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Dwarf Galaxies in the Local Group

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Abstract. Within the Local Universe galaxies can be studied in great detail star by star. The Color-Magnitude Diagram synthesis analysis method is well established as the most accurate way to determine the detailed star formation history of galaxies going back to the earliest times. This approach received a significant boost from the exceptional data sets that wide field CCD imagers on the ground and the Hubble Space Telescope could provide. Spectroscopic studies using large ground based telescopes such as VLT, Magellan, Keck and HET have allowed the determination of abundances and kinematics for significant samples of stars in nearby dwarf galaxies. These studies have shown directly how properties can vary spatially and temporally, which gives important constraints to theories of galaxy formation and evolution.

Keywords. stars: abundances, galaxies: dwarf, galaxies: evolution

1. Introduction

What is a dwarf galaxy? Past definitions always focus on size (e.g., Hodge 1971, Tammann 1994), and the presence of a dark matter halo (e.g., Mateo 1998). Is there any other physical property that distinguishes a dwarf galaxy from bigger galaxies? Or are the differences merely due to the amount of baryonic matter that is retained by a system during its evolution? In general, large late-type galaxies sit on the constant central surface brightness ridge defined by Freeman (1970), and appear to manage to retain most of their baryons. Conversely for galaxies which lie below this limit it seems that the optically fainter they are, the higher the fraction of baryons they have lost. This could be due to Supernova winds and/or tidal interactions, which are effective when a galaxy lacks a suitably deep potential well to be able to hold onto to its gas and/or metals (e.g., MacLow & Ferrara 1999, Ferrara & Tolstoy 2000, Mayer *et al.* 2002). The galaxies above this central surface brightness limit are either currently forming stars very actively, such as Blue Compact Dwarfs (BCDs), or they have had very active star formation activity in the past (e.g., Elliptical galaxies).

The definition of a galaxy as a dark matter halo naturally excludes globular clusters, which are believed not to contain any dark matter, and also do not contain complex stellar populations or any evidence of enrichment from an extended epoch of star formation. The structural properties of globular clusters tend to support the idea that they are distinct from galaxies. This definition also excludes tidal dwarfs, which are more a probe of the disruption of large systems.

The taxonomy of dwarf galaxies typically opens a *Pandora's box*. At a very influential conference held at the Observatoire de Haute-Provence in 1993 G. Tammann gave a working definition: all galaxies that are fainter than $M_B \leqslant -16$ ($M_V \leqslant -17$) and more spatially extended than globular clusters are dwarf galaxies (Tammann 1994). This is broadly consistent with the limit of mass at which outflows tend to significantly affect the baryonic mass of a galaxy. This includes a number of different types: early-type dwarf spheroidals (dSphs); late-type star-forming dwarf irregulars (dIs); the recently discovered very low surface brightness, ultra-faint, dwarfs (uFd); centrally concentrated actively star-forming BCDs. The new class of even more extreme ultra-compact dwarfs (UCDs) are identified as dwarf galaxies from spectra but are of a similar compactness to globular clusters (Drinkwater *et al.* 2003).

There is no clear separation between the global photometric properties of dwarf galaxies and the larger late-type and spheroidal systems. The dIs, BCDs, dSphs, late-type and spheroidal galaxies tend to overlap with each other in this parameter space. The overlapping properties of early and late-type dwarfs has long been shown as convincing evidence that early-type dwarfs are the same as late-type systems that have been stripped of their gas (Kormendy 1985). This is quite different from the distinction between Ellipticals and Spirals (and Spheroidals), which show a more fundamental difference (e.g., Kormendy *et al.* 2009). There is no clear break which distinguishes a dwarf from a larger galaxy, and hence the most simple definition does not have an obvious physical meaning, as recognised by Tammann (1994).

Current evidence suggests that it is time to leave behind the idea that dwarf galaxies are in any way special systems. Many galactic properties (e.g., potential well, metallicity, size) correlate with mass and luminosity, and all types of galaxies show continuous relations in structural, kinematic and population features between the biggest and the smallest of their kind (e.g., Tolstoy, Hill & Tosi 2009). The only justification to segregate dwarf galaxies from other types is to study specific aspects of galaxy formation and evolution on a small scale.

Dwarf galaxies provide an overview of galaxy evolution in miniature which will also be relevant to understand the early years of their larger cousins and important physical processes which govern star formation and its impact on the surrounding interstellar medium. There remain issues over the inter-relations between different types of dwarf galaxies, and what (if any) is the connection with globular clusters. When these relations are better understood we will be a significant step closer to understanding the formation and evolution of all galaxies.

2. Star Formation Histories

A transformation in the field of Colour-Magnitude Diagram (CMD) analysis occurred around 15 years ago, when the power and resolution of a new generation of telescopes (particularly the Hubble Space Telescope, HST) and detectors (large format CCDs) allowed accurate photometry and thus detailed CMDs of individual stars in crowded fields of external galaxies to be made. The CMD of a stellar system retains information about the past star formation history (SFH), as it preserves the imprint of fundamental evolutionary parameters such as age, metallicity and Initial Mass Function (IMF) in such a way that it is possible to disentangle them.

2.1. *Early-Type Galaxies*

Early-type galaxies, such as dSphs, are typically associated with large galaxies like our own. They are among the systems closest to us, with the majority at distances <130 kpc, although there are also several more distant examples. Arguably the new uFds are an extension of the dSph class down to much lower luminosities. The dSphs typically look very much like the old extended stellar populations which appear to underlie most late-type systems. This suggests that the major difference is that they lack gas and recent star formation, an hypothesis supported by their overlapping structural properties. They have typically not formed stars for at least several 100 Myr (e.g., Fnx), and in several

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cases for much longer (e.g., the Scl dSph apparently formed the majority of its stars more than 10 Gyrs ago).

The proximity of dSphs makes it easier to carry out studies of their resolved stellar populations, although this requires wide field instrumentation to efficiently gain an overview as they are typically >1 degree across on the sky. The most famous example is Carina, which has been much studied over the years. It was one of the first galaxies shown, from deep wide field imaging on the CTIO 4m telescope, to have completely distinct episodes of star formation (Smecker-Hane *et al.* 1996, Hurley-Keller *et al.* 1998), identified by three distinct Main Sequence Turnoffs (MSTOs) in the CMD. These distinct MSTOs translate into a SFH which consists of three separate episodes of star formation, with the star formation rate (SFR) apparently going to zero in between. The existence of a complex SFH was already inferred from the properties of its variable stars (Saha *et al.* 1992), and the red clump and Horizontal Branch (HB) morphology (Smecker-Hane *et al.* 1994) but it took synthesis analysis of a CMD going down to the oldest MSTOs to quantify it (Hurley-Keller *et al.* 1998).

2.2. *Late-Type Galaxies*

The dIs have also long been used as probes of metal-poor star formation, both young and old. They still retain HI gas, and are thus, with a few curious exceptions, typically forming stars at the present time as they have probably done over their entire history, with a variety of rates, from extremely low (e.g., Pegasus) to zero (e.g., transition systems DDO 210, LGS 3) to relatively high (e.g., NGC 6822, SMC). The dIs were the first systems to which synthetic CMD analysis was applied (e.g., WLM, Sextans B). They are a numerous and often fairly luminous class within the Local Group. They are typically at a distance >400 kpc (the SMC being a notable exception). Studies down to the oldest MSTOs of dIs typically require HST-like sensitivity and image stability.

HST has had a large impact on studies of these systems. The exceptionally detailed CMDs from WFPC2 allowed for the first time the clear distinction between the main sequence and the blue loop sequence in young metal-poor systems (e.g., Sextans A, Dohm-Palmer *et al.* 1997). Photometric errors previously blended these sequences in "the blue plume" and there were debates about the reliability of the theoretical predictions of blue loop stars. These stars have been subsequently shown to be powerful tools for mapping the spatial variations in the SFR over the last 800 Myr.

The HST/ACS CMD of Leo A (Cole *et al.* 2007) is one of the deepest and most accurate ever made for a dI. The SFR as a function of time over the entire history of the galaxy was determined using synthetic CMD analysis, and it was found that 90% of the star formation in Leo A happened during the last 8 Gyr. There is a peak in the SFR 1.5−3 Gyr ago, when stars were forming at a level 5−10 times the current rate. The CMD analysis of Leo A only required a very slight metallicity evolution with time. The mean inferred metallicity in the past is consistent with measurements of the present-day gas-phase oxygen abundance. There appears to have been only a small and uncertain amount of star formation in Leo A at the earliest times, as the HB is very weak. The error bars on the SFH (see Cole *et al.* 2007) show that from CMD analysis alone this ancient population is not well defined. The only definite proof of truly ancient stars in Leo A comes from the detection of RR Lyrae variable stars (Dolphin *et al.* 2002).

2.3. *Beyond the Local Group*

The dwarf galaxies which have been studied using the CMD synthesis method beyond the Local Group are predominantly actively star forming BCDs (e.g., I Zw 18; NGC 1705). These galaxies are typically quite distant, but as there are no obvious BCDs in the Local

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Group (with the possible exception of IC 10 hidden behind a lot of foreground obscuration from the MW) there is no other possibility to study this class of actively star forming, yet low metallicity, systems.

In these galaxies, distance makes crowding more severe, and even HST cannot resolve stars as faint as the MSTO of old populations. The further the distance, the worse the crowding conditions, and the shorter the look-back time reachable even with the deepest, highest resolution photometry (e.g., Tosi 2007). Depending on distance and intrinsic crowding, the reachable look-back time in galaxies more than 1 Mpc away ranges from several Gyrs (in the best cases, when the RGB or even the HB are clearly identified) to several hundreds Myr (when AGB stars are recognized), to a few tens Myr (when only the brightest super-giants are resolved). To date, the unique performances of the HST/ACS have allowed us to resolve individual stars on the RGB in some of the most metal-poor BCDs, e.g., SBS 1415+437 at 13.6 Mpc (Aloisi *et al.* 2005) and I Zw 18 at 18 Mpc (Aloisi *et al.* 2007). The discovery of stars several Gyrs old in these extremely metal-poor galaxies is key information for understanding these systems and placing them in the proper context of galaxy formation and evolution studies.

3. Kinematics & Abundances

Stellar abundances and kinematics have long been known to be excellent tools for disentangling the properties of complex stellar systems like our own Galaxy (e.g., Eggen, Lynden-Bell & Sandage 1962). This approach is the only means we have to separate the diverse stellar populations in the solar neighbourhood. This concept has subsequently been expanded and renamed "Chemical Tagging" (Freeman & Bland-Hawthorn 2002). As large samples of stellar velocities and metallicities have become available for other galaxies this approach remains the only way to obtain a detailed understanding of a multi-component stellar system.

The kinematics and metallicities of early (dSph/dE) and late (dI) type dwarf galaxies in the Local Group have almost always been measured using different tracers. This is due to the different distances and stellar densities which are typical for the two types of systems. It is also because dIs contain an easily observable ISM in the form of HI gas and dSphs do not. Because early-type galaxies usually do not contain any (observable) gas nor any young star forming regions, most of what we know of their internal properties comes from studies of their evolved stellar populations (e.g., RGB stars). Late-type galaxies are typically further away (the SMC being a clear exception), which can make the accurate study of individual RGB stars more challenging, and they contain HI gas and several HII regions. Thus, most of what we know about the kinematics and metallicity of dIs comes from gas and massive (young) star abundances. RGB stars have the advantage that they are all old (>1 Gyr) and their properties are most likely to trace the gravitational potential and chemical evolution throughout the entire galaxy up to the epoch when they formed, and not the most recent star formation processes and the final metallicity. It is only with detailed studies of the same tracers that kinematics and metallicities in these different dwarf galaxies types can be accurately compared to make confident global statements about the differences and similarities between early and late-type galaxies.

3.1. *Early-Type Galaxies*

Dwarf Spheroidal galaxies are the closest early-type galaxies that contain sufficient numbers of well distributed RGB stars to provide useful kinematic and metallicity probes. Moreover, dSphs are considered to be interesting places to search for dark matter, since there is so little luminous matter to contribute to the gravitational potential. The velocity

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dispersion of individual stars can be used to determine the mass of the galaxy. It is also possible to determine metallicities for the same stars. This allows a more careful distinction of the global properties based on structural, kinematic and metallicity information (e.g., Battaglia 2006, 2008a).

As instrumentation and telescopes improved, a significant amount of work on the kinematic properties of dSphs has become possible. This field has benefited particularly from wide-field multi-fibre spectrographs on 6–8m-class telescopes (e.g., VLT/FLAMES and Magellan/MIKE), but also WYFOS on the WHT and AAOmega on the AAT. These facilities have allowed samples of hundreds of stars out to the tidal radii. These velocity measurements often have sufficient signal-to-noise to also obtain metallicities from the Ca II triplet, the Mg B index or a combination of weak lines. This approach resulted in the discovery of surprising complexity in the "simple" stellar populations in dSphs. It was found that RGB stars of different metallicity range (and hence presumably age range) in dSphs can have noticeably different kinematic properties (e.g., Tolstoy *et al.* 2004, Battaglia *et al.* 2006). This has implications for understanding the formation and evolution of the different components in these small galaxies. It is also important for correctly determining the overall potential of the system (e.g., Battaglia *et al.* 2008a).

The VLT/FLAMES DART survey (Tolstoy *et al.* 2006) determined kinematics and metallicities for large samples of individual stars in nearby dSphs. There have also been similar surveys by other teams on VLT and Magellan telescopes. Traditionally the mass distribution of stellar systems has been obtained from a Jeans analysis of the line-of-sight velocity dispersion, assuming a single stellar component embedded in a dark matter halo. This analysis suffers from a degeneracy between the mass distribution and the orbital motions presumed for the individual stars, the mass-anisotropy degeneracy. From DART the mass of the Scl dSph was determined taking advantage of the presence of the two separate components distinguished by metallicity, spatial extent and kinematics (Battaglia *et al.* 2008a). Here it was shown that it is possible to partially break the mass-anisotropy degeneracy when there are two components embedded in the same dark matter halo. The new dynamical mass of the Scl dSph is $M_{\rm dyn} = 3 \times 10^8 M_\odot$, within 1.8 kpc, which results in an M/L$\sim$160. This corresponds to a dark matter density within 600 pc, for the best fitting model of $0.22 M_\odot pc^{-3}$ and is largely independent of the exact distribution of dark matter in the central region of the Scl dSph. This same study also found evidence for a velocity gradient, of $7.6^{+3.0}_{-2.2}$ km s^{-1} deg^{-1}, in Scl, which has been interpreted as a signature of intrinsic rotation. This is the first time that rotation has been detected in a nearby dSph, and it was a faint signal that required a large data set going out to the tidal radius.

Another aspect of these surveys has been the determination of metallicity distribution functions (MDFs), typically using the Ca II triplet metallicity indicator (Battaglia *et al.* 2006, Helmi *et al.* 2006). This uses the empirical relation between the equivalent width of the Ca II triplet lines and [Fe/H], and its accuracy was also tested (Battaglia *et al.* 2008b, Starkenburg *et al.* 2009, submitted). The Ca II triplet method will start to fail at low metallicities, [Fe/H] < -2.5, but this is starting to be better understood on physical as well as empirical grounds from following up stars with Ca II triplet metallicities, [Fe/H] < -2.5 (Tafelmeyer *et al.* 2010, in prep). This means that the effect can be corrected for, and these corrections suggest an increase in the fraction of very metal poor stars from 1-2% to 6% and significantly extend the tail to metal poor stars (Starkenburg *et al.* 2010). Thus it seems likely that there are very few extremely metal poor stars ([Fe/H] < -4) in most classical dSph but not zero. This result has to be verified by careful follow up of Ca II triplet measurements of stars with [Fe/H] < -2.5.

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3.2. *Late-Type Galaxies*

Most of what we know about the kinematics of dI galaxies comes from observations of their HI gas (e.g., Young *et al.* 2003), which is strongly influenced by recent events in the systems. For example, the velocity dispersion measured in the HI gas is predominantly influenced by on-going star formation processes. Thus the HI velocity dispersion is almost always $\sim$10kms^{-1} in any system, from the smallest dIs to the largest spiral galaxies, regardless of the mass or rotation velocity of the HI. This makes it difficult to compare the kinematic properties of dI and dSph galaxies.

Likewise, most of the metallicity information comes from HII region spectroscopy or spectroscopy of (young) massive stars. For a few BCDs the FUSE satellite has also provided abundances for the neutral gas. Thus the metallicity measures come from sources which are only a few million years old and the product of the entire history of star formation in a galaxy. By contrast, in dSphs the abundances are typically measured for stars older than $\sim$1 Gyr, and the value quoted is some form of a mean of the values measured over the entire SFH. This makes it difficult to accurately compare the properties of early and late-type dwarf galaxies, as there are few common measurements that can be directly compared.

From studies of the HI gas in these systems it has been found that for the smallest and faintest dIs if rotation is detected at all, it is at or below the velocity dispersion (e.g., Young *et al.* 2003). Despite this, in all dIs the HII regions in a single galaxy, even those widely spaced, appear to have, within the margins of error of the observations, identical [O/H] abundances (Kobulnicky *et al.* 1997). So it appears that the enrichment process progresses uniformly galaxy wide.

3.3. *Detailed Abundances*

The detailed chemical abundance patterns in individual stars of a stellar population provide a fossil record of chemical enrichment over different timescales. As generations of stars form and evolve, stars of various masses contribute different elements to the system, on timescales directly linked to their mass. Of course, the information encoded in these abundance patterns is always integrated over the lifetime of the system at the time the stars studied were born. Using a range of stars as tracers provides snapshots of the chemical enrichment stage of the gas in the system throughout the SFH of the galaxy. This approach also assumes that the chemical composition at the stellar surface is unaffected by any connection between interior layers of the star, where material is freshly synthesised, and the photosphere. This assumption is generally true for main-sequence stars, but evolved stars (giants or super-giants) will have experienced mixing episodes that modified the surface composition of the elements involved in hydrogen burning through the CNO cycle, i.e. carbon, nitrogen and possibly also oxygen.

These studies require precise measurements of elemental abundances in individual stars and this can only be done with high-resolution and reasonably high signal-to-noise spectra. It is only very recently that this has become possible beyond our Galaxy with efficient high-resolution spectrographs on 8−10m telescopes it is possible to obtain high resolution ($R > 40000$) spectra of RGB stars in nearby dSphs and O, B and A supergiants in more distant dIs. These stars typically have magnitudes in the range $V = 17-19$. Before the VLT and Keck, the chemical composition of extra-galactic stars could only be measured in super-giants in the nearby Magellanic Clouds yielding present day (at most a few 10^7yr ago) measurements of chemical composition. Looking exclusively at young objects however makes it virtually impossible to uniquely disentangle how this enrichment built up over time.

The first studies of detailed chemical abundances in dSph galaxies are those of (17 stars in Draco, Ursa Min & Sextans, Shetrone *et al.* 1998, 2001, using Keck-HIRES and 2 stars in Sgr Bonifacio *et al.* 2000 using VLT-UVES). These early works were shortly followed by similar studies slowly increasing in size. From these small samples it was already clear that dSph galaxies follow unique chemical evolution paths, which are distinct from that of any of the MW components (e.g., Shetrone *et al.* 2001, Tolstoy *et al.* 2003, Venn *et al.* 2004).

Most recently, high-resolution spectrographs with high multiplex capabilities have resulted in large samples (>80 stars) of high resolution spectra of individual stars to determine abundances in a relatively short time. The FLAMES multi-fiber facility on VLT has so far been the most productive in this domain. There are a number of FLAMES high resolution spectroscopy studies in preparation, but some results are already published for Sgr and its stream (e.g., 39 stars, Monaco *et al.* 2007), Fnx (81 stars Letarte 2007), Carina (18 stars, Koch *et al.* 2008) and Scl (89 stars, Hill *et al.* in preparation).

These new extensive studies not only provide abundances with better statistics, but they also allow statistical studies over the total metallicity range in each galaxy. This allows for an almost complete picture of their chemical evolution over time, with abundance *trends* as a function of metallicity for each system. Only the most metal-poor regime in these systems is perhaps still somewhat under-represented in these samples, although this is in part because they are rare (Helmi *et al.* 2006), and in part because these large samples of abundances have been chosen in the inner parts of the galaxies, where younger and/or more metal-rich populations tend to dominate (Tolstoy *et al.* 2004, Battaglia *et al.* 2006). New studies to fill in this lack of measured abundances in low metallicity stars are in progress (e.g., Aoki *et al.* 2009, Tafelmeyer *et al.* 2010, in prep.).

4. The Future: Extremely Large Telescopes

Elliptical galaxies, represent the majority of luminous mass in the Universe and all the indirect observational indications, from the discovery of Elliptical galaxies in high red-shift surveys, to studies of integrated stellar populations, suggest that they are predominantly very old systems, however the main theory of galaxy formation predicts that these objects assembled their mass relatively recently, and should therefore be dynamically young. It is important to accurately quantify this apparent contradiction. The only way to uniquely resolve this issue is to make detailed studies of the resolved stellar populations in Elliptical galaxies, using the techniques developed for studies of Local Group dwarf galaxies. This is a very challenging goal, as there is no giant elliptical galaxy in the Local group and the nearest example, Centaurus A, is at 3.5Mpc, and is quite a peculiar example. We really need to reach the Virgo cluster, 17Mpc away, to look at the properties of large galaxies in high-density regions of the Universe.

The different environments in which individual stars can be resolved and studied (imaging and spectroscopy) with an ELT include: Elliptical Galaxies, Spiral Galaxies, Star clusters that surround other galaxies, intra-cluster stars, supernovae and their environment. We can also probe the faintest stellar component in nearby systems such as the low mass cut-off of the Initial Mass Function, white dwarfs and other stellar remnants through-out the Local Group. We can also resolve evolved stars undergoing mass-loss (e.g., Planetary Nebulae, AGB stars, Massive stars etc) and also supernova remnants and their environment and thus hope to understand in detail how metals are transferred from stars into the surrounding Interstellar Medium.

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