a function of mass and environment, and place our results in the context of the broader universe using data from the literature. In Section 4, we quantify delay times between infall and quenching by comparing our results with the model analysis presented in Rocha et al. (2012). Finally, we summarize our findings in Section 5. Throughout this paper, the conversion between age and redshift assumes the cosmology as detailed in Planck Collaboration (2014). We recognize that several definitions of a quenching epoch can be found in the literature. For direct comparison, we have provided all SFH data in a tabulated digital form in Weisz et al. (2014a).

2. THE DATA

2.1. Galaxy Sample and SFHs

Our sample contains 38 LG dwarf galaxies that all have deep archival $HST$/WFPC2 imaging. The sample includes 25 diverse quenched galaxies (dwarf spheriodals, dSphs; and dwarf ellipticals, dEs) spanning a large dynamic range in stellar mass ($10^4 \lesssim M_\star \lesssim 10^8 M_\odot$). Our sample also contains 5 transition dwarfs (dTrans), which have H$\alpha$ but no evidence of ongoing star formation (i.e., no detectable H$\alpha$; e.g., Mateo 1998), and 10 star-forming dwarfs (dwarf irregulars, dlrs), both of which provide good control and comparison samples. The properties of our galaxy sample are listed in Table 1.

We selected the galaxies based on the availability of deep archival $HST$/WFPC2 observations. All photometry was carried out using $HSTPHOT$,8 a photometry package designed specifically for the undersampled point-spread function of WFPC2 (Dolphin 2000) as part of the Local Group Stellar Populations Archive project9 (LOGPHOT; Holtzman et al. 2006). To characterize completeness and observational biases in the photometry, we ran $10^5$ artificial star tests per $HST$ field, i.e., we inserted stars of a known magnitude into our images and recovered their photometry in an identical manner to the photometry of real stars. Details of the photometric reduction process can be found in Holtzman et al. (2006).

All SFHs used in this paper were derived using the CMD fitting package MATCH (Dolphin 2002), as discussed extensively in Weisz et al. (2014a); we refer the reader to that paper for full details. Throughout the paper, we quote the 68% confidence interval of the total uncertainties, including both random (i.e., statistical uncertainties) and systematic (i.e., a proxy for variations in the SFH as if they were solved with different stellar models) components. Details of the uncertainty calculations for this sample are presented in Weisz et al. (2014a), and the general methodological details of the systematic and random uncertainty determinations are presented in Dolphin (2012, 2013), respectively.

2.2. Defining an Epoch of Quenching

As a first step, we must define a quenching epoch for galaxies in our sample. Identifying the quenching epoch for such a diverse collection of galaxies using CMD-based SFHs involves some subtlety, primarily owing to the presence of blue straggler stars (BSs). BSs—believed to be the result of merged or extreme mass transfer among low-mass, main-sequence stars (e.g., Davies 2015 and references therein)—have similar optical colors and luminosities as intermediate-age, main-sequence stars (2–5 Gyr old). Therefore, they may be mistaken as a signpost of intermediate-age star formation, particularly in lower-mass, quenched galaxies, where the “blue plume” is typically sparse.

Unfortunately, accounting for BSs in CMD-based SFH measurements is non-trivial. Because there are no generative models for BSs, it is impossible to explicitly include them in the CMD fitting process. One often-used solution is to simply exclude putative BSs from a CMD when measuring an SFH. While this may be suitable for galaxies in which there is a strong prior belief that the “blue plume” is composed of only BSs (e.g., the faintest MW satellites; Brown et al. 2012, 2014), it is challenging to implement this approach in a large, diverse sample of galaxies. Several studies have shown that increasingly luminous galaxies have blue plumes that contain a larger fraction of genuine main-sequence stars (e.g.,

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8 http://amarisco.dolphinsoft.com
9 http://astronomy.nmsu.edu/logphot
Table 1
Observational Properties of Our Local Group Dwarf Sample

| Galaxy Name | Morphological Type | \( M_V \) | \( M_\odot \) \( (10^9 M_\odot) \) | \( M_V \) | \( M_\odot \) \( (10^9 M_\odot) \) | \( D_{\text{Host}} \) | \( r_V \) | \( \log(t_{90}) \) |
|-------------|-------------------|---------|----------------|---------|----------------|------------|--------|--------------|
| Andromeda I | dSph              | −11.7   | 3.9            | 0.0     | 58             | 672        | 9.86    | 0.030,0.15 |
| Andromeda II | dSph              | −12.4   | 7.6            | 0.0     | 184            | 1176       | 9.75    | 0.011,0.07 |
| Andromeda III | dSph            | −10.0   | 0.83           | 0.0     | 75             | 479        | 9.72    | 0.015,0.03 |
| Andromeda V | dSph              | −9.1    | 0.39           | 0.0     | 110            | 315        | 9.87    | 0.023,0.13 |
| Andromeda VI | dSph             | −11.3   | 2.8            | 0.0     | 269            | 524        | 9.73    | 0.063,0.09 |
| Andromeda XI | dSph             | −6.9    | 0.049          | 0.0     | 104            | 157        | 10.11   | 0.001,0.23 |
| Andromeda XII | dSph            | −6.4    | 0.031          | 0.0     | 133            | 304        | 9.56    | 0.06,0.34  |
| Andromeda XIII | dSph           | −6.7    | 0.041          | 0.0     | 180            | 207        | 10.1    | 0.44,0.64  |
| Carina | dSph              | −9.1    | 0.38           | 0.0     | 107            | 250        | 9.46    | 0.011,0.12 |
| Canes Venatici I | dSph         | −8.6    | 0.23           | 0.0     | 218            | 564        | 9.92    | 0.011,0.11 |
| Canes Venatici II | dSph        | −6.9    | 0.0079         | 0.0     | 161            | 74         | 9.92    | 0.014,0.05 |
| DDO 210 | dTrans            | −10.6   | 1.6            | 4.1     | 1066           | 458        | 9.58    | 0.07,0.52  |
| Draco | dSph              | −8.8    | 0.29           | 0.0     | 76             | 221        | 10.01   | 0.01,0.06  |
| Fornax | dSph              | −13.4   | 2.0            | 0.0     | 149            | 710        | 9.43    | 0.02,0.14  |
| Hercules | dSph              | −6.6    | 0.037          | 0.0     | 126            | 330        | 9.91    | 0.01,0.90  |
| IC 10 | dIrr              | −15.0   | 86.0           | 50.0    | 252            | 612        | 9.21    | 0.02,0.15  |
| IC 1613 | dIrr              | −15.2   | 100.0          | 65.0    | 520            | 1496       | 9.33    | 0.07,0.12  |
| Leo A | dIrr              | −12.1   | 6.0            | 11.0    | 803            | 499        | 8.78    | 0.02,0.22  |
| Leo I | dSph              | −12.0   | 5.5            | 0.0     | 258            | 251        | 9.23    | 0.01,0.05  |
| Leo II | dSph              | −9.8    | 0.74           | 0.0     | 236            | 176        | 9.81    | 0.05,0.05  |
| Leo IV | dSph              | −5.8    | 0.019          | 0.0     | 155            | 206        | 10.05   | 0.05,0.37  |
| Leo T | dTrans            | −8.0    | 0.14           | 0.28    | 422            | 120        | 9.23    | 0.02,0.05  |
| LGS 3 | dTrans            | −10.1   | 0.96           | 0.38    | 269            | 470        | 9.58    | 0.02,0.09  |
| M32 | dE                | −16.4   | 320.0          | 0.0     | 23             | 110        | 9.23    | 0.04,0.49  |
| NGC 147 | dE                | −14.6   | 62.0           | 0.0     | 142            | 623        | 9.43    | 0.02,0.53  |
| NGC 185 | dE                | −14.8   | 68.0           | 0.11    | 187            | 42         | 9.56    | 0.02,0.05  |
| NGC 205 | dE                | −16.5   | 330.0          | 0.4     | 42             | 590        | 9.34    | 0.04,0.04  |
| NGC 6822 | dIrr            | −15.2   | 100.0          | 130.0   | 452            | 354        | 9.02    | 0.04,0.58  |
| Phoenix | dTrans           | −12.2   | 6.61           | 5.9     | 474            | 562        | 9.23    | 0.02,0.82  |
| SagDIG | dIrr         | −11.5   | 3.5            | 8.8     | 1059           | 282        | 8.91    | 0.035,0.05 |
| Sagittarius | dSph            | −13.5   | 21.0           | 0.0     | 18             | 2587       | 9.53    | 0.04,0.84  |
| Sculptor | dSph            | −11.1   | 2.3            | 0.0     | 89             | 283        | 10.03   | 0.02,0.05  |
| Sex A | dIrr              | −14.3   | 44.0           | 77.0    | 1435           | 1029       | 8.85    | 0.01,0.17  |
| Sex B | dIrr              | −14.4   | 52.0           | 51.0    | 1430           | 440        | 9.26    | 0.03,0.08  |
| Tucana | dSph              | −9.5    | 0.56           | 0.0     | 882            | 284        | 8.91    | 0.01,0.19  |
| Ursa Minor | dSph           | −8.8    | 0.29           | 0.0     | 78             | 181        | 9.96   | 0.01,0.07  |
| WLM | dIrr             | −14.2   | 43.0           | 61.0    | 836            | 2111       | 8.85    | 0.06,0.27  |

Note. The physical properties for the galaxies in our sample, taken from Connachie (2012). The stellar mass listed in column (4) is computed from the integrated V-band luminosity and assumes \( M_V/L_V = 1 \). Column (8) indicates the epoch at which 90% of the stellar mass formed, including the random uncertainties (first error term) and the total uncertainty (second error term). Both reflect their respective 68% confidence intervals. Note that for completeness we have also included these values for galaxies that are not currently quenched, i.e., dIrr/dTrans morphological types.

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Mapelli et al. 2007, 2009; Momany et al. 2007). Thus, excluding blue stars in all early-type systems a priori would mute the signatures of true intermediate-age star formation. Alternatively, excluding BSs in some galaxies and not in others is equally challenging, due to ambiguities in the point at which the “blue plume” is no longer purely BSs. Further, such an approach would compromise the homogeneity of our analysis. Thus, as discussed in Weisz et al. (2014a), we have elected to not account for blue stragglers in the CMD modeling process, and instead rely on judicious interpretations of the resulting SFHs.

For the purposes of this paper, we use the lookback time at which a galaxy formed 90% of its total stellar mass (hereafter \( t_{90} \)) as a proxy for the epoch at which it galaxy quenched. This value was selected to minimize the impact of BSs on determining the quenching epochs of the least luminous systems in our sample. The presence of BSs tends to shift the youngest bona fide star formation to younger ages, while...
keeping about the same total mass formed in the system. To estimate the impact of BSs on the SFHs, we re-ran the SFHs of several lower luminosity dSphs having masked out the “blue plume” and found a typical mass contribution from BSs of \( \sim 5\% \), with an upper limit of \( \sim 10\% \). Thus, while our adoption of \( \tau_90 \) is a conservative choice, it does avoid potential confusion of the quenching epoch due to the presence of BSs. Readers who wish to explore other quenching metrics can electronically obtain all tabulated SFH data from Weisz et al. (2014a).

We list the values of \( \tau_90 \) for each galaxy in Table 1. These values were computed by interpolating the cumulative SFHs in linear time for each galaxy, including both random and systematic uncertainties, onto a fine time grid of 10 Myr in spacing. This was done to pick out the exact 90% value for each galaxy and avoid abrupt changes in the cumulative SFH that would compromise homogeneity in computing \( \tau_90 \) from the native SFHs. For example, suppose the SFH abruptly jumps from 85% in one bin to 98% in a younger bin with a lull in star formation in between. Without interpolation we would be forced to pick the value closest to 90%, whereas the interpolation allows us to consistently select a value of \( \tau_90 \) across all galaxies. The assumption underlying the interpolation is that the SFH is constant across each bin. However, the error introduced by this assumption is small compared to other sources of uncertainty (e.g., systematics).

We plot \( \tau_90 \) as a function of mass and distance from the nearest central galaxy in Figure 1. This plot shows a few well-known trends: (1) currently star-forming galaxies are located at large distances from the MW or M31 (e.g., Grucevich & Putman 2009); and (2) lower-mass systems tend to be preferentially quenched compared to higher-mass systems (e.g., Tolstoy et al. 2009). However, there appears to be an interesting scatter in both trends, particularly when the values of \( \tau_90 \) are considered. We discuss these empirical relationships in more detail in Section 3.

2.3. Sample Completeness

Sample completeness plays an important role in assessing quenching in low-mass systems. Our sample is neither complete nor unbiased, as it was assembled based on the availability of HST/WFPC2 archival imaging. However, as shown in Figure 1, the sample is reasonably representative of the LG dwarf population in terms of stellar mass and proximity to a massive host. Specifically, our sample is \( \gtrsim 80\% \) complete for systems with \( M_* \gtrsim 10^6 \, M_\odot \), but only \( 10\%–40\% \) complete for galaxies with \( 10^3 \lesssim M_* \lesssim 10^6 \, M_\odot \). Similarly, our sample contains \( \sim 50\% \) of the galaxies known to exist within the virial radius of the MW or M31, and 80% of those located in the field. Thus, while our sample has variable completeness in both mass and proximity to a host, it spans the entire range of properties of the LG dwarf population (dashed lines on the side panels). In instances where completeness may compete with physical interpretation of the data, we qualitatively discuss how it may affect our results.

3. TIME EVOLUTION OF THE QUENCHED GALAXY FRACTION

Having defined a proxy for the quenching epoch, we now examine the relationship between \( \tau_90 \) and physical properties such as stellar mass and proximity to a massive host.
3.1. Quenched Fraction as a Function of Stellar Mass and Lookback Time

In Figure 2 we plot the fraction of quenched galaxies as a function of lookback time in four equally spaced logarithmic bins of present-day stellar mass (log(M*/M⊙) = 4.0–5.0, 5.0–6.0, 6.0–7.0, >7.0; hereafter we refer to these mass bins by their unweighted mean masses). We have defined the quenched fraction to be the fraction of galaxies that quenched at an earlier epoch than the specified lookback time (i.e., τ quench ≥ t). The shaded envelopes reflect the narrowest 68% confidence interval of the total uncertainty (i.e., random and systematic, which are inclusive of Poisson variance) that includes the best fit value of τ quench (traced by the solid line). These uncertainty estimates are slightly conservative (i.e., too large) as they include possible co-variances in the SFHs that were derived from the CMDs of similar depths, as discussed in Weisz et al. (2014a).

Figure 2 shows a clear trend for lower-mass dwarfs: they have a larger quenched fraction than more massive dwarfs at every epoch. By ~10 Gyr ago, ~50% of the lowest-mass systems (log((M*/M⊙)) = 4.5) were quenched, which is at least a factor of 5 higher than the quenched fraction in the other three mass ranges considered. The quenched fraction in the lowest-mass bin steadily grows until ~4–5 Gyr ago, by which time the quenched fraction has reached unity.

In the second lowest-mass bin (log((M*/M⊙)) = 5.7), the quenched fraction grows steadily from ~10% at ~10 Gyr ago to ~70% at ~3 Gyr ago. At higher masses, the quenched fraction is even lower. In the second highest-mass bin (log((M*/M⊙)) = 6.6), the quenched fraction reaches 50% at ~2.5 Gyr ago. In the highest-mass bin (log((M*/M⊙)) = 8.0), the quenched fraction in the present is only ~40%.

The temporal evolution of the quenched fraction can also provide clues as to how quickly dwarf galaxies can undergo quenching. For example, in the lowest-mass systems, nearly 40% appear to be quenched by ~12 Gyr ago, which implies a quenching timescale of ≤2–3 Gyr. Such a timescale is consistent with quenching due to reionization or early-time environmental processes. Interestingly, the quenched fraction of the lowest-mass galaxies continues to grow toward the present, indicating that not all low-mass systems were equally affected by quenching mechanisms that operated exclusively in the early universe (e.g., reionization). In contrast, galaxies in all other mass ranges have low quenched fractions at comparable earlier epochs. This broad trend is consistent with predictions from some reionization models, in which only the lowest-mass systems were significantly affected by reionization (e.g., Ricotti & Gnedin 2005). However, other models suggest that the influence of reionization on low-mass galaxies is more complex than permanently quenching star formation ~12 Gyr ago (e.g., Benitez-Llambay et al. 2014; Ofiorbe et al. 2015). We refer the reader to Weisz et al. (2014b) for an in-depth discussion of signature reionization in the SFHs of low-mass galaxies.

In the two intermediate-mass ranges, the nearly uniform increase in quenched fraction toward the present provides little information about the quenching timescale. In contrast, the highest-mass galaxies are more informative for learning about the rapidity of quenching. In this mass range (log((M*/M⊙)) = 8.0), the quenched fraction grew from 0% to 40% between 2 and 4 Gyr ago. This rapid rise indicates that galaxies of this mass can quench on fairly rapid timescales, although without knowledge of the infall times we cannot determine the exact quenching timescale (see Section 4). Furthermore, the six systems in this mass range may not be broadly representative of galaxies in this mass range, given that four are dEs in the M31 group (M32, NGC 147, NGC 185, NGC 205) and the other two are MW companions Fornax and Sagittarius. The nearly synchronized quenching of M31 dEs may be indicative of a global event in the M31 group (e.g., simultaneous satellite accretion, major merger; Fardal et al. 2008; Hammer et al. 2010), which may detract from the generality of this finding. For a further discussion of quenching in M31 satellites, we refer the reader to Section 3.3 and Weisz et al. (2014c).

Up to this point, we have not considered the role of uncertainties and selection effects in our results and interpretation. The uncertainties on the quenched fraction are most noticeable for the lowest-mass galaxies, which typically show broad 68% confidence intervals on their values of τ quench. This breadth is the result of a small number of stars on the CMDs of the lowest-mass systems, as well as the presence of BSs, which introduce a large dispersion into τ quench. For the more massive systems, which have more populated CMDs, the effects of uncertainties in the quenched fraction are noticeably less pronounced.

The completeness of the sample can also affect our findings. Many of the faint MW galaxies that are not in our sample appear to have quenched at lookback times of ≥10–12 Gyr ago (e.g., de Jong et al. 2008; Sand et al. 2009, 2010, 2012; Brown et al. 2012, 2014; Okamoto et al. 2012). A naive completeness correction, in which we assume that all missing galaxies are similar to the faint MW companions, implies that the quenched fraction could be as high as ~80% by 10–12 Gyr ago. However, as demonstrated in Weisz et al. (2014c), not all quenched low-mass systems in the LG stopped forming stars >10 Gyr ago. Deep imaging of Andromeda XVI (M* > 10^5 M⊙) reveals a quenching epoch of ~5 Gyr ago. Similarly, other low-mass galaxies in our sample, such as Andromeda XII and Leo T, have significant amounts of star formation <10 Gyr ago, even when full uncertainties are considered. Thus, on the whole, the simple assumption that all of the lowest-mass quenched galaxies are similar to the faintest MW satellites may not be an accurate extrapolation. Finally, we note our sample is 80% complete for M* > 10^6 M⊙, indicating that incompleteness in this regime is not as important as for lower-mass systems.

3.2. Quenched Fraction as a Function of Environment

In Figure 3, we plot the quenched fraction as a function of lookback time in bins of current distance from a massive host. We have divided the sample into four equally spaced radial bins in multiples of r_virial, ranging from R < 0.5 r_virial to R > 1.5 r_virial, where we adopt r_virial = 300 kpc for both M31 and the MW (McConnachie 2012).

From this plot, it is clear that environment plays an important role in quenching low-mass galaxies. At the present day, few dwarfs located outside r_virial are quenched, while those located inside r_virial are almost entirely quenched. This trend is essentially a re-statement of the long-established LG morphology–density relationship (e.g., Mateo 1998; van den Bergh 2000; Greveich & Putman 2009, and references therein).

For dwarfs located inside r_virial, the temporal evolution of the quenched fraction is essentially independent of the current proximity to M31 or the MW, and is statistically indistinguishable in both bins within R < 300 kpc. The small differences at
recent times are due to the presence of the gas-rich galaxies LGS 3 and IC 10 inside the virial radius of M31. The independence between quenching time and current proximity to a massive host is consistent with a picture in which quenching occurs when or soon after a galaxy enters the virial radius. This conclusion does not depend on selection effects and uncertainties in the values of $\tau_{90}$.

In principle, the SFHs may also provide clues to the planar satellite structures that are known to exist around the MW and M31 (e.g., Lynden-Bell 1976; Kroupa et al. 2005; Ibata et al. 2013). For example, if the planes were to be accreted as a group at the same time, the process of accretion may leave systematic signatures in the quenching epochs that are different from off-plane systems. Unfortunately, we do not detect any such clear trends. In the case of M31, only two of our galaxies, And II and And V, are off-plane, limiting any general comparison. Similarly, for the MW sample there is no clear difference in the SFHs of planar and non-planar satellites. The lack of a correlation does not rule out any large scale accretion scenario, as dynamical mixing may have erased the initial conditions of any such event.

3.3. Quenching Properties of the MW and M31 Satellites

As discussed in Section 3.1, there are hints that the M31 and MW satellites may have different quenching characteristics. We compare these two systems in detail in Figure 4. Here, the quenched fractions show qualitatively different trends. While the quenched fraction for the MW satellites steadily increases toward the present, the quenched fraction for M31 dSphs jumps from 20% at $\sim$7 Gyr ago to 100% by $\sim$5 Gyr ago. Further, the M31 dEs appear to have rapidly quenched between $\sim$2 and 4 Gyr ago, a different timescale than both sets of dSphs.

Taken at face value, these results suggest that the satellites in the two sub-groups may have systematically different quenching characteristics, despite the MW and M31 having similar stellar masses. The broader implication is that satellite behavior may be sensitive to the specific accretion history of the host galaxy, as opposed to simply scaling with host mass. However, our data only provide hints of these differences due to large uncertainties.
uncertainties in the SFHs of M31 satellites and incompleteness in both the MW and M31 satellite samples. Indeed, the uncertainties allow there to be identical quenching timescales between the two systems. Upcoming HST programs aimed at systematically imaging the M31 satellites (GO-13739, PI: Skillman; GO-13699, PI: Martin) should provide the data necessary to make more definitive statements about the quenching epochs of M31 satellites (e.g., Weisz et al. 2014c).

3.4. The Quenched Fraction over 7 dex in Stellar Mass

The fraction of quenched galaxies as a function of redshift and stellar mass is widely used as an observational constraint for modeling quenching processes in groups and clusters of galaxies (e.g., Mandelbaum et al. 2006; van den Bosch et al. 2008; Peng et al. 2010; Bauer et al. 2013; Moustakas et al. 2013; Wetzel et al. 2013). However, the majority of such studies have been limited to galaxies with $M_* \gtrsim 10^9-10^{10} M_\odot$, since fainter galaxies are extremely challenging to detect beyond the very nearby universe. As a result, there is no unified picture of quenching properties and processes over a full complement of galaxy masses and lookback times.

At the same time, the observational evidence that quenching in lower-mass galaxies is strongly driven by environment is steadily growing. For example, Geha et al. (2012) show that the fraction of quenched galaxies with $M_* \sim 10^{8.5} M_\odot$ is small at distances $>$1.5 Mpc from a massive host. Within the nearest few Mpc, KKR 25 and KKs3 are the only known examples of quenched, isolated dwarf galaxies (e.g., Weisz et al. 2011; Makarov et al. 2012; Karachentsev et al. 2015). The presumed$^{\text{10}}$ rarity of quenched, low-mass field galaxies suggests that most low-mass galaxies quenched in higher-density environments, although it is not possible to rule out completeness effects in the current surveys.

Therefore, exploring a broader picture of quenching requires comparing galaxies with respect to both mass and environment. In the remainder of the section, we compare quenching in the LG dwarfs with higher-mass galaxies from all environments. In the next section, we discuss the LG dwarfs alongside satellite populations to assess the specific role of environment.

In Figure 5 and Table 2, we illustrate the evolution of the quenched fraction from $z = 0-1$ ($\sim$0–8 Gyr ago) for galaxies spanning a range of 7 dex in stellar mass. In the top panel, we have combined the quenched fractions derived in this paper for galaxies with $M_* \lesssim 10^9 M_\odot$ from Wetzel et al. (2013) ($M_* \sim 10^{10} \lesssim M_* \lesssim 10^{11.5} M_\odot; z = 0-1$). This figure provides a first view of the quenched fraction over large ranges in stellar mass and redshift. Note that for consistency with the analysis of Wetzel et al. (2013), we compute the LG dwarf stellar masses at the specified redshift. These masses are generally negligibly different than the $z = 0$ masses used elsewhere in the paper, as most dwarfs only formed a small fraction of their mass at $z \lesssim 1$.

The most notable feature in this plot is the minimum of the quenched fraction as a function of mass at a given redshift. At each redshift considered, the quenched fraction steadily declines from maxima at the highest and lowest stellar masses toward a minimum at $M_* \sim 10^9-10^{10} M_\odot$. The “U” shape in the fraction of quenched galaxies may provide clues for which quenching mechanisms operate at different mass scales, which we now discuss in more detail.

At the highest masses ($M_* \gtrsim 10^{11} M_\odot$), quenching may be driven by several internal processes including active galactic nucleus feedback, virial shock heating, restricted gas accretion, stellar feedback, and/or disk instabilities (e.g., Silk & Rees 1998; Kereš et al. 2005; Birnboim et al. 2007; Dekel et al. 2009; Woo et al. 2013). Although the relative contribution of each mechanism to quenching remains unclear, the broad picture is that the depth of the potential well (i.e., halo mass) largely drives the initial quenching by depleting gas and suppressing cooling. Furthermore, star formation may be prevented by a combination of mechanisms (such as those above) or via other pathways such as heating from asymptotic giant branch stars (e.g., Conroy et al. 2014) that appear incapable of initial quenching, but may provide sufficient heating to maintain a massive galaxy’s quenched state.

At slightly lower masses ($M_* \sim 10^{10} M_\odot$), halo mass may play a diminished role in quenching. The ratio of stellar-to-halo mass reaches a global maximum at $M_* \sim 10^{10.5} M_\odot$ (e.g., Moster et al. 2010; Behroozi et al. 2013), suggesting that stellar feedback may play a more important role in quenching in this mass range (e.g., Moster et al. 2010; Hopkins et al. 2011, 2012, 2014).

The next lowest-mass data points ($M_* \lesssim 10^8 M_\odot$) are from the LG sample. Compared to the Wetzel et al. (2013) data, these galaxies are highly dark matter-dominated, and represent an obvious transition to a group environment. As a result, qualitatively different quenching mechanisms may be at work. Typically, the quenching of galaxies in this mass range is ascribed to environmental processes such as ram pressure or tidal stripping (e.g., Mayer et al. 2001, 2006), both of which require the presence of a massive galaxy, i.e., a group.

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$^{10}$ It is not possible to rule out completeness effects in the current low-mass galaxy surveys. However, any attempts to quantify the numbers and characteristics of undiscovered low-mass field galaxies would be pure speculation. We therefore take the current results at face value while acknowledging the competing effects of completeness.
environment, to be effective. Putative environmentally independent quenching mechanisms such as stellar feedback and gas consumption due to star formation (e.g., Dekel & Silk 1986) are not highly viable quenching mechanisms. Stellar feedback creates outflows of hot gas, but is not energetic enough to completely unbind cold gas from dark matter halos (e.g., mac Low & Ferrara 1999; Governato et al. 2010, 2012). Similarly, gas consumption from star formation is not a likely quenching mechanism. Gas consumption timescales for most gas-rich dwarfs are tens to hundreds of Gyr (e.g., van Zee et al. 1997; Skillman et al. 2003), and, if acting alone, would produce few quenched dwarfs in a Hubble time.

At the lowest masses ($M_* < 10^6 M_\odot$), reionization may be potentially playing a role in quenching (e.g., Efstathiou 1992; Bullock et al. 2000; Ricotti et al. 2002). Although it is often treated as a global, and thus an environmentally independent process, detailed simulations suggest that reionization is not necessarily uniform in time, intensity, and/or environment; therefore its impact on low-mass systems may be highly variable (e.g., Busha et al. 2010; Ocvirk et al. 2013). As discussed in Weisz et al. (2014b) and in Section 3.1, a large variability in the SFHs of the lowest-mass galaxies may be consistent with an inhomogenous reionization scenario.

Unfortunately, data from LG and Wetzel et al. (2013) provide no sampling in the minimum mass range ($M_* \sim 10^5$–$10^6 M_\odot$). However, nearby galaxy surveys can fill in this range at $z = 0$, providing some sampling for the behavior of these systems. In the bottom panel of Figure 5 we add the quenched fractions for all types of system masses and field galaxies from the SDSS-based study of Geha et al. (2012) and from the nearby galaxy catalog of Karachentsev et al. (2013). For the former data set, field galaxies are those with projected distances $>0.5$ Mpc from a massive host.

For the latter, we have estimated the quenched fraction from the nearby galaxy catalog (1 < D < 11 Mpc) of Karachentsev et al. (2013) as follows. We first convert all listed $M_B$ values into stellar masses assuming $M_B/L_\odot = 1$ and $M_{B, \odot} = 5.45$. We designate all galaxies with $M_* > 10^{10} M_\odot$ to be “central” galaxies, and compute the 3D distances (based on the listed line of sight distances and sky coordinates) between each central and the other 861 galaxies in the catalog. Galaxies that are within 0.5 Mpc of a central are considered to be satellites, and more distant non-centrals are designated as field galaxies. We

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**Table 2**

Quenched Fraction of Dwarfs as a Function of Redshift and Mass

| $\log(M_*(z))$ | Quenched Fraction | $\log(M_*(z))$ | Quenched Fraction |
|---------------|------------------|---------------|------------------|
| $z = 0$       | 1.00             | 4.5           | 1.0              |
| 4.5           | 0.73             | 5.7           | 0.73             |
| 6.6           | 0.56             | 6.5           | 0.44             |
| 8.0           | 0.50             | 7.9           | 0.25             |
| $z = 0.4$     | 0.83             | 4.5           | 0.67             |
| 4.5           | 0.64             | 5.5           | 0.55             |
| 6.5           | 0.33             | 6.5           | 0.2              |
| 7.9           | 0.00             | 7.9           | 0.00             |
| $z = 0.8$     | 0.57             | 4.5           | 0.57             |
| 4.5           | 0.40             | 5.6           | 0.3              |
| 6.4           | 0.2              | 6.4           | 0.1              |
| 7.8           | 0.00             | 7.8           | 0.00             |

**Note.** The fraction of quenched LG dwarf galaxies as a function of stellar mass and redshift. This table corresponds to the values plotted in Figures 5 and 6. We emphasize that due to selection effects, these values should be considered in a qualitative sense, as discussed in Section 3.4.
then compute the quenched fraction by comparing listed morphologies; those with $T < 0$ are considered to be quenched and those with $T \geq 0$ are not. At $M_* \leq 10^7 \, M_\odot$, the Karachentsev et al. (2013) suffers from decreasing completeness, and the authors also note that there is some ambiguity in morphological typing between star-forming transition objects that have faint GALEX fluxes but no detectable Hα (i.e., dTrans) and gas-free, non-star forming dSphs. To mitigate the latter effect, we have computed the morphological-based quenched fractions in both cases (i.e., all are dTrans are quenched or all dTrans are star-forming). These ranges are reflected by the envelopes in the bottom panel of Figure 5. Throughout this process, all LG galaxies were excluded from consideration. As discussed below, the quenched fractions determined by this method may not be as quantitative as those of Geha et al. (2012), but this method does provide an extension to lower masses that is not possible with SDSS. As a sanity check, the morphological approach provides very good overall agreement with expectations from both LG and ANGST SFHs. We list the quenched fractions derived from the Karachentsev et al. (2013) in Table 3.

The addition of literature data at $z = 0$ nicely fills in the missing mass range from the top panel of Figure 5 and helps paint a picture of quenching trends over a wider range of stellar masses. For the intermediate-mass range ($M_* \sim 10^8$–$10^{10} \, M_\odot$), the quenched fractions from Geha et al. (2012) and Karachentsev et al. (2013) are nearly zero. Both exhibit a small to modest upturn at $M_* \gtrsim 10^{10} \, M_\odot$, which is qualitatively consistent with the results of Wetzel et al. (2013).

At $M_* \lesssim 10^8 \, M_\odot$ the Karachentsev et al. (2013) quenched fractions show a significant upturn. This is particularly interesting for the field sample, as is it not clear which mechanisms can effectively quench such galaxies in the absence of environment. One possibility is that there are so-called “backsplash” galaxies, which had an interaction with a massive host and have since been ejected outside of the virial radius, placing them into the quenched field galaxy category. Similarly, analysis of the ELVIS N-body simulations (Garrison-Kimmel et al. 2013) by Deason et al. (2014) suggests that dwarfs outside the virial radius of a massive galaxy have a moderately high merger rate, which may be capable of inducing quenching. Alternatively, it may be the case that lower-mass systems are more vulnerable to gas loss due to feedback than current simulations suggest, which would introduce a mass-dependent quenching trend in isolated systems. Suggestions that dwarfs do not follow the stellar-halo mass relation from higher-mass galaxies (e.g., Garrison-Kimmel et al. 2014), i.e., they form more stars for a given halo mass, may also play a role in this possibility. Taken at face value, these data indicate that there are a modest number of quenched low-mass galaxies in the nearby universe, although there does not remain a clear physical reason for the observed quenched fraction in the field, particularly as the majority of galaxies in this sample are too massive to have been completely

| $\log(M_*/M_\odot)$ | Quenched Fraction | $N_{\text{Total}}$ | $N_{\text{Quenched}}$ dTrans $= \text{star-forming}$ | Quenched Fraction | $N_{\text{Quenched}}$ dTrans $= \text{not star-forming}$ |
|---------------------|-------------------|-------------------|---------------------------------|-------------------|---------------------------------|
| (1)                 | (2)               | (3)               | (4)                            | (5)               | (6)                            |
| All Galaxies        |                   |                   |                                |                   |                                |
| 5.68                | 0.60              | 15                | 9                              | 0.67              | 10                             |
| 6.74                | 0.35              | 139               | 49                             | 0.50              | 70                             |
| 7.60                | 0.13              | 310               | 38                             | 0.15              | 47                             |
| 8.55                | 0.04              | 201               | 8                              | 0.04              | 8                              |
| 9.53                | 0.04              | 94                | 4                              | 0.04              | 4                              |
| 10.32               | 0.19              | 31                | 6                              | 0.19              | 6                              |
| Field Galaxies      |                   |                   |                                |                   |                                |
| 5.80                | 0.67              | 6                 | 4                              | 0.67              | 4                              |
| 6.77                | 0.19              | 74                | 14                             | 0.33              | 25                             |
| 7.60                | 0.05              | 237               | 12                             | 0.07              | 16                             |
| 8.55                | 0.03              | 164               | 5                              | 0.03              | 5                              |
| 9.51                | 0.01              | 80                | 1                              | 0.01              | 1                              |
| Satellite Galaxies  |                   |                   |                                |                   |                                |
| 5.58                | 0.56              | 9                 | 5                              | 0.67              | 6                              |
| 6.71                | 0.54              | 65                | 35                             | 0.69              | 45                             |
| 7.60                | 0.36              | 72                | 26                             | 0.43              | 31                             |
| 8.53                | 0.08              | 37                | 3                              | 0.08              | 3                              |
| 9.60                | 0.21              | 14                | 3                              | 0.01              | 3                              |

Note. The $z = 0$ quenched fraction of galaxies as determined from an analysis of the Karachentsev et al. (2013) nearby galaxies catalog ($D < 11$ Mpc). The quenched fractions were computed using a comparison of listed morphological types and 3D distances as described in Section 3.4. Due to a potential confusion between dSph and dTrans morphological types at low stellar masses, we have included quenched fractions in which dTrans are counted as star-forming (columns (4) and (5)) or are counted as quenched (columns (5) and (6)). LG galaxies have been excluded from this analysis.

Table 3
Quenched Fraction for the Nearby Galaxy Catalog (Karachentsev et al. 2013)
are not resistant to quenching, while those of decreasing mass are more vulnerable to quenching. This suggests that secular processes may not be the only mechanism that can quench or strongly suppress star formation in galaxies that are otherwise in the lower mass range assumed to be affected by reionization, a new generation of low-mass galaxy simulations suggests that the effects of reionization may extend to lower masses as well.

The overall finding of these studies is that satellites with $M_* \geq 10^8 \, M_\odot$ have nearly constant quenched fractions over a large range of stellar mass ($M_* \sim 10^8$–$10^{11} \, M_\odot$). There are some minor inconsistencies in the trends reported by Slater & Bell (2014) and Wheeler et al. (2014), which applied different selection criteria to the same Geha et al. (2012) data set. This disagreement highlights another challenge in quantitatively interpreting data on quenching from different studies, a point that can be extended to our derivation of the satellite quenched fraction from the Karachentsev et al. (2013) catalog.

Despite subtle catalog differences, the general belief is that satellites with $M_* \geq 10^8 \, M_\odot$ are fairly resistant to quenching, even when acted on by ram pressure and/or tidal effects. The exact timescales of quenching are still sensitive to choices in running and interpreting simulations. However, commonly referenced timescales for becoming quenched after a satellite enters the virial radius of a massive galaxies are $\gtrsim 9$ Gyr (Slater & Bell 2014; Wheeler et al. 2014; Phillips et al. 2015). However, Slater & Bell (2014) suggest that following a pericentric passage, quenching must have more rapid timescales of $\sim 1$–2 Gyr, which is consistent with our current understanding of Leo I. We discuss more details on the relationship between model-based infall times and SFH-based quenching epochs in the next section.

For galaxies with $M_* \leq 10^8 \, M_\odot$, the increase in the quenched fraction with decreasing mass suggests that lower-mass systems are more vulnerable to environmental quenching effects in a group environment. However, a comparison with the Karachentsev et al. (2013) field data points in Figure 5 suggests that secular processes (e.g., feedback) may also be important. It is unclear how to reconcile these two figures based on the current paradigms about gas loss in low-mass galaxies, which do not make a clear prediction for mass-dependent quenching in the field. While this observation may hint at new insight into the physics of quenching in low-mass galaxies, it is also clouded by potential selection effects and small number statistics, as discussed in Section 3.4. It is further complicated by our primitive understanding of the effects of reionization on low-mass galaxies (e.g., Benitez-Llambay et al. 2014; Ofirbe et al. 2015). While many systems in this sample are above the stellar mass range assumed to be affected by reionization, a new generation of low-mass galaxy simulations suggests that the effects of reionization may extend to higher-mass systems (e.g., Benitez-Llambay et al. 2014). In such cases, it may be that reionization, in tandem with other effects (e.g., feedback), can quench or strongly suppress star formation in galaxies that are more massive than posited by the first generation of models (e.g., Ricotti & Gnedin 2005). For a deeper empirical and theoretical understanding, more extensive surveys of low-mass galaxies in isolated environments are needed to understand the significance of the trends revealed in this paper.

### 3.5. Satellite Quenching

Although we have just discussed the LG in the context of all galaxy quenching (i.e., centrals and satellites), a more conventional approach is to analyze only centrals or only satellites. Thus, in Figure 6, we plot the redshift evolution of our LG data along with satellite quenched fractions from several $z = 0$ satellite quenching studies.

The redshift evolution in Figure 5 is consistent in a picture of essentially monotonic quenching. That is, once a galaxy becomes quenched, it is unlikely to go back to being star-forming. There are many mechanisms that can induce and maintain a galaxy’s quenched status (e.g., feedback, ram pressure), but essentially only gas accretion can re-ignite star formation. Given that this single process must compete with a plethora of quenching mechanisms, it is unlikely to observe significant decreases in the quenched fraction toward the present. Indeed, this trend is observed in both the LG and Wetzel et al. (2013) data.

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proportional to the half-light radii, and error bars represent the total (random uncertainties). For example, Hercules quenched its efficiency can come from comparing the infall time and quenching time. The “delay time” between the two is a proxy for how long a galaxy can retain its gas and continue forming stars after entering the virial radius of a massive host. Alternatively, if quenching happens prior to infall, this may indicate that non-environmentally driven processes (e.g., reionization) were responsible.

While quenching epochs come directly from our SFH measurements, infall times cannot be measured directly and instead must be inferred from models. A common approach is to match sub-halos from N-body simulations with observed galaxies by comparing their masses (via abundance matching) and available phase space information (e.g., tangential and radial velocities). Rocha et al. (2012) provide a clear example of this type of modeling as applied to galaxies associated with the MW. Using Via Lactea II (Diemand et al. 2008), they quantify the correlation between the present-day orbital energy and the epoch at which a galaxy most recently entered the virial radius of the MW. Combined with available radial and proper motions (when available), they predict the infall time probability distribution functions for a dozen dwarf galaxies associated with the MW. In the remainder of this section, we compare their infall time predictions with our quenching timescales and explore the implications for quenching mechanisms.

Figure 7 shows several interesting trends in the comparison between $\tau_{90}$ and the predicted infall times. First, several of the lowest-mass galaxies appear to have quenched before infall. For example, Hercules quenched $\sim 12$ Gyr ago, but only entered the virial radius of the MW $\sim 5$ Gyr ago, suggesting that it spent the majority of its life away from the environmental influence of the MW. Six other galaxies (Leo IV, CVn I, CVn II, Leo II, Sculptor, and Draco) also have earlier quenching than infall times. Of these six galaxies, more than half (Hercules, Leo IV, CVn I, and CVn II) have been previously identified as putative “fossils of reionization,” i.e., their star formation was quenched due to reionization (e.g., Bovill & Ricotti 2011; Brown et al. 2012, 2014). If they were located outside the virial radius of the MW prior to quenching, the likelihood of quenching due to environmental processes (e.g., ram pressure) seems drastically lower, increasing the likelihood that reionization played a significant role in quenching their star formation.

Second, at the other extreme, Carina and Fornax appear to have quenched several Gyr after their infall times. Figure 7 suggests a delay of $\sim 5$ Gyr between when these galaxies fell in, and when their star formation stopped. This scenario would be qualitatively similar to the “delayed-then-rapid” quenching scenario for more massive satellites ($M_* \gtrsim 10^9-10^{10} M_\odot$) that was proposed by Wetzel et al. (2013). In this scenario a satellite continues to form stars for $2-4$ Gyr after infall, before rapidly quenching in less than 1 Gyr. We will explore more detailed modeling of this scenario in a future paper.

Third, there are a handful of galaxies that quenched near or shortly after their infall time. One example is Leo I. Leo I appears to have fallen into the MW’s halo $\sim 2.3$ Gyr ago (Rocha et al. 2012; Sohn et al. 2013). $\sim 1$ Gyr ago, Leo I appears to have reached pericenter at $\sim 90$ kpc from the MW, which is coincident with its value of $\tau_{90}$. This suggests an extremely small delay time, which is in stark contrast to the comparably luminous MW dSph Fornax. However, Leo I is believed to be on a highly inclined orbit, while Fornax is more circular, suggesting that the exact orbital trajectory may play a role in the delay time between infall and quenching.

Carina, which has a lower stellar mass than Fornax, also quenched $\sim 5$ Gyr after infall, supporting the idea that mass may not be the sole determinant for the quenching timescale, and the exact orbital history may matter. Interestingly, in the case of Carina, there is an open question as to whether its SFH shows multiple distinct bursts followed by periods of little or no star formation (e.g., Smecker-Hane et al. 1994; Hurley-Keller et al. 1998; Bono et al. 2010). Interpreted in the context of infall, it could be that Carina has made more than one passage around the MW, but only lost all of its gas and became completely quenched within the last few Gyr. As shown in Weisz et al. (2014a), our SFH of Carina has similar bursts and lulls in its SFH to previous literature derivations. However, when all uncertainties are considered, it is possible that the SFH was never completely quiescent between bursts.

Finally, Rocha et al. (2012) suggest that Leo T only entered the MW virial radius within the last Gyr. Observationally, the impact of this recent accretion appears to be minimal. Leo T has a large baryonic gas fraction (0.8) and displays spatially symmetric H I and stellar distributions (e.g., Irwin et al. 2007; Ryan-Weber et al. 2008). Furthermore, Leo T has nearly constant star formation over the last few Gyr, showing little evidence for Leo I-like enhancement upon infall. It does lack detectable H$\alpha$ emission, which could be interpreted as a break in the SFH. However, it could also be due to stochastic sampling of the stellar IMF and/or cluster mass function, which is believed to be common in such low-mass systems (e.g., Fumagalli et al. 2011; da Silva et al. 2012).
5. SUMMARY

We have used the SFHs of 38 LG dwarf galaxies to explore the quenching characteristics of low-mass galaxies (10^4 ≤ M⋆ ≤ 10^8 M☉). The SFHs were uniformly measured from the analysis of resolved star CMDs based on HST/WFPC2 imaging that was presented in Weisz et al. (2014a). Using a proxy for the quenching epoch as the lookback time when 90% of a galaxy’s stellar mass formed, we found the following results.

1. Lower-mass galaxies tend to quench prior to higher-mass galaxies. Specifically, the quenched fraction of the lowest-mass galaxies (log(M⋆/M☉) = 4.5) is 0.4 at ~10 Gyr ago and 1.0 at ~3–4 Gyr ago. In contrast, at the same epochs, the highest-mass systems (log(M⋆/M☉) = 8.0) have a quenched fraction of <10% and ~40%. The quenched fraction appears to vary smoothly as a function of mass and lookback time between these extremes. Due to the incompleteness of our sample, the quenched fraction of the lowest-mass galaxies may be larger at earlier times. However, several of the lower-mass dSphs in the LG show evidence of extended SFHs, so the assumption that all low-mass galaxies quenched early may not be entirely accurate.

2. Within Rvir of either the MW or M31, there is little correlation between the present distance to a host and the quenching epoch. Outside of Rvir, the quenched fraction is effectively zero at all lookback times.

3. There are hints of systematic differences in the quenching epochs of M31 and MW dSphs. The quenched fraction of M31 dSphs jumps from 0.2 at ~7 Gyr ago to 1.0 by ~5 Gyr ago, whereas the quenched fraction of MW dSphs steadily increases over cosmic time. Furthermore, the four M31 dEs all appear to have quenched between ~3 and 4 Gyr ago. However, the sample size and shallow CMDs of the M31 companions make it difficult to draw any definitive conclusions.

4. There are clear trends in the quenched fraction over ~7 dex in stellar mass. The lowest (M⋆ ≤ 10^6 M☉) and highest-mass (M⋆ ~ 10^{11.5} M☉) galaxies always have the highest quenched fractions at z = 0–1, while galaxies with M⋆ ~ 10^8–10^{10} M☉ always have the lowest quenched fraction. Given that the quenched fraction essentially monotonically increases toward the present, we conjecture that galaxies with M⋆ ~ 10^8–10^{10} M☉ are universally the most difficult to quench.

5. A comparison with the predicted infall times from Rocha et al. (2012) for select galaxies associated with the MW allows us to estimate delay times (i.e., the time between infall and quenching). We find that lower-mass systems tended to have quenched prior to infall, while higher-mass systems quenched after infall, and exhibit delay times of ~1–4 Gyr.

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