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THE ACS LCID PROJECT: ON THE ORIGIN OF DWARF GALAXY TYPES—A MANIFESTATION OF THE HALO ASSEMBLY BIAS?*

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ABSTRACT

We discuss how knowledge of the whole evolutionary history of dwarf galaxies, including details on the early star formation events, can provide insight on the origin of the different dwarf galaxy types. We suggest that these types may be imprinted by the early conditions of formation rather than only being the result of a recent morphological transformation driven by environmental effects. We present precise star formation histories of a sample of Local Group dwarf galaxies, derived from color–magnitude diagrams reaching the oldest main-sequence turnoffs. We argue that these galaxies can be assigned to two basic types: *fast dwarfs* that started their evolution with a dominant and short star formation event and *slow dwarfs* that formed a small fraction of their stars early and have continued forming stars until the present time (or almost). These two different evolutionary paths do not map directly onto the present-day morphology (dwarf spheroidal versus dwarf irregular). Slow and fast dwarfs also differ in their inferred past location relative to the Milky Way and/or M31, which hints that slow dwarfs were generally assembled in lower-density environments than fast dwarfs. We propose that the distinction between a fast and slow dwarf galaxy primarily reflects the characteristic density of the environment where they form. At a later stage, interaction with a large host galaxy may play a role in the final gas removal and ultimate termination of star formation.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: formation

1. INTRODUCTION

The origin of the different dwarf galaxy types and the possible evolutionary links between them are the subject of much research and debate. Dwarf spheroidals (dSphs; devoid of gas and with no star formation), dwarf irregulars (dIrrs; gas-rich, star-forming systems usually located in the field), and the so-called transition types (dTs; with properties intermediate between the other two) have similarities and differences that can yield information on their possibly linked evolution. On one hand, they obey the same mass–metallicity relation (Kirby et al. 2013) and follow similar relationships between central velocity dispersion, core radius, central surface brightness, and total luminosity (Kormendy & Bender 2012). On the other hand, they have different gas content and are preferentially found in different environments, the dSphs usually inhabiting denser locations—the so-called morphology–density relation. This classification is based on current properties, which may not reflect past history, i.e., actual evolution.

Through such reliable indicators as RR Lyrae variable stars, a bona fide old population was routinely found in any dwarf galaxy that was adequately searched. Therefore, at early times, dwarfs of all types must have been star-forming galaxies. Then, at some point, *some* lost their gas and stopped star formation. The transformation from a star-forming, dIrr-like galaxy to a dSph galaxy has been explored by many authors, and the common implicit assumption has led to the definition of a "transition class" of dwarf galaxies. Even if there are plausible mechanisms to transform a gas-rich, star-forming dwarf into a pressure-supported, gas-poor dwarf, a question about the origin of the dwarf galaxy types (Skillman & Bender 1995) remains: were the properties of dwarfs imprinted during their early assembly, or do they result from events happening later? A crucial piece of information is their very early star formation history (SFH).

Here, we show that the availability of precise SFHs over the whole lifetime of a diverse sample of Local Group dwarf galaxies opens the door to an alternative classification based on evolution. The *early* SFHs of dwarf galaxies can be obtained reliably for the nearest examples, for which deep color–

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magnitude diagrams (CMDs) can be obtained from the ground or using the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope* (*HST*). Observation of the *whole* main sequence—down to the oldest main-sequence turnoff (oMSTO) —with good photometric accuracy and precision is essential for obtaining SFHs that include details of the earliest star formation events (Gallart et al. 2005). The reason is twofold. First, on the main sequence—which spans many magnitudes in the CMD—stars are distributed in a sequence of age as a function of magnitude that is subject to lower age–metallicity degeneracy than other CMD regions, where stars of all ages and metallicities occupy a narrow interval of color and magnitude. Second, the main sequence is the best understood phase from theory and, therefore, SFH determinations are much less affected by model uncertainties.

As high-quality SFHs are being obtained, some cosmological hydrodynamical simulations on the formation and evolution of dwarf galaxies are becoming available (Brooks & Zolotov 2014; Shen et al. 2014; Oñorbe et al. 2015; Sawala et al. 2015). In this context, precise SFHs of dwarf galaxies with different characteristics and in different environments can provide firm observational constraints, shedding new light into the origin of the different dwarf galaxy types and the possible relationships between them.

We will analyze the available *precise* SFHs for Local Group dwarfs of different types, paying special attention to the detailed information they provide on their earliest evolution. We will exclusively discuss galaxies where SFHs have been derived from CMDs reaching the oMSTOs. This is a fundamental difference compared to other studies analyzing the SFHs of galaxies with CMDs reaching different, usually shallower *absolute* depths (Weisz et al. 2014a).

2. NEW DWARF GALAXY TYPES BASED ON FULL EVOLUTIONARY HISTORIES

2.1. The SFHs of Currently Isolated Dwarfs

The Local Cosmology from Isolated Dwarfs (LCID) project[16] obtained the first CMDs reaching the oMSTOs and precise SFHs for six relatively isolated Local Group dwarf galaxies. The observations were designed to achieve a 2 Gyr age resolution at old ages, and this has been achieved as shown by Hidalgo et al. (2013). Two dIrrs, IC1613 and Leo A (Cole et al. 2007; Skillman et al. 2014); two dTs, LGS3 and Phoenix (Hidalgo et al. 2009, 2011); and two isolated dSphs in the Local Group, Cetus and Tucana (Monelli et al. 2010a, 2010b) were studied. The reader is referred to the above papers for details on the SFH determination. Subsequently, another dIrr galaxy, DDO210, has been studied (Cole et al. 2014).

Figure 1 (upper panel) displays the SFHs for the two dSph and the two dT galaxies of the LCID sample. Tucana and Cetus share the common characteristic of having formed over 90% of their stars before 10 Gyr ago, and they host no stars younger than 8–9 Gyr. The SFHs of the two dT galaxies are remarkably similar to those of the dSphs: they formed over 80% of their stars before 9 Gyr ago in spite of having maintained residual star formation during the rest of their evolution. The lower panel of Figure 1 displays the SFHs of the two dIrrs in our sample, Leo A and IC1613. In contrast to the former SFHs, those of the dIrrs do not show a dominant early

[16] http://www.iac.es/proyecto/LCID/

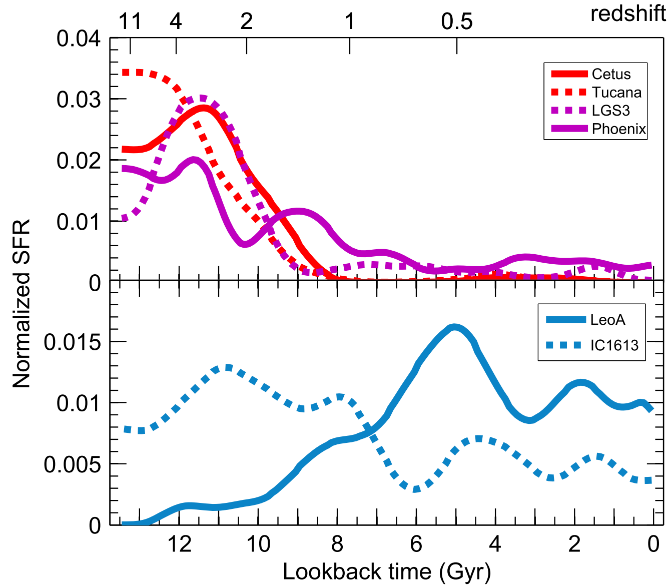

Figure 1. Homogeneously derived SFHs for the six LCID galaxies. Upper panel: SFHs for the dSphs and dTs. Lower panel: SFHs for the dIrr.

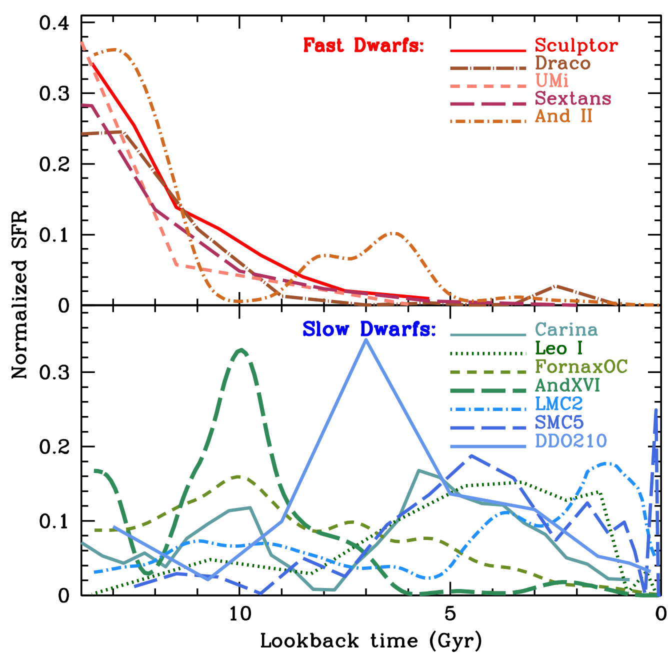

Figure 2. SFHs of Local Group fast (upper panel) and slow (lower panel) dwarfs from the literature. Note that in the lower panel both slow dwarfs currently classified as dSphs (in green shades) and dIrrs (in blue shades) are represented.

burst of star formation; instead, over 60% of their stars formed at intermediate and young ages.

2.2. The SFHs of Satellite Dwarfs

We now consider dwarfs that are, *at present*, found close to the large spirals. Precise SFHs are available for a number of dSph satellites of the Milky Way (MW; Gallart et al. 1999; Aparicio et al. 2001; Carrera et al. 2002; Dolphin 2002; Lee et al. 2009; de Boer et al. 2012, 2014; del Pino et al. 2013; Weisz et al. 2014a), for the Magellanic Clouds (e.g., Noël et al. 2009; Cignoni et al. 2013; Meschin et al. 2014), and for two M31 satellites: AndXVI and AndII (Weisz et al. 2014b; M. Monelli et al. 2015, in preparation). We have represented some of these in Figure 2, together with that of DDO210. Even though they are not homogeneous among themselves or with the LCID SFHs, these results generally agree that most MW satellites (UMi, Draco, Sextans, Scl, CnVI, plus the very faint dwarfs; Brown et al. 2014) formed most of their stars before $\simeq$10 Gyr ago. The more distant dSph satellites, Fornax, Leo I, and Carina, show substantial intermediate-age populations: their SFHs peaked at ages younger than 10 Gyr, and most of their star formation occurred at intermediate ages. In fact, *the SFHs of these dSphs are similar to those of dIrr galaxies for most of their lifetimes*: they have low initial star formation rates (SFRs) and high SFRs at intermediate ages. The main difference occurs in the last $\simeq$2 Gyr or less, when they stopped star formation. They are classified as dSphs for their current properties, but their history is similar to that of dIrr galaxies.

2.3. Slow Dwarfs and Fast Dwarfs: A Classification Based on Evolution

The availability of precise SFHs reaching the earliest star formation events for a growing sample of dwarf galaxies enables us to take a fresh look into dwarf galaxy types based on evolutionary histories rather than current properties. Although this is currently possible only for a limited number of objects in the Local Group, it provides new insight on possible mechanisms producing these dwarf galaxy types.

Based on their full evolutionary histories, we propose that dwarf galaxies can be grouped in two classes.

1. *Fast dwarfs* are those that started their evolution with a dominant star formation event, but their period of star formation activity was short ($\lesssim$few Gyr; see the upper panel of Figures 1 and 2).
2. *Slow dwarfs* formed a small fraction of their stellar mass at an early epoch, and continued forming stars until the present (or almost; see the lower panel of Figures 1 and 2).

These two evolutionary paths do not map directly onto the current, commonly adopted dwarf galaxy classification (in dIrrs, dTs and dSphs). Most notably, some dSphs have important intermediate-age and young populations, and thus SFHs that resemble those of dIrrs: in our sample, all dIrrs are slow dwarfs, while some dSphs are fast and others are slow.

What else, besides similar SFHs, do slow dwarfs share? The distant dIrr galaxies with known full SFHs, IC1613, Leo A, and DDO210, are all located over 400 kpc away from the MW or M31, and have negative (or small for DDO210) radial velocities with respect to MW, M31, and/or the Local Group center of mass (Figure 3). Among the closest slow dwarfs, the Magellanic Clouds and Leo I have been found to have first entered the MW virial radius just a few Gyr ago (Sohn et al. 2013; Kallivayalil et al. 2013). This might indicate that all these slow dwarfs *assembled* in a low-density environment and are only recently entering the Local Group.

In contrast, most fast dwarfs are close MW satellites, or isolated dSphs (Cetus and Tucana). The latter break the morphology–density relation in the Local Group. However, they have radial velocities (Lewis et al. 2007; Fraternali et al. 2009; see Figure 3) compatible with their having been close to the Local Group barycenter at early times, presumably when their assembly was taking place.

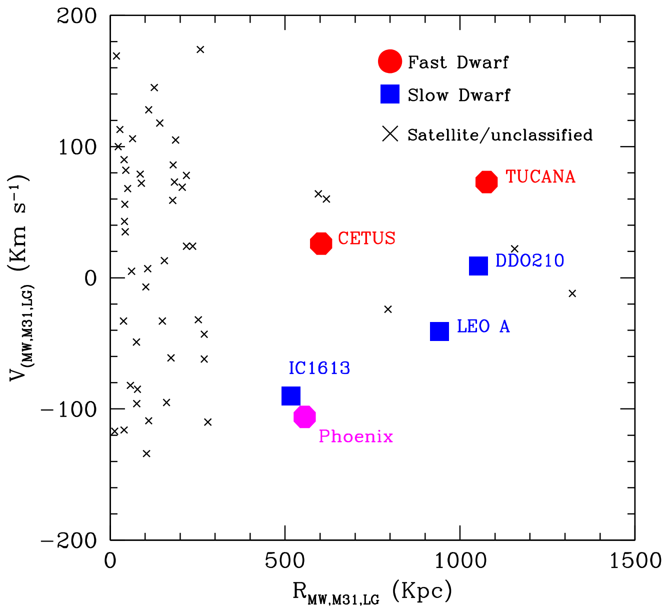

Figure 3. Radial velocities and distances relative to the MW or M31, or to the Local Group barycenter for Local Group dwarf galaxies in the McConnachie (2012) compilation. For dwarfs located within 300 Kpc of either galaxy (small crosses), the slow and fast dwarf classification has not been highlighted since they have an uncertain dynamical history, and may have orbited more than once about the host.

3. ON THE ORIGIN OF THE DWARF GALAXY TYPES

Is the role of environment in creating the different dwarf galaxy types more closely related to its early influence on the mass-assembly process of the dwarf (which is expected to depend on formation location) than to its effects in removing the gas later?

3.1. Quenching a Dwarf: Gas Removal Scenarios

Most (mostly theoretical) research into the transformation from a gas-rich to a gas-poor dwarf galaxy has focused on determining how dSph galaxies lost their gas. Dekel & Silk (1986), Mac Low & Ferrara (1999), Salvadori et al. (2008), and Sawala et al. (2010), among others, have explored internal feedback and the efficiency of gas ejection through supernova-driven outflows. In general, models indicate that feedback should be able to totally remove the gas only in extremely low-mass (few $10^6\,M_\odot$ of baryonic mass) dwarf galaxies. The inability of feedback alone to totally remove the gas from currently gas-free galaxies, together with the existence of a striking morphology–density relation, has led to the current consensus that environmental processes such as ram-pressure or tidal stripping by a massive central halo must play an important role in stripping the gas from dwarf galaxies and halting star formation (see Mayer 2010 for a review). Finally, including the effects of an ionizing UV background has been shown to increase the efficiency of gas loss due to both internal feedback (Salvadori & Ferrara 2009; Sawala et al. 2010) and ram-pressure stripping (Mayer 2010).

However, it is important to note that most MW dSph satellites stopped forming stars at a very similar (within 2–3 Gyr) early time ($\simeq$10 Gyr ago). If environmental effects were crucial in removing their gas, one would expect that they entered the virial radius of the MW or other massive companion, also at very *similar and early* times, for their SFHs to share a common

Table 1
Basic Properties of LCID Galaxies

Galaxy	M_V [a]	R_h [a]	M_T [g]	M_{HI} [a]	$(m-M)_0$	R_{MW}, V_{MW} [a]	R_{M31}, V_{M31} [a]	R_{LG}, V_{LG} [a]
	mag	(')	$(\times 10^6 M_\odot)$	$(\times 10^6 M_\odot)$	mag	Kpc, Km s^{-1}	Kpc, Km s^{-1}	Kpc, Km s^{-1}
Phoenix	−9.9	3.76	3.2 ± 0.3	0.12	23.09 ± 0.1[b]	415, −103	868, −104	556, −106
LGS3	−10.1	2.10	1.9 ± 0.1	0.38	24.07 ± 0.15[c]	773, −155	269, −43	422, −74
IC1613	−15.2	6.81	100[a]	65	24.44 ± 0.10[d]	758, −154	520, −64	517, −90
LeoA	−11.7	2.15	6.0[a]	11	24.50 ± 0.10[e]	803, −19	1200, −46	941, −41
Cetus	−11.2	3.20	7.0 ± 0.3	⋯	24.46 ± 0.12[f]	756, −27	681, 46	603, 26
Tucana	−9.5	1.10	3.2 ± 0.1	⋯	24.74 ± 0.12[f]	882, 99	1355, 62	1076, 73

Notes.
[a] From McConnachie (2012).
[b] Hidalgo et al. (2009).
[c] Hidalgo et al. (2011).
[d] Bernard et al. (2010).
[e] Bernard et al. (2013).
[f] Bernard et al. (2009).
[g] Hidalgo et al. (2013).

pattern. Cosmological simulations are not conclusive on this point. Several studies show that infall times around $z \sim 1$ are most typical inside MW-sized halos (e.g., Rocha et al. 2012; Wetzel et al. 2015), which would be too late to explain the early star formation truncation in many fast satellites. However, other studies of halos that assemble earlier than average, and that lead to a realistic replica of the MW (Guedes et al. 2011), find that a fraction of dSphs could be hosted in subhalos accreting at $z \sim 2$–2.5 (Tomozeiu et al. 2015).

3.2. A Possible Alternative Scenario

We now examine whether or not there are theoretical indications that progenitors of slow and fast dwarfs may be different, and whether or not this difference can be linked to the location of the progenitor's halo when the majority of its mass assembly took place.

As discussed in Section 2.3, the current positions and space motions seem to indicate that slow dwarfs formed preferentially in lower-density environments than fast dwarfs. This could imply a delayed assembly history for the dwarf dark matter halos, as predicted for lower peaks in the field of density fluctuations (e.g., Lagos et al. 2009) and reflected in a number of theoretical investigations that will be discussed next.

Sawala et al. (2014) present mass-assembly histories for present-day satellites and isolated dwarfs in 12 cosmological volumes resembling the Local Group. They find that for dark matter subhalos in the mass range $M = 10^{9-10} M_\odot$, which are expected to host the majority of Local Group dwarfs, the redshift at which a halo progenitor reached $1/2$ of its peak mass was $z_{1/2} \simeq 1.5$–2 for field dwarfs and $z_{1/2} \simeq 4$ for satellites. Brooks & Zolotov (2014) also find that satellites accrete most of their mass earlier than field dwarfs and show an earlier peak in their SFHs than the simulated field dwarfs. While in our scenario there is no one-to-one correspondence between satellites and fast dwarfs, or between field galaxies and slow dwarfs, this correspondence is expected to happen in most cases. Thus, we expect that the characteristics of fast and slow dwarfs would emerge in theoretical studies if grouped according to their early, rather than current, locations.

The scenario proposed by Benítez-Llambay et al. (2015) also fits well within the slow versus fast dwarf hypothesis. They use a high-resolution cosmological simulation of the Local Group to discuss the dramatic effects of reionization on the baryonic component of halos with virial temperatures at $z_{\rm reion}$ similar to or below 10^4 K. This characteristic temperature defines a "threshold" mass at $z_{\rm reion}$ that strongly influences the future SFH of the system. (i) Systems collapsing early with mass at reionization just above the threshold are able to form stars before reionization, but their star formation is abruptly truncated by the combined effects of reionization and feedback from the early stellar population. They are usually characterized by a population of old stars. (ii) In halos with masses below the threshold for star formation at $z_{\rm reion}$ and gas densities high enough to survive photoevaporation due to self-shielding, star formation can instead be delayed and only (re-)started at later times (e.g., Ricotti 2009) when the host halo becomes massive enough to allow some of the gas to cool and fragment. These two types of systems can be associated with fast and slow dwarfs, respectively. Finally, in their simulation of a sample of seven dwarf galaxies in a low-density environment, Shen et al. (2014) find that although above a virial mass of $10^9 M_\odot$ star formation commences quite early ($z > 4$), all of their dwarfs would be classified as slow.

These scenarios for the formation and evolution of slow and fast dwarfs are still compatible with final star formation shutdown when a slow dwarf enters the host halo area of influence. In fact, tidal effects could play a role in the final removal of gas at late times in some slow MW satellites, such as Leo I or Fornax, which stopped their star formation only recently, as opposed to isolated slow dwarfs, like Leo A or IC1613, that are still forming stars and retain sizable amounts of gas.

4. SUMMARY, CONCLUSIONS, AND OUTLOOK

We have discussed the properties of the subsample of Local Group dwarfs with precise lifetime SFHs, derived from CMDs reaching the oMSTOs. These SFHs reveal two distinct evolutionary paths that do not lead directly to the current morphological classification (in dSphs, dIrrs, and dTs). One evolutionary path is characterized by an initial dominant and short (a few Gyr) star-forming event, with little or no star formation thereafter. The other leads to dwarf galaxies dominated by intermediate-age populations that have continued forming stars until the present (or almost). We have called the galaxies displaying these evolutionary paths *fast* and *slow* dwarfs, respectively. In our sample, all dIrrs are slow dwarfs, while some dSphs are fast and others are slow. In addition to SFHs, slow and fast dwarfs also differ in their inferred early location relative to the local large galaxies: as opposed to fast dwarfs, slow dwarfs' positions and radial velocities are compatible with a late first infall into the Local Group, which would imply that they were assembled in lower-density environments than fast dwarfs.

We thus suggest that the nature of fast or slow dwarfs is determined early, depending on the formation conditions of the galaxy. The progenitor halos of fast dwarfs assembled early and quickly in high-density environments, where interactions triggering star formation were common, likely leading to high SFRs even before reionization. Strong gas loss would follow as a consequence of the effects of reionization and feedback acting together. Slow dwarfs resulted from delayed, slower mass assembly occurring in lower-density environments, which in turn led to a delayed onset of star formation, occurring when the halo had grown massive enough to allow the gas to cool and form stars. This implies milder feedback and gas loss, and the possibility of keeping forming stars on a long timescale. A strong interaction with a large host could play a role in the late, final removal of gas from the dwarf galaxies that infall late. The morphology–-density relation observed (with exceptions) in Local Group dwarf galaxies today would thus be a consequence of their formation in more or less dense environments around the Local Group.

It is interesting to note that the proposed scenario can be seen as a consequence of the so-called halo assembly bias (Gao et al. 2005): at the same halo mass, halos that assemble earlier cluster more than halos that assemble later, hence they automatically evolve in a higher-density environment. Then, if baryons—as expected—trace the assembly of the dark halo, it is conceivable that more clustered dwarfs will also be faster at assembling their stellar component. This is because gas feeding will be more efficient in a denser region of the cosmic web, presumably achieving earlier the density required for efficient star formation. The effect of assembly bias might be amplified at the scale of dwarfs because their shallow potential well makes them more sensitive to processes that can keep gas density low enough to prevent radiative cooling and star formation, such as the cosmic ionizing background. Likewise, star formation of dwarfs born near massive halos could be terminated earlier than in similar dwarfs formed in "average cosmic regions" because of the effect of *local* radiative feedback.

In our scenario, we expect that the very faint galaxies that may be discovered far from the MW or M31 in forthcoming deep photometric surveys, such as with the LSST, will not necessarily be extremely old galaxies like the faintest dwarfs close to the MW, but some may contain relatively young stellar populations. They may have started star formation late at a low rate, and being less affected by reionization and internal feedback, may have undergone a very extended SFH despite their very low mass. A few examples of such galaxies have already been found, like Leo P (McQuinn et al. 2013) or Leo T (Weisz et al. 2012).

To gain further insight regarding the hypothesis presented in this Letter, it is extremely important to increase the sample of distant Local Group dwarf galaxies with oMSTO photometry available over a significant fraction of their body; in the near future, this will only be possible with the ACS on *HST*. Additionally, knowledge of the orbits of Local Group galaxies will allow us to contrast our hypothesis by better constraining the type of environment in which they were formed. Finally, this scenario may be explored with current and forthcoming cosmological hydrodynamic simulations by taking a slightly different vantage point, that is, by grouping samples of simulated dwarfs according to their early location when assembling their mass, rather than according to their present location as satellites or field dwarfs.

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