Plenary Session

Dwarf Galaxies: From the Deep Universe to the Present
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The Future of Dwarf Galaxy Research: What Telescopes Will Discover

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Abstract. Dwarf galaxies make ideal laboratories to test galaxy evolution paradigms and cosmological models. Detailed studies of dwarfs across the spectrum allow us to gauge the efficacy of astrophysical processes at play in the lowest mass halos such as gas accretion, feedback, turbulence and chemical enrichment. Future observational studies will deliver unprecedented insights on the orbits of dwarf companions around the Milky Way, on their star formation histories and on the 3-D internal motions of their stars. Over large volumes, we will assess the impact of local environment on baryon cycling and star formation laws, leading to a full picture of the evolution of dwarfs across cosmic time. In combination, future discoveries promise to trace the history of assembly within the Local Group and beyond, probe how stars form under pristine conditions, and test models of structure formation on small scales.

Keywords. galaxies: dwarf, galaxies: abundances, galaxies: halos, galaxies: evolution, galaxies: formation, (galaxies:) Local Group, (cosmology:) dark matter, cosmology: theory, methods: n-body simulations

1. Introduction

The low mass, low luminosity dwarfs are the most common galaxies in the universe but, because of their diminutive characteristics, are hard to detect except at nearby distances. Despite their numerical dominance, dwarf galaxies do not contribute much to luminosity or mass functions but they are exceptional in other ways. Most of them are dark matter (DM) dominated, many by a large factor. Both their stars and interstellar media have low metallicities, comparable to the abundances expected of the early universe. Since hierarchical models suggest that low mass halos are the fundamental building blocks of massive galaxies, dwarf galaxies may serve as local analogs of the earliest galaxies and thus reflect the physical conditions of early star formation (SF). Likewise, because of their low mass, they are expected to be much more strongly affected both by internal feedback processes and by external environmental influences. Thus dwarf galaxies serve as excellent cosmological probes and laboratories for galaxy evolution studies.

Numerous published reviews of the state of dwarf galaxy research contain more through and elaborate detail than presented here. Among the most important reviews focusing on the Local Group (LG) dwarf population are those of Hodge (1971), Mateo (1998) and McConnachie (2012)). Driven by the discovery of their dominance by number in the Virgo cluster (Binggeli, Sandage & Tammann 1985), the early type dwarf population was reviewed by Ferguson & Binggeli (1994). Tolstoy, Hill & Tosi (2009) presented a excellent summary of the star formation histories (SFHs), chemical abundances and kinematics of LG dwarfs while most recently, Bullock & Boylan-Kolchin (2017) discuss how the number, distribution and structural properties of dwarf galaxies challenge current cosmological models.

Many papers in this volume contribute significant insight into particular directions and are more focused than this review. An excellent overview of dwarf galaxies is presented by Andrew Cole in this volume and Laura Sales discusses the successes and challenges of numerical simulations. Following on those works, in this review I briefly discuss the state of dwarf galaxy observations in the context of the future research directions where observations play a key role in understanding. I apologize to those whose exciting work I am unable to call out because of page limitations; this was an amazing and stimulating conference.

2. The Dwarf Galaxy Population

The classification of a galaxy as a "dwarf" has historically revolved around its small optical luminosity, size and, in most cases, surface brightness. In his review, Hodge (1971) set the maximum luminosity ($M > -15$) of a dwarf one magnitude fainter than the Small Magellanic Cloud (SMC; $M \sim -16$). More recently Bullock & Boylan-Kolchin (2017) have categorized a galaxy as a "dwarf" if it has a stellar mass $M_* < 10^9$ $M_\odot$. They further subdivide the dwarf class into "bright" dwarfs with $10^7 < M_* < 10^9$ $M_\odot$, "classical" dwarfs with $10^5 < M_* < 10^7$ $M_\odot$, and "ultra-faint" dwarfs (UFDs; Willman *et al.* 2005) with $10^2 < M_* < 10^5$ $M_\odot$.

Many other authors have used other descriptors to subcategorize dwarfs according to distinguishing characteristics such as morphology: dwarf ellipticals (dE), dwarf spheroidals (dSph), dwarf irregulars (dIrr or dI). Although in most categorizations the Magellanic Clouds (MCs) are brighter than dwarfs, galaxies comparable especially to the SMC are sometimes referred to as Magellanic type dwarfs (dIm). The "transition" dwarfs (dTrans) show a mixture of early- and late-type dwarf characteristics, and may be in an intermediate stage of transitioning between types. Some dwarf ellipticals are nucleated (dE,N) while others are not. The ultra compact dwarfs (UCD), (Hilker *et al.* 1999; Drinkwater *et al.* 2000) are extremely small, with half-light radii of < 100 pc, as compact as globular clusters, but with typical masses greater than 10^6 $M_\odot$. UCDs have been found in many clusters, from Virgo (Zhang *et al.* 2015) to distant ones, and also in groups and around relatively isolated spirals. Blue compact dwarfs (BCD) are small low luminosity, star-bursting systems characterized by low metallicity and ofter showing evidence suggestive of interactions. Prototypical examples are IZw18 (Searle & Sargent 1972, Lebouteiller *et al.* 2017) and SBS0335 (Izotov *et al.* 1990). Tidal dwarf galaxies (TDG) are systems formed out of the debris of galaxy encounters such as the Antennae (Mirabel, Dottori & Lutz 1992). TDGs are distinguished among the dwarf population by their lack of dark matter (Lelli *et al.* (2015)) and greater metallicity for their luminosity (Duc *et al.* 2007; Lee-Waddell *et al.* 2018), matching better the expectations of their brighter parent galaxies. As discussed by Kristine Spekkens in this volume, recent attention has been focused on galaxies of extreme low surface brightness, the ultra diffuse galaxies, UDGs (van Dokkum *et al.* 2015). UDGs are very extended with effective radii comparable to that of the MW but with stellar masses of ~100 times less. While the majority of the UDGs are found in clusters, others appear to be relatively isolated (Martinez-Delgado *et al.* 2016, Greco *et al.* 2018). Some actually contain abundant supplies of neutral gas (Leisman *et al.* 2017).

Noted also by many previous authors, Tolstoy, Hill & Tosi (2009) point out in their Figure 1 that the dSphs, dIrrs and the star-bursting BCDs trace similar relations in the luminosity-size and luminosity-surface brightness planes. In fact, their updated Figure 1 reaffirms the conjecture by Kormendy (1985) that dwarfs fall along the same relations defined by the more luminous galaxies without discontinuity. While the UFDs are clearly separated in luminosity, they show similar trends to those of the brighter dwarfs, suggesting some commonality. Various arguments propose that outliers result from environmental processes, particularly those which reduce the size and/or luminosity of the original galaxy.

2.1. *Dwarfs and their Environment*

The close relationship between dwarf galaxy morphology and local environment is long known, even before the discovery of the UFDs. Most of the dwarfs in the LG lie within the virial radius of the Milky Way (MW) or Messier 31 (M31; Andromeda), but most of the gas-rich and currently star-forming ones are found beyond 300 kpc from the host (Tolstoy, Hill & Tosi 2009, McConnachie 2012). The observed MW morphological segregation suggests strong links between the local environment and the processes which shut down and/or trigger SF episodes.

While the environments of the LG and nearby groups are relatively benign, rich clusters offer a glimpse of dwarf evolution under extreme conditions of interaction. Deep surveys of clusters are revealing increasing populations of diverse dwarf galaxies, extending across the full range of dwarf sub-classes. For example, the similarity in compactness of UCDs to globular clusters (GCs) hints of a common linkage, that they may form by mergers of large numbers of GCs. Alternatively, UCDs may be the central nuclei of normal dwarfs stripped by tidal interactions in the rich cluster environment (Zhang *et al.* 2015).

3. Dwarf Galaxies as Cosmological Probes

In their recent review of “dwarf problems” with ΛCDM, Bullock & Boylan-Kolchin (2017) discuss numerous critical areas where dwarf galaxies raise challenges for our current cosmological models. These have been to a large extent reviewed by Laura Sales in her plenary talk included in this volume. Here, I review the observational constraints on the number, structure and distribution of dwarf galaxies which future observations will address.

3.1. *The Census of Dwarf Galaxies*

Although ΛCDM simulations predict the existence of thousands of low mass halos with masses large enough to support the molecular cooling needed to form stars, there is a strong mismatch between the number of dark matter (DM) subhalos predicted by the simulations and the number of satellites of the Milky Way that have been observed (e.g. Klypin *et al.* 1999). As mentioned above, the pace of discovery of faint galaxies in the LG has advanced rapidly with the deployment of facilities that offer both sensitivity and wide area coverage. The discoveries of new UFD MW satellites by the Sloan Digital Sky Survey (SDSS) prompted the reexamination of the predictions of the MW satellite luminosity function with a better understanding of completeness limits and the biases introduced by sky coverage and Galactic extinction (Tollerud *et al.* 2008). In the intervening years, advances in the predictions of simulations and observations have diminished but not yet fully eliminated the mismatch. As noted by Andrew Cole in his talk included in this volume, 20 new LG dwarfs have been discovered in the last year, bringing the census of galaxies closer than 1.5 Mpc to 107, including more than 50 MW satellites and more than 35 around M31.

ΛCDM predicts than DM halos should be filled with smaller substructures and thus that the satellites of the MW should have satellites of their own. Sales *et al.* (2013) have predicted based on semi-analytic models of galaxy formation that analogs of the LMC should host one SMC mass satellite as well as between 5 and 40 satellites of mass within 1/1000th of the LMC. The recent report by Kallivayalil *et al.* (2018) that four of the

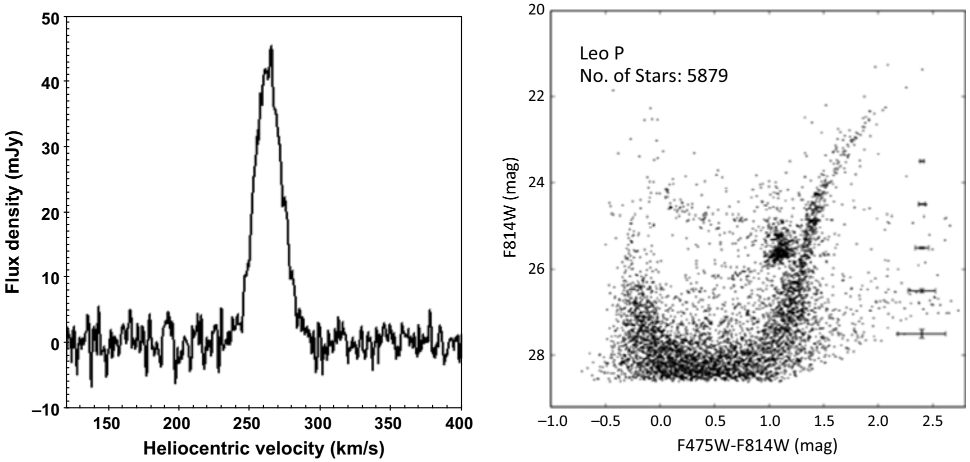

Figure 1. Left: High resolution spectrum of the global HI line emission obtained with the L-band wide receiver at Arecibo. Right: Color-magnitude diagram of Leo P from HST ACS imaging included as Figure 2 of McQuinn *et al.* (2015).

recently discovered satellites in the general direction of the MCs are in fact associated with the Magellanic system is confirmation that "satellites of satellites" exist. The continued study of these objects will be crucial to our understanding of the relationship between stellar mass and halo mass at the lowest masses: how low mass halos can hang onto their baryons in the presence of both internal feedback and environmental processes.

Blind HI 21 cm line surveys offer an alternate path toward the discovery of gas-bearing dwarf galaxies. The recently-completed ALFALFA extragalactic HI survey (Haynes *et al.* 2018) covered 7000 sq. deg. of high latitude sky out to $cz \sim$ 18000 km s^{-1}, detecting thousands of galaxies with baryonic masses less than 10^9 M$_\odot$, and more than 100 with HI masses less than 3 $\times 10^7$ M$_\odot$. As discussed separately by Betsey Adams and Julio Navarro in this volume and Giovanelli *et al.* (2010), it is possible that some low velocity ALFALFA HI detections may be very low mass LG subhalos with few, or no, stars.

A challenge to the identification of gas-bearing but optically-dark dwarfs is that their HI line signals overlap in velocity with galactic and circumgalactic ISM phenomena, particularly the HI high velocity clouds (HVCs). Furthermore, there is no way to determine the distance to the galaxy by the HI line alone. Adams, Giovanelli & Haynes (2014) presented a first catalog of candidate objects, identified within the ALFALFA survey database by relatively small size and isolation as Ultra Compact High Velocity Clouds, (UCHVCs). As summarized by Adams in this volume, on-going work aims to determine the distances to several other UCHVCs identified in ALFALFA (Janesh *et al.* 2017).

The nearby dwarf Leo P is a prototype of a nearby dwarf galaxy discovered by its HI line emission as detected by the ALFALFA survey. While the HI emission from Leo P meets the criteria of an UCHVC, its optical counterpart was noticed immediately (Giovanelli *et al.* 2013) because it has a single HII region (Rhode *et al.* 2013) evident in public imaging datasets. Figure 1 shows a high resolution HI line global profile (obtained with the Arecibo single beam, higher gain L-band wide receiver system) and the color magnitude diagram based on HST imaging used to determine the distance, confirming its location on the outskirts of the LG. The HI line signal is strong and corresponds to 8.1×10^5 M$_\odot$ at the distance of 1.62 ± 0.15 Mpc (McQuinn *et al.* 2015). The spectrum shown in Figure 1 has a resolution of about 1.4 km/s; the best fit Gaussian has a full width at half maximum of 22.4 ± 0.3 km s^{-1}; Bernstein-Cooper *et al.* (2014) derive a rotational velocity of 15 ± 5 km s^{-1} from the VLA velocity field. Uncertainties remain in the inclination of the disk, the contribution of turbulence to the observed line width, and the relationship of the velocity traced by the HI to the halo circular velocity. But the fact remains that Leo P has a very low SF rate despite the fact that its baryonic mass is dominated by HI.

Based on its CMD (left panel of Figure 1), McQuinn *et al.* (2015) find that Leo P has formed stars at a relatively constant rate over its lifetime and that it may be what a low mass dSph would look like today if it managed, because of its relative isolation, to hold onto its HI gas.

3.2. *The Structure of Dwarf Galaxy Halos*

ΛCDM simulations with dark matter only predict that halos should have density profiles that rise steeply at small radius $\rho \propto r^{-\gamma}$ with γ in the range (0.8,1.4) on the scale of dwarf galaxies (Navarro *et al.* 2010). However, as inferred from the observational surface brightness and kinematic data, the central regions of dark-matter dominated dwarfs seem less dense and less cuspy than predicted by the simulations. Deriving the density profiles at very small radii is difficult, complicated by resolution and seeing issues as well as geometry. For example, Genina *et al.* (2018)) point out that the distribution of stellar populations within dwarfs can be significantly elongated. Such departures from sphericity can hide cuspiness and even suggest a core when there is a cusp. The addition of baryonic processes such as feedback into the simulations similarly can modify their predictions so that a discrepancy between observations and predictions is not yet proved.

3.3. *Scaling Relations for Dwarf Galaxies*

As discussed in some detail by Bullock & Boylan-Kolchin (2017), it is quite surprising that the baryonic components of galaxies seem so tightly related to the dynamical properties inferred for their host halos, given the very wide range of their morphologies, star formation histories, dark-to-luminous matter fractions and locations within larger scale structures. Figure 2, adapted from Bernstein-Cooper *et al.* (2014) shows one example of such scaling relations, the baryonic Tully-Fisher relation (BTFR: McGaugh *et al.* 2000). Based mainly on data compiled by McGaugh (2012), the right panel of Figure 2 shows that the BTFR holds over 6 orders of magnitude to at least $M_{baryon} \sim 10^6\ M_\odot$. At baryonic masses below that, the UFDs deviate from the relation, possibly due to the effects of their local environment.

An extension of the BTFR known as the radial acceleration relation (RAR) has been noted by McGaugh, Lelli & Schombert (2016). As discussed in greater depth by those authors and by Bullock & Boylan-Kolchin (2017), real galaxies show a much wider diversity in rotation curve shape at fixed velocity compared to what is predicted by the simulations. A tight coupling of the total baryon content (gas plus stars) with the halo mass introduces lots of astrophysical complications whose impact on the interpretation of the observational data need to be understood (Verbeke *et al.* 2017).

3.4. *Satellite Planes*

ΛCDM simulations do not predict the existence of large departures from isotropy in the distribution of satellites nor departures from random motions. However, in 1976, Lynden-Bell and, independently, Kunkel and Demers (Lynden-Bell 1976) noticed the possible association of distant globular clusters and dwarf galaxies; their proposed planes were offset by 30° with Lynden-Bell's overlapping the recently discovered Magellanic Stream. With the discovery of additional dwarfs and the measurement of more precise distances, better definition of the Milky Way satellite plane was made by Kroupa, Theis & Boily

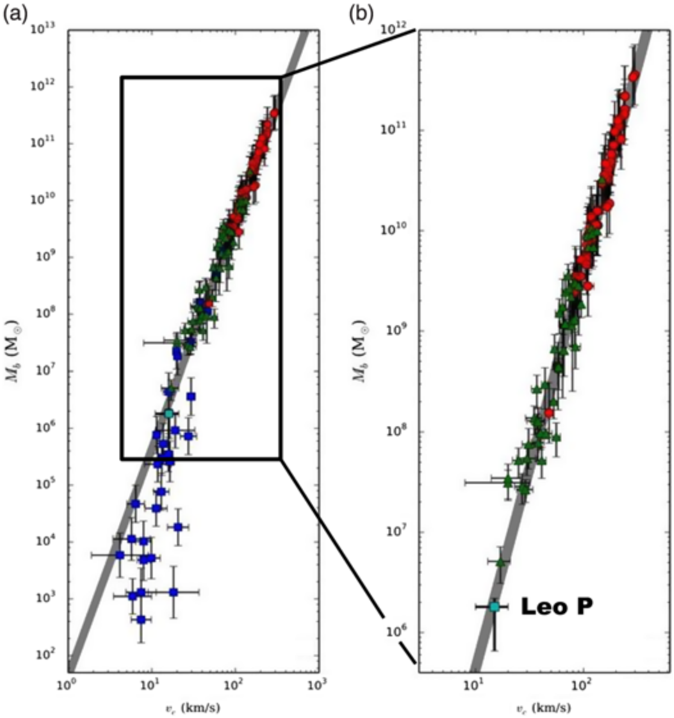

Figure 2. The baryonic Tully-Fisher relation for local galaxies, adapted from Bernstein-Cooper *et al.* (2014). The dataset is reproduced from McGaugh (2012). The left panel shows the full range of the observational dataset, including the LG dSphs, while the right panel covers only the range explored by the gas-dominated galaxies. The gray shaded line shows the best fit to the gas-dominated galaxies as derived in McGaugh (2012). The labeled point in the right panel shows the location of the dwarf irregular galaxy Leo P, discovered by its HI line emission in the ALFALFA survey.

(2005) and Metz, Kroupa & Jerjen (2007). Now dubbed the “Vast POlar Structure” (VPOS), Pawlowski, McGaugh & Jerjen (2015) have shown that the system forms a flattened body with half-thickenss ∼ 15 kpc and radius ∼40 kpc. Furthermore, a similar preferential arrangement has been identified around M 31 (McConnachie & Irwin 2006, Ibata *et al.* 2013) Canonical thought has suggested that these flattened structures might be explained by the preferential accretion of satellites along filaments. However, work presented at this conference by Oliver Müller (Müller *et al.* 2018) has shown not only that a plane of satellites exists around the nearby galaxy Centaurus A, but also that the statistical analysis of their observed kinematics suggests that the satellites are co-rotating, a feature not predicted by current simulations. Better distances and proper motions of more MW and M31 satellites and studies of dwarfs in more distant systems will be needed to understand the occurrence of such anisotropic structures and their origin.

4. Dwarf Galaxies as Probes of Galaxy Evolution

Because of their proximity, the stellar constituents of LG dwarf galaxies can be studied in great detail both through color-magnitude diagrams and spectroscopic studies of resolved stars. With increasing resolution, the atomic and molecular constituents of nearby dwarfs offer clearer insight into the interstellar media in low mass, low metallicity systems. Together the body of evidence enables the exploration of how dwarfs acquire, enrich and retain their gas while building up their stellar mass.

4.1. *Star Formation Histories*

The availability of detailed color-magnitude diagrams (CMDs) for growing numbers of LG dwarfs reinforces the concept of morphological segregation in terms of star formation histories, particularly among the dwarfs which are not satellites of the MW or M31. As shown by, among others, Tolstoy, Hill & Tosi (2009), Weisz *et al.* (2014) and Gallart *et al.* (2015), dwarfs in the LG show a remarkable variety of SFHs. Whereas the more isolated dwarfs show a wide variation in their SFHs, the CMDs of closest-in MW UFDs all suggest that SF ceased 10 Gyr ago. More distant dSph satellites show evidence of young and intermediate age populations. Skillman *et al.* (2017) find that a small sample of M31 dSphs show a significant range of quenching times but none that could be considered recent (< 5 Gyr). For a larger sample with somewhat shallower photometric data, Martin *et al.* (2017) also found that a large fraction of the M31 dwarf galaxies have extended SFHs inconsistent with early star formation episodes that were rapidly shutdown. Further studies will extend the depth of the CMDs in larger samples, allowing inferences on the importance of quenching at reionization and possible relationships to orbital parameters and location relative to satellite planes.

An impressive clue to the evolution of dwarf galaxies is contained in the luminosity-metallicity relation or the alternative version, the stellar mass-metallicity relation. Combining stellar abundances [Fe/H] from Kirby *et al.* (2013) with nebular ones [O/H] from Berg *et al.* (2012), Figures 2 and 3 of Hidalgo (2017) demonstrate the similarity in the two versions as measured by the two techniques. It is quite amazing that dwarfs with the same mass (or luminosity) but very different SFHs can apparently end up with the same metallicity. Such an outcome may arise because the least massive systems lose so many of their heavy elements during bursts that SF has only a slow impact on their buildup.

Locally, spectroscopic studies of individual resolved stars provide a detailed look at the chemical enrichment history in dwarfs, complementary to their SFHs. Sylvia Ekström, in this volume, reviewed the importance of metallicity in the role that massive stars play in chemical enrichment. As discussed by Tolstoy, Hill & Tosi (2009), because stars of different masses contribute different elements on different timescales, studies of the pattern of abundance variations of individual resolved stars can reveal how chemical enrichment has taken place during the galaxy's SFH. At low metallicity, the abundance ratios of heavy elements are expected to deviate from those of normal populations (Emerick *et al.* 2018). Indeed, extremely-metal poor stars in the MW, believed to be among the oldest population, are strongly overabundant in carbon and often also in Ni, O and Mg. Detailed studies of the abundance of various chemical species in individual stars in UFDs offer evidence that those objects may in fact represent very low mass halos whose stars were formed at very early times (Spite *et al.* 2018). Future high sensitivity, high spatial and spectral resolution studies will make use of the wealth of information conveyed by studies of abundances and their patterns.

4.2. *The Interstellar Medium in Dwarf Galaxies*

Observations of the interstellar medium (ISM) in dwarf galaxies offer insights into the processes that lead to the conversion of gas into stars in low metallicity environments as well as those that lead to the shut-down of SF due to feedback, stripping, etc. In this volume, Suzanne Madden presents an overview of the ISM properties of dwarfs, looking in particular at what observations of interstellar gas and dust tell us about how the gas phases operate and what processes control dust and gas evolution. The low metallicity of low mass dwarfs bears importantly on cooling rates and therefore on dust and molecule formation. Among other effects, the grain size distribution, composition and structure are encoded on the efficiency of photoelectric heating. The dust-to-gas ratio (D/G) shows a roughly linear relation with metallicity at higher values of Z but at $Z/Z_\odot < 0.1$, D/G plummets steeply (Rémy-Ruyer *et al.* 2015). In spirals, H_2 formation on the surfaces of grains is quite efficient but in dwarfs, the timescale for formation becomes very long, exceeding a Hubble time. Although the process is not fully understood, it seems that metals are not incorporated into dust at low metallicity in the same way as at higher Z, with the result that low metallicity galaxies require more time to accumulate heavy elements for efficient grain growth.

Alberto Bolatto, in this volume, has reviewed the status of our understanding of the formation and cooling of molecular gas and its relationship to SF, particularly in the Magellanic Clouds. The cold ISM is notoriously difficult to detect in dwarf systems, but recent CO detections (e.g., Elmegreen *et al.* 2013, Shi *et al.* 2016) have shown that such gas does exist in their low metallicity environments. However, at low metallicity, CO becomes a poor tracer of H_2. Bolatto, Wolfire & Leroy (2013) have shown that the H_2 to CO conversion factor blows up at low metallicities. H_2 can exist outside of the denser regions where the CO is dissociated but the H_2 remains self-shielded. This distinction makes the denser CO core considerably smaller and thus makes much of the molecular mass "CO-dark". In low metallicity dwarfs, the CO dark gas may harbor the bulk of the H_2 reservoir.

While there is molecular gas in low metallicity dwarfs, it is accompanied apparently by a decreased SFR per gas mass. Of particular relevance to probe SF in pristine conditions such as found in the early universe, future studies will need to understand the role of HI vs H_2 in how dwarfs form stars and the impact of their often-bursty SFHs.

4.3. *The Regulation of Star Formation in Dwarfs*

The fraction of gas in cold phases depends on the processes governing the collapse of cold gas (what triggers star formation) and on the ones that heat it up, thereby preventing collapse (what keeps the star formation rate so low?). The star formation laws at work in the Milky Way and spirals in general do not seem to apply in low mass, low surface brightness, low metallicity dwarfs (e.g., Kennicutt 1998, Kennicutt & Evans 2012). Recent works by Shi and colleagues, summarized most recently in Shi *et al.* (2018), have used spatially resolved measurements of the SFR as well as stellar and gas masses to explore the deviations seen in low surface brightness galaxies and the outer disks of spirals and dwarfs from the usual relationship between the SFR surface density and the local gas surface density $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^N$ with $N \sim 1.4$, the "Kennicutt-Schmidt Law". Rather, they propose an "extended Schmidt law", $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}\Sigma_*^N$, which includes an additional dependence on the stellar mass surface density arising from the role the gravity of the stellar population plays in setting the pressure of the ISM. Those authors further point out that, under similar conditions, SF was inefficient in the early universe. Using aperture synthesis HI maps from the Faint Irregular Galaxy GMRT Survey (FIGGS), Roychowdhury, Chengalur & Shi (2017) have shown that this extended law provides a much better fit than the simpler relation.

Additionally, it is well understood that feedback associated with the evolution of massive stars play an important role in regulating star formation in fragile dwarf disks. A number of talks at this conference discussed recent results on how various feedback mechanisms can influence low mass galaxies. As reviewed by Samantha Penny in this volume, recent observations conducted as part of the SDSS-IV MaNGA survey have presented evidence for AGN feedback in galaxies just at the top end of the dwarf class considered here ($M_* \sim 10^9$ $M_\odot$, Penny *et al.* 2018). Volker Heesen discussed using radio continuum emission as an extinction free tracer to probe the influence of stellar feedback in dwarfs using IC 10 as an example (Heesen *et al.* 2018). Vianney Lebouteiller presented results showing that the heating of the neutral gas in the ever-enigmatic IZw 18 mainly results from photoioniozation by radiation from a bright X-ray binary in that galaxy (Lebouteiller *et al.* 2017). Conference organizer Kristy McQuinn presented a poster on winds in starbursting low mass galaxies following on previous work showing that the massive star wind timescales are comparable to the starburst duration (McQuinn *et al.* 2018). As a result, the gas is driven to larger distances and less material is recycled than might have been expected.

Future studies combining multiwavelength tracers will provide a holistic understanding of how different internal and external factors influence the mechanisms that trigger, sustain and shut down star formation in dwarfs. The importance of environment will require studies not just of galaxies close to their hosts or in clusters, but also ones in voids (Makarov *et al.* 2017) or in pairs of isolated dwarfs (Privon *et al.* 2017).

5. Conclusion: The Future of Dwarf Galaxy Research

In the preceding sections, I have tried to call out some of the most intriguing recent results related to observations of dwarf galaxies and what questions they raise. Here I summarize some of questions that future observations are likely to answer or at least provide significant insight into their answers.

How many dwarf galaxies are there? To appreciate the rapid rate of dwarf discovery, it should be noted that the majority of LG dwarfs identified today are fainter than any galaxy known in 2000 and, as Andrew Cole noted in his overview talk, that more than 20 new LG dwarfs have been found in the last year. Following on this tremendous pace of discovery, future wide area and highly sensitive surveys at optical wavelengths including the on-going Dark Energy Survey, the Hyper Suprime-Cam survey and ultimately, the Large Synoptic Survey Telescope will provide a truly robust census of the LG down to the minimum halo mass expected to host a bona fide galaxy. For example, Newton *et al.* (2018) have assessed the current limitations in observational constraints on the number of dwarf MW satellites and make predictions for future surveys. Their analysis estimates that there should be 124 (+40, −27) (68%, statistical error) dwarfs brighter than $M_V \sim 0$ within $R < 300$ kpc of the MW. And, they conjecture that the LSST will be able to detect half of them, despite the large swath of sky hampered by galactic extinction and sky coverage limitations.

In parallel with the optical surveys, the suite of 21 cm wide area mapping programs conducted with Arecibo/ ALPACA, FAST, WSRT/APERTIF, MeerKAT and ASKAP will probe the low mass end of the HI mass function to find any gas-bearing halos even if they do not have associated stars. Some of the latter may be the reionization-limited HI-bearing low mass haloes dubbed RELHICS (Benítez-Llambay *et al.* 2017) and discussed by Julio Navarro in this volume. Not only will the next generation of HI surveys discover many additional dwarfs, but the resolved HI surveys with interferometers will provide further insight into how the observed disk rotation reflects the halo circular velocities (Papastergis & Shankar 2016). Furthermore, they will explore the lowest HI mass population in hundreds to thousands of dwarfs in nearby groups beyond the LG.

How do satellites exist within halos? A main objective of the Gaia mission was to unravel the assembly history of the MW. Its recent second data release has shown its success in enabling the analysis of the spatial distribution, kinematics, age and abundance of stars across the MW. Future studies will aim to link together the clues to assembly history in order to construct a self-consistent time sequence of what happened when, why and how. Initial works based on Gaia have already suggested the association of MW components with satellite accretion events (Helmi *et al.* 2018). Among the objectives of future programs to identify larger and larger samples of dwarfs and to study their individual stars and stellar populations will be to trace, with the obvious distance-dependence of detail, the assembly history of dwarfs throughout and beyond the LG. As discussed in this volume by Isabel Santos-Santos, interpretation of the current observational data on satellite planes remains a challenge, particularly because of the relatively small numbers of dwarfs used in defining planes and limitations in sky coverage particularly due to Galactic extinction. Future deeper and wider observational studies of satellites not just in the Local Group but beyond will be required to test the advances in understanding made in the simulations.

How does star formation in low metallicity gas proceed? Theoretical predictions of the internal structure of ISM clouds in dwarfs suggest that in low metallicity environments there should be a lower number of gas clumps and that, because they do not fragment as much, the clumps should be larger. Future observations of the dust and all gas phases with comparable resolution in the Milky Way, Magellanic Clouds and elsewhere in the local universe will reveal how stars form in low abundance gas locally and thereby inform models of how stars formed in the similarly-pristine early universe.

How do dwarf galaxies build up their stellar mass? As local analogs of low mass halos in the early universe, the nearby dwarf galaxies offer unique insight into the processes by which halos build up their stellar populations across cosmic time. Future deep fields will explore the progenitors of today's brighter dwarfs during the era of Cosmic Noon (Boylan-Kolchin *et al.* 2015), yielding analogs of both the star-forming dwarfs and the dSphs. Future deep observations will explore a broad range of environments yielding insight into the relative importance of the mechanisms that imprint the observed morphological segregation. With increasing depth, CMDs of LG dwarfs will drive down the uncertainty on individual SFHs and allow the evaluation of satellite populations. As noted by Andrew Cole in his overview talk, it is critical to push photometry to below 28th or 29th magnitude even for dwarfs within 1 Mpc, setting the benchmark for studies of the LG. Spectroscopic studies of individual stars spanning the full lifetime will probe the chemical evolution and dynamics over a galaxy's history (Kirby *et al.* 2017). In combination with detailed orbital reconstructions, it will be possible to correlate important epochs of a galaxy's SFH with with the corresponding timesteps in its orbital history.

What do today's dwarfs tell us about reionization? Current consensus models suggest that reionization was contributed in large part by the progenitors of today's dwarf galaxies. Boylan-Kolchin *et al.* (2015) discuss the importance of the LG dwarfs to understanding the role of dwarfs in reionization and predict the range of the rest-frame UV luminosity function accessible to current and future surveys. Future deep fields with HST and JWST will probe deeper and deeper, especially through lensing, down the UV luminosity function. Of notable importance, Figure 4 of Boylan-Kolchin *et al.* (2015) demonstrates that JWST will be able to probe systems of luminosity comparable to the LMC at redshifts ~ 7; similar objects which benefit from gravitational lensing should be contained among the faintest objects visible in the HST Frontier Fields. At the same time, since the progenitors of the lowest mass LG dwarfs will not be visible at high redshift, it is of critical importance to understand the relative contributions of galaxies of LMC mass and lower by detailed studies of their local analogs. As pointed out by Weisz *et al.* (2011), deep studies of the LG dwarfs will set much more robust constraints on the nature and state of their progenitors at early times. And, the detailed study of massive stars in local low metallicity dIs will provide a better understanding of massive star formation in the early universe and how the processes associated with the evolution of massive stars leaves an imprint on the evolution of their host dwarf galaxies.

Is the Local Group representative? Detailed observations of the stars, gas and dust in LG dwarfs drive constraints on numerical simulations and models of galaxy formation that explore the low mass regime. However, we should ask whether the LG really serves as a fair laboratory into galaxy assembly and evolution given its relatively, but not entirely, quiescent state. As mentioned previously, work on the satellites of M31 (Martin *et al.* 2017) are beginning to test our understanding of MW dwarfs in comparison, but the picture is not yet clear. Weisz *et al.* (2011) have explored the SFHs and morphological segregation of LG galaxies with those of the more distant and widely distributed ANGST sample. Within the limitations of the data available to that study, the LG dwarfs appear to be fairly representative of other nearby systems though studies of comparable depth over considerably larger samples will undoubtedly provide insights beyond today's cursory picture. As Andrew Cole has reminded us in this volume, the uncertainty in the SFH is a strong function of limiting depth, so that comparison is really only fair if it is made over the same luminosity range.

The next generation of telescopes on the ground and in space will offer tremendous new capabilities that promise the exploration of other local volumes for comparison with the LG. Observations are just beginning to probe nearby groups with sufficient depth. For example, Danieli *et al.* (2017) derive the luminosity function of the M101 group and find that it is flatter at faint magnitudes than that of the LG. Furthermore, they find an apparent lack of intermediate mass galaxies in the M101 group. However, kinematic measurements are are critical to determining whether there is really a “too big to fail” challenge in the M101 group.

Intriguingly, D'Souza & Bell (2018) have suggested that M32 results from the merger 2 Gyr ago of M31 with a large galaxy of stellar mass $\sim 2.5 \times 10^{10}$ $M_\odot$, the third largest galaxy in the LG. Hence, we need to understand better the assembly history of the LG in order to ascertain how typical the present time is. Only then will we know how representative the LG is. Given the current uncertainties, we should keep an open mind and not rely on the LG too much for assumptions about how galaxies across the universe and cosmic history might behave.

Future observations of dwarf galaxies will provide critical tests of cosmological and astrophysical theories and simulations particularly through the interplay of their luminous and dark components and will refine the constraints placed by the tiniest galaxies on our understanding of galaxy formation and evolution over cosmic time. Given the promised capabilities of the next generation of instruments and facilities, dwarf galaxy research offers a most promising prospectus for the enterprise of astronomical discovery.

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Discussion

QUESTION: Something about dwarfs vs gc's at high z