A STELLAR MASS THRESHOLD FOR QUENCHING OF FIELD GALAXIES

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Received 2012 April 17; accepted 2012 July 31; published 2012 September 6

ABSTRACT

We demonstrate that dwarf galaxies (10\textsuperscript{7} < M\textsubscript{stellar} < 10\textsuperscript{9} M\textsubscript{\odot}, −12 > M\textsubscript{r} > −18) with no active star formation are extremely rare (<0.06\%) in the field. Our sample is based on the NASA-Sloan Atlas which is a reanalysis of the Sloan Digital Sky Survey Data Release 8. We examine the relative number of quenched versus star-forming dwarf galaxies, defining quenched galaxies as having no H\textalpha{} emission (EW\textsubscript{H\textalpha{}} < 2 Å) and a strong 4000 Å break. The fraction of quenched dwarf galaxies decreases rapidly with increasing distance from a massive host, leveling off for distances beyond 1.5 Mpc. We define galaxies beyond 1.5 Mpc of a massive host galaxy to be in the field. We demonstrate that there is a stellar mass threshold of M\textsubscript{stellar} < 1.0 \times 10\textsuperscript{9} M\textsubscript{\odot} below which quenched galaxies do not exist in the field. Below this threshold, we find that none of the 2951 field dwarf galaxies are quenched; all field dwarf galaxies show evidence for recent star formation. Correcting for volume effects, this corresponds to a 1σ upper limit on the quenched fraction of 0.06\%. In more dense environments, quenched galaxies account for 23\% of the dwarf population over the same stellar mass range. The majority of quenched dwarf galaxies (often classified as dwarf elliptical galaxies) are within 2 virial radii of a massive galaxy, and only a few percent of quenched dwarf galaxies exist beyond 4 virial radii. Thus, for galaxies with stellar mass less than 1.0 \times 10\textsuperscript{9} M\textsubscript{\odot}, ending star formation requires the presence of a more massive neighbor, providing a stringent constraint on models of star formation feedback.

Key words: galaxies: dwarf – galaxies: stellar content – methods: statistical

Online-only material: color figures

1. INTRODUCTION

A well-established color bimodality is seen in the local distribution of luminous galaxies (e.g., Baldry et al. 2006; Tanaka et al. 2005; Blanton et al. 2005a; Blanton & Moustakas 2009) and appears already in place at redshifts above z ∼ 1 (Bell et al. 2004; Cooper et al. 2007). The galaxy population divides between blue, star-forming systems and red, quenched systems. The relative fractions between these two populations depend on both stellar mass and environment. Luminous red galaxies exist both in the field and in denser regions; however, at fixed stellar mass the fraction of luminous red galaxies is higher in denser environments (e.g., Kauffmann et al. 2004; van den Bosch et al. 2008).

The red/quenched fractions for less massive galaxies are lower regardless of environment as compared to their higher mass counterparts. Kauffmann et al. (2003) found a characteristic stellar mass of 3 \times 10\textsuperscript{9} M\textsubscript{\odot} below which galaxies tend to be star forming and have lower surface brightnesses. In the framework of “central” and “satellite” galaxies (Yang et al. 2003; Zehavi et al. 2011), where central galaxies are defined as the most massive galaxy in their dark matter halo based on group catalogs, Wang et al. (2009) and Peng et al. (2010) showed that the red fractions for central galaxies decrease as a smooth function of declining stellar mass, reaching red fractions around 10\% for the lowest stellar masses (M\textsubscript{stellar} ∼ 10\textsuperscript{9} M\textsubscript{\odot}) available in large numbers in the Sloan Digital Sky Survey (SDSS). Using spectroscopic diagnostics to define quenched galaxies, Wetzel et al. (2012) and Tinker et al. (2011) also showed that quenched fractions decrease with stellar mass for central galaxies, reaching slightly lower quenched fractions for central galaxies at the same stellar mass.

Many galaxy formation models predict lower quenched fractions for lower mass central galaxies. Currently favored models suggest that massive galaxies are quenched because they can maintain a hot gaseous halo, due to processes such as heating from supernovae or active galactic nuclei (e.g., Croton et al. 2006; Dekel & Birnboim 2008; Kimm et al. 2009). These processes suppress gas cooling, either heating gas within the galaxy or preventing additional cold gas from accreting, and effectively shutting off star formation (Kere\v{s} et al. 2005). Low-mass galaxies which are satellites of more massive objects are quenched because of the many physical mechanisms available in the group environment, such as ram pressure, harassment and tidal stripping. However, below some threshold, small central galaxies are not expected to be quenched (Gabor & Davé 2012). Testing such a framework requires a large well-understood sample of low-mass galaxies across a range of environments.

Quantifying the quenched fractions of dwarf galaxies, defined here as galaxies fainter than M\textsubscript{r} > −18 or stellar mass below 10\textsuperscript{9} M\textsubscript{\odot}, is challenging, largely because the colors and apparent sizes of low luminosity galaxies are similar to those of more luminous, and far more numerous, background objects. This necessitates spectroscopic samples. In the Local Group, quenched galaxies dominate the dwarf satellite population within 500 kpc of either the Milky Way or M31, while star-forming gas-rich galaxies tend to lie at larger distances (Einasto et al. 1974; Mateo 1998; Grecoevich & Putman 2009; Weisz et al. 2011). Similarly, in the nearby Virgo or Coma galaxy clusters, quenched dwarf galaxies dominate the clusters’ center and transition to a more star-forming population in the outskirts (Binggeli et al. 1985; Ferguson & Sandage 1991; Lisker et al. 2007). Haines et al. (2008, 2007) found no quenched galaxies fainter than M\textsubscript{r} = −18 in the SDSS Data Release 4. In this paper, we perform a similar analysis, confirming this result with a much larger sample of dwarf galaxies.

We construct a clean sample of nearly 10,000 dwarf galaxies in the stellar mass range 10\textsuperscript{7} < M\textsubscript{stellar} < 10\textsuperscript{9} M\textsubscript{\odot} (−12 >
whose structural parameters are fit to the in all bands. Fluxes are based on two-dimensional S´ersic models mosaicked image which is deblended and analyzed consistently are analyzed (Figure1). For each galaxy, the NSA contains a is not optimized for nearby low luminosity objects, we instead 3 http://www.nsatlas.org

The Astrophysical Journal, 757:85 (8pp), 2012 September 20

2. CONSTRUCTING THE SDSS DWARF GALAXY SAMPLE

2.1. The NASA-Sloan Atlas

Our dwarf galaxy sample is derived from the SDSS Data Release 8 spectroscopic catalog (DR8; Aihara et al. 2011), covering 7966 deg^2 of the sky. Since the SDSS main catalog is not optimized for nearby low luminosity objects, we instead select objects from the NASA-Sloan Atlas (NSA). The NSA is a reprocessing of the SDSS photometry using the SDSS ugriz images with an improved background subtraction technique (Blanton et al. 2011), combined with Galaxy Evolution Explorer (GALEX) images in the near and far UV. The NSA photometry is a significant improvement over the standard SDSS DR8 photometric catalog, as described in Blanton et al. (2011). All galaxies with redshifts z < 0.055 within the SDSS footprint are analyzed (Figure 1). For each galaxy, the NSA contains a mosaicked image which is deblended and analyzed consistently in all bands. Fluxes are based on two-dimensional Sérsic models whose structural parameters are fit to the r-band image. The NSA catalog galaxy also provides a reanalysis of the SDSS spectroscopic data for each galaxy using the techniques of Yan & Blanton (2012) and the SDSS spectrophotometric recalibration of Yan (2011). This analysis yields fluxes, equivalent widths and associated errors.

To estimate stellar masses, we use those reported by the kcorrect software of Blanton & Roweis (2007) which assumes a Chabrier (2003) initial mass function and is based on fits to both the SDSS optical and, when available, GALEX fluxes. Distances are estimated based on the SDSS NSA redshift and a model of the local velocity field (Willick et al. 1997). Distance errors are folded into our error estimations for stellar mass.

In this paper, we focus largely on dwarf galaxies with stellar masses between $10^7 < M_{\text{stellar}} < 10^9 M_\odot$. In the NSA catalog this corresponds to 9399 galaxies. A search for objects in the same stellar mass and redshift range in the DR7 NYU-Value Added Galaxy Catalog (VAGC; Blanton et al. 2005c) yields nearly 16,000 objects over the same area. The standard SDSS photometry used by the VAGC catalog is not optimized for extended nearby galaxies; the excess of “dwarfs” in this catalog are primarily shredded pieces of massive galaxies which have been properly accounted for in the NSA catalog.

2.2. Environment and Nearest Luminous Neighbors

We calculate environments for our dwarf galaxy sample relative to more luminous neighbor galaxies. We want to maximize our ability to identify luminous neighbors, despite the large angular distances for this nearby sample. For example, searching a 1 Mpc region around a galaxy 30 Mpc away corresponds to 2 deg on the sky. Many of our dwarf galaxies are on the SDSS Southern stripes, which are only 2.5 deg wide. For this reason, instead of the NSA catalog, which is limited to the area with SDSS imaging, we use the Two Micron All Sky Survey (2MASS) Extended Source Catalog to identify luminous galaxy hosts. For redshifts, we use SDSS spectroscopy plus several other sources: the Two-degree Field Galaxy Redshift Survey (2dFGRS) (Colless et al. 2001), the Six-degree Field Galaxy Redshift Survey (Jones et al. 2004), ZCAT, ALFALFA (Giovanelli et al. 2005) as well as every redshift within z < 0.055 from the NASA Extragalactic Database (NED). By using this all-sky catalog, we can best identify luminous neighbors even for dwarf galaxies near the edges of the SDSS imaging.

To quantify environment, we determine the distance, $d_{\text{host}}$, for each of our dwarf galaxies to its nearest “luminous” neighbor. In this context, we define galaxies as luminous if $M_K < -23$ corresponding to a stellar mass of approximately $2.5 \times 10^{10} M_\odot$ (assuming a mean stellar mass-to-light ratio

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3. http://www.nsatlas.org

4. http://www.cfa.harvard.edu/~dfabricant/huchra/zcat/
in the K_s-band of unity). The 2MASS sample is complete within our dwarf galaxy volume for this choice of \( M_K \). Because we use several different redshift surveys, the sample of luminous galaxies is non-uniform, especially outside the area covered by SDSS main sample spectroscopy. However, we prefer to have as complete a sample of luminous galaxies as possible, in order to most reliably identify isolated dwarf galaxies. To define the environment for each dwarf galaxy, we search for the closest luminous galaxy within 1000 km s\(^{-1}\) in redshift and within a projected comoving distance \( d_{\text{host}} < 7 \) Mpc. A small number of dwarfs have no luminous galaxy within this volume; we set the \( d_{\text{host}} \) values for these galaxies to 7 Mpc.

2.3. Definition of Quenched Dwarf Galaxies

We divide our sample between galaxies with active star formation and “quenched” galaxies that are not forming stars. We differentiate between these two populations using SDSS spectroscopic diagnostics. We define quenched galaxies as having both no H\(\alpha\) emission (EW H\(\alpha\) < 2 Å) and a criterion based on the 4000 Å break, \( D_{\alpha,4000} \). The \( D_{\alpha,4000} \) index is a measure of the light-weighted age of the stellar population (Balogh et al. 1999). Because it is measured in two 100 Å windows separated by 50 Å, it is less affected by dust reddening than broadband galaxy colors. Analogous to color indicators, we find that the \( D_{\alpha,4000} \) strength is a function of stellar mass (Figure 2) and therefore define quenched galaxies as having \( D_{\alpha,4000} > 0.6 + 0.1 \log_{10}(M_{\text{stellar}}/M_\odot) \). At a stellar mass of \( 10^{10} M_\odot \), this is equivalent to the \( D_{\alpha,4000} > 1.6 \) criterion used by Tinker et al. (2011).

Figure 3 shows \((g-r)\) color, H\(\alpha\) EW, and \( D_{\alpha,4000} \) index as a function of nearest neighbor distance, \( d_{\text{host}} \). We compare the distributions of these quantities for two stellar mass bins: \( 10^{9.25} < M_{\text{stellar}} < 10^{9.75} M_\odot \) (top panels), and \( 10^8 < M_{\text{stellar}} < 10^{9.25} M_\odot \) (bottom panels). These two stellar mass bins were chosen to have a roughly similar number of galaxies and straddle the stellar mass threshold of \( 1.0 \times 10^9 M_\odot \) discussed in Section 3.2. In both bins, the majority of quenched galaxies have red \((g-r)\) colors and tend to lie close to a massive parent galaxy, at values of \( d_{\text{host}} < 1 \) Mpc. Similarly, the majority of galaxies with strong \( D_{\alpha,4000} \) index, an indicator of older stellar populations, exist in close proximity to a larger galaxy. At all masses, galaxies show a wide range of H\(\alpha\) EW which extend to values larger than the plotted region. At higher stellar masses, there are a number of galaxies which show no H\(\alpha\) emission and high values of \( D_{\alpha,4000} \) at large values of \( d_{\text{host}} \); however, these objects are missing in the lower mass panels. We explore these quantities further below.

2.4. \( V_{\text{max}} \) Corrections and Surface Brightness Completeness

The SDSS spectroscopic apparent magnitude limit of \( r < 17.77 \) restricts the volume over which dwarf galaxies can be found (Figure 1). We will compare quantities as a function of stellar mass and do not want to use a volume-limited sample which would further reduce the number of available dwarf galaxies. Galaxies in a given stellar mass bin will have a range of absolute magnitudes, and therefore a range of volume over which they could be detected in SDSS. To account for this difference, we weight our sample using the \( 1/V_{\text{max}} \) method, determining the maximum volume \( V_{\text{max}} \) for which each galaxy could have been found, given the spectroscopic apparent magnitude limit. The NSA catalog includes galaxies with redshifts less than \( z < 0.055 \), thus only galaxies with \( M_r < -19.1 \) are found throughout the full sample volume. We have compared our \( 1/V_{\text{max}} \) weighted results to those of a volume-limited sample for objects with stellar mass greater than \( 10^9 M_\odot \). The volume-limited results are far noisier due to the significantly smaller volume probed, but are qualitatively similar.

The SDSS is incomplete for low surface brightness galaxies. The SDSS spectroscopic survey completeness as a function of half-light surface brightness drops below 50% at \( \mu_{50,r} \sim 23.5 \) mag arcsec\(^{-2}\) (Blanton et al. 2005b), and below 10% at \( \mu_{50,r} = 24.0 \) mag arcsec\(^{-2}\). For dwarf galaxies with stellar mass below \( 10^9 M_\odot \), the median surface brightness of our sample is \( \mu_{50,r} = 22.3 \) mag arcsec\(^{-2}\). Given the surface brightness incompleteness, we would miss, for example, one out of the five brightest satellites around the Milky Way (Mateo 1998).

For the purposes of this study, we are concerned only with whether or not low surface brightness galaxies are preferentially missing from our quenched sample, relative to the full catalog. In dense environments (\( d_{\text{host}} < 1 \) Mpc), where we detect both quenched and star-forming dwarf galaxies, the surface brightness distribution of quenched systems peaks at slightly lower surface brightnesses (\( \mu_{50,r} = 22.5 \) mag arcsec\(^{-2}\)) as compared to the star-forming sample (\( \mu_{50,r} = 22.3 \) mag arcsec\(^{-2}\)). However, comparing the shape of the distributions via the Kolmogorov–Smirnov test suggests that the quenched galaxies in dense environments could plausibly be drawn from the surface brightness distribution of star-forming galaxies (\( P_{KS} = 0.1 \)). Unless there is a population of quenched low surface brightness galaxies that exists only in the field below the detection limits of SDSS, our red fractions should not be biased by the surface brightness incompleteness of the survey.

3. RESULTS

In the sections below, we calculate the quenched fraction, \( f_{\text{quenched}} \). Weighting each galaxy by the total volume over which
it could be observed, the quenched fraction is

\[ f_{\text{quenched}} = \frac{\sum_{i=1}^{N_{\text{quenched}}}}{N_{\text{quenched}} + N_{\text{SF}}}, \]

where \( N_{\text{quenched}} \) and \( N_{\text{SF}} \) are the number of quenched and star-forming galaxies, respectively. We calculate 1σ errors for \( f_{\text{quenched}} \) by propagating Poisson counting statistics errors on the independent quantities \( N_{\text{quenched}} \) and \( N_{\text{SF}} \). For cases where the number of quenched galaxies equals zero, we calculate the 1σ upper limits directly according to Gehrels (1986).

3.1. Quenched Fractions as a Function of Environment

We first explore the fraction of quenched dwarf galaxies as a function of our environment parameter, \( d_{\text{host}} \). Figure 4 shows the quenched fraction \( f_{\text{quenched}} \) for various bins in stellar mass. Quenched galaxies are preferentially found near a massive host. The observed quenched fraction decreases with increasing values of \( d_{\text{host}} \), and then flattens to a constant level for \( d_{\text{host}} \) distances greater than 1.5 Mpc. In our most massive stellar bin, between \( 10^{9.5} \) and \( 10^{10} M_\odot \), the quenched fraction levels off at a value of \( f_{\text{quenched}} = 5\% \) at large distances from a host galaxy. For stellar mass less than \( \sim 10^9 M_\odot \), the quenched fractions beyond 1.5 Mpc are effectively zero (see Section 3.3 for further discussion). In dense environments, \( d_{\text{host}} < 0.25 \) Mpc, the quenched fraction does not appear to be a strong function
of stellar mass, approaching \( f_{\text{quenched}} = 30\% \) in all our stellar mass bins.

Based on Figure 4, we define “field” or “isolated” galaxies as those with \( d_{\text{host}} > 1.5 \) Mpc. Our definition is motivated by Figure 4: we see evidence of environmental processes, in the form of increased quenched fractions, out to at least 1 Mpc. The host galaxies in our sample cover a range of masses: as those with mass bins.

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In the sections below, we focus on the properties of field galaxies. Our measured quenched fractions for field dwarf galaxies with stellar mass less than \( 10^9 \) \( M_\odot \) are effectively zero, while published red fractions in the same stellar mass range, based only on \( g - r \) colors, are between 5% and 10% of isolated galaxies (Wang et al. 2009; Peng et al. 2011). Using colors only, we reproduce the Wang et al. result (Wang et al., Figure 2), finding a red (as opposed to quenched) fraction of 6% in the mass range \( 10^8 - 10^9 \) \( M_\odot \) beyond 1.5 Mpc. We find that the major of these red galaxies (46 out of 49) have strong H\( \alpha \) emission; none of these galaxies would not pass our combined H\( \alpha \) plus D\( \alpha \),0000 criteria for quenching. The distribution of axis ratios (\( b/a \), based on the two-dimensional Sérsic r-band profile fits) for blue galaxies in this stellar mass range is peaked at 0.5, as expected for a population of disky systems viewed at random viewing positions. The 49 isolated star-forming systems are preferentially disky, peaking at an axis-ratio of 0.32, implying that most of these objects are edge-on star-forming galaxies which appear red due to dust-reddening. This confirms that color selection alone is not a good indicator in selecting quenched galaxies and motivates our spectroscopic criteria.

3.2. A Stellar Mass Threshold for Quenched Field Galaxies

Previous studies have shown that massive galaxies which are the central galaxy in their dark matter halo are predominantly quenched: the quenched fractions of central galaxies is 100% for galaxies with stellar mass above \( 10^{11} \) \( M_\odot \), decreasing to 20% of galaxies with stellar mass of \( 10^{10} \) \( M_\odot \) (Wetzel et al. 2012; Peng et al. 2011; Woo et al. 2012). None of these SDSS-based studies include galaxies less massive than \( 10^9 \) \( M_\odot \). With our cleaned SDSS dwarf galaxy sample, we next ask whether the quenched fractions of central galaxies continue to decrease with stellar mass and if there is a threshold below which this fraction reaches zero.

We compare our dwarf galaxy sample to a modified version of the group catalog from Tinker et al. (2011) based on the SDSS DR7. This is a volume-limited \((z \leq 0.06)\) catalog including galaxies brighter than \( M_r = -18 \). To ensure homogeneity with our dwarf galaxy sample, we remeasure physical properties of galaxies in the Tinker et al. catalog, using spectral measurements from Yan & Blanton (2012) and stellar masses from the NYU-VAGC. We define quenched galaxies using the same criteria as our dwarf sample: EW H\( \alpha \) < 2 \( \AA \) and \( D_\alpha \),0000 > 0.6 + 0.1 \( \log_{10}(M_{\text{stellar}}) \).

The Tinker et al. catalog includes galaxies with stellar mass down to \( 10^6.6 \) \( M_\odot \), providing direct overlap with our NASA dwarf galaxy sample. We compare our isolated field dwarf galaxies to their sample of central galaxies. By definition, our isolated dwarf galaxies will be central galaxies, but central galaxies are not necessarily isolated. Tinker et al. (2011) define central galaxies as those that do not exist within the halo radius of a larger halo. The halo radius is defined as the radius within which the average density is 200 times the background density. We note this is larger than the virial radius in \( \Lambda \)CDM, within which the average density corresponds to \( \sim 360 \) times the background density (Equation (6), Bryan & Norman 1998). The halo radius of a smaller galaxy may overlap with a larger galaxy, but will not be considered a satellite until the smaller galaxy itself is within the larger’s halo radius. This motivates us to use a more restrictive definition of central galaxy. We have shown in Figure 4 that galaxies below a stellar mass of \( 10^{10} \) \( M_\odot \) show environmental effects out to as much as 1 Mpc away from a massive galaxy, several times larger than the host galaxy halo radius. We therefore recalculate the number of central galaxies in the Tinker et al. catalog, searching for associated objects within three times the halo radius. Using this definition, 75% of central galaxies in the Tinker et al. catalog have \( d_{\text{host}} > 1.5 \) Mpc in the overlapping stellar mass range of our dwarf galaxy catalog. This means that our definition of field galaxies is slightly more isolated than that of central galaxies in the Tinker et al. group catalog. This can be seen as slightly lower quenched fractions in the region of overlap shown in Figure 5.

In Figure 5, we plot the fraction of quenched galaxies as a function of stellar mass for central/field galaxies. At high stellar masses, quenched galaxies make up the majority of the central galaxy population. While Tinker et al. and others have shown that the quenched fraction of central galaxies is 100% for stellar masses greater than \( 10^{11} \) \( M_\odot \), our H\( \alpha \) cut removes objects with strong active galactic nucleus (AGN) activity, decreasing \( f_{\text{quenched}} \) at these masses. The quenched fraction decreases with stellar mass, reaching zero at a stellar mass between 1 and \( 2 \) \( \times 10^9 \) \( M_\odot \). The least massive quenched field galaxy in our sample has a stellar mass \( 1.02 \times 10^9 \) \( M_\odot \). We therefore conclude that there is a threshold of \( 1.0 \times 10^9 \) \( M_\odot \) below which quenched galaxies are not found in the field. This threshold represents a fundamental stellar mass scale. Dwarf galaxies with stellar mass below this scale cannot quench star formation on their own. The threshold stellar mass does not change significantly for reasonable variations of our quenched definition. We list in Table 1 the number of galaxies, \( 1/V_{\text{max}} \) corrections, and quenched fractions for our NSA sample.

A stellar mass threshold of \( 1.0 \times 10^9 \) \( M_\odot \) below which isolated quenched galaxies do not exist, is consistent with extrapolations of previously published work (Peng et al. 2010; Wetzel et al. 2012) and confirms, with a larger sample, the conclusions of Haines et al. (2007, 2008) who found no isolated quenched galaxies in the SDSS DR4 in the absolute magnitude range \(-16 < M_r > -18 \). These authors use somewhat different definitions of both “isolated” and “quenched,” but also conclude that there is an absence of low-mass isolated quenched galaxies.

3.3. The Absence of Quenched Dwarf Galaxies in the Field

We establish above that quenched central galaxies with stellar masses below \( 1.0 \times 10^9 \) \( M_\odot \) do not exist in the field. Dwarf galaxies with stellar mass below this scale cannot quench star formation on their own; all field galaxies in our sample below this threshold are forming stars (see Section 3.5). We detect 2951 field galaxies in the stellar mass range \( 10^7 - 10^9 \) \( M_\odot \). Accounting for \( 1/V_{\text{max}} \) corrections, we calculate an upper \( 1\sigma \) limit on the quenched fraction of \( f_{\text{quenched}} < 0.0006 \), or 0.06% using Gehrels (1986). In denser regions, defined here as \( d_{\text{host}} < 0.25 \) Mpc, we find that 148 out of 1504 galaxies are quenched in the same stellar mass regime, corresponding to...
Table 1
Quenched Field Galaxy Fractions for NSA Dwarf Catalog

| $M_{\text{stellar}}$ (log$_{10}(M_{\odot})$) | $N_{\text{quenched}}$ | $N_{\text{total}}$ | $\Sigma (N_{\text{quenched}}/V_{\text{max}})$ | $\Sigma (N_{\text{total}}/V_{\text{max}})$ | $f_{\text{quenched}}$ | $\sigma_{f_{\text{quenched}}}$ |
|-----------------------------------------|---------------------|---------------------|-----------------------------------------------|---------------------------------------------|---------------------|--------------------------|
| 9.9                                    | 238                 | 2843                | 0.000070                                       | 0.000826                                    | 0.084               | 0.0052                   |
| 9.7                                    | 71                  | 2910                | 0.000027                                       | 0.000900                                    | 0.031               | 0.0032                   |
| 9.5                                    | 24                  | 2620                | 0.000017                                       | 0.000991                                    | 0.017               | 0.0023                   |
| 9.3                                    | 5                   | 2071                | 0.000007                                       | 0.001148                                    | 0.007               | 0.0016                   |
| 9.1                                    | 1                   | 1594                | 0.000003                                       | 0.001397                                    | 0.002               | 0.0014                   |
| 8.9                                    | 0                   | 999                 | 0.000000                                       | 0.001435                                    | 0.000               | 0.0019                   |
| 8.7                                    | 0                   | 686                 | 0.000000                                       | 0.001653                                    | 0.000               | 0.0028                   |
| 8.5                                    | 0                   | 448                 | 0.000000                                       | 0.001803                                    | 0.000               | 0.0043                   |
| 8.3                                    | 0                   | 296                 | 0.000000                                       | 0.002142                                    | 0.000               | 0.0065                   |
| 8.1                                    | 0                   | 215                 | 0.000000                                       | 0.003076                                    | 0.000               | 0.0091                   |
| 7.8                                    | 0                   | 210                 | 0.000000                                       | 0.006973                                    | 0.000               | 0.0093                   |
| 7.3                                    | 0                   | 105                 | 0.000000                                       | 0.016505                                    | 0.000               | 0.0193                   |

Notes. Quenched fractions for field galaxies with $d_{\text{host}} > 1.5$ Mpc. Bins are 0.2 dex in stellar mass or larger to contain a minimum of 100 galaxies.

3.4. Quenched Dwarf Galaxies Within 4 $r_{\text{virial}}$ of a Massive Host

We next investigate the distribution of quenched dwarf galaxies relative to their host galaxy. Our sample contains 223 quenched galaxies below a stellar mass of $10^9 M_{\odot}$, all of which are within 1.5 Mpc and 1000 km s$^{-1}$ of a more luminous host galaxy. We calculate the virial masses of the hosts using the prescriptions of Behroozi et al. (2010) based on stellar mass. We calculate a virial mass for each host galaxy and determine its virial radius ($r_{\text{vir}}$) assuming the average enclosed density is 360 times the background density.

In the top panel of Figure 6, we show the distribution of quenched galaxies with stellar mass below $1 \times 10^9 M_{\odot}$ as a function of distance from the host galaxy, in units of the host’s virial radius. In the bottom panel of Figure 6, we compare this distribution to that of star-forming dwarf galaxies (defined as galaxies with detected $H\alpha > 2$ Å, see Section 3.5) in the same stellar mass range. The majority (87%) of quenched dwarf galaxies are within $2 r_{\text{vir}}$ of a massive host galaxy and would thus be considered “satellite” galaxies, while 97% of objects are within $4 r_{\text{vir}}$. For comparison, less than 50% of star-forming dwarf galaxies are within $4 r_{\text{vir}}$ of a massive neighbor. The furthest quenched galaxy is $8 r_{\text{vir}}$ from its host, while the furthest star-forming dwarf galaxy is over $50 r_{\text{vir}}$ from a massive neighbor.

There are numerous proposed mechanisms to quench satellite galaxies within the virial radius of a massive galaxy. Processes such as ram pressure stripping or tidally induced star formation can quickly remove or use up gas as a satellite enters the virial radius of a massive host. The handful of quenched dwarf galaxies between 2 and $8 r_{\text{vir}}$ may be evidence for quenching processes which act at larger distances from the primary halo. Alternatively, these may be “backsplash” galaxies which have previously been within the host virial radius, but are on either highly eccentric orbits or have been dynamical ejected from the host halo (Ludlow et al. 2009; Wang et al. 2009). Numerical simulations suggest that up to 10% of satellites associated with a massive galaxy host can reside as far as 4
their member dwarf galaxies. We will explore the properties of dwarf–dwarf systems in a future contribution.

3.5. Continuous Star Formation in Isolated Dwarf Galaxies

We identify 2951 galaxies with stellar mass less than $1 \times 10^9 \, M_\odot$ that are in the field (as defined here, these are also central/isolated galaxies). All of our field dwarf galaxies show evidence for recent star formation. We briefly examine the properties of these galaxies, deferring a full analysis for a future paper.

The vast majority of field dwarf galaxies have detected Hα flux: 2940 out of 2951 (99.6%) with stellar mass less than $10^9 \, M_\odot$ have Hα EW $> 2$ Å, with a median EW of 32 Å. The presence of Hα emission implies star formation within the past 50 Myr (Bruzual & Charlot 2003). The median star formation rate for these isolated galaxies is 0.03 $M_\odot \, yr^{-1}$, based on FUV GALEX fluxes (Salim et al. 2007). This rate is comparable to that expected by extrapolating the star formation rate versus stellar mass relationship seen at higher stellar masses (e.g., Wuyts et al. 2011). We note that none of these galaxies show evidence for AGN activity based on their position in an [O iii]/Hβ versus [N ii]/Hα line ratio diagnostic plot (Kewley et al. 2001; Yan & Blanton 2012). The overwhelming fraction of isolated galaxies with very recent star formation suggests that this population is in a state of continuous star formation.

There are 11 field dwarf galaxies (0.4% of the population) which do not show Hα emission. These objects have $D_{4000} = 1.1–1.3$, suggesting a luminosity-weighted stellar age between 100 and 200 Myr based on Bruzual & Charlot (2003) models. We have examined the broadband SDSS images and spectra of these 11 galaxies: 9 are strong post-starburst galaxies (e.g., K+A galaxies) according to the criteria defined by Yan et al. (2009) through spectral decomposition, and 2 are borderline cases, satisfying the more inclusive K+A criteria defined by Balogh et al. (1999) based on Hα absorption EW. We conclude that these galaxies have shut off star formation within the past few hundred million years, and less than 1 Gyr even for the two weaker K+As. The fact that we do not find old quenched galaxies in the field suggests that these rare occasions of post-starburst galaxies are a transient phase in the life of isolated dwarf galaxies: they will soon have star formation again. This population constrains the “burstiness” of star formation, suggesting that star formation rarely shuts off in isolated dwarf galaxies and, if so, for less than a few hundred million years.

4. DISCUSSION AND CONCLUSIONS

We demonstrate that quenched dwarf galaxies are rare in isolation, existing almost exclusively in the vicinity of a more massive neighbor. For field galaxies, we find a stellar mass threshold of $1.0 \times 10^9 \, M_\odot$ below which quenched galaxies do not exist. Most quenched galaxies below this stellar mass threshold are found within 2 $r_{\text{vir}}$ of a massive host galaxy, and 97% of all quenched dwarf galaxies are found within 4 $r_{\text{vir}}$.

With the SDSS DR8 data, we can state that quenched galaxies in the field do not exist below $1.0 \times 10^9 \, M_\odot$, but we cannot test this statement below $10^7 \, M_\odot$. The SDSS does not contain a sufficient number of galaxies below this stellar mass. Studies of dwarf galaxies within 10 Mpc with stellar masses below $10^7 \, M_\odot$ are consistent with our results: low-mass quenched galaxies exist only within a few virial radii of the Milky Way, M31 or the nearby M81 group (Grcevich & Putman 2009; Weisz et al. 2011). Below the detection limits of any current

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**Figure 6.** Distribution of host distance for all quenched (top) and star-forming (bottom) galaxies with stellar mass below $1 \times 10^9 \, M_\odot$. Distances are plotted in units of host galaxy virial radius. 97% of quenched dwarf galaxies are found within 4 virial radii (red dotted line), while only 49% of star-forming galaxies are found within a similar distance (blue dotted line). The most distant quenched dwarf galaxy in our sample is 8 $r_{\text{vir}}$ from its host, while the most distant star-forming objects (not shown in this figure) are over 50 $r_{\text{vir}}$ from a massive host galaxy.

(A color version of this figure is available in the online journal.)
The quenched fractions of field galaxies may rise again at extremely low stellar masses. Ultra-faint galaxies ($M_V > -5, M_{\text{stellar}} < 10^5 M_\odot$) are currently detectable out to only 50 kpc in the Milky Way halo (Walsh et al. 2009). These galaxies are thought to form their stars only after reionization (Brown et al. 2012). If counterparts of the ultra-faint galaxies exist in the field, these will appear as quenched objects. Thus, the quenched fractions of field galaxies may rise again at extremely low masses.

There are claims in the literature of isolated quenched dwarf galaxies; however, there are no definitive examples which pass our definition of isolated/field galaxies. At slightly lower stellar mass than the present sample, the dwarf spheroidal galaxies Cetus and Tucana ($\sim 10^6 M_\odot$), discussed in Section 3.4, are often cited as isolated quenched galaxies, but lie within 1.5 Mpc (3 to 4 virial radii) of the Milky Way. Karachentseva et al. (2011) list ten candidate isolated dwarf spheroidal galaxies which they identify via visual searches. Several of these candidates lie within the SDSS footprint, but are well below the spectroscopic magnitude limits. These objects were not detected in H\textsc{i} surveys, and have no measured radial velocities or secure distance estimates. Spectroscopic follow-up of these candidates will be an excellent test of our conclusions. Finally, we note no contradiction with the results of Wang et al. (2009) who find a percentage of isolated dwarf galaxies with red broadband colors at similar stellar masses: we demonstrate in Section 3.1 that these are dust-reddened star-forming galaxies.

The absence of isolated quenched galaxies below $10^6 M_\odot$ provides strong constraint on the internal feedback processes regulating star formation. We find that all galaxies below this stellar mass threshold are forming stars in the field: 99.6% of isolated field galaxies have formed stars within the past 50 Myr, while the remaining galaxies have had star formation with the past few million years. A future paper will explore the properties of these star-forming field dwarf galaxies (M. R. Blanton et al., in preparation). In Geha et al. (2006), we presented H\textsc{i} follow-up for SDSS dwarf galaxies, concluding that external processes were required to fully remove gas from a dwarf galaxy. Exploring the H\textsc{i} and other properties of isolated dwarf galaxies above and below our stellar mass threshold will provide insight into the internal physical mechanisms, such as heating from supernovae or AGNs, operating to quench galaxies at higher masses. Our stellar mass threshold provides a strong boundary condition for any of these mechanisms to completely shut off star formation in low-mass galaxies.

M.G. acknowledges support from NSF grant AST-0908752 and the Alfred P. Sloan Foundation. We acknowledge R. Davé, J. Moustakas, F. van den Bosch, R. Wechsler, A. Wetzel, and B. Willman for productive discussions. Funding for the NASA-Sloan Atlas has been provided by the NASA Astrophysics Data Analysis Program (08-ADP08-0072). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.