

Dwarf Galaxies: Important Clues to Galaxy Formation

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Abstract. The smallest dwarf galaxies are the most straight forward objects in which to study star formation processes on a galactic scale. They are typically single cell star forming entities, and as small potentials in orbit around a much larger one they are unlikely to accrete much (if any) extraneous matter during their lifetime (either intergalactic gas, or galaxies) because they will typically lose the competition with the much larger galaxy. We can utilise observations of stars of a range of ages to measure star formation and enrichment histories back to the earliest epochs. The most ancient objects we have ever observed in the Universe are stars found in and around our Galaxy. Their proximity allows us to extract from their properties detailed information about the time in the early Universe into which they were born. A currently fashionable conjecture is that the earliest star formation in the Universe occurred in the smallest dwarf galaxy sized objects.

Here I will review some recent observational highlights in the study of dwarf galaxies in the Local Group and the implications for understanding galaxy formation and evolution.

Keywords: GALAXIES: ABUNDANCES GALAXIES: DWARF GALAXIES

1. Introduction

One of the fundamental pillars of current structure formation models (the CDM paradigm) is that small galaxies are the building blocks of larger ones (*e.g.*, Navarro, Frenk & White 1995). Thus, the dwarf galaxies around our Galaxy are arguably the remnants of the formation of the Milky Way and as such provide a unique laboratory for the detailed study of generic galactic assembly processes. Whilst CDM has been quite successful at modelling clusters of galaxies and large-scale structure it currently faces problems on the small, dwarf galaxy, scale. It appears to over-predict the number and the mass spectrum of satellites seen around galaxies such as our own (*e.g.*, Moore *et al.* 1999) and there also appear to be inconsistencies with regard to the timescale of the build up of larger galaxies (*e.g.*, Prantzos & Silk 1998), and the differences in the stellar populations of large and small galaxies (*e.g.*, Tolstoy *et al.* 2002). These problems might arise only because we have not yet made detailed enough studies of our neighbours; there are still quite a number of uncertainties in our interpretation of current observations. However, results to date provide some fairly sizeable obstacles to the current standard implementation of CDM on small scales.



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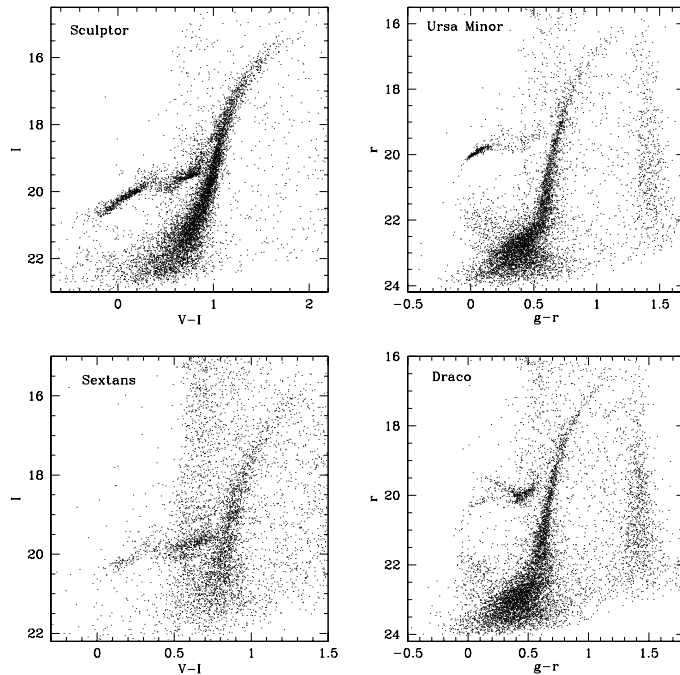


Figure 1. Wide Field CMDs of Sculptor, Ursa Minor, Draco & Sextans, taken with the INT/WFC and the ESO2.2m/WFI covering $30'$ field of view for each galaxy (Letarte, Irwin & Tolstoy 2003, in prep.). These are all old galaxies, but their CMDs look different in several crucial respects.

2. The Local Group Dwarf Population

The majority of galaxies in the Local Group, by number, are Dwarf Galaxies (35 out of 42 at the last count; 17 dSph, 5 dEs and 13 dIs, e.g., van den Bergh 2000). The definition of a dwarf galaxy is not a fixed one (cf. Tammann 1993). Half the galaxies in the Local Group have a total mass, $M_{tot} \leq 3 \times 10^7 M_{\odot}$, and these fall into two classes: dwarf Spheroidals (dSph) and dwarf Irregulars (dI). These are the galaxies considered in this review.

2.1. DWARF SPHEROIDAL GALAXIES

Dwarf spheroidal galaxies (dSph) are the smallest, faintest galaxies we know of. Within the Local Group they are mostly satellites of larger systems such as our Galaxy and M 31. Some of these dSph formed all their stars more than 10–12 Gyr ago and have apparently done nothing at all since then, some have formed the majority of their

stars at intermediate times (6–8 Gyr ago), and a few have experienced star formation as recently as 1–2 Gyr ago (see Mateo 1998, and references therein). All of the dSph galaxies, without exception, have an ancient stellar population. Even the oldest and simplest have had a complex star formation history (SFH), and these systems, with virtually identical SFHs, still have different CMDs from each other (see Figure 1). Perhaps this is a result of different environmental influences (e.g., Mayer *et al.* 2001). The evolution of dSph must be influenced, maybe strongly, by the presence of our Galaxy. The dynamical friction of their orbits may have a strong (and varying) influence on the rate of star formation (SFR). No dSph around our Galaxy currently has an (obviously) associated ISM.

2.2. DWARF IRREGULAR GALAXIES

Dwarf Irregular (dI) galaxies have many similarities to dSph, but they typically contain HI gas, often a large fraction by mass, and also recent star formation. They all contain an underlying old stellar population. It is possible that they are dSph witnessed in a more active state. If a small dI stops forming stars for a few 100 Myr it may look like a dSph. However, in general, dI appear to have had a more constant, less disrupted, SFR over time and have also typically attained higher metallicities than dSph. Perhaps dI, unlike dSph, are sufficiently massive to attain the threshold for retaining their ISM during supernova explosions (e.g., Ferrara & Tolstoy 2000) or are not so disrupted by their environment, being typically more distant from larger systems, they can sustain a more or less constant SFR, albeit at a low level, over their history.

3. Observations of Nearby Dwarf Galaxies

There are many different approaches to studying the evolutionary history of a galaxy and the most reliable is to look directly at the detailed properties of individual stars. This is, however, restricted to galaxies in the very nearby Universe. Although there is much to be learnt from studies of integrated properties of more distant dwarf galaxies (>2 Mpc away) I will not address this subject at all.

3.1. IMAGING

The only way to measure the properties of a significant fraction of the resolved stellar population in a galaxy is through multi-colour imaging. The Hubble Space Telescope (HST) has produced significant advances

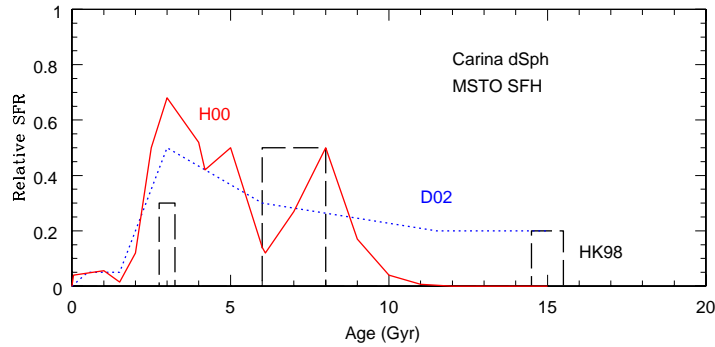


Figure 2. Different SFHs for Carina dSph from the literature (arbitrarily normalised). Dashed lines from Hurley-Keller *et al.* (1998 = HK98) from wide-field ground-based CTIO imaging. The solid line (Hernandez *et al.* 2000 = H00) and dotted line (Dolphin 2002 = D02) use the same HST/WFPC2 dataset. There are clear differences between the three. HK98, in contrast to H00 and D02 see discrete bursts of star formation. This might be because HK98 are better able to resolve such details because they cover a much larger area of the galaxy and hence all the MSTOs are much better populated than in the tiny HST field used by the other two studies. Also D02 and HK98 find evidence of ancient star-formation (as expected from the RR Lyr population detected by Saha, Seitzer & Monet 1986), whereas H00 do not. The most critical difference is the assumed metallicity, not only the absolute value, but the spread. D02 finds $[\text{Fe}/\text{H}] = -1.2 \pm 0.4$, whereas HK98 assumes $[\text{Fe}/\text{H}] = -2.1 \pm 0.1$ and H00 $[\text{Fe}/\text{H}] = -2.0 \pm 0.2$.

in this field over the last ten years (e.g., see Tolstoy 2000 and references therein). It has allowed the detailed analysis of Colour-Magnitude Diagrams (CMDs) of resolved stellar populations to determine SFHs out to distances around 5 Mpc. However, the most detailed studies come from galaxies within the Local Group at less than 1 Mpc distance (see Tolstoy 2000, and references therein).

The dSph around the Milky Way are among the few galaxies in the Universe for which we have accurate main sequence turnoff (MSTO) ages going back to the epoch of earliest star formation (e.g., Carina: Hurley-Keller, Mateo & Nemeč 1998; Leo I: Gallart *et al.* 1999; Fornax: Buonanno *et al.* 1999). MSTOs are the most accurate measurements of the age distribution of a stellar population and even so there are problems in converting turnoff luminosities and colours into accurate *absolute* ages, and thus CMDs into SFHs (see Figure 2). This revolves around the well known and much lamented age-metallicity degeneracy. It means that without *independent* metallicity information it is not possible to uniquely determine the age of a star from its colour and magnitude alone. A major difference between the SFH determinations

in Figure 2 is the different metallicity evolution determined or assumed by each study.

3.2. SPECTROSCOPY

As telescopes are increasing in size and spectrographs are becoming more sensitive and multiplexing capabilities are increasing it is possible to take spectra of a significant number of individual stars in nearby galaxies and determine the abundances of many different elements and thus help to overcome the degeneracy inherent in photometric measurements. FLAMES on the VLT with its 130 fibres over a 25' diameter field of view is eagerly awaited in this respect.

3.2.1. *Medium Resolution: The Ca II Triplet*

The VLT instruments FORS1 and FORS2 in multi-object spectroscopy mode are ideal for intermediate resolution spectroscopy of individual stars in dwarf galaxies to determine metallicities (e.g., Tolstoy *et al.* 2001) and radial velocities (e.g., Tolstoy & Irwin 2000; Irwin & Tolstoy 2002) from the Ca II triplet (CaT) lines for a significant number of RGB stars. Although the CaT provides a basic estimate of $[Fe/H]$ it was found to be broadly consistent with subsequent high resolution UVES observations (Tolstoy *et al.* 2002). This is thus a valuable method of obtaining $[Fe/H]$ estimates at distances beyond the limits of high resolution spectroscopy (≥ 250 kpc). This is the only way to determine abundances of RGB stars of different ages in dI galaxies, all of which are more distant than 450 kpc.

3.2.2. *High Resolution: Full Abundance Analysis*

With High Resolution Spectrographs such as UVES on the VLT, we can observe individual stars in nearby dwarf galaxies and seek answers to detailed questions about the enrichment *history* of a variety of different elements within galaxies other than our own (e.g., Tolstoy *et al.* 2002; Shetrone *et al.* 2002). Abundance patterns can constrain the effects of the SFH on chemical evolution (e.g., McWilliam 1997).

A wealth of information is available in every high resolution spectrum. The elemental abundances that can be measured fall into four broad categories:

The Light Elements (e.g., O, Na, Mg, Al) allow us to trace “deep-mixing” abundance patterns in RGB stars. This is a very distinctive pattern that is markedly different in globular cluster and field stars.

The α -elements (e.g., O, Mg, Si, Ca, Ti), the production of which is dominated by Type II Supernovae. The α -abundance limits the number that can have polluted the gas from which the star was made. They also

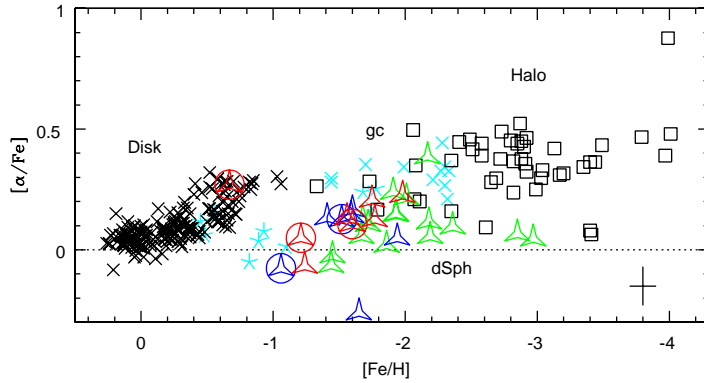


Figure 3. The α -abundances for dSph stars from Tolstoy *et al.* (2002) and Shetrone *et al.* (2001) plotted versus $[\text{Fe}/\text{H}]$. The triangle and circle symbols are the individual stars observed in Carina, Leo I, Sculptor, Fornax, Draco, Ursa Minor and Sextans (see Tolstoy *et al.* for more details). The crosses (at $[\text{Fe}/\text{H}] < -1$) are Galactic disk star measurements from Edvardsson *et al.* 1993; the open squares are halo data from McWilliam *et al.* 1995 and the stars are UVES data from a study of LMC star clusters of different ages from Hill *et al.* 2000. Crosses (at $[\text{Fe}/\text{H}] > -1$) are Galactic globular cluster measurements (gc). A representative error bar is also plotted. This plot highlights the differences between the α -element abundances of stars observed in different environments.

affect the age estimates based on RGB isochrones, as lower α -tracks are bluer than high α -tracks.

The Fe-Peak elements (*e.g.*, V, Cr, Mn, Co, Ni, Cu, Zn) are mostly believed to be the products of explosive nucleosynthesis. They can (in principle) limit the most massive progenitor to have exploded in a galaxy (*e.g.*, Woosley & Weaver 1995).

Heavy Metals (*e.g.*, Y, Ba, Ce, Sm, Eu) enable a distinction to be made between the fraction of s-process and r-process elements in a star, and thus put detailed constraints on the number and type of past Supernovae explosions. The $[\text{Ba}/\text{Eu}]$ ratio appears to be an indicator of the contribution of AGB stars to the chemical evolution process which provides yet another measure of the timescale for chemical enrichment,

4. Understanding the Chemical Evolution of Galaxies

A sample of 15 RGB stars were observed in 4 southern dSph (Sculptor, Fornax, Carina and Leo I) with VLT/UVES (Shetrone *et al.* 2002; Tolstoy *et al.* 2002), and 17 RGB stars were observed in 3 northern dSph (Draco, Ursa Minor, Sextans) with Keck/HIRES (Shetrone, Bolte & Stetson 1998; Shetrone, Côté & Sargent 2001). Combining these surveys gives us detailed abundances for individual stars in dSph around

our Galaxy covering a range of SFHs. There have also been detailed abundance studies in LMC star clusters (e.g., Hill *et al.* 2000) and also in the disk of our Galaxy (Edvardsson *et al.* 1993) and in our halo (McWilliam *et al.* 1995) which allow us to compare dSph with other environments (e.g., the α -elements, see Figure 3).

The α -abundances can be plotted both in the “traditional” manner, against $[\text{Fe}/\text{H}]$ (see Figure 3) and against age (see Figure 4). Both provide differing insights as to how galaxies are evolving with time, and also how observations of stars in dSph compare to those in our Galaxy and in the Magellanic Clouds. Plotting against age is more useful from the point of view of understanding chemical evolution, but it is not easy to find suitable measurements with which to compare dSph results as it is challenging to determine accurate ages for stars in our Galaxy. It is somewhat more straight forward in the simpler environment of dSph, although care is still required.

The dSph α -abundances when plotted against age appear to follow the same distribution as those for our disk and the LMC star clusters (see Tolstoy *et al.* 2002). However, if we look at the plot of α versus $[\text{Fe}/\text{H}]$ in Figure 3, the properties of dSph are significantly different from the disk in the sense that although the levels and the variation with stellar age of the α -elements are similar this is occurring at significantly lower $[\text{Fe}/\text{H}]$ in the dSph. Figure 3 shows that the properties of the dSph differ from those typical of halo stars, although there is overlap, such that the $[\alpha/\text{Fe}]$ of the halo stars are typically higher. It is as if all stars know the mass of the potential in which they are forming.

4.1. INTERPRETATION OF ABUNDANCES

The low $[\alpha/\text{Fe}]$ found in the disk stars of our Galaxy has been interpreted as evidence for star-formation in material with a large fraction of Supernovae Ia ejecta (e.g., Tinsley 1979; Gilmore & Wyse 1991). This is perhaps not surprising for our disk, with high metallicity, and typical predictions of fairly recent formation (from pre-enriched material). It is not clear that the same assessment can be made of the similarly low $[\alpha/\text{Fe}]$ for stars in dSph galaxies. The same low $[\alpha/\text{Fe}]$ is also found in the oldest stars, which is at odds with the Supernovae Ia time scale. This might be a remnant of the initial enrichment of the dSph gas in the early universe, by a process quite different from the star formation we see today.

Everything we know about dwarf galaxies suggests that they have never had very high SFRs. The stars in dSph typically have much lower $[\text{Fe}/\text{H}]$ and $[\text{O}/\text{H}]$ than in our disk. The low SFR means that Supernovae II products may predominately come from low mass ($8\text{--}12M_{\odot}$)

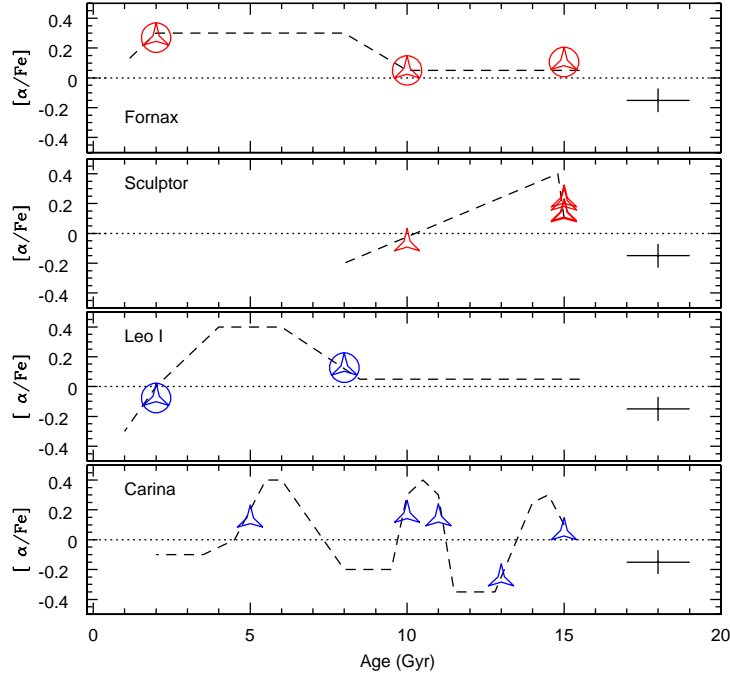


Figure 4. An illustrative scenario which might allow us to tie in our determinations of star formation history with $[\alpha/\text{Fe}]$ for each galaxy (see Tolstoy *et al.* 2002 for more details and caveats). The symbols are defined as in Figure 3. Representative error bars are plotted. It is obvious that the dashed lines cannot be constrained with the few data we have.

progenitors, which result in lower $[\alpha/\text{Fe}]$ than their higher mass cousins (*e.g.*, Woosley & Weaver 1995). This is (unfortunately) effectively a truncated IMF, but it is motivated by the likelihood that in the physical conditions to be found in small galaxies the probability of forming high mass molecular clouds (and thus high mass stars) is low.

With the recent results of Tolstoy *et al.* (2002) and Shetrone *et al.* (2001) it is for the first time possible to directly *measure* the $[\alpha/\text{Fe}]$ evolution (as well as other elements) of the stellar populations of dSph over Gyr time scales, back from the earliest epoch of formation to the most recent star formation. The range of variation in $[\alpha/\text{Fe}]$ is quite small (which means accurate measurements are required to observe it), and it never reaches the parameter space where the disk and halo are stars predominantly to be found. So probably star formation, when it occurs, always occurs at similarly low levels in these small galaxies.

In Figure 4 the $[\alpha/\text{Fe}]$ vs. age for stars in four dSph galaxies is plotted separately, and over-plotted is an illustrative *estimate* of the variation of $[\alpha/\text{Fe}]$ for each galaxy *given the star formation rate variation*. There really are not sufficient data on these galaxies to be certain that we are seeing direct evidence of evolution in $[\alpha/\text{Fe}]$, but the results are highly suggestive. The dashed lines are not derived from the SFH directly, but a knowledge of the SFH is used to find the most likely pattern with time in $[\alpha/\text{Fe}]$. Carina, for example, has the most impressive evidence for evolution of abundances due to variations in star formation rates. The variations seen in the α abundances are supported by consistent variations in Ba, La, Nd and Eu (see Shetrone *et al.* 2002). However, more data are needed to confirm these speculations.

4.2. THE BOTTOM LINE FOR CDM

The most recent VLT/UVES results (Tolstoy *et al.* 2002) combined with Keck/HIRES data (Shetrone *et al.* 2001) unequivocally show that the stars observed in dSph galaxies *today* (many of which are extremely old) *cannot* be used to make up a significant fraction of the stellar mass in our Galaxy, neither in the disk nor in the inner-halo (nor the bulge) because their nucleosynthetic signatures are not compatible. This places a limit on the time (redshift) at which the majority of merging of small halos must have occurred to create the Milky Way, if this is indeed to be the formation mechanism. This is of course assuming that the initial small halos are similar to the dwarf galaxies we see today. These recent abundance measurements require that the majority of these kinds of mergers must have occurred very early, in the first few Gyr of structure formation, because this is the only way to ensure that the majority of star formation will occur in a deep potential with the requisite conditions for massive star formation to explain the abundance patterns seen in our Galaxy, but not in dSph (i.e. mergers will add mostly gas to the larger system, but few stars). More data is needed to put these initial results on a firm statistical basis, and of course dSph results do not place any limits on the effect of significantly larger accretions, (*e.g.*, LMC like objects). However, there are suggestions that the abundance patterns of stars in the Clouds and other nearby Irregulars do not resemble our Galaxy anymore than the dSph do (*e.g.*, Hill *et al.* 2000; Venn *et al.* 2002, in prep).

The only component of our Galaxy which could plausibly contain a significant contribution from stars formed in accreted dwarf galaxies is the halo (*e.g.*, Nissen & Schuster 1997), and it contains only about 1% of the stellar mass of our Galaxy (*e.g.*, Morrison 1993), and only a

fraction of this, the outer-halo ($\sim 10\%$), could plausibly include stars accreted from dwarf galaxies (e.g., Unavane, Wyse & Gilmore 1996).

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