Abundances as Tracers of the Formation and Evolution of (Dwarf) Galaxies

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Abstract. This aims to be an overview of what detailed observations of individual stars in nearby dwarf galaxies may teach us about galaxy evolution. This includes some early results from the DART (Dwarf Abundances and Radial velocity Team) Large Programme at ESO. This project has used 2.2m/WFI and VLT/FLAMES to obtain spectra of large samples of individual stars in nearby dwarf spheroidal galaxies and determine accurate abundances *and* kinematics. These results can be used to trace the formation and evolution of nearby galaxies from the earliest times to the present.

1 Introduction

Dwarf galaxies are the most numerous type of galaxy we know of and they are commonly assumed to be if not the actual building blocks of larger galaxies then they most closely resemble them. The Local Group contains ∼36 dwarf galaxies out of a total of ∼42 members covering a large range of properties [1], and including more than one example of most if not all the known classes of dwarf galaxy. There are nucleated dwarfs (e.g., NGC205, NGC185); extremely low surface brightness dwarfs (e.g., Sextans, Ursa Minor); interacting dwarfs (e.g., Sagittarius); star bursting dwarfs (e.g., IC10, Sextans A); isolated dwarfs (e.g., Tucana, Cetus). They fall predominantly into two classes - those with gas which are still forming stars and those which appear not to have gas and are not presently forming stars.

The abundance patterns of individual stars of different ages and environments enable us to unlock the evolutionary history of galaxies. Many physical characteristics of a galaxy may change over time, such as shape and colour, however the metal content and abundance ratios of stellar atmospheres are not so easy to tamper with. Stars retain the chemical imprint of the interstellar gas out of which they formed, and metals can only increase with time. This method to study galaxy evolution has been elegantly named *Chemical Tagging* [2].

There have been a number of detailed abundance studies of stars in nearby galaxies which cast ever more serious doubt on the premise that the galaxies we see today are in any way related to galactic building blocks (e.g., [3], [4], [5]). The [α/Fe] ratios of stars in dwarf spheroidal (dSph) galaxies are generally lower than similar metallicity Galactic stars. There is marginal overlap in the [α/Fe] ratios between dSph stars and Galactic halo stars but this similarity does not extend to other element ratios where, for example, a significant over abundance in [Ba/Y] is typically observed in dSph stars compared to Galactic stars (see Venn, this volume). The stars in larger galaxies, such as the LMC and Sagittarius are also chemically distinct from the majority of the Galactic stars (see Hill, this volume; Bonifacio, this volume; McWilliam, this volume). This makes a merging hypothesis difficult to explain any component of our Galaxy, unless the merging were to occur predominantly at very early times. These observations can thus be interpretated in two ways - either to say that dwarf galaxies are not building blocks of larger galaxies, which begs the questions - what are they then? and how do they avoid too much merging with larger galaxies? or we can say that perhaps the whole idea of heirarchical structure formation as it currently stands needs some serious revision because dwarf galaxies really don't fit the picture. Both interpretations have merit and neither can be ruled out.

2 Initial Results from DART: Sculptor Dwarf Spheroidal

The DART large programme at ESO made v_{hel} and [Fe/H] measurements from FLAMES spectroscopy of 401 red giant branch (RGB) stars in the Sculptor (Scl) dSph [6]. The relatively high signal/noise, S/N ($\approx$ 10-20 per pixel) resulted in both accurate metallicites ($\approx$ 0.1 dex from internal errors) and radial velocities ($\approx \pm 2$ km/s). This is the first time that a large sample of accurate velocities *and* metallicities have been measured in a dwarf galaxy.

Scl is a close companion of the Milky Way, at a distance of 72 $\pm$5 kpc [7], with a low total (dynamical) mass, $(1.4 \pm 0.6) \times 10^7 M_\odot$ [8], and modest luminosity, $M_V = -10.7 \pm 0.5$, and central surface brightness, $\Sigma_{0,V} = 23.5 \pm 0.5$ mag/arcsec^2 [9] with no HI gas [10]. CMD analysis, including the oldest Main Sequence turnoffs, has determined that this galaxy is predominantly old and that the entire star formation history can have lasted only a few Gyr [11].

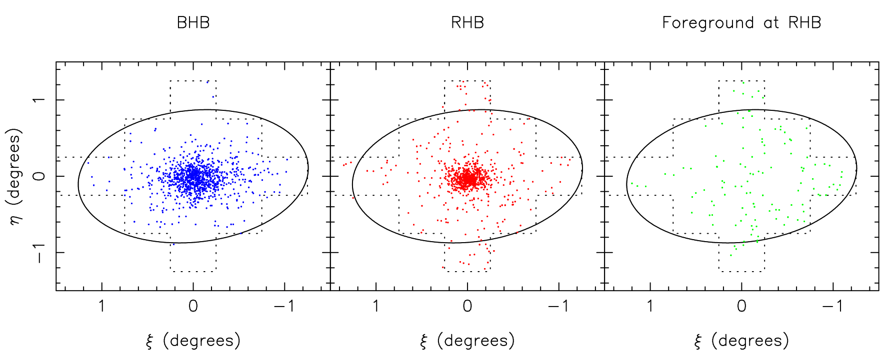

Fig. 1. The distribution of Horizontal Branch stars from WFI imaging of the Scl dSph showing the different spatial distributions of BHB and RHB as selected from a M_v, V−I Colour-Magnitude Diagram [6]. Also shown, to illustrate the foreground contamination in the RHB distribution, are a CMD-selected sample of foreground stars to match the RHB contamination density. The ellipse is the tidal radius of Scl.

Imaging: Previous studies already suggested that the spatial distribution of the Horizontal Branch stars in Scl shows signs of a gradient, with the red horizontal branch stars (RHB) being more centrally concentrated than the blue horizontal branch (BHB) stars [12], [13]. The DART WFI imaging data extends beyond the nominal tidal radius and with an average 5-σ limiting magnitude of V=23.5 and I=22.5 also probes well below the Horizontal Branch. This has enabled us to unequivocally demonstrate that the BHB and RHB stars have markedly different spatial distributions (see Fig. 1).

The different spatial occupancy of the two populations, taking into account the foreground contamination present in the RHB sample, is striking and provides strong evidence that we are seeing two distinct components. The characteristics of the BHB and RHB are also consistent with different ages (e.g., $\leq$2 Gyr), or different metallicities (Δ[Fe/H]$\sim$0.7 dex), from theoretical modelling of globular cluster Horizontal Branches [14].

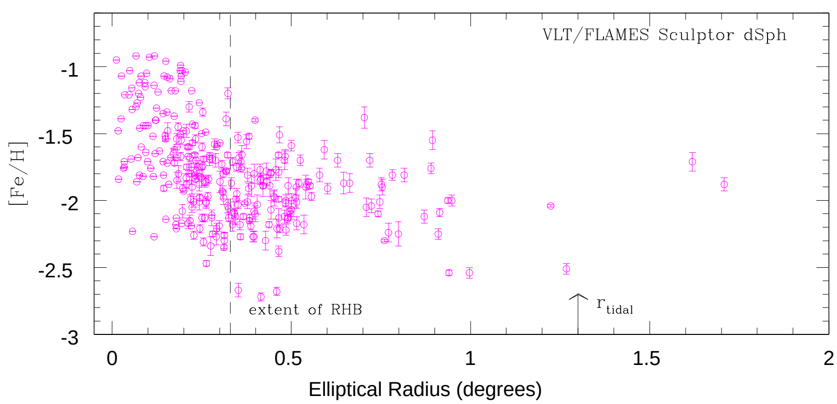

Fig. 2. VLT/FLAMES [Fe/H] measurements for 308 potential members of Sculptor dSph versus elliptical radius. Also marked, is the extent of the RHB distribution (as a dashed line) and the tidal radius, r_{tidal}.

Spectroscopy: The WFI images were used to select samples of stars on the RGB in Scl to take spectra in the Ca II triplet region with VLT/FLAMES. This resulted in radial velocity measurements and metallicity estimates for more than 400 stars in Scl over the fields outlined in Fig. 1, of which 300 have a high membership probability.

In Fig. 2 we show the distribution of [Fe/H] as a function of elliptical radius (the equivalent distance along the semi-major axis from the centre of Scl) for those RGB stars which were determined to have a high probability of membership. A well-defined metallicity gradient is apparent with a similar scale size to the RHB versus BHB spatial distributions.

In the central region of Sculptor we have high resolution spectra providing direct abundance measurements for numerous elements (Hill et al., in prep). In Fig. 3 we show the preliminary results for the α-elements (Ca, Mg & Ti) compared with similar observations of stars in our Galaxy. It is clear that the overall distribution of [α/Fe] versus [Fe/H] in Scl does not match our Galaxy, except for a small number of the most metal poor stars in Scl which overlap with Galactic halo stars.

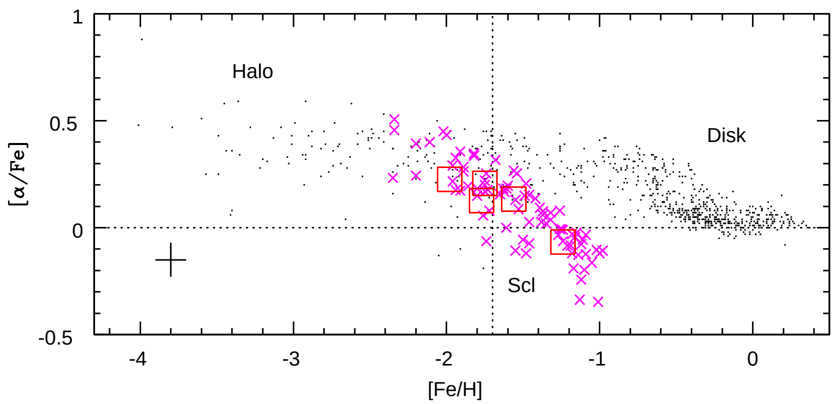

Fig. 3. The α-abundance (average of Ca, Mg and Ti) for stars in our Galaxy compared to those in Scl. The VLT/FLAMES high resolution measurements of 92 members in the central field are shown as crosses (from Hill et al., in prep). The Galactic stars come from standard literature sources (see [5] for references). The 5 open squares are UVES measurements of individual stars in Scl [3].

3 Two Stellar Components

Our FLAMES results clearly show that Scl contains two distinct stellar components with different spatial, kinematic and abundance properties [6]. There appears to be a metal-rich, $-0.9 >$ [Fe/H] > -1.7, and a metal-poor, $-1.7 >$ [Fe/H] > -2.8 component. The metal-rich component is more centrally concentrated than the metal poor, and on average appears to have a lower velocity dispersion, $\sigma_{metal-rich} = 7 \pm 1$ km/s, whereas $\sigma_{metal-poor} = 11 \pm 1$ km/s (see Battaglia, this volume).

There are indications that the presence of two populations is a common feature of dSph galaxies. Our preliminary analysis of HB stars, v_{hel} and [Fe/H] measurements in the other galaxies in our sample (Fornax and Sextans dSph; Battaglia et al., in prep) also shows very similar characteristics to Scl, especially in the most metal poor component. Pure radial velocity studies [15], [16] have also considered the possibility that kinematically distinct components exist in Ursa Minor, Draco and Sextans dSph galaxies.

What mechanism could create two ancient stellar components in a small dwarf spheroidal galaxy? A simple possibility is that the formation of these dSph galaxies began with an initial burst of star formation, resulting in a stellar population with a mean [Fe/H] ≤ -2. Subsequent supernovae explosions from this initial episode could have been sufficient to cause gas (and metal) loss such that star formation was inhibited until the remaining gas could sink deeper into the centre [17]. Thus the subsequent generation(s) of stars would inhabit a region closer to the centre of the galaxy, and have a higher average metallicity and different kinematics. Another possible cause is external influences, such as minor mergers, or accretion of additional gas. It might also be that events surrounding the epoch of reionisation influenced the evolution of these small galaxies [18] and resulted in the stripping or photoevaporation of the outer layers of gas in the dSph, meaning that subsequent more metal enhanced star formation occured only in the central regions.

The full abundance analysis of the FLAMES HR data (Hill et al. in prep) will provide more details of the chemical enrichment history of Scl. This will hopefully enable us to distinguish between two episodes of star formation or more continuous star formation, manifested as a gradient in velocity dispersion and metallicity from the centre of the galaxy. Fig. 3 suggests that [α/Fe] differs for the two populations, such that the metal poor (presumably older) population has high [α/Fe] consistent with the halo of our Galaxy, and the more metal rich population doesn't match any of the Galactic stars. The dotted line is drawn at [Fe/H]$= -1.7$ to show the proposed dividing line between the two populations, although as can be seen in Fig. 2 there is not a clear division, however the kinematics provide clear support[6].

4 Dwarf Galaxies and Galaxy Formation

It is clear from Fig. 3 that the Scl dSph does not, in the mean, have stellar abundance properties consistent with our Galaxy, and the evidence points to this also being the case for most other nearby galaxies. This suggests that nearby dwarf galaxies are not the building blocks left over from the heirarchical formation of galaxies like our own. If we wish to retain a heirarchical formalism to explain the formation and evolution of our Galaxy then a mechanism has to be found by which those objects which did merge to form our Galaxy evolved differently from the similar mass (dwarf) galaxies we see around today. It might be, for example, that the building blocks formed and evolved much closer in to the central potential and thus their star formation history and chemical evolution were affected such that these processes proceeded much more rapidly than in their more distant cousins. Although this can be understood in qualitative generalised terms there is no particular evidence to support this. You would think that a difference in the abundance patterns of stars formed close to the centre of a potential and further out would then suggest some kind of gradient in properties, or at least that today we might pick up an unabsorbed building block in the form of a dwarf galaxy. So far detailed abundances have been determined for all the dwarf galaxies in our halo (Shetrone 2004, this volume), including Sagittarius (Bonifacio 2004, this volume), which is in the process of merging with our Galaxy and they all show an astonishing uniformity of abundance ratios, for [α/Fe] as well as r- and s- process elements like [Ba/Eu], and [Y/Ba] even if [Fe/H] varies between -3 and -0.5 dex (see Venn 2004, this volume). We also see evidence for similar abundance ratios in young massive stars in more distant higher mass dwarf irregular galaxies (see Kaufer 2004, this volume) and in RGB stars in the Magellanic Clouds (Hill 2004, this volume). This uniformity in of itself suggests a remarkably stable enrichment process. This is even more striking considering that all these galaxies are so different in their star formation histories, but their mean stellar abundance patterns *for stars of all ages* are very similar to each other and very different to our Galaxy.

So, although we cannot rule out the possibility that we are living at a particular time where all recent (and future) mergers will be of different types of objects than created the bulk of our Galaxy, it might be wise to start to consider some variations on the standard scenario. It is possible to argue that the most metal poor tail of stars in Scl dSph overlap the properties of the Galactic halo stars, suggesting evidence for extremely early (gas rich) merging meaning that most of the stars we see in our Galaxy were actually formed there, and only the metal poor stars in the halo may have been formed in the satellites themselves.

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