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/S174392131000061X

Complexity in small-scale dwarf spheroidal galaxies

Andreas Koch[1], Daniel Adén[2], Eva K. Grebel[3], and Sofia Feltzing[2]

[1]University of Leicester, University Road, LE1 7RH Leicester, UK
email: `ak326@astro.le.ac.uk`

[2]Lund Observatory, Box 43, SE-221 00 Lund, Sweden

[3]Astronomisches Rechen-Institut, Mönchhofstrasse 12-14, 69120 Heidelberg, Germany

Abstract. Our knowledge about the chemical evolution of the more luminous dwarf spheroidal (dSph) galaxies is constantly growing. However, little is known about the enrichment of the ultrafaint systems recently discovered in large numbers in large Sky Surveys. Low-resolution spectroscopy and photometric data indicate that these galaxies are predominantly metal-poor. On the other hand, the most recent high-resolution abundance analyses indicate that some of these galaxies experienced highly inhomogenous chemical enrichment, where star formation proceeds locally on the smallest scales. Furthermore, these galaxy-contenders appear to contain very metal-poor stars with [Fe/H]< -3 dex and could be the sites of the first stars. Here, we consider the presently available chemical abundance information of the (ultra-) faint Milky Way satellite dSphs. In this context, some of the most peculiar element and inhomogeneous enrichment patterns will be discussed and related to the question of to what extent the faintest dSph candidates and outer halo globular clusters could have contributed to the metal-poor Galactic halo.

Keywords. stars: abundances, Galaxy: evolution, Galaxy: halo, globular clusters: individual (Pal 3), galaxies: abundances, galaxies: dwarf, galaxies: evolution, galaxies: individual (Hercules), galaxies: stellar content

1. Introduction

Dwarf spheroidal (dSph) galaxies are intriguing for a plentitude of reasons: Owing to their very low luminosities ($M_V \geqslant -14$ mag) they have been characterized as faint systems ever since their first discovery. They further have low total masses of only a few 10^7 $M_\odot$ and a puzzling deficiency of gas (e.g., Grebel *et al.* 2003; Bailin & Ford 2007; Gilmore *et al.* 2007). Over the past three years, the faint end of the galaxy luminosity function has been traced even further down, towards the *ultrafaint* regime. These "ultrafaint" dSphs, discovered in large number in sky surveys such as the SDSS, are now the faintest galaxies known to exist in the Universe, with absolute magnitudes above $M_V > -6$, and stellar masses of up to a mere few ten thousand Solar masses (e.g., Martin *et al.* 2008).

Furthermore, the dSphs are fairly metal-poor systems, with mean metallicities starting at -1 to -2 dex and decreasing. The range of metallicity in a given dSph is normally large and of up to 0.5 dex. Typically these spreads greatly exceed the measurement errors. Despite deep photometric studies and complementing spectroscopy for selected stars, the detailed properties of these ultrafaint galaxies remain poorly investigated until now. Interestingly, the ultrafaint dSphs are more metal-poor on average than their more luminous counterparts; their mean metallicities reach as low as about -2.5 dex (e.g., Simon & Geha 2007). While no star more metal-poor than [Fe/H]< -3 dex had been found in any of the classical dSphs until recently (e.g., Koch *et al.* 2006; Helmi 2006;

cf. Cohen & Huang 2009), several such metal-poor stars, down to −3.3 dex have been detected in the ultrafaint galaxies (Kirby *et al.* 2008; Norris *et al.* 2008; Frebel *et al.* 2009).

Although cosmological simulations like ΛCDM predict a wealth of small-scale substructures that hierarchically merge into larger structures like the present-day Milky Way (MW), a number of arguments against such a simplistic view has arisen over the years (Moore *et al.* 1999). Those comprise the oft-cited missing satellite problem, which is, however, nowadays much alleviated (e.g., Robertson *et al.* 2005; Simon & Geha 2007). Another problem is the discrepancy between the chemical abundances of the dSph stars compared to the halo stars (Sect. 2). Furthermore, the aforementioned apparent lack of very metal-poor stars in the dSphs was long considered a major contradiction to the large number of such stars, below −3 dex, found in the Galactic halo. This leaves us with the question of how and when the (ultrafaint) dSphs formed and evolved, and how they fit into the cosmological ΛCDM models. In particular, what fraction of dSph-like systems contributed to the build-up of the stellar halo of the MW?

2. Chemical abundances – The general picture

In Fig. 1 we show the [Ca/Fe] ratio, as an example of the α-element distribution, for the currently available data for dSphs (see Koch 2009 for a detailed review and the source of those data), in comparison to the Galactic disks and local halo stars. Since the first observations by Shetrone *et al.* (2001) that the dSph stars are systematically depleted in those elements relative to halo stars at the same metallicity (as already predicted by the models of Unavane *et al.* 1996), the abundance data have now vastly grown, with up to several tens of stars in a few of the more luminous systems (e.g., Koch *et al.* 2008a, 2009; Tolstoy *et al.* 2009) and progressive measurements in the fainter ones (e.g., Koch *et al.* 2008b; Frebel *et al.* 2009). The first thing to note is that this picture of α-depletion remains valid also when taking the new data into account. However, the new picture that slowly emerges is that there are in fact metal-poor stars below −3 dex found in the classical dSphs (Cohen & Huang 2009; Frebel *et al.*, this meeting [S265-o:18]) and in particular the ultrafaint dSphs appear to host a large number of those stars (Kirby *et al.* 2008; Norris *et al.* 2008; Frebel *et al.* 2009). For many of those stars, high-resolution abundance data are currently being gathered. The overlap of these metal-poor stars'

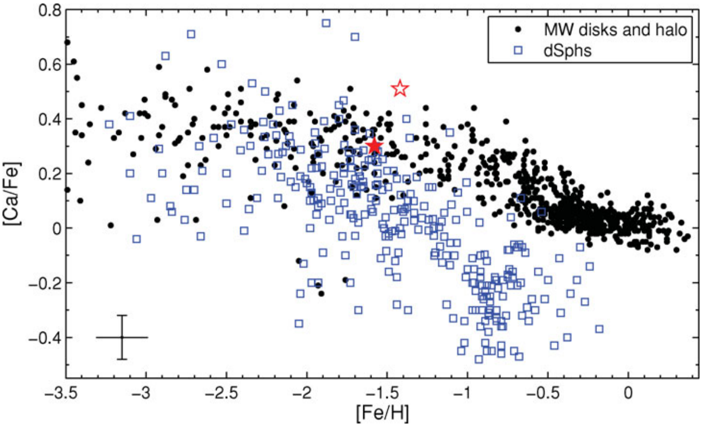

Figure 1. Currently available abundance data for Galactic stars (black dots) and dSphs (squares). See Koch (2009) for a detailed review of the sources for these data. Red symbols indicate the outer halo GCs Pal 3 (Koch *et al.* 2009) and Pal 4 (Koch & Côté in prep.)

abundances with those of the Galactic metal-poor halo plateau at [α/Fe]$\sim$+0.4 dex then underlines the picture in which the accretion and disruption of dSph-like systems had a major contribution to the *metal-poor halo at most*.

3. A case study – the Hercules dSph

Hercules (hereafter Her) is one of the “ultrafaint” dSph galaxies discovered in the SDSS (Belokurov *et al.* 2007). Past studies have established a low mean metallicity and indications of a low mass and a high mass-to-light ratio (Simon & Geha 2007).

3.1. *Chemical element abundances*

In Koch *et al.* (2008b) we showed that the elemental abundance patterns in Her are peculiar. Firstly, neither of the only two red giants analyzed in the literature to date show any evidence for heavy elements (e.g., Ba, Eu) above the noise in the spectra. Secondly, we found remarkably high abundance ratios of the hydrostatic (O, Mg) to the explosive α-elements (Si, Ca, Ti), see Fig. 2. This suggests that very massive stars were the main drivers for the chemical enrichment in Her. For instance, the high [Mg/Ca] of 0.6–1.0 dex in the Her stars suggests that stars of at least 30 $M_\odot$ governed the enrichment (Heger & Woosley 2008). Thus we may be seeing the results of stochastical enrichment in terms of an incompletely sampled IMF. Such abnormally high [Mg/Ca] ratios are also found in the low-mass dSph Boo I (Feltzing *et al.* 2009).

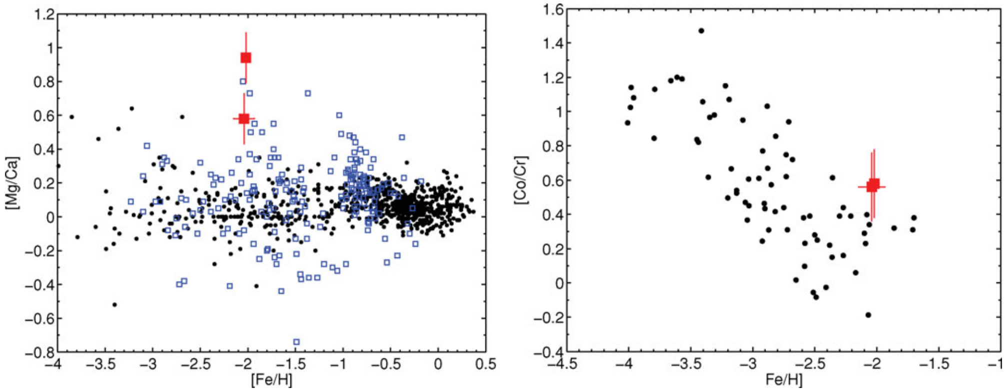

Figure 2. Left panel: [Mg/Ca] ratios for the same MW and dSph stars as in Fig. 1. Highlighted as red squares are the two stars in Her. The right panel shows the Her [Co/Cr] abundance ratio in comparison to the metal-poor Galactic halo stars of McWilliam *et al.* (1995).

Another peculiarity is the unusally high [Co/Cr] ratio (Fig. 2): at [Co/Cr]$\sim$0.58 dex, the two moderately metal-poor Her stars ([Fe/H] of −2 dex) rather resemble the metal-poor Galactic halo below $\sim$−2.5 dex. This is explicable, if we assume that Her was enriched towards its observed higher Fe-abundances through standard SNe Ia contributions according to its IMF, but it experienced an early enrichment from a first generation of metal-free, very massive Population III stars, the models of which reproduce the high [Co/Fe] and low [Cr/Fe] ratios very well. If this scenario is supported by further observations in other (fainter) stars in Her and other dSphs, it would mean that the ultrafaint dwarfs may in fact be the site of the very first generations of stars in the Universe.

3.2. *Clean member selection*

One difficulty in the interpretation of resolved galaxy properties from low- or medium resolution data is the inevitable contamination with Galactic foreground stars. While the member selection in some dSphs is straightforward, thanks to their high radial velocities of (positive or negative) several hundred km s^{-1} (e.g., Draco, Carina) and/or high Galactic latitudes, pure color-magnitude and radial velocity criteria in low-resolution mode fail for those cases where the dSphs are deeply embedded in the foreground. With a systemic mean velocity of 45 km s^{-1}, Hercules is in fact strongly affected.

In Adén *et al.* (2009a) we showed, however, that the dwarf contamination can be efficiently identified using Strömgren photometry: this filter system is able to discern the evolutionary stages of stars, based on a set of gravity sensitive index definitions (e.g., Faria *et al.* 2007). Using this we removed all the contaminating foreground dwarf stars. As a result, we could isolate a bona fide member sample of 45 red giants, AGB, RHB, and BHB stars. As it turned out, about five of the stars that overlap with previous studies (Simon & Geha 2007; Kirby *et al.* 2008) are likely foreground stars. The cleaned member candidate sample then yields a lower velocity dispersion and thus significantly lower mass by a factor of $\sim$3 (Adén *et al.* 2009b) compared to the literature (e.g., Simon & Geha 2007; Strigari *et al.* 2008). Furthermore, our sample is slightly more metal-rich than the previous estimates. Both from our calcium triplet spectroscopy and from the calibration of the Strömgren photometry onto metallicity, we find a mean [Fe/H] of -2.35 dex with a 1σ scatter of 0.31 dex. Currently, there are four objects known that have systemic radial velocities comparable to the Galactic foreground around 0–50 km s^{-1}, viz. CVn I, Willman I, Leo T, and Her. Therefore we emphasize the importance of a clear member selection for all future studies, by means of sophisticated photometric and spectroscopic techniques. High-resolution follow-up is vital for assessing the true stellar properties and sampling the true, full metallicity (preferably, iron) ranges of the dSphs.

4. The outer halo GC Palomar 3

Now that we argued about the role of the dwarf galaxies for building up parts of the Galactic halo, we can move on to the *outermost* halo and its globular clusters (GCs). It has long been known that there is a distinct dichotomy in the field star populations of the Milky Way (e.g., Hartwick 1987; Carollo *et al.* 2007) and also M31 (Koch *et al.* 2008c). Secondly, the lack of a metallicity gradient within the outer halo GC system as well as the occurrence of a pronounced second parameter problem had prompted the original scenario of the accretion origin of the Galactic halo by Searle & Zinn (1978). It is thus natural to ask, whether the outermost GCs are either potential building blocks of the halos or whether those systems have been donated to the halo themselves by disrupting dSph-like galaxies.

In order to look for chemical differences or similarities between those components, we carried out a spectroscopic study of the remote GC Pal 3 (R$\sim$92 kpc; e.g., Hilker 2006). This cluster is also one of the most extended GCs of the MW system (r_h $\sim$15 pc), and its proper motion, within its uncertainties, does not exclude the possibility that it is not bound to the MW at all. Our sample of 4 red giants, observed with the Magellan/MIKE spectrograph, supplemented by integrated abundances of 19 stars targeted with Keck/HIRES, however, showed that Pal 3 bears close resemblance to the majority of both inner and outer halo GCs (Koch *et al.* 2009). Its α-elements are enhanced to the halo value of $\sim$0.4 dex (Fig. 1), and its iron peak elements are compatible with Solar values. In fact, 80% of its abundance ratios are identical to those of the archetypical inner halo GC M 13 within the uncertainties; the same holds for a comparison with the outer halo cluster NGC 7492 (Cohen & Meléndez 2005a,b). On the other hand, Pal 3 does not resemble dSph field stars in any regard: the enhanced α abundances and most other abundance patterns are incompatible with, e.g., the α-depletions seen in the dSph stars. The situation is, however, slightly different for the GC system of the Fornax dSph

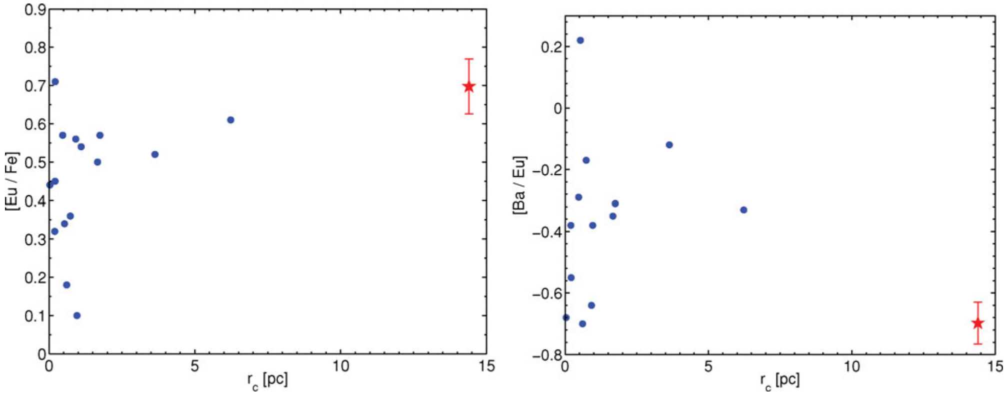

Figure 3. Abundance ratios of a sample of Galactic GCs (blue points) as function of their core radii. Pal 3 is denoted as a red star symbol.

(Letarte *et al.* 2006). Its abundance patterns are unlike the surrounding dSph field stars and rather appear to be similar to the patterns found in the Galactic halo and its GCs and a possible resemblance with Pal 3 cannot be refuted by the present data. However, the observed very small scatter of the Pal 3 stars advocates against the large abundance spreads detected in all of the Local Group dSphs analyzed to date and we conclude that Pal 3 (and Pal 4, Koch & Côté, in prep.) did likely not contribute any major fraction to the outermost halo, but rather are part of an underlying, genuine halo population.

There is yet one peculiarity found in Pal 3 that deserves notion: All the heavy elements in this cluster are fully compatible with a pure r-process origin without any need to invoke any significant contribution from the s-process. Such a behaviour has so far only been observed in very metal-poor field stars (e.g., Honda *et al.* 2007) and in the GC M 15 (Sneden *et al.* 2000) and its surrounding stellar stream (Roederer 2009, this meeting [S265-p:8]). Contrary to the massive progenitors that dominated the enrichment in the low-mass environment of the Her dSph, the n-capture patterns in Pal 3 do not require any such enrichment by massive stars, but are explicable by a standard r-process in $\sim$8 $M_\odot$ SNe II (e.g., Qian & Wasserburg 2003). A detailed interpretation of this loss of s-process material is beyond the scope of this work. We just remark that the large spatial extent of this loose cluster and the corresponding shallow potential could have favored an early loss of the ejecta of a first generation of AGB stars, followed by efficient star formation with a high SNe II rate leading to strong r-enrichment through this second generation of cluster stars (cf. D'Antona & Caloi 2008). While it is clearly unwarranted to discern any trend of the [r/Fe] and [r/s] ratios with structural parameters in Fig. 3, it is certainly noteworthy that Pal 3, with its large radius, also exhibits the highest [Eu/Fe] (likewise [Dy/Fe]), lowest [Ba/Eu] ratios, respectively. A complete and homogeneous survey of the n-capture elements within the Galactic GC system is clearly necessary.

References

Adén, D., *et al.* 2009a, *A&A*, in press (astro-ph/0908.3489)
Adén, D., *et al.* 2009b, *ApJL*, submitted
Bailin, J. & Ford, A. 2007, MNRAS, 375, L41
Belokurov, V., *et al.* 2007, *ApJ*, 654, 897
Carollo, D., *et al.* 2007, *Nature*, 450, 1020
Cohen, J. G. & Huang, W. 2009, *ApJ*, 701, 1053
Cohen, J. G. & Meléndez, J. 2005a, *AJ*, 129, 303

Cohen, J. G. & Melendez, J. 2005b, *AJ*, 129, 1607
D'Antona, F. & Caloi, V. 2008, *MNRAS*, 390, 693
Faria, D., *et al.* 2007, *A&A*, 465, 357
Feltzing, S., Eriksson, K., Kleyna, & Wilkinson, M. 2009, ApJL, in press
Frebel, A., Simon, J. D., Geha, M., & Willman, B. 2009, *ApJ*, submitted (arXiv:0902.2395)
Gilmore, G., *et al.* 2007, *ApJ*, 663, 948
Grebel, E. K., Gallagher, J. S., III, & Harbeck, D. 2003, *AJ*, 125, 1926
Hartwick, F. D. A. 1987, *NATO ASIC Proc. 207: The Galaxy*, 281
Heger, A. & Woosley, S. E. 2008, *ApJ*, submitted (arXiv:0803.3161)
Helmi, A., *et al.* 2006, *ApJL*, 651, L121
Hilker, M. 2006, *A&A*, 448, 171
Honda, S., Aoki, W., Ishimaru, Y., & Wanajo, S. 2007, *ApJ*, 666, 1189
Kirby, E. N., Simon, J. D., Geha, M., Guhathakurta, P., & Frebel, A. 2008, *ApJL*, 685, L43
Koch, A., *et al.* 2006, *AJ*, 131, 895
Koch, A., *et al.* 2008a, *AJ*, 135, 1580
Koch, A., McWilliam, A., Grebel, E. K., Zucker, D. B., & Belokurov, V. 2008b, *ApJ*, 688, L13
Koch, A., *et al.* 2008c, *ApJ*, 689, 958
Koch, A. 2009, *Astronomische Nachrichten*, 330, 675
Koch, A., Côté, P., & McWilliam, A. 2009, *A&A*, in press (astro-ph/0908.2629v1)
Letarte, B., Hill, V., Jablonka, P., Tolstoy, E., François, P., & Meylan, G. 2006, *A&A*, 453, 547
Martin, N. F., de Jong, J. T. A., & Rix, H.-W. 2008, *ApJ*, 684, 1075
Moore, B., *et al.* 1999, *ApJL*, 524, L19
Norris, J. E., *et al.* 2008, *ApJL*, 689, L113
Qian, Y.-Z. & Wasserburg, G. J. 2003, *ApJ*, 588, 1099
Robertson, B., Bullock, J. S., Font, A. S., Johnston, K. V., & Hernquist, L. 2005, *ApJ*, 632, 872
Searle, L. & Zinn, R. 1978, *ApJ*, 225, 357
Shetrone, M. D., Côté, P., & Sargent, W. L. W. 2001, *ApJ*, 548, 592
Simon, J. D. & Geha, M. 2007, *ApJ*, 670, 313
Sneden, C., Pilachowski, C. A., & Kraft, R. P. 2000, *AJ*, 120, 1351
Strigari, L. E., *et al.* 2008, *Nature*, 454, 1096
Tolstoy, E., Hill, V., & Tosi, M. 2009 *ARA&A*, in press (arXiv:0904.4505)
Unavane, M., Wyse, R. F. G., & Gilmore, G. 1996, *MNRAS*, 278, 727

Discussion

NOMOTO: Your abundance patterns in Hercules could also be explained by enrichment from faint Supernovae with progenitor masses of ∼25 $M_\odot$ [this meeting; S265-i:26].

KOCH: That is an interesting possibility and one should look into fits to the entire abundance distribution of the stars. In any case, 25 $M_\odot$ still leaves us in the high-mass regime for Her's enrichment.

SARAJEDINI: Are you saying from your data in only two GCs that the outer and inner halo are coeval? There is evidence that parts of the Galactic GCs were accreted from dSphs (e.g., the Sagittarius clusters).

KOCH: Our two clusters appear to have experienced a similar chemical evolution as the inner halo clusters. Furthermore, as opposed to the Sgr clusters, Pal 3 is not a member of any currently known stream.