The Dwarf galaxy Abundances and Radial-velocities Team (DART) Large Programme – A Close Look at Nearby Galaxies

Eline Tolstoy[1]
Vanessa Hill[2]
Mike Irwin[3]
Amina Helmi[1]
Giuseppina Battaglia[1]
Bruno Letarte[1]
Kim Venn[4]
Pascale Jablonka[5,6]
Matthew Shetrone[7]
Nobuo Arimoto[8]
Tom Abel[9]
Francesca Primas[10]
Andreas Kaufer[10]
Thomas Szeifert[10]
Patrick Francois[2]
Kozo Sadakane[11]

[1] Kapteyn Institute, University of Groningen, the Netherlands
[2] Observatoire de Paris, France
[3] Institute of Astronomy, University of Cambridge, United Kingdom
[4] Department of Physics and Astronomy, University of Victoria, Canada
[5] Observatoire de Genève, Laboratoire d'Astrophysique, Ecole Polytechnique Fédérale de Lausanne, Switzerland
[6] on leave from Observatoire de Paris, France
[7] University of Texas, McDonald Observatory, Fort Davis, Texas, USA
[8] National Astronomical Observatory, Tokyo, Japan
[9] KIPAC, Stanford University, Menlo Park, California, USA
[10] ESO
[11] Astronomical Institute, Osaka Kyoiku University, Japan

We review the progress of ESO/WFI Imaging and VLT/FLAMES spectroscopy of large numbers of individual stars in nearby dwarf spheroidal galaxies by the Dwarf galaxy Abundances and Radial-velocities Team (DART). These observations have allowed us to show that neither the kinematics nor the abundances nor the spatial distributions are easy to explain in a straightforward manner for these smallest galaxies. The main result is that dwarf galaxies show complex and highly specific evolutionary and metal-enrichment processes, especially at ancient times. This conclusively proves that these small galaxies are not the building blocks of the larger galaxies in the Local Group.

The dwarf galaxies we have studied are the lowest-luminosity (and mass) galaxies that have ever been found. It is likely that these low-mass dwarfs are the most common type of galaxy in the Universe, but because of their extremely low surface brightness our ability to detect them diminishes rapidly with increasing distance. The only place where we can be reasonably sure to detect a large fraction of these objects is in the Local Group, and even here, 'complete samples' are added to each year. Within 250 kpc of our Galaxy there are nine low-mass galaxies (seven observable from the southern hemisphere), including Sagittarius which is in the process of merging with our Galaxy. We will show that only the closest galaxies can be observed in detail, even with an 8-m telescope.

The lowest-mass galaxies are dwarf irregular (dI) and dwarf spheroidal (dSph) type galaxies. The only difference between these low-mass dSphs and dIs seems to be the presence of gas and current star formation in dIs. It has already been noted that dSphs predominantly lie close to our Galaxy (< 250 kpc away), and dIs predominantly further away (> 400 kpc away). This suggests that the proximity of dSph to our Galaxy played a role in the removal of gas from these systems. However, the range of properties found in dSph and dI galaxies does not allow a straightforward explanation, particularly not the large variations in star-formation histories and chemical-evolution paths that have now been observed in different systems (e.g., Dolphin et al. 2005).

It is perhaps not a surprise that there is apparently a lower limit to the mass of an object which is able to form more than one generation of stars, which is related to the limit below which one supernova will completely destroy a galaxy. Numerical and analytic models tell us that this must be around a few $\times 10^6$ $M_\odot$. Globular clusters typically have much lower masses than this limit.

Observations

VLT/FLAMES with fibre-feeds to the Giraffe and UVES spectrographs has made a revolution possible in spectroscopic studies of resolved stellar populations in nearby galaxies. The modes of operation, the sensitivity and the field of view are an almost perfect match to requirements for the study of Galactic dSph galaxies. For example, it is now possible to measure the abundance of numerous elements in nearby galaxies for more than 100 stars over a 25′-diameter field of view in one shot. A vast improvement on previous laborious (but valiant) efforts with single-slit spectrographs to observe a handful of stars per galaxy (e.g., Tolstoy et al. 2003; Shetrone et al. 2003; Geisler et al. 2005).

The DART Large Programme has measured abundances and velocities for several hundred individual stars in a sample of four nearby dSph galaxies: Sculptor, Fornax, Sextans and Carina. We have used the VLT/FLAMES facility in the low-resolution mode (LR 8, R ~ 8000) to obtain Ca II triplet metallicity estimates as well as accurate radial-velocity measurements over large areas in Sculptor, Fornax and Sextans out to the tidal radius (Tolstoy et al. 2004; Battaglia et al. 2006, in prep.), see Figure 1 for the example of Sculptor. In Figure 1 we show the area on the sky around the Sculptor dSph galaxy. The large ellipse is the tidal radius of Sculptor as determined by Irwin and Hatzidimitriou (1995). The positions observed with VLT/FLAMES are marked as circles, where the solid circles represent the 10 individual FLAMES pointings analysed so far, and the dashed-line circles are the positions of five additional fields that were observed in November 2005. Also plotted for the analysed fields are the positions of the stars that are probable members (small red squares) and the non-members (black crosses). Each of the four galaxies has been observed at high resolution (Giraffe settings HR 10, 13 and 14) in the central region to obtain detailed abundances for a range of interesting elements such as Mg, Ca, O, Ti, Na, Eu to name a few (Hill et al. 2006 in prep.; Letarte et al. 2006a in prep.) for about 100 stars. During the Giraffe HR observations we were also able to use the fibre feed to the UVES spectrograph to obtain greater wavelength coverage and higher resolution for a sample of seven to 14 stars per galaxy (e.g., Venn et al. 2006 in prep.; Shetrone et al. 2006 in prep.). The comparison we can make between results from UVES spectroscopy (R ~ 40000) and Giraffe spectroscopy

(R ~ 20 000) for the same stars is very useful in convincing ourselves, and others, that we are able to obtain reliable results with lower resolution spectra than was previously thought possible or advisable. This lower-resolution is less of a problem at lower metallicity (e.g., Sculptor) than at higher metallicity (e.g., Fornax).

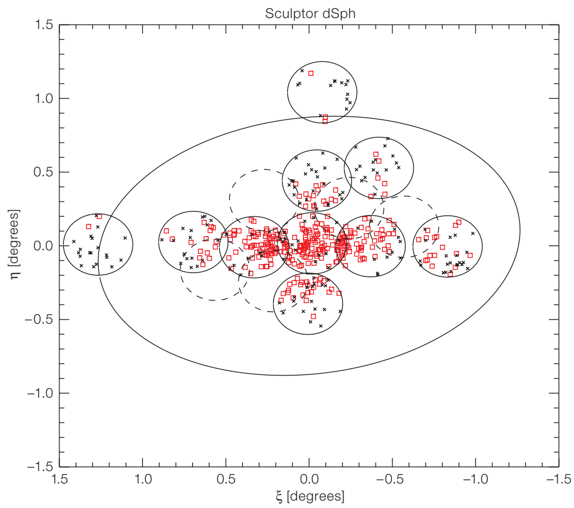


Figure 1: The area on the sky around the Sculptor dSph galaxy. The positions observed with VLT/FLAMES are marked as circles. Also plotted are the positions of the stars that are probable members (red squares) and the non-members (black crosses).

Colour-magnitude diagrams

The first step in a detailed analysis of the resolved stellar population of a galaxy is an accurate colour-magnitude diagram (e.g., Figure 2), ideally down to the oldest main-sequence turnoffs ($M_V \sim +3.5$). In Figure 2 is plotted the colour-magnitude diagram of the Sculptor dSph from ESO/WFI imaging out to the tidal radius. The coloured symbols are the stars we observed with VLT/FLAMES. The probable members of Sculptor are shown as purple circles and the non-members are shown as green stars. A careful analysis leads to the star-formation history all the way back to the first star formation in the Galaxy. This approach is the most accurate for intermediate-age populations, but for stars older than about 10 Gyr the time resolution gets quite poor (and the stars are getting very faint), and it becomes hard to distinguish a 12-Gyr-old star from a 10-Gyr-old star. Here it becomes useful to consider the Horizontal Branch stars ($M_V \sim 0$) which are the bright He-burning phase of low-mass stars > 10 Gyr old. The ratio of red to blue horizontal-branch stars (see Figure 2) tells us about the age and metallicity variation. In Figure 2 regions used to define the Blue Horizontal Branch (BHB), the Red Horizontal Branch (RHB) and foreground comparison (FG) stellar populations in Sculptor are outlined in blue boxes. The spatial distribution of red and blue horizontal-branch stars in Sculptor is shown in Figure 3. In this Figure the outline of the extent of the ESO/WFI imaging is shown, as is the tidal radius of Sculptor.

We can also consider the much brighter Red Giant Branch (RGB, $-3 < M_V < 0$) stars which have ages > 1 Gyr old, back to the oldest stars in the Galaxy, however, the interpretation of the RGB using only photometry is plagued by the age-metallicity degeneracy (graphically illustrated

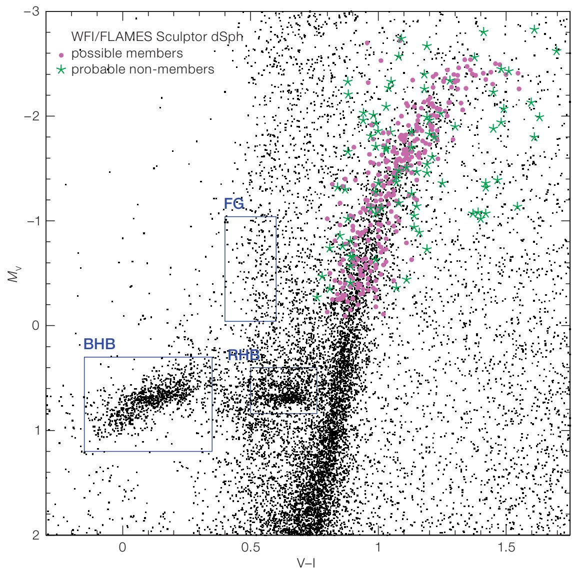


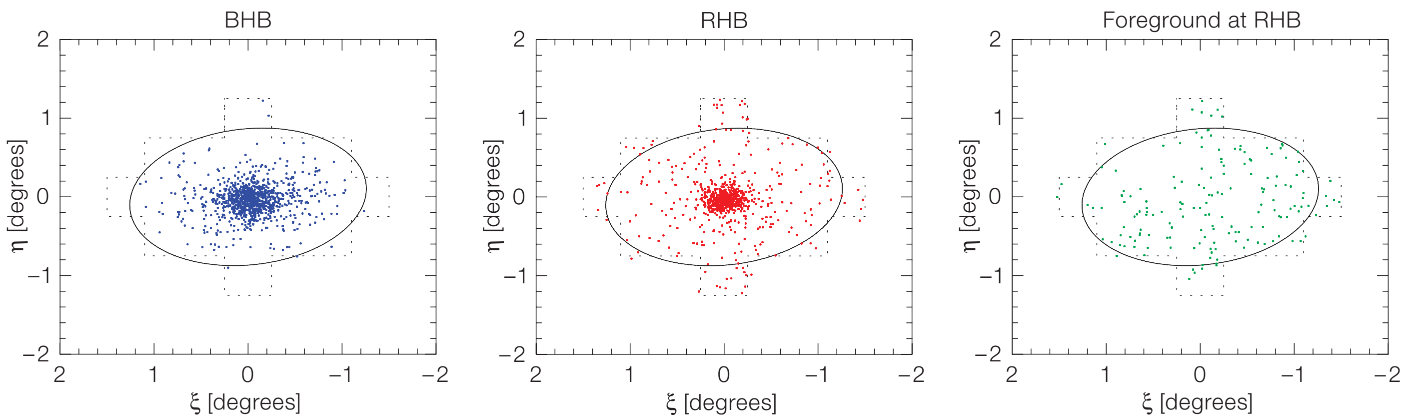
Figure 2: Colour-magnitude diagram of the Sculptor dSph from ESO/WFI imaging. The coloured symbols are the stars observed with VLT/FLAMES. The probable members of Sculptor are shown as purple circles and the non-members are shown as green stars. Also shown outlined in blue are the regions used to define the Blue Horizontal Branch (BHB), the Red Horizontal Branch (RHB) and foreground comparison (FG) stellar populations.

by Cole et al. 2005; their Figure 8). The observed magnitude and colour (e.g., M_V, V–I) of a star combined with a measured [Fe/H], allows us to effectively remove the age-metallicity degeneracy and determine the age of an RGB star from an isochrone, and thus to trace the enrichment patterns of as many elements as we can measure with time.

Detailed abundance analysis

In the majority of RGB stars it is believed that the atmosphere of the star remains an unpolluted sample of the interstellar medium out of which it was formed. This means we have small pockets of interstellar medium of different ages (enriched by different numbers of processes) conveniently covering the nuclear burning core of stars. This hot stellar core provides a useful bright background source to be absorbed in the stellar atmosphere allowing very detailed studies of the elemental abundances in these ancient gas samples. Thus, a spectroscopic analysis of the variation of the abundances of different elements seen in absorption in atmospheres of different age stars allows us to trace the detailed chemical enrichment history of a galaxy with time. Different elements are created in different circumstances and if we are able to determine the abundance of elements known to be created in a particular

Figure 3: The distribution of horizontal-branch stars from ESO/WFI imaging of the Sculptor dSph selected as shown in Figure 2.



set of physical conditions, we can assess the importance and frequency of these conditions during the history of star formation in a galaxy.

For example, the abundances of light elements (e.g., O, Na, Mg, Al) are considered to be tracers of 'deep mixing' patterns which are found only in globular-cluster environments, which gives a limit to the number of dissolved globular clusters which can exist in a stellar population. These typical (Galactic) globular cluster abundance patterns have also been recently found in the globular clusters of Fornax dSph (Letarte et al. 2006b in prep.), but not (so far) in the field star populations (e.g., Shetrone et al. 2003).

The creation of α-elements (e.g., O, Mg, Si, Ca, Ti) occurs predominately in supernovae type II explosions, i.e. the explosion of massive stars a few 10^6–10^7 yrs after their formation. The abundance of the different α-elements is quite sensitive to the mass of the SNII progenitor so the α/Fe ratio traces the mass function of the stars which contributed to the creation of the α-elements, and ratios of different α-elements themselves can put limits on the highest-mass star which has enriched a galaxy and also the typical mass range (e.g., McWilliam 1997).

Heavy Elements (Z > 30) are a mix of r- and s-process elements. That is to say elements which were produced by rapid or slow neutron capture which tells us about the environment in which enrichment occurred. Rapid capture (r-process) is assumed to occur in high-energy circumstances, such as supernovae explosions. For example Eu is considered to be an element produced almost exclusively by the r-process. The slow capture (s-process) is thought to be created by more quiescent processes such as the stellar winds common in AGB type stars of intermediate age (and mass). Typical elements which are thought to be created by the s-process are Ba and La. The ratio between r- and s-process element abundances gives an indication of the relative importance of these different enrichment processes during the history of star formation in a galaxy. Dwarf spheroidal galaxies are found to have a strong evolution from r-process domination to s-process domination as a function of the metallicity of the stars. This may indicate that supernovae products are typically lost to a shallow potential well, or that the slow star formation rate means that massive stars are not very common (e.g., Tolstoy et al. 2003; Venn et al. 2004).

Our latest results for the α-elements are shown in Figure 4. The α-element abundance is an average of Ca, Mg and Ti abundances from high-resolution spectroscopy for stars in Sculptor and Fornax dSphs. The VLT/FLAMES measurements of 92 stars in the centre of Sculptor are shown in the upper panel as purple crosses (Hill et al. 2006 in prep.) and the preliminary measurements for 55 stars observed in Fornax are shown as green crosses in the lower panel (Letarte et al. 2006a, in prep.). The open blue squares, five in Scl and three in Fnx are UVES measurements of individual stars (Shetrone et al. 2003). The four open red squares are Geisler et al. (2005) measurements of Scl, and the 10 open green squares are FLAMES fibre fed UVES spectra of Scl, taken at the same time as the Giraffe spectra (Venn et al. 2006, in prep.). A representative error bar is also given in the bottom left hand of each panel. The Fornax VLT/FLAMES results are preliminary, as the problems with the appropriate stellar models for such cool stars as are found in Fornax have not yet been fully resolved. We can compare the detailed abundance patterns that we see in dSph galaxies, with other galaxies such as the Milky Way. This is shown in Figure 4, where the Galactic stars shown in both panels as black dots come from various literature sources (see Venn et al. 2004 for references), and the disc and halo component are also labelled. This can also be done for Saggitarius and the Magellanic Clouds (e.g., Venn et al. 2004). These comparisons show that enrichment patterns differ strongly between different types of galaxy, making it hard to build one type of galaxy out of another once they have formed a significant number of stars.

The Ca II triplet and kinematics

The ideal is to be able to obtain high-resolution spectra for individual stars in nearby dSph over a large wavelength range, and make a detailed analysis of a range of different elements along with accurate velocities. However, this is quite time consuming both in telescope time (even with VLT/FLAMES) and in analysis. One of the most simple ways to get an estimate of the metallicity of RGB stars is with the Ca II triplet. This is a basic metallicity indicator requiring only low or intermediate spectral resolution, based on three lines around 8 500 Å which have been empirically calibrated from obser-

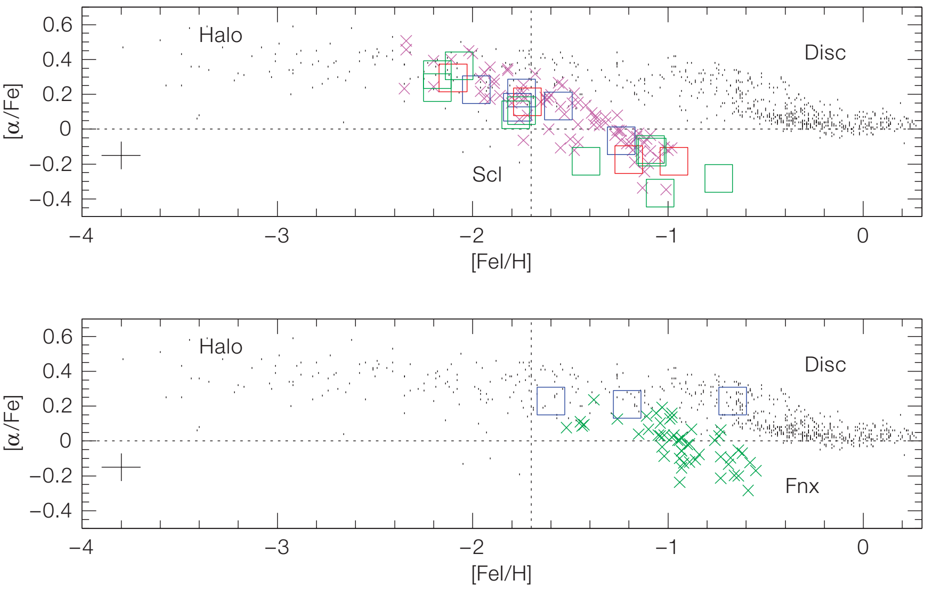


Figure 4: The α-element abundances from high-resolution spectroscopy for stars in the Sculptor dSph (upper panel, Hill et al. 2006 in prep) and also preliminary results for the Fornax dSph (lower panel, Letarte et al. 2006a, in prep.). The open squares are UVES measurements of individual stars (Shetrone et al. 2003; Geisler et al. 2005; Venn et al. 2006, in prep.). Galactic stars coming from various literature sources (see Venn et al. 2004 for references) are shown for comparison in both panels as black dots and labelled as disc and halo components.

vations of stars in globular clusters with high-resolution abundances. Assuming sufficient signal-to-noise spectra (S/N > 10) it provides [Fe/H] within typical (internal) errors of ± 0.1 dex, and also the radial velocity of each star with ± 2 km/s accuracy. These accuracies are well suited for 'quick look' surveys of the resolved stellar population of a galaxy. In the DART project these Ca II triplet measurements are complementary to the high-resolution observations made in the centre of each dSph. In the low-resolution observations a much larger area is surveyed and we can assess how representative the detailed study is of the stellar population of the whole galaxy.

Our first VLT/FLAMES results (Tolstoy et al. 2004), were based upon Ca II triplet measurements, which clearly showed that Sculptor dSph contains two distinct stellar components with different spatial, kinematic and abundance properties (see Figure 5). The upper panel shows the VLT/FLAMES spectroscopic measurements of [Fe/H] for 307 probable velocity members of Sculptor (with S/N > 10). We see a clear trend of metallicity with radius. The lower panel shows v_{hel} as a function of elliptical radius for all stars satisfying S/N > 10. Likely Sculptor members are clearly seen clustered around the systemic velocity of 110 km/s. The stars which are potential members are plotted as red stars ([Fe/H] > −1.7) and blue circles ([Fe/H] < −1.7), while the green crosses are assumed to be non-members. 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. A similar effect is seen in Fornax, where the metal-rich stars are centrally concentrated, and the metal-poor stars appear more uniformly and diffusely distributed.

It is clear from the histogram of [Fe/H] measurements that both Sculptor and Fornax lack a low metallicity tail (see Figure 6). In Figure 6 are plotted in the left-hand histogram distributions of [Fe/H] for Sculptor dSph: the 91 stars within the central, r < 0.2 degree region (solid black line); and the 216 stars beyond r > 0.2 degrees (dashed red line). In Figure 6 in the right-hand histogram is the [Fe/H] distribution for the Fornax dSph: the 332 stars within the central, r < 0.5 degree region (solid black line); and the 229 stars beyond r > 0.5 (dashed red line). Clearly the distributions are very different. Most noticeably Fornax has a substantial 'metal-rich' population. The lowest metallicity star in our combined sample of more than 850 stars for both galaxies is [Fe/H] = −2.7. We find a similar lack of low-metallicity stars in Sextans and Carina. Although it is difficult to make an accurate comparison with the Galactic surveys, where the completeness can be hard to quantify, there appears to be a significantly different distribution between all the dSph and the (metal-poor) halo of the Milky Way. It can be seen that there is a clear difference in the distribution of the metal-rich and metal-poor stars in both Fornax and Sculptor.

Future work

There are indications that the presence of two distinct populations is a common feature of dSph galaxies. Our preliminary analysis of Horizontal Branch stars, v_{hel} and [Fe/H] measurements in the other galaxies in our sample (Fornax and Sextans dSph; Battaglia et al. 2006, in prep.) also show similar characteristics to Sculptor, especially in the most metal-poor component. Pure radial-velocity studies (e.g., Wilkinson et al. 2004) have also considered the possibility that kinematically distinct components exist in Ursa Minor, Draco and Sextans dSph galaxies. Interestingly, the Carina dSph appears to go counter to this trend, and another VLT/FLAMES study finds no obvious evidence for more than one component, or even a gradient within Carina dSph (Koch et al. 2006).

What mechanism could create two or more distinct 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 supernova 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. Thus the subsequent generation(s) of stars would form in a region closer to the centre of the galaxy, and have a higher average metallicity and different kinematics. Another possible cause are external influences, such as minor mergers, accretion of additional gas or the kinematic stirring by our Galaxy. It might also be that events surrounding the epoch of reionisation influenced the evolution of these small galaxies and resulted in the stripping or photo-evaporation of the outer layers of gas in the dSph, meaning that subsequent more metal-enhanced star formation occurred only in the central regions.

Acknowledgements

Eline Tolstoy gratefully acknowledges support from a fellowship of the Royal Netherlands Academy of Arts and Sciences. The data presented here were collected under ESO Large Programme 171.B-0588 and GTO programme 71.B-0641.

References

Cole A. A. et al. 2005, AJ 129, 1465
Dolphin A. E. et al. 2005, Resolved Stellar Populations, eds. D. Valls-Gabaud and M. Chavez (astro-ph/0506430)
Geisler, D. et al. 2005, AJ 129, 1428
Irwin M. and Hatzidimitriou D. 1995, MNRAS 277, 1354
Koch A. et al. 2006, AJ, in press (astro-ph/0511087)
McWilliam A. 1997, ARA&A 35, 503
Shetrone M. D. et al. 2003, AJ 125, 684
Tolstoy E. et al. 2003, AJ 125, 707
Tolstoy E. et al. 2004, ApJL 617, 119
Venn K. et al. 2004, AJ 128, 1177
Wilkinson M. et al. 2004, ApJL 611, 21

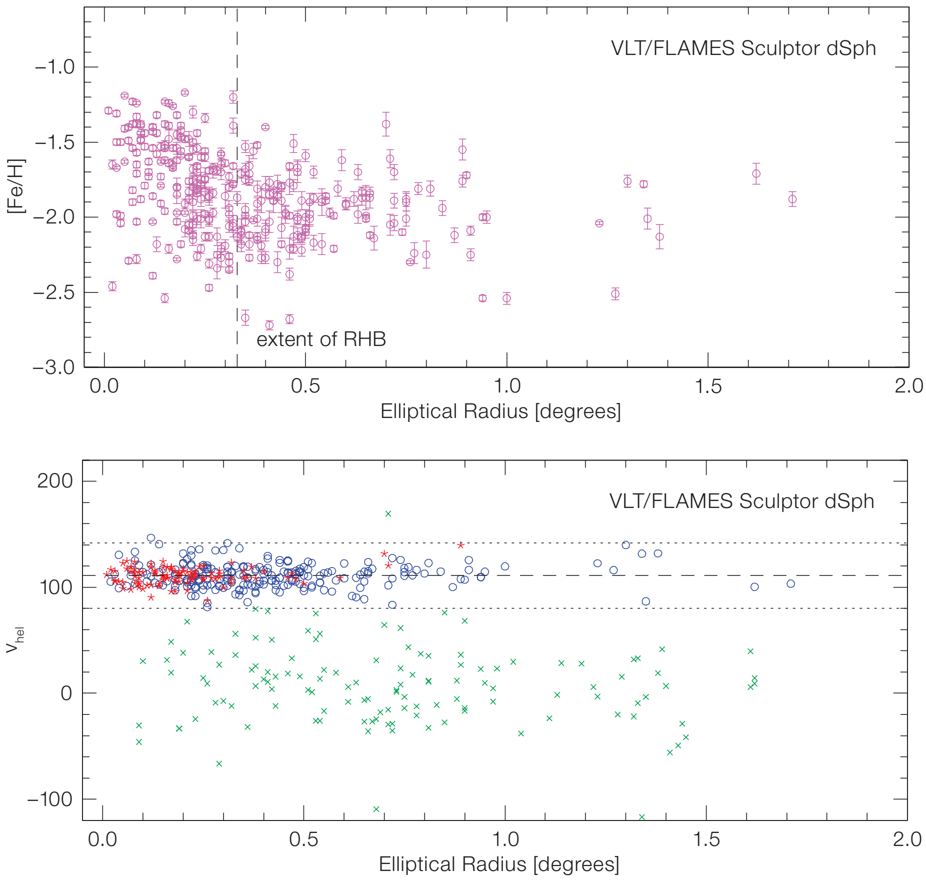


Figure 5: The upper panel shows the VLT/FLAMES spectroscopic measurements of [Fe/H] for 307 Red Giant branch stars in Sculptor plotted as a function of distance from the centre of the galaxy. The lower panel shows v_{hel} as a function of elliptical radius. The stars that are probable members are plotted as red stars ([Fe/H] > −1.7) and blue circles ([Fe/H] < −1.7), showing metal-rich and metal-poor stars respectively. The 128 green crosses are unlikely to be members of Sculptor.

Figure 6: In the left panel is the histogram distribution of [Fe/H] measurements for the Sculptor dSph: inner region, solid black line outer region dashed red line. In the right panel is the same for the Fornax dSph.