

Chapter 1

Introduction

Dwarf galaxies are in principle the most simple and straightforward type of galaxy and their study can be used to test numerous theories of the formation and evolution of stars and galaxies in a range of environments. This thesis concentrates on the detailed study of the chemical elements in individual stars in the nearby dwarf spheroidal galaxy, Fornax. A dwarf spheroidal galaxies are small roughly spherical galaxies that are typically found in the vicinity of larger galaxies, such as the Milky Way. They typically do not have any ongoing star formation, nor do they appear to have any gas associated to them. The abundance ratios of different elements in individual stars with a range of ages provide a detailed insight into the various chemical enrichment processes (e.g., supernovae, stellar winds) which in turn improves our understanding of the global processes of formation and evolution of a galaxy as a whole.

1.1 The Cosmological Importance of Dwarf Galaxies

The most straightforward model of galaxy formation is that all galaxies form in the early Universe in a rapid collapse scenario (so called monolithic collapse, [Eggen, Lynden-Bell, & Sandage 1962]). These galaxies then evolve solely by changing their gas mass into a stellar mass with time. This model assumes that the majority of the mass of all galaxies was in place at their formation. However this basic picture was updated (e.g., Searle & Zinn 1978) to a model which assumes that galaxies are not formed in a single collapse, but that they are built up in time from smaller fragments. This theory came in parallel with the very successful “cold dark matter” (CDM) vision of structure formation in the Universe which assumes that the dark matter content of a galaxy is built up through the continuous accretion of small clumps, to build up the galaxies and clusters of galaxies we see today (e.g., White & Rees 1978; Navarro, Frenk, & White 1995).

If we take the CDM model of structure formation and assume that the ratio of baryonic to dark matter is roughly constant and known then this naturally results in the concept of numerous “building blocks”, or small galaxies, which are continuously being accreted onto larger galaxies over the history of the Universe. These small galaxies, with
a similar mass to the dwarf galaxies we see today, might act as stellar nurseries, creating the stars we see in the Milky Way (MW) today. Stars within the Galactic halo are some of the oldest objects ever observed and they should be representative of the earliest star formation in the Local Group (LG). These stars either formed in the proto-Milky Way or they may have formed in smaller satellite galaxies that were accreted to the Milky Way at a later time. CDM based models thus suggest that a considerable fraction of the stars in the Milky Way today should have formed in smaller building blocks. For example, the Sagittarius dwarf galaxy behaves exactly like a CDM building block, showing signs of being tidally disrupted and merging in its entirety into the Milky Way \cite{Ibata1994}.

As required by the CDM view of the Universe small galaxies do appear to be dark matter dominated \cite{Mateo1998}. Observations of dwarf spheroidal galaxies in the Local Group, such as Fornax dSph, suggest that dwarf galaxies must be considerably more massive than the visible mass would suggest \cite{Mateo1991, Walker2006, Battaglia2006}. However there are inconsistencies in the predicted properties of the DM profiles of the observed dwarfs and the predictions of CDM \cite{Wilkinson2006}. It also appears that the properties of the stellar populations, the dark to baryonic matter ratio, and the kinematic properties of dwarf galaxies we see today are inconsistent with the requirements of building blocks of the Milky Way, i.e., adding together all the small galaxies we see today, or at any time in the past, will not result in a galaxy like the Milky Way \cite{Shetrone2003, Tolstoy2003, Venn2006, Helmi2006}.

CDM also appears to over-predict the number of small satellite galaxies around larger galaxies such as our own, an inconsistency that is known as the “missing dwarf problem” \cite{Moore1999}. However, recent discoveries of several faint satellites around the Milky Way in the last couple of years are changing our view about the LG \cite{Belokurov2006a, Belokurov2006b, Willman2005a, Willman2005b, Zucker2006a, Zucker2006b}. These studies suggest that the dwarf spheroidal galaxies we have studied to date are only the tip of the iceberg; they are the most massive satellites of a larger population of fainter, lower mass satellites \cite{Stoehr2002}, which could bring our Milky Way environment back into consistency with the CDM predictions for the amount of sub-structure. However, our knowledge about these new faint galaxies, especially their dark matter content, is still quite limited as they have been discovered relatively recently.

Thus dwarf galaxies are useful probes of our understanding of galaxy formation and evolution on the smallest scales and potentially also as building blocks of the largest galaxies. By studying the nearest examples we can obtain the kind of detailed comparisons between theory and observation that are required to test current theories and provide a solid observational basis for future models. More specifically, studying the abundance patterns of stars of a range of age allows us to understand in detail the evolutionary processes that shape galaxies everywhere. Thus looking at individual stars in dwarf galaxies in the Local Group is an important component in understanding the big picture of galaxy formation and evolution throughout the Universe.
1.2 The Formation of the Elements

It is believed that the Universe started as an explosion, known as the Big Bang, where hydrogen, deuterium, helium and lithium were created. These are thus considered to be primordial elements and all other elements are formed subsequently by nucleosynthesis in stars. Stellar nucleosynthesis is thus responsible for almost all of what we see around us on the Earth today. It was first explained in the 1950s in work done by Fowler and Hoyle, culminating in the B2FH (Burbidge, Burbidge, Fowler, & Hoyle 1957) paper.

The first most fundamental process of converting hydrogen into heavier elements is hydrogen burning, which is the conversion of hydrogen nuclei into helium, via the proton-proton chain in low mass stars with low core temperatures, and via proton captures by carbon, nitrogen, and oxygen atoms (in the CNO cycles) in more massive stars with higher temperatures. The CNO cycle traces the origin of most of the observed nitrogen today, while most of the helium produced is consumed in the next stage: helium burning. As helium builds up in the core of the star the core contracts until the temperature and density increase enough to allow for another reaction in which helium is the fuel. This thermonuclear phase is the triple-$\alpha$ process in which three $^4$He nuclei fuse to form a carbon nucleus. The next stage is shell burning: carbon burning, oxygen burning, silicon burning. This can produce elements as heavy as $^{56}$Fe which is the most massive element that can be formed by fusion in the core of a star.

The most significant group of heavier elements are the so called alpha elements, with nuclei that are multiples of He, e.g., O, Mg, Ca, Si and Ti. They are predominantly synthesised by alpha capture during the various burning phases in massive stars, and expelled into the ISM by SN II explosions. Another significant and important group of elements is the iron-peak, including Fe itself. It is predominantly produced and expelled into the ISM by SN Ia, supernovae thought to be due to the explosion of a white dwarf in an evolved binary with a less massive progenitor star. Those typically occur $\sim$1 Gyr after the first episode of star formation, contrary to SN II which have short-lived massive star progenitors (as short as $\sim$10 Myrs). As a consequence, elemental ratios of the type $[\alpha/Fe]$ inform us of the relative contribution from the two types of supernovae at a given time, indicative of star formation timescale. Figure 1.1 sketches how the $[\alpha/Fe]$ ratio can be viewed as a kind of chronometer (starting to decrease after 1Gyr) while the $[Fe/H]$ metallicity index provides the efficiency with which star formation has occurred. When the star formation rate (SFR) is high, the gas will reach higher $[Fe/H]$ before the first SN Ia occur and $\alpha$-elements start to decrease (the “knee”). The formation efficiency and time scale of a stellar system can be estimated by the position of this “knee”. And, because more massive stars are more efficient in producing $\alpha$-elements, the level of $[\alpha/Fe]$ at low metallicity (before the “knee”) is an indication of the mass of the stars that contributed to enrich the ISM and therefore provides a indirect measure of the IMF.

Heavier elements beyond the iron peak are created by neutron capture, where the two most important processes (in the astrophysical context) are the $s$- and $r$- processes. The $s$-process (or slow-process) occurs when the neutron flux is not very high, so that the intervals between neutron captures are long compared to the beta decay characteristic timescale of an unstable nucleus. These conditions are found in the envelopes of ther-
mally pulsating AGB stars, and are most efficient in 3-5 $M_\odot$ stars. Because of the slow evolution of intermediate-mass stars, $s$- process will only enter the chemical enrichment of a galaxy several 100 Myrs after the first episode of star formation. In addition, it requires pre-existing iron-peak elements seeds in the AGB envelope, and is therefore inefficient at very low metallicity. The $s$- process is unlikely to be significant in the earliest stages of star formation in a galaxy.

The $r$-process (or rapid-process) occurs when there is sufficient neutron flux which allows rapid captures of neutrons. This is believed to occur predominantly in environments like those produced by SNe II. With such rapid successive captures, neutrons can accumulate on an unstable nuclei before it has time to either beta or alpha decay. The stars responsible for these explosions are massive, therefore have a short lifetime and are believed to be the first objects that will contribute heavy elements to the ISM. Observing the relative abundances of $s$- and $r$- process nuclei can therefore constrain the impact of AGB stars on chemical evolution and probe star formation timescales.

1.3 Abundances in Galaxies

Because elemental abundances are preserved at the stellar surface during the whole stellar lifetime, and can be (relatively) easily measured from absorption lines in high-resolution stellar spectra, they have become a very important tool to understand the genesis of a stellar population. Abundances of various elements can be measured in stars of different ages and, thanks to their different nucleosynthetic origin, allow us to infer what enrichment processes have been dominant at different epochs of galaxy formation. Not surprisingly our earliest studies have concentrated on the Milky Way, and it is only relatively recently that similarly detailed studies have been made of other galaxies, such as the Magellanic Clouds and most recently the nearby dwarf spheroidal galaxies.

* Except for a few light elements which may be affected by internal mixing: Li, C, N.
1.3.1 The Milky Way

The Milky Way contains several stellar components which are distinguished by different spatial distribution, kinematics and stellar populations, namely the halo, the thick disk, the thin disk, and the bulge. Each component has clearly had a different formation history and their stars show marked differences in their age distribution, metallicity distribution and most importantly here, abundance ratios. Ever since the discovery by Chamberlain & Aller (1951) that two stars with high radial velocities (halo stars) had their iron and calcium abundances an order of magnitude lower than that of the Sun, it gradually became clear that the various stellar populations that comprise the Milky Way have both kinematics and chemical signatures associated to each of them, and that combining the two properties was necessary to better understand galaxy evolution (Wyse & Gilmore 1995).

A review by McWilliam (1997), covering the Galactic disk, halo and bulge suggest that the environment plays an important role in chemical evolution and that supernovae come in many flavors, with a range of element yields. Below are a some recent examples of detailed abundance studies of the Milky Way:

The detailed abundance studies of extremely metal poor stars in the halo of our Galaxy have given us a clearer picture of its earliest enrichment history. The high [Zn/Fe] observed and absence of very strong depletion of odd-numbered elements have ruled out pair instability SN (from 130-300 M\textsubscript{⊙} progenitors) as a dominant source of enrichment (Cayrel et al. 2004). The dispersion in heavy neutron-capture element abundances of the most metal poor stars suggests incomplete mixing of the ejecta from individual supernovae into the galactic interstellar medium (McWilliam 1997).

Studies of large samples (∼200) nearby disk stars (F and G dwarf) provide observational constraints by linking chemical abundance of up to 30 chemical elements to precise kinematics and photometric ages (e.g., Edvardsson et al. 1993; Chen et al. 2000; Reddy et al. 2003). This has allowed to understand that the thin disk formed stars at a steady rate over the last 4-8 Gyrs, allowing a full evolution of the abundance ratios from almost pure SN II ejecta to a full mix of SN II, stellar winds and SN Ia. Although the mean metallicity increases with time, the age-metallicity relation is neither well defined nor tight in the galactic disk, ruling out the “instantaneous mixing” assumption of simple models of galaxy chemical evolution.

Recent precision work has shown that the [$\alpha$/Fe] ratio for thick-disc stars shows a clear enhancement compared to thin-disc members of the same metallicity, which is a sign that star formation was more efficient and restricted to a shorter period of time in the thick disk (e.g., Bensby et al. 2003, 2005; Reddy et al. 2006). Several hypotheses have been proposed for the origin of the thick disk: the debris of a merger, a merger that heated a preexisting thin disk into a thick disk, etc. The first indications of a population that could be ascribed to debris from the satellite whose merger caused the thick disk was presented in Gilmore et al. (2002): thick disk stars should then bear the chemical signature of the star formation history of the merging (dwarf ?) galaxy. Galactic stars seen along lines of sight to some dSph galaxies seem to have the expected properties of “satellite debris” in the thick disk-halo interface, which is interpreted as remnants of the
merger that heated a preexisting thin disk to form the thick disk (Wyse et al. 2006). Thick disk stars would then have the chemical signature of the former thin disk.

In studies of Galactic bulge stars, two $\alpha$-element ratios, [O/Fe] and [Mg/Fe] have been found to be higher than in thick disk stars, which are known to be more oxygen rich than thin disk stars (e.g., Zoccali et al. 2006; Fulbright et al. 2006; Lecureur et al. 2006). This supports a scenario in which the bulge formed before and more rapidly than both the thin and thick disks, and therefore the MW bulge can be regarded as a prototypical old spheroid, with a formation history similar to that of early-type (elliptical) galaxies.

1.3.2 The Magellanic Clouds & Dwarf Galaxies

Other galaxies are in principle simpler to interpret than the Milky Way as we have an external view of the entire system and distance differences are unimportant. Stars in the Magellanic Clouds (at $\sim 50$ kpc distance) were the first extragalactic stars targeted for detailed abundance studies and the results of these studies gave us the first insights into a more metal poor star forming environment than is available in the disk of our galaxy. At the end of the 80’s and in the 90’s, 4m-class telescopes were used to study detailed abundances of supergiant stars in both the Large and Small Magellanic Clouds, reflecting the current interstellar medium within these galaxies (Russell & Bessell 1989; Hill et al. 1995; Hill 1997; Venn 1999). Probing the chemical composition of stars as a function of age and therefore chemical evolution per se had to wait until 8-10m class telescopes gave access to high-resolution spectra of RGB stars in the Large Magellanic Cloud, initially in small numbers, (Hill et al. 2000; Smith et al. 2002), followed by the first abundance study of a large sample (Pompeia et al. 2006).

Similarly, the Sagittarius dSph has also been targeted in high resolution studies of some tens of RGB stars (Bonifacio et al. 2000; Monaco et al. 2005). These studies revealed distinctive evolutionary paths for the Large Magellanic Cloud and the Sagittarius dSph, showing a different chemical enrichment process from the Milky Way and other dwarf galaxies (Bonifacio et al. 2000).

However the Magellanic Clouds and Sagittarius are clearly in the process of interacting strongly with our galaxy and so the lessons they have to teach about galaxy formation and evolution are not so straightforward to interpret. Dwarf galaxies, on the other hand, especially the nearby dSph are arguably simpler and more clearly preserved environments. These are however twice as distant as the Magellanic Clouds, and thus detailed abundances require 8-10m class telescopes.

Using Keck to look at individual stars in the Draco, Sextans and Ursa Minor dSph (Shetrone et al. 1998; 2001), and soon after the VLT for four southern dSph (e.g., Shetrone et al. 2003; Tolstoy et al. 2003), studies of LG dSph were initially based on very small samples of stars and yet they provided fundamental insights into galaxy formation and evolution. From these studies it became evident that, whereas the metallicity of dSph stars seemed to lie between the bulk of Galactic disk and halo stars, $\alpha$-elements were typically under abundant when compared to MW stars of similar metallicity (hence lower than in the halo), while $r$- and $s$- process elements in dSph stars were typically halo-like.
This suggests that the satellite galaxies we see today cannot be significant recent contributors to the stellar population of our Galaxy, with the possible exception of the outer halo. However, the lack of statistically significant samples of objects (2–5 stars per dSph) undermined the strength of this conclusion.

More importantly still, although dSph are simpler systems when compared to the MW, with most of them having typically much lower star formation rates, each of them has a unique and different star formation history. Abundance ratios were yet to be studied in large enough samples in several different dSph to understand the internal evolution of these systems.

1.4 The DART project

DART is an acronym for Dwarf Abundance and Radial-velocity Team (Tolstoy et al. 2004, 2006). It involves more than 16 persons, from 10 institutes in 10 different countries. The main goal of the project is to obtain detailed chemical abundances (requiring high resolution) and radial velocities (low resolution) for a large sample of stars in four nearby dSph galaxies, Sculptor, Fornax, Sextans and Carina (for which we obtained high resolution spectroscopy only). The project is primarily based on two observing proposals, the ESO Large Programme 171.B-0588 (PI: Tolstoy) entitled: “Dwarf galaxies: remnants of galaxy formation and corner stones for understanding galaxy evolution” and the Meudon GTO Programme 71.B-0641 (PI: Hill) entitled: “Star formation history of the Sculptor dwarf spheroidal galaxy” which began obtaining data in August 2003.

1.4.1 Photometry

Wide-field accurate photometry was needed both to select targets for our spectroscopic survey, and to allow a colour-magnitude diagram analysis of the global properties (mean ages and metallicities) of the stellar populations in the galaxy and the underlying star formation history. Precise astrometry (better than 0.3″) of the targets selected for spectroscopic follow-up is also required to insure a proper placement of FLAMES fibres (1.2″ fibre entrance on the sky).

The instrument we used for our photometric survey is the wide field imager WFI, (Baade et al. 1999) on the 2.2-m MPG/ESO telescope on La Silla. The large field of view (33′ × 34′) of this instrument allowed us to efficiently map out dwarf galaxies to beyond their tidal radius. Our photometric survey was conducted in the visible band V and I. Figure 1.2 shows the spatial distribution of our imaging for Fornax. We have also plotted the low-resolution spectroscopic survey, with bigger black points representing the FLAMES LR targets (Battaglia et al. 2006).

1.4.2 Spectroscopy

We used VLT/FLAMES, described in Pasquini et al. (2002) as well as in chapter 4 of this thesis, to carry out our spectroscopic survey. For each of the four galaxies, we obtained one FLAMES pointing in high resolution mode, each consisting of ~100 target stars for which we will obtain chemical abundances (and radial velocities). To obtain sufficient
wavelength coverage for an accurate analysis of the abundances and to include a variety of chemical elements, we used several different setups that cover different wavelength ranges. Three setups were obtained in order to perform an abundance analysis, totalling almost 30h of observation per galaxy (see chapter 4).

On the other hand, a low resolution pointing can be obtained in about an hour, allowing for a greater number of stars for which we get a basic metallicity tracer (Ca II triplet, or CaT) and a radial velocity. The Fornax study in LR consisted of 11 pointings and 1063 targets, as illustrated in Figure 1.2 (see Battaglia et al. 2006).

The DART studies to date, as well those of other groups, (e.g., Koch et al. 2006, 2007) have shown that neither the kinematics nor the metallicities nor the spatial distributions of dSph are easy to explain in a straightforward manner even for these smallest galaxies. Dwarf galaxies show complex and highly specific evolutionary and metal-enrichment processes. Details of these results coming from low resolution CaT spectroscopy are presented in Tolstoy et al. (2004) (for Sculptor) and in Battaglia et al. (2006) for Fornax. Specifically, in Fornax, we have shown that the galaxy contains at least two morphologically (concentration), chemically (metallicity) and kinematically (velocity dispersion) distinct intermediate to old components. The centre of Fornax is dominated by the more metal-rich and kinematically cooler (and younger) component. This is the population from which our high-resolution sample was drawn.
1.4: The DART project

1.4.3 This Thesis

The main emphasis of this thesis is to determine detailed chemical abundances of individual stars in the nearby Fornax dwarf spheroidal galaxy, based on high resolution observations with VLT/FLAMES. We have targeted stars in the central 25′ diameter region of Fornax, as well as in three of its globular clusters. An image of Fornax is shown in Figure 1.3 where the central FLAMES field we observed in HR is identified, as well as the location of the five globular clusters of Fornax. The goal was to make a consistent study of the chemical properties of a representative sample of the stellar population of Fornax, and to make a comparison between the properties of stars in its old globular clusters (GCs) and predominantly intermediate age field stars. Detailed abundance analysis from HR spectroscopy is necessary for the full understanding of a complicated star formation history, where classic colour-magnitude diagram (CMD) analysis is not sufficient to provide a definitive answer.

Although earlier studies have provided hints of the evolutionary processes in dwarf galaxies the unparallelled multi-tasking capability of VLT/FLAMES allows us to map out the large scale processes which are important on the scale of a dSph and also to distinguish “the weather from the climate” in these galaxies – with regard to the chemical evolution with time.

Figure 1.3: Digital Sky Survey (DSS) image of the central region of Fornax (85′ x 62′ or 3.4 x 2.5 kpc) with the central 25′ field identified by a big circle and the five globular clusters with smaller circles.