Session IV

Chemical Abundances Constraints on Mass Assembly and Star Formation

2 - Dwarf galaxies

Anna Frebel during her talk.

Monika Petr-Gotzens, Vanessa Hill, Denise Gonçalves, Corinne Charbonnel and Francesca Primas at the IAU banquet at Morro da Urca (Sugar Loaf mountain).

https://doi.org/10.1017/S1743921310000608 Published online by Cambridge University Press

Chemical Abundances in the Universe:
Connecting First Stars to Planets
Proceedings IAU Symposium No. 265, 2009
K. Cunha, M. Spite & B. Barbuy, eds.

doi:10.1017/S1743921310000608

Abundance patterns and the chemical enrichment of nearby dwarf galaxies

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Abstract. As the least massive galaxies we know, dwarf spheroidal galaxies (dSph) allow to probe chemical enrichement on the smallest scales, and perhaps in its simplest expression. Particularly interesting are the issues concerning the efficency with which metals are retained or lost in these shallow potential wells (supernovae feedback), and the effect of this on star formation itself. Another fundamental issue concerns the earliest epochs of star formation: are first stars formed in similar ways and proportions in all halos ? Finally, as the smallest galaxies know, dSph have been suggested to be the surviving cousins of galaxy building blocs that (in λ-CDM) assemble to make larger galaxies. This parenthood would not necessarily hold at all late times, when survivors have lived their own differentiated life, but is expected at least at the earliest epochs.

I review here the chemical abundances of individual stars in the nearest dwarf spheroidal galaxies, that have become available in increasing numbers (sample size and galaxies probed) in the last decade. Special emphasis is given to: a) recent results obtain with FLAMES on VLT, highlighting the power of detailed chemical abundance patterns of large samples of stars to unravel the various evolutionnary paths followed by dSph; b) the oldest and most metal-poor populations in dSph.

Keywords. stars: abundances, galaxies: abundances, galaxies: evolution, galaxies: formation, Local Group

1. Introduction

The detailed chemical abundance patterns in individual stars of a stellar population provide a fossil record of chemical enrichment over different timescales. As generations of stars form and evolve, stars of various masses contribute different elements to the system, on timescales directly linked to their mass. These studies require precise measurements of elemental abundances in individual stars, only achievable with high-resolution and reasonably high signal-to-noise spectra. It is only very recently that this has become possible beyond our Galaxy. It is efficient high-resolution spectrographs on 8−10m telescopes that have made it possible to obtain high resolution (R>40000) spectra of RGB stars in nearby swarf spheroidals (dSphs) and O, B and A super-giants in more distant dwarf irregulars (dIs). These stars typically have magnitudes in the range V=17 − 19. After the pioneering works of Shetrone *et al.* (1998, 2001) and Bonifacio *et al.* (2000) in dSphs, or Venn *et al.* (2003) and Kaufer *et al.* (2004) in dIs, samples have slowly started to grow. In the following, I will concentrate on the case of classical dSph galaxies, in which samples now reach for the first time samples sizes within in a given galaxy large enough to actually follow its chemical enrichment. Further considerations about dIs and the faintest dSph (known as ultra-faint dwarf spheroidal galaxies) can be found in Tolstoy, Hill & Tosi (2009).

2. Alpha elements

α/Fe, is commonly used to trace the star-formation timescale in a system, because it is sensitive to the ratio of SNII (massive stars) to SNIa (intermediate mass binary systems with mass transfer) that have occurred in the past. SNIa progenitors have a longer lifetime than SNII and as soon as they start to contribute they dominate the iron enrichment and [α/Fe] decreases. This is seen as a *knee* in a plot of [Fe/H] vs. [α/Fe], see Fig. 1. The knee position indicates the metal-enrichment achieved by a system by the time SNIa start to contribute to the chemical evolution, i.e. a galaxy that efficiently produces and retains metals will reach a higher metallicity by the time SNIa start to contribute than a galaxy which either loses significant metals in a galactic wind, or simply does not have a very high astration. The position of this knee is expected to be different for different dSphs because of the wide variety of star formation histories. The level of α/Fe in metal-poor stars (before the *knee*) is on the other hand sensitive of the high-mass IMF and selective galactic winds.

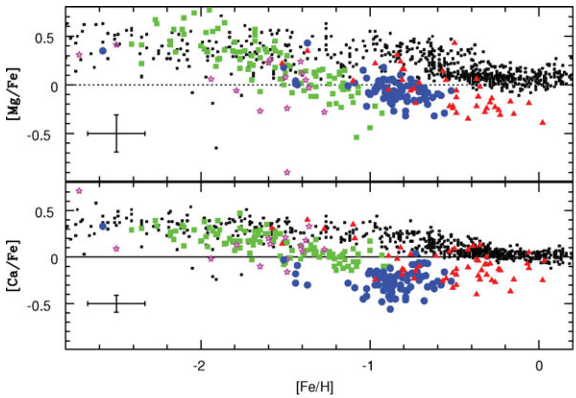

Figure 1. Abundances of two α-elements Mg and Ca in dSPhs (large coloured symbols), compared to the Milky-Way disc and halo (small black dots Venn *et al.* 2004). Sgr (red triangles: Sbordone *et al.* 2007, Monaco *et al.* 2005, McWilliam & Smecher-Hane 2005), Fnx (blue circles: Letarte *et al.* 2009, Shetrone *et al.* 2003), Scl (green squares: Hill *et al.* in prep, Shetrone *et al.* 2003, Geisler *et al.* 2005) and Carina (magenta stars: Koch *et al.* 2008a, Shetrone *et al.* 2003).

The knee : The apparent paucity of α-elements (relative to iron) in dSph galaxies compared to the MW disk or halo was first noted by (Shetrone *et al.* 1998, 2001, 2003, Tolstoy *et al.* 2003) from small samples. Fig. 1 shows this convincingly over most of the metallicity range in each system. However, it also appears that each of these dSphs starts, at low [Fe/H], with [α/Fe] ratios similar to those in the MW halo at low metallicities, thereby defining the location of the *knee*. At present the available data only cover the knee with sufficient statistics to quantify the position in the Sculptor (Scl) dSph, a system which stopped forming stars 10 Gyr ago, and the knee occurs at [Fe/H]≈ -1.8. This is the same break-point as the two kinematically distinct populations in this galaxy Tolstoy *et al.* (2004). This means that the metal-poor population has formed before any SNIa enrichment took place, which means on a timescale shorter than 1 Gyr. In other dSphs the knee is not well defined due to a lack of data, but limits can be established that suggest that not all dSphs have a knee at the same position. The Carina dSph has had an unusually complex SFH, with at least three separate bursts of star formation (Hurley & Tout 1998). The abundance measurements in Carina are presently too scarce to confidently detect these episodes in the chemical enrichment pattern, but Carina appears to possesses [α/Fe] poor stars between [Fe/H] $= -1.7$ and -2.0, which suggests

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that the knee occurs at lower [Fe/H] than in Scl. As shown by Cohen & Huang (2009), Draco may be an even more drastic example where the *knee* may appear as low as [Fe/H] ~ -2.8. At the other extreme, Sagittarius (Sgr) has enhanced [α/Fe] up to [Fe/H] ≈ -1.0, which is significantly more metal-rich than the position of the *knee* in Scl. This is consistent with what we know of the SFH of Sgr, which has steadily formed stars over a period of 8−10 Gyrs, and only stopped forming stars about 2−3 Gyr ago (e.g., Dophin & Kennicutt 2002). In the Fornax (Fnx) dSph, another galaxy with a complex SFH, the sample does not include a sufficient number of metal-poor stars to determine even an approximate position of the *knee*. From this (small) sample of dSph galaxies, it appears that the position of the *knee* correlates with the total luminosity of the galaxy, and the mean metallicity of the galaxy, suggesting that the presently most luminous galaxies are those that must have formed more stars at the earliest times and/or retained metals more efficiently than the less luminous systems.

Low-metallicity stars The abundance ratios observed in all dSphs for stars on the metal-poor side of the *knee*, tend to be indistinguishable from those in the Milky-Way halo. It therefore seems that the first billion year(s) of chemical enrichment gave rise to similar enrichment patterns in small dwarf galaxies and in the Milky-Way halo, at least in systems as luminous as Scl, Fnx or Sgr.. This is comsistent with a constant IMF, with no need to resort to incomplete IMF sampling as was proposed early on (Tolstoy *et al.* 2003, Carigi & Hernandez 2008). Furhermore, this opens up a window for merging dSph-like Milky-Way halo building blocks, at a time when their internal chemical evolution was not yet visible.

On the other hand, there is now a hint that the slightly less luminous Sextans (Mv=-9.5) could display a scatter in the α/Fe ratios at the lowest metallicities, including [α/Fe] close to solar Aoki *et al.* (2009). Such a scatter is so far observed only in this purely old system, and suggests a very inhomogeneous metal-enrichement in this system that presumably never retained much of the metal it produced. The true extent of this scatter in Sextans remains to be investigated, and extension to other similar sytems is needed before general conclusions can be reached on the mechanisms leading to the chemical homogeneity -or not- of dwarf galaxies. Note that based on hydrodynamical Nbody simulations, Revaz *et al.* (2009) suggest that the degree of inhomogeneity is linked to the galaxy total mass (through low-level star formation stochasticity), and that the least massive systems are expected to be inhomogeneous.

3. Neutron capture elements

Despite their complicated nucleosynthetic origin, heavy neutron capture elements can provide useful insight into the detailed chemical evolution of galaxies. The *r*-process production site is clearly associated with massive star nucleosynthesis. The most plausible candidate being SNII, although the exact mechanism to provide the very large neutron densities needed is still under debate (e.g., Sneden *et al.* 2008 and references therein). The *r*-process elements should therefore contribute to the chemical enrichment of a galaxy with very little delay, if any. The *s*-process is well constrained to occur in low to intermediate-mass ($1 - 4M_{\odot}$) thermally pulsating AGB stars (see Busso *et al.* 1999 and references therein), and therefore provide a contribution to chemical enrichment that is delayed by $\sim 100 - 300$ Myrs from the time that the stars were born. Thus *r*-process over *s*-process elements ratios can in principle be used to probe star formation on similar timescales to [α/Fe]. Fig. 2 compares the abundances of Ba (that can be produced both by the *r*- and the *s*- processes) and Eu (predominantly an *r*-process element) in four dSph galaxies and in the Milky-Way. In the MW, the Ba and Y are dominated by the

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r-process for [Fe/H] $\leqslant -2.0$ (e.g., Travaglio *et al* 2004), while the s-process dominates at higher metallicities.

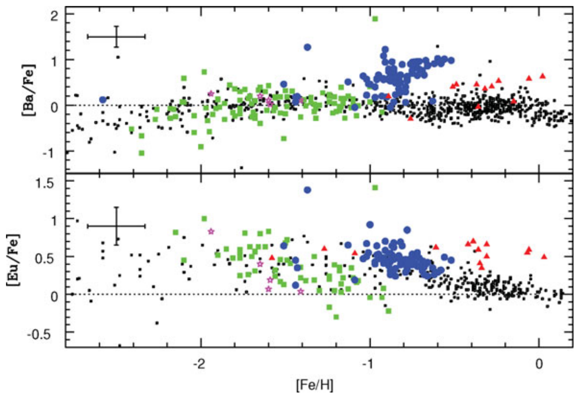

Figure 2. Abundances of two neutron-capture elements Ba (s- and r- processes) and Eu (r-process element) in dSphs (large coloured symbols), compared to the Milky-Way disc and halo. Symbols and references as in Fig.1

At early times (at [Fe/H] < -1) there seems to be little difference between the various dSphs, and the MW halo in Fig 2. The scatter and downturn of [Ba/Fe] at and below [Fe/H] $= -3$ is a well known feature in the MW halo and references therein]Francois07, Barklem05. In the dwarfs however, there is a hint that this may occur already at higher metallicities ([Fe/H] < -1.8). This hint is confirmed in Fig. 5 which includes very metal-poor stars in other dSphs, although from much smaller samples (see figure caption). This should still be regarded as a tentative hint, because of the low number statistics for dSph low-metallicity stars. But if confirmed with larger samples, these low r-process values at higher [Fe/H] than in the Galactic halo would either mean that the dwarf galaxies enriched faster than the halo at the earliest times or that the site for the r-process is less common (or less efficient) in dSphs.

The Ba/Eu ratio, shown in Fig. 3 (left panel), indicates the fraction of Ba produced by the s-process to that produced by the r-process. In dSph, as in the MW, the early evolution of all neutron-capture elements is dominated by the r-process (as was already noted by Shetrone *et al.* 2001, 2003). In each system, however, the low and intermediate mass AGB stars contribute s-process elements, that soon start to dominate the Ba (and many other neutron capture elements) production. The metallicity at which this switch from r- to s-process is only somewhat constrained in the Scl dSph. It is found to occur at [Fe/H]~ -1.8, which is the same as the [α/Fe] *knee*. This turnover needs to be better constrained in Scl and even more so in other galaxies to provide timing constraints on the chemical enrichment rate. It could reveal the metallicity reached by the system at the time when the s-process produced in AGBs starts to contribute.

For the more metal-rich stars ([Fe/H] > -1) there is also a distinctive behaviour of [Ba/Fe] in dSphs (Fig. 2). In the Scl dSph the [Ba/Fe] values never leave the MW trend, but this galaxy also has almost no stars more metal-rich than [Fe/H]< -1. Fnx, on the other hand, and to a lesser extent Sgr, display large excesses of barium for [Fe/H]> -1. This is now barium produced by the s-process, and it shows the clear dominance of the s-process at late times in dSphs. Furthermore, Fig. 3 (left panel) shows that, in the domain where the neutron-capture enrichment is dominated by the s-process, [Y/Ba] in dSphs are exceedingly low. The most straight-forward interpretation assumes that low-metallicity AGB stars dominate the s-process, following the expectation that low-metallicity AGBs

https://doi.org/10.1017/S1743921310000608 Published online by Cambridge University Press

nucleosynthesis favours high-mass nuclei over lower mass ones (Busso *et al.* 1999). Note however that another interpretation put forward by Lanfranchi *et al.* (2008) is that chemical evolution models, in which low [Y/Ba] is reached by simply decreasing the r-/s-fractions at late times (as above, due to galactic winds loosing preferentially r-process elements).

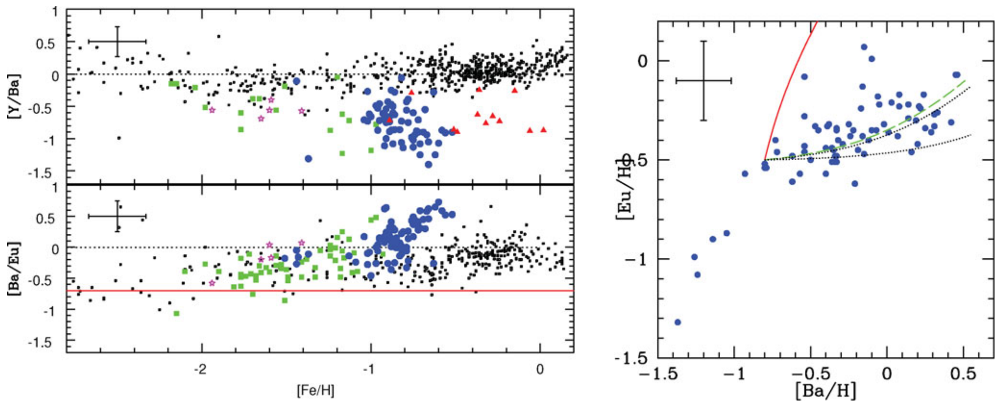

Figure 3. *(Left panel) :* Ba/Y and Ba/Eu abundance ratios in dSphs (large coloured symbols), compared to the Milky-Way disc and halo. Symbols and references as in Fig.1. *(Right panel) :* Eu/H run versus Ba/H in Fornax (large circles, Letarte *et al.* 2009), compared to simple models assuming, starting at [Ba/H] = −0.8 [Ba/H] = −0.5 (where the Ba/Fe rise occurs in Fnx, see Fig. 2): a pure r-process enrichment (solid red line), a 90% s-process and 10% r-process contribution (long dashed green line), a pure s-process enrichment using respectively solar and −1.14 metallicity AGB Ba/Eu yields (Cristallo *et al.* 2009; dotted black lines)

Finally, let us remark an interesting consequence of the drastic s-process enhancement in the late evolution of Fnx (and perhaps Sgr). At first glance, the Eu evolution in dSph galaxies (Fig. 2) resembles that of their respective α-elements (see Fig. 1), as expected for an r-process originating in massive stars. However, Eu/Fe in both Fnx and Sgr, fail to decrease to subsolar values as their corresponding α/Fe do (an alternative way to look at this is to note that the r-/α increase noticeably in these two galaxies at high metallicity). This has been noted by various authors (Bonifacio *et al.* 2000, McWilliam *et al.* 2005, Letarte *et al.* 2009): with a constant IMF and an r-process originating in massive stars, r-/α should be insensitive to star formation histories. We propose here (as in Letarte *et al.* 2009 an alternative explanation (Fig. 3, right panel), noting that new s-process yields as a function of AGB initial metallicity (Cristallo *et al.* 2009) feature a varying Eu to Ba production ratio, with Eu/Ba increasing with decreasing AGB metallicity (by a factor ~ 4 between a solar and ~ -1.14 metallicity AGB). Assuming the increased Eu/Ba ratios in low-metallicity AGB yields, we suggest a significant part (if not all) of the Eu at high metallicities in Fnx may originate in the s-process rather than the $r-$process, thereby relieving the r-/α increase in this galaxy.

4. Low metallicity tails in dwarf galaxies

In the paper of Helmi *et al.* (2006), the DART collaboration found that dwarf spheroidal galaxies lacked the most metal-poor stars, compared the galactic halo as probed by the Hamburg ESO Survey (HES, Christlieb *et al.* 2004). Indeed, when considering the whole sample of stars in the four dSph galaxies Fornax, Sculptor, Sextans and Carina, a distinctive lack of stars with metalicities [Fe/H] < -3 was found. This conclusion was based on metallicities obtained from low resolution spectra at the infrared Ca II triplet, empirically calibrated using globular clusters and high-resolution metallicities of stars in Sculptor and Fornax (Battaglia *et al.* 2008). In the meantime, the low metallicity tail of the galactic halo distribution has been revised downwards, taking into account biases arising from the design of the HES to find the most metal-poor stars, and bringing the halo closer to the dSph metallicity distributions (Schörk *et al.* 2009). More importantly still, we have undertaken a systematic study of the low-metallicity tail of the four abovementioned galaxies by :

(i) building up a new calibration of the Ca II triplet based on synthetic spectra rather than observed globular clusters stars (Starkenburg *et al.* in prepartion). Indeed, because of the Ca II triplet lines change regime, from strongly wing dominated in giants of metallicities > -2 to core dominated in very metal-poor giants (< -3), the empirical simple linear relation between the equivalent width of the Ca II triplet lines (reduced, by folding in a luminosity-dependent factor) and the metallicity is not expected to hold down to the lowest metallicities. The new synthetic spectra based calibration overlays nicely the empirical relation down to metallicities of ~ -2.0, but deviates strongly at the lowest metallicities: as illustrated in Fig.4 left panel, the slope of the equivalent widths versus luminosities differs from the empirical one, and the metallicity dependency becomes shallower. Both these effects concur to produce a bias in the Ca II metallicity estimates based on the empirical calibration at the lowest metallicities.

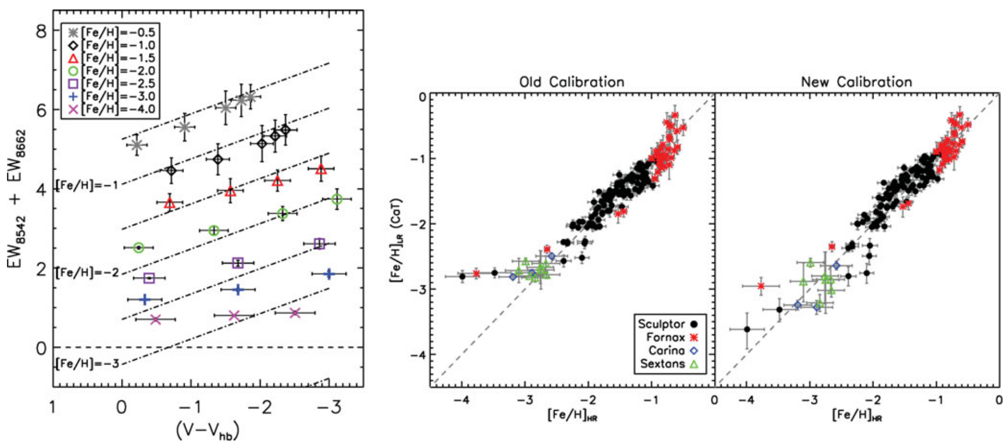

Figure 4. *(left panel):* empirical (dotted lines) and synthetic spectra based (symbols according to metallicity) relations between the Ca II triplet equivalent widths (sum of the two strongest lines) and luminosity for various metallicities. The two relations agree for metallicities $\geqslant -2$; at low metallicities, the empirical relation is too steep and lines of iso-metallicities are too far appart compared to the synthetic spectra expectations. *(middle and right panels):* metallicities deduced from Ca II triplet ($[Fe/H]_{LR}$) using the empirical (*middle*, Battaglia *et al.* 2008) and synthetic spectra based (*right*) calibrations are compared to metallicities measured in high-resolution spectra of DART samples ($[Fe/H]_{HR}$). The clear bias observed at the lowest metallicities with the empirical relation disapears once the true (synthetic spectra) behaviour of the Ca II lines is taken into account in our new calibration.

(ii) endertaking a high resolution follow-up of the most promissing candidates (Taflemeyer *et al.* in preparation, Aoki *et al.* 2009 and Venn *et al.* in preparation). This has allowed us to firmly establish the presence of very low metallicity stars in dSph (down to -4 in Sculptor, Tafelmeyer *et al.* in prepartion), and to build a comparison sample to validate the new Ca II calibration (Fig. 4).

Using the new calibration, we revisit the metallicity distribution of dSph (Starkenburg in prep.). Fig. 5 (left panel) shows that while the metallicity distribution is globally unchanged, the shape of the metal-weak tail is altered, the new calibration providing a more extended tail. It is thus now clearly established that dSph contain, albeit in small numbers, extremely metal poor stars, at least down to ~ -4 metallicity. There does not seem to be a clear difference between classical dSph galaxies and the ultra-faint dwarfs in this respect anymore (Kirby *et al.* 2008).

Thanks to the high-resolution follow-up of the extremely metal-poor candidates ([Fe/H] < -3) from these galaxies (by the DART collaboration, but also other groups, Fulbright, Rich & Castro 2004, Cohen & Huan 2009, Frebel *et al.* 2009, Frebel *et al.* 2009, this conference), not only the metallicity, but also the detailed chemical composition extremely metal poor stars can also be probed, and Fig. 5 shows Mg/Fe and Ba/Fe for a compilation of known stars in classical and ultra-faint dwarf galaxies below [Fe/H] < -2.3. There is a global agreement in the abundance ratios of extremely metal poor stars ([Fe/H] < -3) in dwarfs galaxies and the Milky-Way halo.

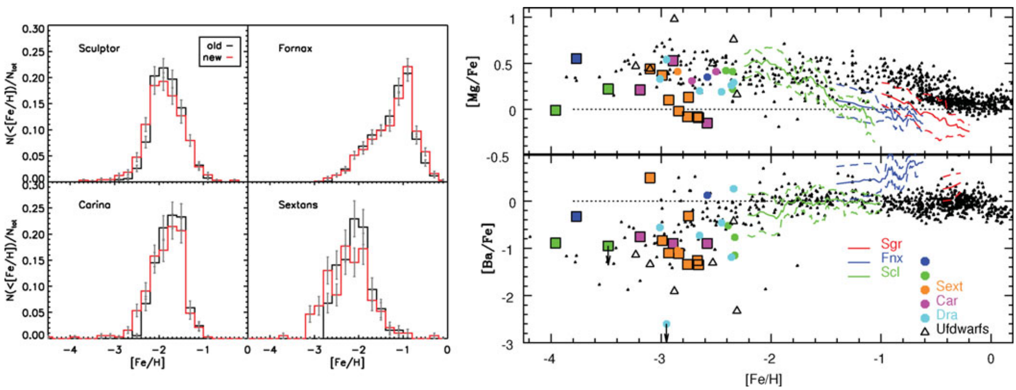

Figure 5. (*Left panel*) Metallicity distributions of Sculptor, Fornax, Carina and Sextans, with the Battaglia *et al.* (2008) (black) and new Starkenburg *et al.* (in preparation) (red/grey) calibrations. The metallicity distribution now clearly extends down to [Fe/H] $= -3$ and below. (*Right panel*) Abundance ratios Mg/Fe and Ba/Fe as a function of metallicity for stars with [Fe/H] < -2.3 in classical (large squares: DART follow-ups, Tafelmayer *et al.* in preparation (Scl, Fnx, Sext), Venn *et al.* in preparation (Car), Aoki *et al.* 2009 (Sext); filled circles: see refs in Fig 1 and Cohen et & Huang 2009 (Draco)) and ultrafaint (triangles: Frebel *et al.* 2009, Koch *et al.* 2008b). The mean trends (running average on 10 points) and dispersion of Scl, Fnx and Sgr (as of Figs. 1 and 2) are indicated as lines.

Acknowledgements

This paper is mostly based on the work of the DART *Dwarf Abundances and Radial velocity Team* collaboration, and on the review paper of Tolstoy, Hill & Tosi (2009)

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