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Detailed Studies of the Sculptor Dwarf Spheroidal Galaxy in the Milky Way halo

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Abstract. In and around the Milky Way halo there are a number of low mass low luminosity dwarf galaxies. Several of these systems have been studied in great detail. I describe recent photometric and spectroscopic studies of the Sculptor dwarf spheroidal galaxy made as part of the DART survey of nearby dwarf spheroidal galaxies.

Keywords. stars:abundances, stars: Hertzsprung-Russell Diagram, galaxies: dwarf, galaxies: individual (Sculptor dwarf spheroidal), galaxies: stellar

1. Introduction

There has been much effort expended over the past decades in improving our ability to interpret the properties of resolved stellar populations in nearby galaxies in terms of star formation histories and also chemical evolution. The most powerful new approach comes from the combination of accurate main sequence turnoff photometry and detailed spectroscopy of red giant branch (RGB) stars.

The classic tool to interpret photometric data is the Colour-Magnitude Diagram (CMD). This can be used to determine the accurate star formation history of a complex stellar population (e.g., Tosi *et al.* 1991; Tolstoy & Saha 1996; Dolphin 2002; Aparicio & Gallart 2004; de Boer *et al.* 2012). They have been used to study a variety of different types of galaxies, from very nearby dwarf galaxies, within the halo of the Milky Way (e.g., Sculptor, de Boer *et al.* 2012) to distant blue compact dwarf galaxies such as I Zw 18 (e.g., Aloisi *et al.* 2007) which is at a distance of 18 Mpc. The detail with which these systems can be studied is of course very different. Beyond the Local Group even with the deepest HST images available it is not possible to accurately determine star formation histories going back more than 1−3 Gyr in time.

The VLT/FLAMES multi-fibre spectrograph (Pasquini et al. 2002) has allowed significant progress in the studies of resolved stellar populations in and around the halo of the Milky Way. This instrument has ∼130 fibres which can be placed over a $25'$ diameter field of view, with a range of relatively high spectral resolution, R$\sim 6000 - 20000$ gratings. This instrument has led to significant breakthroughs in our understanding of the abundance patterns of stellar populations in the nearest southern dwarf spheroidal (dSph) galaxies (e.g., DART, Tolstoy *et al.* 2006). DART has taken large numbers of Ca II triplet spectra in 4 dwarf spheroidal systems over the last few years (e.g., Helmi *et al.* 2006; Starkenburg *et al.* 2010), and also significant numbers of intermediate/high resolution spectra of the central regions of the same galaxies (e.g., Tolstoy, Hill & Tosi 2009; Letarte *et al.* 2010; Lemasle et al. 2012; Hill *et al.* 2013, in prep.).

There have been a number of recent studies, both spectroscopic and photometric, looking in detail at a range of Local Group dwarf galaxies. Here I will describe new results for the Sculptor dSph, and particularly our efforts to combine both photometric and spectroscopic data sets for this galaxy.

2. The Sculptor dwarf spheroidal galaxy

One of the first faint dwarf galaxies to be found in the Milky Way halo (by Shapley in the late 1930s) is the Sculptor dSph galaxy. It is a very nearby (85 kpc) low luminosity ($M_V = -11.2$) system at high Galactic latitude with low reddening. Sculptor is also dominated by an old stellar population (e.g., de Boer *et al.* 2011) which makes it a useful location to study the earliest star formation in the Local Group, as it is undisturbed by subsequent star formation on top of the most ancient population, which can hide significant details. Of course it remains challenging to disentangle the effects of age and metallicity at ancient times in a CMD, especially because of the low metallicities which prevailed at these earliest times. Likewise with spectroscopy it can be difficult to make accurate measurements of the weak lines that are the typical characteristic of very metal poor stars. Here I am going to describe new works, spectroscopic and photometric, which have improved our understanding of the old, metal poor stars in the Sculptor dSph.

2.1. *Searching for the most metal poor stars*

It has been a long standing challenge to accurately determine the metallicity distribution function (MDF) in dSph galaxies. The RGB contains representatives of all stars older than 1 Gyr, however the age-metallicity degeneracy makes the width of the RGB an uncertain measure. However, our ability to efficiently take spectra of a large sample of RGB stars has only been possible during the last decade with the advent large multi-object spectrographs on 8m-class telescopes (e.g., FLAMES on the VLT).

As part of the DART project we determined the spectroscopic MDF along the RGB for a sample of 4 nearby dSph using the simple to use Ca II triplet metallicity indicator which was calibrated on globular clusters (Helmi *et al.* 2006; Battaglia *et al.* 2008). We did not find evidence for stars with $[\mathrm{Fe/H}] \lesssim -2.5$. This was a surprise, given that the average metallicity of most of the dSph is typically around, or below that of the Milky Way halo. Subsequently this indicator was re-calibrated from first principles for very metal poor stars, and a bias was found in the original calibration for $[\mathrm{Fe/H}] < -2.5$, as globular clusters do not have these metallicities and the linear extrapolation of the indicator we assumed beyond the range of the calibration was not correct (Starkenburg *et al.* 2010). This new calibration led to the discovery of a (very small) very metal poor population in all the DART sample of dSph (Starkenburg *et al.* 2010). The number of stars with $[\mathrm{Fe/H}] < -2.5$ remains only a few percent of the total but there is always a weak but significant metal poor tail (e.g., Tafelmeyer *et al.* 2010; Starkenburg et al. 2010, 2013). Presently the largest sample of abundance measures for very metal poor stars ($[\mathrm{Fe/H}] < -2.5$) in a single dwarf galaxy are in the Sculptor dSph. The work of Starkenburg *et al.* (2013) added 7 stars with $[\mathrm{Fe/H}] < -2.5$ to make a total of 10 stars confirmed in this range. These stars seem to follow the alpha-iron pattern of the halo stars at similar metallicity, with perhaps a little more scatter towards lower values of $[\alpha/\mathrm{Fe}]$ (see Fig. 1). Of these 10 stars none are enhanced in Carbon, as is common in the Milky Way halo at these metallicities (e.g., Norris *et al.* 2010).

The stars in the Sculptor dSph with detailed chemical abundances at $[\mathrm{Fe/H}] > -2.5$ (Hill *et al.* 2013, in prep., see Tolstoy, Hill & Tosi 2009) show a very clear “knee” in the distribution of their alpha-elements. This knee occurs at $[\mathrm{Fe/H}] \sim -1.7$ (see Fig. 1), and is expected to represent the metallicity at which SNIa start to contribute to the chemical enrichment of the interstellar medium. This same feature is seen in the stars of the Milky Way disc, but at a much higher $[\mathrm{Fe/H}] \sim -0.6$. This is presumed to represent the different speeds with which metal enrichment can occur in different galaxies before SNIa start.

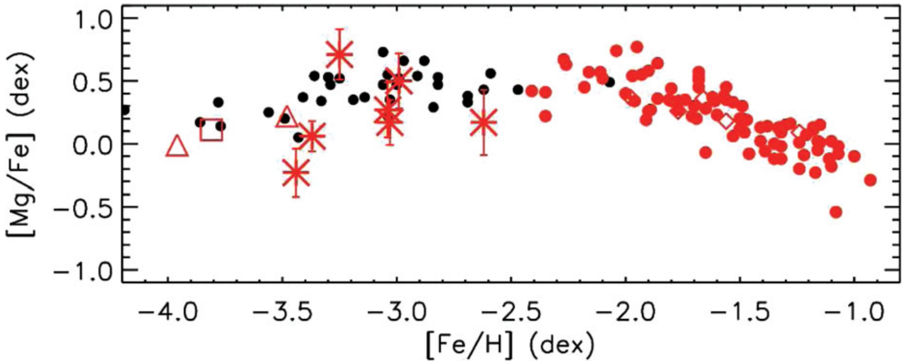

Figure 1. The [Mg/Fe] abundance measurements for the Sculptor dSph galaxy (in red), with the 7 star shaped symbols the new X-shooter measurements from Starkenburg *et al.* (2013), and the 3 large open symbols from Tafelmeyer *et al.* (2010) (triangles) and Frebel *et al.* (2010) (square). The red solid circles come from Hill *et al.* 2013, in prep; with the small open diamonds underneath showing the UVES survey of Shetrone *et al.* (2003). The black solid circles are from the Galactic halo sample of Cayrel *et al.* (2004).

2.2. *Combining Colour-Magnitude Diagrams & Spectroscopy*

The most powerful way to determine the ages of distant resolved stellar populations is a detailed analysis of the Main Sequence turnoff region (e.g., see Tolstoy, Hill & Tosi 2009, and references therein). Detailed elemental abundances can only be determined with reasonably high resolution spectroscopy, and only for RGB stars in the nearest by galaxies (e.g., Sculptor dSph). The challenge is to combine these very different measurements to make a consistent and detailed analysis of the entire stellar population. This has been done in detail for the first time for the Sculptor dSph; combining the new wide-field deep CMDs (de Boer *et al.* 2011), and the DART spectroscopy (Tolstoy, Hill & Tosi 2009; Starkenburg *et al.* 2010; Hill *et al.* 2013, in prep.). Adding the spectroscopic measurements to the CMD analysis makes it possible to remove the age-metallicity degeneracy that can plague the accurate interpretation of CMDs, and also allows the independent determination of the timescale for chemical evolution. However this kind of analysis does still require a number of assumptions. It is clear for example that an independent CMD analysis does not predict the same spread on the RGB as is measured spectroscopically. This, among other things, means that actually adding more information in the form of the spectroscopically determined metallicities does not actually improve the comparison between the model and the data in the CMD analysis. Another issue is that the spectroscopic metallicities are all determined on the RGB, whereas the ages are most constrained by the Main Sequence Turnoff region. These two different regions are notoriously difficult to model simultaneously in a self-consistent way and often CMD models which make an an excellent match on the Main Sequence do not accurately match the colour or the stellar density to be found on the RGB, or of course vice-versa. There are a number of intrinsically difficult problems in the theoretical treatment of stellar evolution that contribute to this problem. Another uncertainty is whether the few blue stars seen above the oldest (most populated) main sequence turnoff are an indicator of relatively young star formation, or a blue-straggler-like population.

What has been done in the analysis of Sculptor is to maximise the agreement between spectroscopic and photometric data and the predictions of these properties from the best fitting star formation and chemical evolution histories (see de Boer *et al.* 2012 for details). This works surprisingly well, with only a small fraction of the observed population

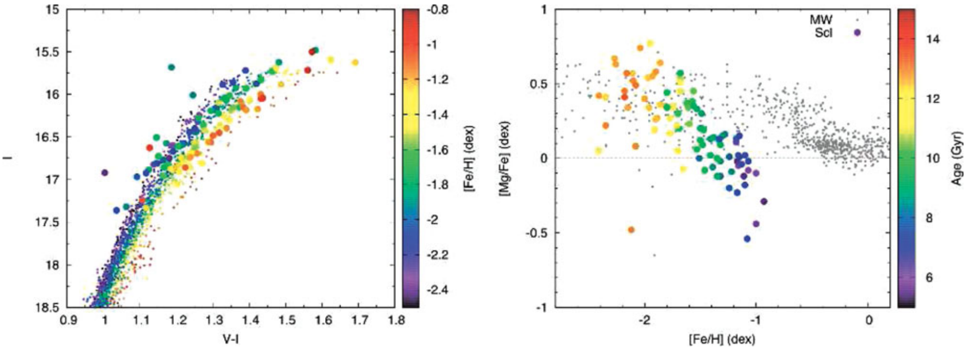

Figure 2. On the left, the model CMD for the RGB of Sculptor dSph from de Boer *et al.* (2012), as small coloured points, where the colour code shows the metallicity of each star, as given in the scale. Over-plotted as large coloured circles are the actual spectroscopic measurements of red giants in Sculptor, and their measured metallicities with the same colour code. On the right, also from de Boer *et al.* (2013) is an alpha(Mg)-Fe plot where these same stars with measured metallicities (from Hill *et al.* 2013, in prep.) are assigned ages from the model stars with which they most closely overlap. The colour code now shows the ages of these stars. The underlying grey points are Milky Way star measurements.

not accounted for by the model. This suggests that broadly speaking, including all the information we have for the Sculptor stellar population, we obtain an accurate broad brush picture of how star formation and chemical evolution has progressed.

This careful modelling of all the data available for the Sculptor dSph galaxy leads to the most accurate star formation history that has been determined for the old stellar population in a dSph galaxy. This approach also allows us to determine ages consistent with the star formation history for the RGB stars, including those for which there are spectroscopic metallicities (see Fig 2). This means we can determine an internally consistent star formation and chemical evolution history of the Sculptor dSph, and thus the timescale for the enrichment of the different chemical elements. The primary example is that of the alpha-elements (Fig 2, right), which can be accurately determined for the stars from high resolution spectra. These abundances can thus be linked to the time scale derived from the CMD analysis, and hence the time it takes for Sculptor to enrich in both iron and alpha-elements can be determined. This measures the time-scale on which SNIa explosions start to contribute to the chemical properties of the Sculptor interstellar medium. This time scale for the first SNIa in the Sculptor dSph is found to be 2±1 Gyr (de Boer *et al.* 2012). This is somewhat longer than theory predicts, but arguably consistent with what might be expected from a small galaxy which has always had very inefficient and relatively low level star formation.

3. Conclusions

It seems that the resolved stellar populations of dwarf galaxies, like the Sculptor dSph, show fairly elaborate star formation and chemical enrichment histories, and each one seems to be different from the other. Sculptor, despite being predominantly old, has already been shown to have complex kinematics (Tolstoy *et al.* 2004; Battaglia *et al.* 2008) and these studies have determined that the kinematics and metallicity distributions appear to be split into two different components. Namely a metal poor old population with a relatively high velocity dispersion and a more metal rich, centrally concentrated population with a lower velocity dispersion. This picture of Sculptor split into two "populations" does not appear to be required by either the high resolution spectroscopy (Hill *et al.* 2013, in prep) or the star formation history (de Boer *et al.* 2012) analyses. Of course the populations are not markedly different, so fairly small errors driven by the limitations of the observations of high resolution abundances and CMD analyses could smooth out these two components into one. The break in the two populations seen by Tolstoy *et al.* (2004) occurs at [Fe/H]~ -1.7, and this is also where the "knee" in the high-resolution alpha-iron plot appears. Thus it could be that the alpha-rich and the alpha-declining populations are two distinct episodes; one a relatively short peak of star-formation, and the other a slowly declining star formation episode. This may show the galaxy evolving from an initial burst of star formation which then slowly declines over time. This means there is only one population with properties that change slowly over time. This would suggest that the interpretation of the metallicity distributions and kinematics in terms of two distinct components is not correct. It not possible to rule out that Sculptor is made up of two components, that formed stars independently and then merged. This would however mean that the alpha-enrichment of one component could not be directly related to the lower alpha values of the other.

From all detailed observations of the stars in Sculptor dSph and also the other dwarf galaxies around the Milky Way (including Sagittarius) it is impossible to construct any significant stellar component of the Milky Way solely from the nearby systems we observe today. There are similarities for the most metal poor population of the halo and faint dwarf galaxies, but this clearly breaks down once the "knee" in the alpha-elements is reached, and this knee is different for different galaxies. This means that any merging timescale for collecting significant numbers of dwarf galaxies into the halo of the Milky Way has to be short and ancient ($<$ 1 Gyr after star formation began). It also leaves open the question - where do the high [α/Fe] stars for the more metal rich Galactic halo stars come from? Larger systems such as the LMC, Sagittarius and Fornax also have knees which are different from that seen in the Milky Way (Tolstoy, Hill & Tosi 2009). Both the thick and thin disks are far too metal rich to contain significant numbers of merged dwarf galaxies. Thus, our observations show that the swarms of large and small dwarf galaxies that are seen merging continuously over a long time frame in dark matter simulations, must have a stellar population which no longer exists around the Milky Way. They cannot have looked like the galaxies we see today.

Whenever detailed observations are made of the properties of individual stars in Milky Way and its environment these stars differ depending upon were they are found. This is true whether they are ancient or newly formed. This is seen for the comparison between large and small galaxies around the Milky Way, and between the different components of the Milky Way (halo, disk, bulge) and between all galaxies and globular clusters. This suggests that most star formation in and around the Galaxy occurs in situ and it is rare that stellar populations are merged together in the Milky Way environment.

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Discussion

NICOLAS MARTIN: Doesn't the presence of gradients in the stellar populations of dwarf galaxies complicate your analysis of the formation and evolution of dwarf galaxies?

ELINE TOLSTOY: Yes, if you want a complete model you have to take this into account. When determining abundance properties the full range of metallicity is found only in the central region, so looking here only biases you to sample the mean population.

CHIAKI KOBAYASHI: The estimates of timescale of the decrease of $[\alpha/\text{Fe}] = 2 \pm 1$ Gyr is very important. From the observations of SNeIa in nearby galaxies we know that there is a prompt population of SNIa which have a 0.1 Gyr timescale. Can you rule that out?

ELINE TOLSTOY: We do not see any evidence of this, but also our ages are probably not accurate enough to rule it out. But I think the prompt enrichment scenario is typically applied to very massive galaxies (Elliptical galaxies). I think that star formation and chemical enrichment progress differently in these very different environments.

BACHAM E. REDDY: In RGB stars due to 1st dredge-up carbon is expected to be depleted significantly. Have you taken this into account when you state there are no "carbon-rich" stars?

ELINE TOLSTOY: Yes, even taking into account depletion (see Aoki *et al.* 2009) stars in the Sculptor dSph are not "carbon-rich", see also Starkenburg *et al.* (2013).

VASILY BELOKUROV: You mentioned that carbon enriched stars are not observed in classical dSph, what is the situation in UFDs?

ELINE TOLSTOY: There is one example of a carbon rich star in Segue I (Norris *et al.* 2010). However, this is a peculiar case in a peculiar galaxy. This is one of the most low mass systems, with only a handfull of red giant stars. It is thus a very strange occurrence that one turns out to be the only carbon rich metal poor star we know of in any galaxy beyond the Milky Way. The statistics in larger dSph, such as Sculptor dSph, are still not complete enough to rule out that we have missed these stars in our surveys to date (see Starkenburg *et al.* 2013 for details).