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On the absence of very metal-poor stars in the dwarf spheroidal satellites of the Milky Way

New views from DART

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Abstract. The currently favoured concordance cosmological model proposes that large galaxies are the result of mergers of smaller systems. The local population of dwarf galaxies could be the direct descendants of these building blocks. Their low content of heavy chemical elements and the very old ages of some of their stars suggest that they are fossils from the early Universe. We present here the results of a large survey of stars in four dSph to determine their chemical histories. In all four systems, we find a significant lack of stars with metallicities below [Fe/H] ~ -3 dex. This suggests that the gas that made up the stars we observe today had been rather uniformly enriched prior to their formation. Furthermore, the metal-poor tail of the dSph metallicity distributions are significantly different from that of the Galactic halo. These findings demonstrate that the progenitors of nearby dwarf galaxies never resembled the building blocks of large galaxies like the Milky Way. This result has critical implications for understanding galaxy formation on all scales and may require a reassessment of current models of galaxy formation.

Key words. Galaxies: dwarf – Local Group – Galaxy: formation – Galaxy: halo – Stars: abundances – Cosmology: early universe

1. Introduction

The galaxies we see today in and around the Local Group are representatives of the general field population of galaxies throughout the Universe and have been evolving for the majority of cosmic time. As our nearest neighbour systems, they can be studied in far more detail than their distant counterparts and hence they are the best cases for understanding star formation and prototypical galaxy evolution over the lifetime of the Universe. Dwarf galaxies are the simplest systems and they have universal relevance as they are potentially directly linked to the building blocks of all larger galaxies. Most of the satellite galaxies of the Milky Way are very low luminosity systems (also known as dwarf spheroidals; dSph). Despite their small size, these systems show a large variety of star formation and chemical evolution histories (Mateo 1998). However at the same time, they all contain a population of very old stars. Their mean metallicities are quite low, and similar to those found in the Galactic stellar halo (Grebel & Gallagher 2004). Because the metallicity of

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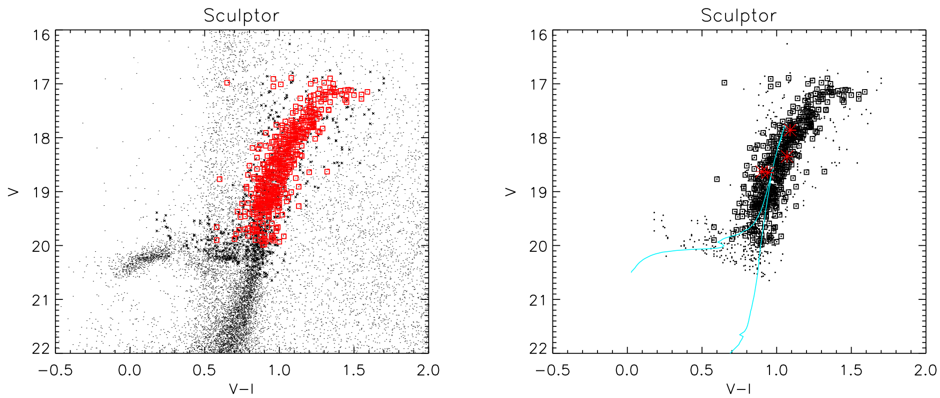

Fig. 1. *Left:* Colour-magnitude diagram for Sculptor obtained with the WFI/ESO. We have spectra for the stars marked with special symbols, where the light squares denote kinematic members and the dark asterisks foreground stars (or stars which produced a poor cross-correlation with our RGB template spectrum). The kinematic members (stars whose velocities are within 3σ from the mean of Sculptor) located off the giant branch are most likely not RGB stars, and hence are not considered further. *Right:* Colour-magnitude diagram for our spectroscopic targets. As in the left panel, the kinematic members are shown as squares. The light asterisks denote the stars with [Fe/H] < -2.6 dex. The solid curve corresponds to a zero metallicity 12.6 Gyr old isochrone from Marigo et al. (2001), and shows that it runs through the targeted RGB candidates.

a galaxy increases in time, this means that the most metal-poor stars must be linked to the first stars formed in the Universe.

2. Observations

In this work, we focus on the metallicity distribution of a large sample of stars in four nearby dSph: Sculptor, Fornax, Sextans and Carina. The data described here were taken using the ESO VLT/FLAMES facility in the low-resolution mode. For each galaxy we derive metallicity estimates as well as accurate radial velocity measurements for several hundred stars located over a large area extending out to the nominal tidal radius (Tolstoy et al. 2004; Koch et al. 2006; Battaglia et al. 2006). The DART (Dwarf Abundances and Radial-velocities Team) program has observed Sculptor, Fornax and Sextans, while the data for Carina comes from the ESO archive.

2.1. Photometry

We use red giant branch stars for our spectroscopic program, since they are bright, cover a range of ages dating back to the oldest stellar populations in these galaxies, and (the majority) are believed to contain in their atmospheres an unpolluted sample of the metallicity of the interstellar medium out of which they formed. To identify candidate red giant branch stars in the dSph we used ESO Wide Field Imager observations to construct colour-magnitude diagrams and selected giant branch stars from their well-defined locii. We have targeted potential red giant branches members over a wide range in colour and in spatial location in these galaxies, as exemplified in Fig. 1 and Fig. 2 for Sculptor. Note that the zero-metallicity isochrone goes right through our selection box in the colour-magnitude diagram.

2.2. Spectroscopy

We measure the metallicity of the stars in our program from low-resolution spectroscopic observations of the CaII triplet region, e.g. Rutledge et al. (1997); Cole et al. (2004). The metallicity is derived from the measured equivalent width of the individual CaII triplet lines, EW, using the relation provided by Tolstoy et al. (2001):

$$[\mathrm{Fe/H}] = -2.66 + 0.42\,[EW_{2+3} + 0.64\,(V - V_{HB})] \quad (1)$$

where EW_{2+3} is the combined equivalent width derived from lines 2 and 3, and $V - V_{HB}$ is the apparent magnitude difference of the star with respect to the horizontal-branch of the system. We find that for reliable [Fe/H] determinations (± 0.2 dex) a continuum signal-to-noise $S/N \geq 10$ per Å is required. In what follows, we consider only those stars with such high S/N spectra and with derived radial velocity errors less than 6 km/s. We consider a generous velocity error (note that our average errors are closer to 2 km/s) to include some possible very metal-poor candidates in our samples.

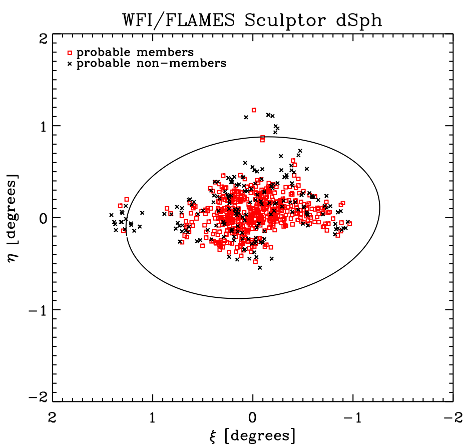

Fig. 2. Sky distribution of spectroscopic targets in Sculptor. Like in Fig. 1 the light squares denote kinematic members, while the dark asterisks are foreground dwarf stars.

We identify kinematic member stars of a particular dwarf galaxy in an iterative procedure. After a pre-selection of candidates (stars with velocities within ±40 km/s of the published mean velocity from Mateo (1998)) we compute the mean velocity and dispersion of the subset. We repeat this analysis, now for stars within 3-σ from the new mean value, until the mean radial velocity and dispersion have converged. This enables us to identify a sample of reliable kinematic members for each of the galaxies. We have 364 member stars in our Carina sample, 933 in Fornax, 513 in Sculptor and 202 in Sextans.

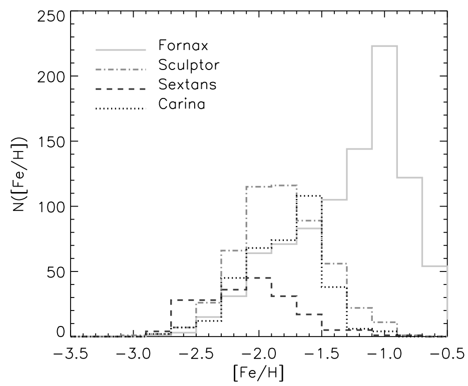

Fig. 3. The metallicity distribution for the stars in the four dSph analysed by DART. There is an evident lack of objects more metal-poor than [Fe/H]< −3 dex.

3. Results

3.1. The metal-poor tail of the dSph

The metallicity distributions of the dSph are shown in Fig. 3. There is great diversity from system to system, which reflects their widely different star formation and chemical enrichment histories. There is, however, a common denominator: contrary to naive expectations, there is a dearth of stars with [Fe/H]< −3 dex.

We have carried out a number of checks to confirm the reality of this result, and we are confident that it is unlikely that systematic errors would prevent us from finding [Fe/H]< −3 dex from our low resolution CaII spectra. These checks include, for example, the comparison to high-resolution measures based directly on FeI and FeII lines. Furthermore, we found very few continuum-only CaII objects, and simple close inspection of the spectra was enough to rule these out as very metal-poor

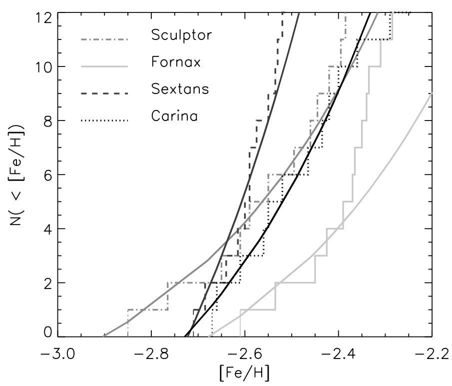

Fig. 4. The histograms correspond to the metal-poor end of the cumulative metallicity distribution of the stars in the dSph. The solid curves denote the closed-box model fits to the observed distributions for [Fe/H] $\lesssim -2.4$ dex.

RGB stars. Only in two cases was high resolution spectroscopic follow-up necessary, and these continuum-only objects turned out to be nearby subdwarfs or distant galaxies.

In a closed-box model of chemical evolution with initial enrichment (Pagel 1998), the number of stars with chemical abundances lower than Z is

$$N(< Z) = A(1 - \exp[-(Z - Z_0)/p]) \quad (2)$$

where A depends on the initial gas mass available for star formation, Z_0 is the initial chemical abundance of the gas, and p is the yield. Since $Z/Z_\odot \ll 1$, and because we can express $Z = Z_\odot 10^{[\mathrm{Fe/H}]}$, then

$$N(< [\mathrm{Fe/H}]) \sim a\,[10^{[\mathrm{Fe/H}]} + c] \quad (3)$$

where $a = AZ_\odot/p$, and $c = -10^{[\mathrm{Fe/H}]_0}$ directly depends on the initial metallicity $[\mathrm{Fe/H}]_0$ of the gas from which the stars formed. Fig. 4 shows that the low-metallicity tail ([Fe/H] $\lesssim -2.4$ dex) of the distribution in all four dSph can be fit very well with this model. The initial metallicity of the interstellar medium in which these stars formed is $[\mathrm{Fe/H}]_0 = -2.9 \pm 0.2$ dex for Sculptor, -2.7 ± 0.3 dex for Fornax, -2.7 ± 0.1 dex for Sextans and -2.7 ± 0.2 dex for Carina.

This analysis shows that the gas in each of these dwarf galaxies had been enriched to [Fe/H] ~ -3 dex prior to the earliest star formation episode that led to the stellar population we observe today. It is intriguing that this metallicity floor is very similar for all four galaxies, despite their widely different characteristics. This suggests that the gas had been enriched very uniformly over a (comoving) volume of ~ 1 Mpc^3 (i.e. that occupied by the Local Group) very early-on.

3.2. The metal-poor tail of the Galactic halo

Ryan & Norris (1991) were the first to show that the metal-poor tail of the Galactic halo distribution extends well below [Fe/H]~ -3 dex (their Fig. 2). More recently the HK and the Hamburg/ESO (HES) surveys (Beers & Christlieb 2005) have dramatically increased the number of metal-poor stars known in the halo. The results of these campaigns are shown in Fig. 5 for the HES giant stars with [Fe/H] < -2.4 dex (Christlieb, Reimers & Wisotzki 2004). The shape is only well-constrained for such low metallicities because a bias is introduced at higher values, due to selection effects. Fig. 5 illustrates the presence of stars in the halo with [Fe/H] $\lesssim -3$ dex .

We have fitted the metal-poor tail of the distribution for the halo with the same simple chemical model used for the dSph (closed box). In the case we allow a metallicity floor, we find $[\mathrm{Fe/H}]_0 \sim -4.5 \pm 0.2$ dex. However, a model with zero initial metallicity also provides a good fit to the data, as shown by the dotted curve in Fig. 5, and is effectively indistinguishable.

3.3. Comparing the dSph to the Galactic halo

To establish the relation between the dwarf satellites of our Galaxy and its putative building blocks, we now compare the metal-poor tail of the metallicity distributions of the dSph and the Galactic halo. By focusing on the most

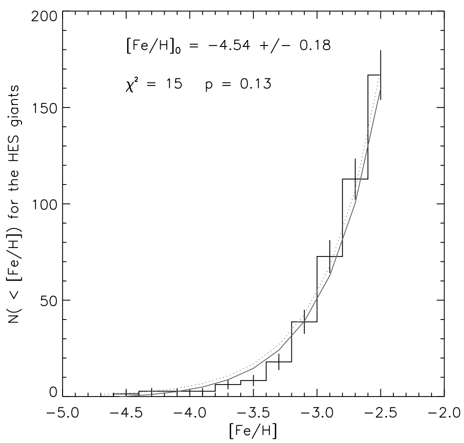

Fig. 5. Distribution of metallicities for Galactic halo giant stars from the HES sample with [Fe/H] < −2.4 dex. The solid and dotted grey curves show the closed box model fit to the metal poor tail with and without pre-enrichment, respectively.

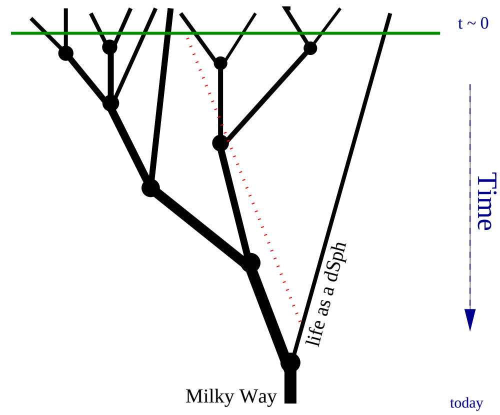

Fig. 6. A schematic merger tree for our Galaxy. The Galactic building blocks have merged at high redshift, while other small galaxies, such as the dSph, evolve independently and become satellites of the Milky Way at late times (right most branch). To establish the link between these classes of objects, their properties should be compared at the same epoch (i.e. along the horizontal axis, and not across time as indicated by the dotted line).

metal poor stars we are probing the very first stellar populations formed in these galaxies.

This approach is completely different from the comparisons carried out in previous works, where the *present-day* properties of the dSph were contrasted to those of the Galactic halo (Unavane, Wyse & Gilmore 1996; Venn et al. 2004). As Fig. 6 illustrates, such a comparison may be misleading. The building blocks accreted at early epochs have had little time as independent entities, while the dSph have been able to evolve at a more leisurely pace over a Hubble time (Font et al. 2006). There is, therefore, no reason to believe *a priori* that they should resemble one another at the present time.

The HES survey contains ~ 40 giants below a −3.0 dex limit; 130 stars with [Fe/H] < −2.5 dex and ~400 stars with [Fe/H] < −2.0 dex (Christlieb, Reimers & Wisotzki 2004). We have 320 stars in the dSphs with [Fe/H] < −2.0 dex, of which only 29 have [Fe/H] < −2.5 dex, and none have [Fe/H] < −3.0 dex. The contrast is stark, but could our inability to find very metal-poor stars (< −3 dex) in the dSph simply be an artifact of the sample size?

We have quantified how significant this issue really is by adopting the conservative approach of only considering stars with [Fe/H] < −2.5 dex, where the HES survey is most likely to be complete. We bootstrapped the HES metallicity distribution below [Fe/H] ~ −2.5 dex to make random subsets of 10 stars, which is the maximum we have below −2.5 dex for any one of our dSph samples. We then derive the mean distribution for 1000 such subsets. By means of a Kolmogorov-Smirnov test, we have quantified the probability that the bootstrapped HES distribution is consistent with the metallicity distribution of each individual dwarf galaxy. We find that the probability is very low in all cases, ranging from 8×10^{-4} for Sextans, to 4×10^{-3} for Carina and 8×10^{-3} for Sculptor and Fornax (see Fig. 7). Therefore, we conclude that the tails of the metallicity distributions of the stars in the dwarf galaxies and in the Galactic halo are very different at highly significant levels. Interestingly, the metallicity distributions at low [Fe/H] of all dwarfs are consistent with one another at the 1-σ level.

4. Summary

We have shown that the Sculptor, Sextans, Carina and Fornax dSph do not contain stars more metal-poor than [Fe/H] $\sim$ -3 dex. This suggests that the first generations of stars in the dSph were formed from a rather homogeneous chemically enriched intergalactic medium. This surprising result leads to the unavoidable implication that any merging, even very early merging, of the progenitors of the nearby dwarf galaxies as a mechanism for building up the Galactic halo is ruled out. The absence of very metal-poor stars in dSph shows that the progenitors of the Milky Way and the dSph must have been different. In this sense, our findings challenge recent models in which the dwarf spheroidals are fossils from the early Universe and indistinct from the Galactic building blocks (Diemand et al. 2005; Gnedin & Kravtsov 2006).

We can think of at least two explanations for why the Galactic building blocks may be different from the high-redshift progenitors of the present-day dwarf galaxies.

The Galactic building blocks formed from the collapse of high-σ density fluctuations in the very early Universe, while the dwarf satellites stem from low-σ peaks, which are predicted to collapse on average at much lower redshifts; e.g., a 1-σ density fluctuation of mass $10^8 M_\odot$ collapses at $z \sim 4$ in a ΛCDM universe (Qian & Wasserburg 2004). It is interesting to note that absorption line spectra towards quasars show that the intergalactic medium at this redshift has a mean metallicity of [Fe/H] $\sim$ -3 dex, a value that is consistent with the lowest metallicity stars found in our dSph sample. This would mean the oldest stars in the dSph are $\sim$ 12 Gyr old, formed after the Universe was reionized and from a pre-enriched intergalactic medium.

A second explanation could be that the initial mass function (IMF) behaved differently in Galactic building blocks and dSph at the earliest times. This is a possible interpretation of the observational fact that the Galactic halo contains some low-mass very metal poor stars which are not seen in dSph. For example, Nakamura & Umemura (2001) suggest that

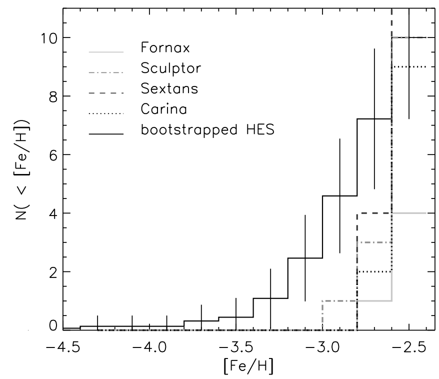

Fig. 7. Comparison of the cumulative metallicity distributions of the stars in the bootstrapped HES sample and in the dSph as derived by DART.

low-mass stars can form even from zero metallicity gas. However, this would only be possible if the initial density of the gas is sufficiently large, and so this would be favoured in high-σ peaks collapsing at very early times.

To summarize, it is tempting to state that the puzzle we have come to discover almost implies that those stars which formed in the high-redshift progenitors of dSph knew they would end up in dwarf galaxies today, and not as field halo stars around large galaxies like the Milky Way.

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