Local Group Dwarf Galaxies

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Dwarf Galaxies: From the Deep Universe to the Present
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Local Group Dwarf Galaxies

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Abstract. Local Group dwarf galaxies are a unique astrophysical laboratory because they are the only objects in which we can reliably and precisely characterize the star formation histories of low-mass galaxies going back to the epoch of reionization. There are of order 100 known galaxies less massive than the Small Magellanic Cloud within ∼1 Megaparsec of the Milky Way, with a vide variety of star formation history, gas content, and mass to light ratios. In this overview the current understanding of the formation and evolution of low-mass galaxies across cosmic time will be presented, and the possibility of drawing links between the properties of individual systems and the broader Local Group and cosmological context will be discussed. Local Group dwarfs will remain a uniquely powerful testbed to constrain the properties of dark matter and to evaluate the performance of simulations for the foreseeable future.

Keywords. Local Group, galaxies: dwarf

1. Introduction

Edwin Hubble first drew attention to the Local Group in 1936, mentioning nine known members and referring to it as comprising "two triple nebulae", plus M33, NGC 6822 and IC1613 as field members Hubble (1936). Within this set of founding members, early and late-type spirals, irregulars, and (dwarf) ellipticals were already represented. A further three possible members at the outskirts were noted, but Hubble's general impression was of a loose group of galaxies relatively isolated in space, with a tendency for smaller systems to cluster around larger.

Almost immediately, new members representing the prototypes of a new class of galaxies, began to be discovered (the Sculptor and Fornax dwarf spheroidals, Shapley 1938). Over the following several decades the number of members roughly tripled by the end of the 20th century, and has roughly tripled again in the first two decades of the 21st. However, the basic features of the Local Group established in the 1930s have persisted: that dwarfs greatly outnumber giants; that satellite galaxies are strongly clustered around the giant members; that more faint members remain to be discovered; and that the Local Group is a fairly typical galactic environment (e.g., the reviews by Mateo 1998, van den Bergh 2000, McConnachie (2012)).

Over time, a number of galaxies have been discovered just outside the zero-velocity surface of the Local Group (e.g., Leo P, McQuinn et al. 2015), tending to diminish the degree of isolation from the field noted by Hubble and emphasizing the filaments in the cosmic web connecting the Local Group to other nearby loose groups. Among the list of galaxies just beyond the zero-velocity surface of the Local Group are the five galaxies of the NGC 3109 subgroup, and the exceptionally isolated galaxy UGC 4879. By this definition, the most distant known members of the Local Group would be the Aquarius dwarf (DDO 210) and Sagittarius dwarf irregular (ESO594-G004). With deep imaging and spectroscopy across the radio, infrared, optical and ultraviolet wavelengths

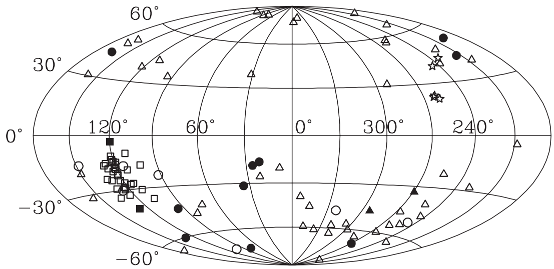

Figure 1. Hammer projection in galactic coordinates (centered on the Milky Way) of known galaxies within 1500 kpc. Galaxies within 300 kpc of the Milky Way are shown as triangles; those within 300 kpc of Andromeda are shown as squares; "field" galaxies are shown as circles. Gas-rich galaxies (with $M(HI)/L_{V,\odot} > 0.1$) are shown with solid symbols and gas-poor galaxies are shown with open symbols. The exceptions are the 5 galaxies in the NGC 3109 subgroup (possible LG non-members), which are shown as open stars. The depth of surveys is strongly variable with location. The areas of highest completeness are around M31 and the region in the lower left quadrant covered by the Dark Energy Survey. The completeness is lowest within the zone of avoidance. The tendency of Milky Way satellites to cluster in a non-random way is evident even given the spatial selection effects.

it has been possible to begin to directly compare the dwarf populations of the field and nearby groups to the Local Group; for example, the prominent M81, M83, Sculptor, and Centaurus groups (e.g., Weisz *et al.* 2011).

The discovery of the class of ultrafaint dwarf spheroidals (e.g., Willman *et al.* 2005, Zucker *et al.* 2006), with stellar masses down to just $\sim 10^3$ $M_\odot$, has revolutionized our view of the Milky Way environment and the evolution of the faintest, darkest galaxies. However, the three major reviews above, along with the reviews of star-formation histories and age-metallicity relations in Tolstoy, Tosi & Hill (2009) and Brown *et al.* (2012) remain essential reading for the study of Local Group dwarfs and form the jumping-off point for this review talk.

For the purposes of this review, the definition of a dwarf from Grebel, Gallagher & Harbeck (2003) and McConnachie (2012) will be adopted: any galaxy fainter than $M_V = -18$ is considered a dwarf. This excludes the Large Magellanic Cloud (LMC). The explosion of detections of systems fainter than $M_V = -8$ over the past decade has brought new scrutiny to the distinction between a galaxy and a star cluster. While many globular clusters and the classical dwarf spheroidal galaxies fall along well-separated loci in the surface brightness-total luminosity plane, it has become increasingly apparent that stellar systems with a continuous distribution of properties in this space can exist. It seems likely that an infallible division based on purely observable parameters is not possible; a working definition based on dark matter content or mass to light ratio could be adopted.

The merits of such a classification scheme are beyond the scope of this talk; for the rest of this work, the galaxy population of the Local Group will be taken from the updated list of McConnachie (2012)†, with the caveat that the nature of several of the recently discovered, very low-luminosity satellites of the Milky Way has yet to be confirmed. This list contains 107 systems with a distance of less than 1.5 Mpc from the closer of M31 or the Milky Way (Figure 1). From this list, only the LMC, M33 (Triangulum), Milky Way, and M31 (Andromeda) are giants. If we adopt the definitions that the virial radii of M31 and the Milky Way are approximately equal, at ≈300 kpc, and that every dwarf within these radii is a satellite, then the Milky Way has over 50 known or candidate satellites,

† http://www.astro.uvic.ca/~alan/Nearby_Dwarf_Database.html

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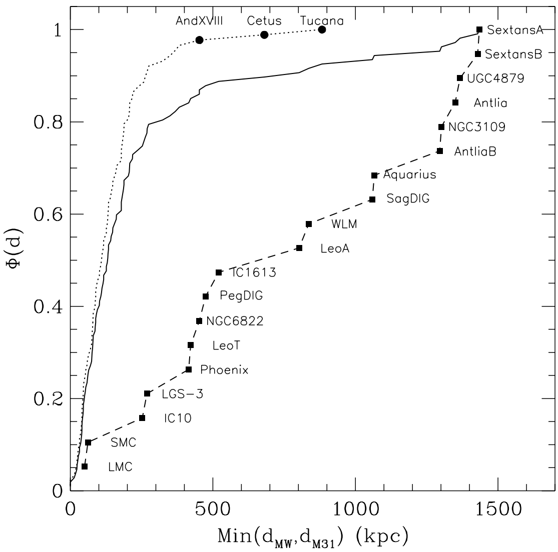

Figure 2. Cumulative fractional radial distribution of Local Group dwarfs (including the Magellanic Clouds). The radial coordinate value of each galaxy is taken to be the smaller of the distance to the Milky Way or to M31. The solid line shows the distribution of 107 galaxies and candidate ultrafaint galaxies listed in McConnachie (2012). The dotted and dashed lines show the gas-poor and gas-rich galaxies, respectively. All of the gas-rich galaxies are labelled by name; of the 88 gas-poor systems, only the three known examples more than 500 kpc from a parent halo are labelled.

and M31 has nearly 40. There are almost certainly on the order of half a dozen more galaxies to be discovered in the zone of avoidance within ≈15° of the Galactic plane.

2. The Local Group in Context

As our nearby laboratory for dwarf galaxy physics, the Local Group is where we build most of our preconceptions and misperceptions for what dwarf galaxies are like. As the best-studied collection of small galaxies it is inevitably where we turn when we seek understanding or confirmation of new results from other systems. There is a wide diversity of dwarfs even in this little volume of space, from highly-isolated gas-rich systems to tidally disrupting gas-free old galaxies of a wide variety of masses and surface brightness. There are extremes of both surface brightness (M32, with $\mu_{0,V} = 11$ mag/arcsec^2, to ultrafaints, e.g., Bootes III with $\mu_{0,V} >31$ mag/arcsec^2) and star formation rate (from starburst IC 10 to several dozen spheroidals which appear to be true fossils with the youngest stars dating back to the end of the era of reionization), and with a broad range of tidal interaction histories.

Many truisms of galactic astronomy were first applied to the Local Group, for example the morphology-density relation (Einasto *et al.* 1974). The observation that most gas-free (spheroidal/elliptical) galaxies are close satellites of giant galaxies and most gas-rich (irregular) dwarfs are found outside the virial radius of their hosts was an early clue to the the different natures of isolated and and satellite galaxies. Decades of subsequent work has led to our present highly nuanced appreciation of the links between galaxy mass, baryon fraction, environment, and mass loss in shaping the kinematics, star formation, and chemical evolution of dwarfs.

The modern perspective on this radial segregation of irregular and elliptical types is seen in Figure 2, which shows the cumulative distribution of distances between Local Group dwarfs and the closer of either M31 or MW. For comparison, the virial radius of

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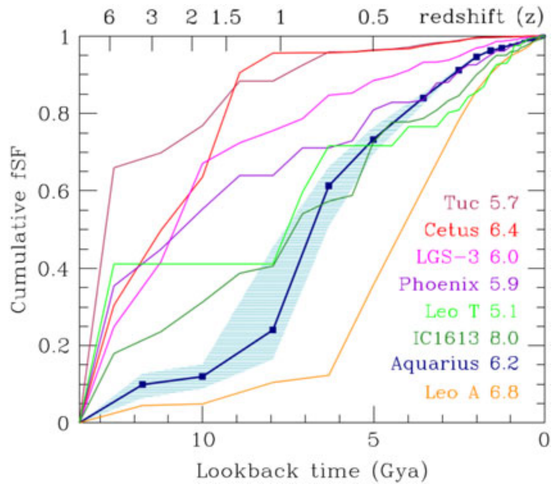

Figure 3. The cumulative fractional star formation of Aquarius (blue, with confidence interval) compared to other Local Group galaxies with comparably precise data. The redshift scale at the top is calculated assuming a concordance ΛCDM cosmology. The estimated stellar mass (log $M/M_{\odot}$); McConnachie 2012) is given for each galaxy. Aquarius and Leo A are the only two galaxies in the sample of eight to show SFRs significantly below their lifetime average for the first few Gyr after reionization.

the two giant spirals is often taken to be approximately 300 kpc; of the known Local Group members, ≈80% may be found within this distance of their respective parent galaxy. However, for the gas-rich galaxies, this figure drops to 4/19, or 4/13 if UGC 4879 and the NGC 3109 subgroup are excluded.

Of the gas-poor, spheroidal systems more than 500 kpc from a host, And XVIII and Cetus are not excluded by their radial velocities from having previously been much closer, and Tucana's very high positive velocity suggests a high probability for previous interactions. Among the gas-rich satellites, the HST and Gaia DR2 proper motions strongly imply that the Magellanic Clouds have only recently fallen into the Milky Way halo, and will not last long as gas-rich galaxies (and the Magellanic Stream is direct evidence of gas-stripping in action). Thus even a very simple observation leads to the implication that for dwarf galaxies with present-day stellar mass on the order of 10^6 $M_{\odot}$, the quenching of star formation and stripping of gas does not efficiently happen in the absence of interactions with neighbors.

If the early star formation among dwarfs that are significantly more massive than the ultrafaints is suppressed by reionization, then based on available data the effect seems to be obscured by random variation or by other, unaccounted for factors. Figure 3, from Cole *et al.* (2014), shows that among isolated galaxies with CMDs of sufficient quality to make a reliable determination of the star formation history at the oldest ages, the two most isolated (Leo A and Aquarius) have the youngest mean age. Data of similar quality for the other two similar examples, SagDIG and WLM, would be of extremely high value to test whether or not this isolation-SFH delay connection is real or merly a coincidence. Among the remaining non-satellites with sufficiently high-quality color-magnitude diagrams to make a determination, if there is a trend of early vs. late star formation with stellar mass, it is not immediately obvious; for example, the most massive and least massive galaxies in this sample both show nearly constant star formation rate over their lifetimes. One caveat to this discussion is that the galaxies, while small, are often larger than the field of view of the HST cameras, so that the star

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formation histories tend to be biased by observing strategies placing the centers of the galaxies in the field of view. In particular, it is known that population gradients exist, such that the outskirts of galaxies in this mass range tend to be older and more metal-poor than their central regions, so this information is subject to revision as wider-field data become available.

3. Observational and Theoretical Challenges

Between the second GAIA data release and the continuing very productive use of HST and wide-field imagers and spectrographs at 8-10 meter class ground-based telescopes, our knowledge of Local Group galaxies is increasing far too fast to summarize in a 25-minute review talk. The prospect of accurate proper motions for galaxies throughout the Milky Way halo raising the possibility of linking complete 6-dimensional phase space trajectories to episodes of star formation as a way to place qualitatively new kinds of constraints on the histories of satellite galaxies (e.g., Sohn *et al.* 2013) could fill an entire conference all on its own. Likewise, the dramatic increase in our ability to obtain high signal-to-noise, medium- and high-resolution spectra for very large samples of stars in nearby galaxies raises the prospect of being able to conclusively break the age-metallicity degeneracy using the observed metallicity distribution function of red giants to characterize populations of all ages (e.g., Kirby *et al.* 2017): a subject far too challenging to cover in a paragraph or three. Instead, I will raise just two recently identified issues that were not on the radar for the previous generation of excellent article-length reviews of the Local Group, and attempt to briefly put them in context with the rest of the talks to be presented at this meeting because they are the subject of intense observational work and get to the heart of whether we can make cosmological inferences from our local laboratory of dwarf galaxy physics.

3.1. *Planes of Satellites*

The non-random distribution of Milky Way satellites was first noted by Lynden-Bell (1976); with the tremendous increase in numbers of known satellites, this inhomogeneity has become highly statistically significant. Kroupa *et al.* (2005) identified a great plane of satellites and noted the statistical unlikelihood of such a configuration arising within standard ΛCDM galaxy formation. Similarly, a dedicated survey of the Andromeda system has identified a vast, thin plane of satellites of M31 (Ibata *et al.* 2013), supported by the radial velocity measurements that show the north half of the plane to be preferentially receding from us as the south side approaches.

The existence of highly-flattened, high angular momentum substructures at the $\sim$0.5 Mpc scale is quite problematic in the current generation of galaxy formation models. While some degree of subhalo anisotropy is expected, it falls dramatically short of the observations. In one model, for example, fewer than 1% of M31-like spiral galaxies have a plane of satellites as flattened and extended as M31's (Wetzel *et al.* 2016). While several suggestions have been made to account for the differences (e.g., tidal dwarfs, cold accretion streams, sub-group infall), each of these is problematic to some degree (Pawlowski 2018). Whether or not the planes of satellites are as dynamically significant as inferred will depend on further work including proper motions. While the Milky Way satellites are accessible to Gaia, the M31 satellites will require a decade of JWST observations in order to constrain their proper motions to the required precision. When completely characterized, the satellite planes may continue to pose a problem for our conception of galaxy formation, or they may simply be written off as indicative of cosmic variance in the merger and accretion history of individual large galaxies.

3.2. *Differences between M31 and Milky Way Satellites*

On a related note, the existence of dozens of satellites of both M31 and the Milky Way raises the possibility to make a comparative analysis of the two satellite systems to see if they are different. Any putative differences could be linked back to the formation of the giant galaxies under a hierarchical accretion scenario, perhaps preserving evidence of ancient major mergers. While it has been relatively easy to accurately measure the star formation histories of Milky Way satellites, the M31 system has been far more challenging because of the greater distance (and, for some satellites, contamination by M31 halo stars).

From shallow observations reaching the horizontal branch/red clump, we see that there are clear differences in the mean horizontal branch color between the M31 and Milky Way satellites for a similar metallicity, indicating differences in the age of the dominant old stellar populations (Martin *et al.* 2017). From deeper observations of a small subset of galaxies, Weisz *et al.* (2015) discovered that the M31 satellites appear to have all been quenched relatively early (prior to ≈6 Gyr ago), lacking the late-quenching satellites such as Carina, Fornax, Leo I and Leo II that characterize the Milky Way population. This has led to the suggestion that the different star formation histories reflect different assembly histories of the M31 and Milky Way halos. In order to make more detailed comparisons, it is necessary to measure the largest possible sample of galaxies, to control for differences in mean host separation, structural parameters, galaxy mass– and possibly even potential differences between members of the great planes of satellites and non-members (which, in the *extremely* small samples observed to date, appear to be indistinguishable; Skillman *et al.* 2017).

These linked avenues of exploration are among the most fertile areas for study in the coming decade, where proper motion measurements, deep, high-angular resolution imaging, and spectroscopy of very large samples of hundreds to thousands of stars per dwarf galaxy have the potential to revolutionize our understanding.

4. Summary & Conclusions

The tyranny of distance and angular resolution mean that the Local Group will always be our fundamental testing ground for dwarf galaxy evolutionary theory. Fortunately we have been blessed with a wide variety of systems and environments within this restricted distance range. The ability to derive star formation histories and metallicity with high time resolution going back to ages 10-13 Gyr is critical to understanding the processes which shape galaxy evolution and the cosmic climate for galaxies at high redshift. Conceptually, the simplest way in which to obtain this information is to combine deep photometry reaching below the oldest main-sequence turnoff with spectroscopic metallicity observations of a large sample of brighter stars. The ability to make such measurements has been a major driver for the next generation of extremely large telescopes and for the planned next generation of space telescopes. The importance of the problem is underscored by the large amount of effort put into improving alternative ways to obtain similar information using shallower observations, for example integrated light spectroscopy of low surface field star populations, e.g., Ruiz-Lara *et al.* (2018).

In many ways the Local Group is a typical loose group of galaxies (Hubble 1936, van den Bergh 2000), and the individual galaxy properties appear typical of dwarfs throughout the Local Volume (Weisz *et al.* 2011). This encourages the practice of using detailed star-formation and chemical evolution properties to infer the details of processes that shape galaxy evolution in a global sense, and to compare Local Group dwarfs to cosmological models. However, the continually increasing amount of information available means that as we explore galaxies as individuals and as groups, we are starting to discern possible unusual details of their distribution, which likely trace back to the specific formation histories of M31 and the Milky Way systems

By examining the early star-formation histories of the best-studied isolated Local Group dwarfs, it is inferred that at their peak, the dwarf galaxies that may have been largely responsible for reionization will be too faint to directly detect for decades to come (e.g., Boylan-Kolchin *et al.* 2015), and so the Local Group will remain a key sample for the understanding of the high-redshift Universe for at least that long. We have yet to identify a single example of any galaxy that experience *no* star formation before ionization and yet managed to begin forming stars after a delay, although the isolated dwarfs seem to have their star formation suppressed in the aftermath of reionization (Cole *et al.* 2007, 2014), and dwarfs in generally have "sputtering", highly variable star formation histories.

To develop a coherent understanding of dwarf galaxy evolution inevitably requires comparison to simulations. Many of the historical problems in simulating dwarfs have been reduced or elimated by increasing numerical resolution and improved treatment of baryonic physics (e.g., Wetzel *et al.* 2016). A consistent picture of the impact of reionization is being formed, where the galaxies with velocity dispersions much less than 10 km/s are very often completely quenched by reionization. However, there is a note of caution to be sounded as very few galaxies smaller than this limit are known to exist outside the virial radius of a massive host galaxy, confounding attempts to disentangle intrinsic from extrinsic effects.

There are a number of outstanding, compelling questions about the formation and evolution of galaxies in the nearby Universe. The discovery of apparently coherent planes of satellites extending over distances of several hundred kiloparsecs is a challenge to the way angular momentum is distributed in the current generation of cosmological simulations under the cold dark matter paradigm. The hints of possible differences between the satellite populations of M31 and the Milky Way likewise provide a potential path to understanding the differences in the individual accretion and merger histories of the two giant galaxies, or be symptomatic of a need for improved treatment of physical processes in the cosmological models.

The ultimate goals of observational studies of the Local Group dwarf galaxies are to combine deep and wide field, global SFH accounting for population gradients, proper motions, and individual stellar abundances to understand satellite and "isolated" galaxy orbits, accretion history, baryon fraction, feedback, and chemical evolution. In addition to the broad importance of satellite galaxy studies, the isolated galaxies of the Local Group have the potential to inform our understanding of the roll of gas stripping and mergers in triggering and quenching star formation in galaxies too massive to be completely quenched by reionization, and reveal the extent to which turnaround and first infall into a group environment may be related to the timing of major episodes of star formation. On the cusp of the launch of JWST, with the completion of the GAIA mission rapidly approaching, and standing a decade away from the era of extremely large telescopes, we are in an excellent position to start formulating the questions that these facilities will be able to answer.

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Discussion

Q1. Metallicity distributions and velocity distributions based on RGB stars are an oversimplification of old and intermediate age stellar populations.

A1. I agree this is something of a blunt instrument but we need to use the tools that we have available. An increasing body of evidence seems to show spatial and kinematic segregation of stellar populations within the classical dwarf spheroidal galaxies. Even among examples where the populations may be broadly characterized as “ancient” and “metal-poor”, it looks like there are distinguishable differences between degrees of just *how* old and *how* metal poor. Characterizing an entire galaxy by a single metallicity distribution function and a single velocity dispersion will become a thing of the past as the amount of high-quality data increases. Detailed patterns of chemical element abundances from different nucleosynthetic channels, and the correlation of those quantities with age, location and kinematics, will open entirely new ways to study nearby dwarf galaxies. It seems reasonable to expect that the dwarf irregulars will show the same sorts of effects; I am very interested to know just how far down the mass spectrum one has to look before finding galaxies that are even approximately homogeneous, simple stellar populations.

Q2. Does mass loss from dynamical stripping impact the JWST EoR observability? What about the IMF?

A2. If one carefully chooses a sample of galaxies that by virtue of their current distance and velocity can *never* have entered the virial radius of either M31 or the Milky Way, then one can hopefully minimize the amount of tidal stripping by interactions. You could argue that we can never eliminate every possibility for dwarf-dwarf interactions, especially in the extreme past when evidence for such interactions in the sense of gas tails or distorted isophotes would have long since been erased. To this I would reply that we must observe as many galaxies as we can to try to smooth out the noise introduced by this kind of cosmic variance, and be very careful to make general conclusions only from well-measured features of the star formation history that are common across the majority of systems. In this effort we also must be guided by simulations that suggest the expected rate of

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such dwarf-dwarf mergers, the importance of mass loss by stellar wind and supernova feedback in isolated dwarfs, and whether the global average star formation rate of a dwarf is readily predictable from a set of initial conditions, or whether it is effectively chaotic and unpredictable due to the number of factors contributing to the observable result.

As for the initial mass function, this is a critical parameter that all estimates of dwarf galaxy star formation history require. At the low-mass end, there is the prospect of directly measuring the IMF at low-metallicity in the local Universe through JWST observations of the ultrafaint satellites of the Milky Way. How this translates into the possibly very different conditions pertaining at redshifts 6–20 is a matter for theory and simulation. Because the oldest surviving main-sequence turnoff stars, which probe star-formation rates around the end of reionization era, vary by at most $\approx$0.2 $M_\odot$ over the 2 Gyr age range corresponding to the redshift range from $z \approx 2.5$–10, modest changes in the slope of the IMF will not dramatically change the conclusions about star formation rates drawn from sufficiently deep photometry – but care must be taken.