Mem. S.A.It. Vol. 85, 519

Memorie della

Chemical substructure and inhomogeneous mixing in Local Group dwarf galaxies

K. A. Venn

University of Victoria, Victoria, BC, V8V 4L8, Canada, e-mail: kvenn@uvic.ca

Abstract. Evidence for inhomogeneous mixing in the Carina, Draco, and Sculptor dwarf galaxies is examined from chemical abundance patterns. Inhomogeneous mixing at early times is indicated in the classical dwarf galaxies, though cannot be ascertained in ultra faint dwarfs. Mixing efficiencies can affect the early metallicity distribution function, the pre-enrichment levels in globular clusters, and also have an impact on the structure of dwarf systems at early times. Numerical models that include chemical evolution explicitly do a better job in reproducing the observations, and make interesting predictions for the nature of dwarf galaxies and their first stars at the earliest times.

1. Introduction

As noted by Gerry Gilmore in the Assembling the Puzzle of the Milky Way conference (2012) "*Dwarf spheroidal galaxies are frequently assumed to represent surviving examples of a vast now destroyed population of small systems ... Ongoing accretion and considerable sub-structure in the outer Galactic halo is direct evidence.*" Obviously the prime example for ongoing accretion are the field stars and globular clusters associated with the Sgr dwarf galaxy remnant, as well as other streams found in the SDSS data, and the incredible substructure found around M31 in the CFHT PAndAS survey (Ibata et al. 1995, Belokurov et al. 2006, McConnachie et al. 2009).

On the other hand, Gilmore also notes that "*Dwarf spheroidal stellar populations are unlike any stars found in significant numbers in the Milky Way ... The overwhelming majority of Milky Way stars, those in the Galactic thick and thin disk, seem to have nothing at all to do with dwarf galaxy origins.*" This is clearly and cleanly shown from a comparison of the elemental abundances determined from high resolution spectroscopy by the ESO DART team, e.g., a comparison o f the [Ca/Fe] ratios and the distribution in the [Fe/H] ratios of stars in the Sculptor, Carina, Fornax, and Sagittarius dwarf galaxies are different from one another as well as from the majority of stars in the Galaxy (see Fig. 11 in Tolstoy et al. 2009).

2. Element ratios in dwarf galaxies

Only the chemical abundances in the lowest metallicity stars seem to have some features in common between some dwarf galaxies and the Milky Way, i.e., stars with [Fe/H] $\lesssim$ -2. Analysis of the [α/Fe] ratios ([Mg and Ca/Fe]) of most of the very metal poor stars in dwarf galaxies show similar ratios to very metal poor stars in the Milky Way as seen in Fig. 1 (Galactic data and ultra faint dwarf galaxy data from the compilation by Frebel et al. 2010a; for Carina from Venn et al. 2012, Lemasle et al. 2012, Koch et al. 2008, and Shetrone

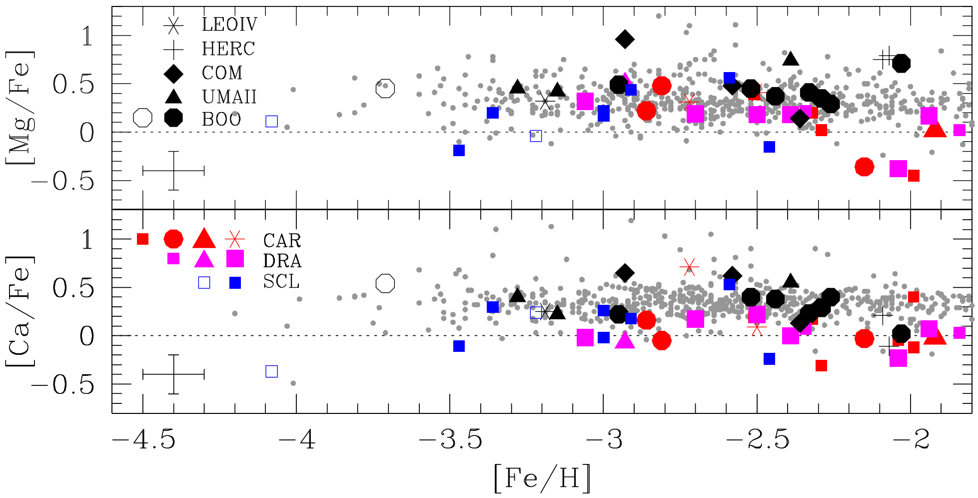

Fig. 1. The [α/Fe] ratios for the most metal-poor stars yet analysed in the Carina (red), Draco (magenta), and Sculptor (blue) dwarf galaxies compared with those in the ultra faint dwarf galaxies (black) and the Milky Way halo (grey). See text for references.

et al. 2003; for Draco from Cohen & Huang 2009 and Shetrone et al. 2001, and for Sculptor from Starkenburg et al. 2013 and Tafelmeyer et al. 2010), as opposed to the larger dispersions and differences seen for stars with [Fe/H] ≥ -2 discussed by Tolstoy et al. (2009).

The [α/Fe] ratios are even more similar for metal poor stars in the ultra faint dwarf galaxies (UFDs), i.e., [Mg/Fe] and [Ca/Fe] in Bootes I, UMa II, Com Ber, and Leo IV in Fig. 1 (from Feltzing et al. 2009, Norris et al. 2010, Frebel et al. 2010b, and Simon et al. 2010), then they are in the classical dwarf galaxies (dSphs, e.g., Carina, Draco, and Sculptor). In the dSphs, the dispersions in the [α/Fe] ratios near [Fe/H] = -2 can be quite large. When compared with the tiny dispersions in the metal poor stars in the Galaxy (Cayrel et al. 2004), this suggests the interstellar medium in the dSph galaxies may be very poorly mixed at early times.

This is further supported by the chemical abundances in one star in Carina (labelled Car-612 in Venn et al. 2012) which appears to be overabundant in iron-group elements (Cr, Mn, and Fe) by ~0.7 dex, causing [X/Fe] ratios to be much lower in this star and for nearly every element than for any other star in Carina. This is shown in Fig. 2 (data from Venn et al. 2012, Lemasle et al. 2012, Koch et al. 2008, and Shetrone et al. 2003). While various chemical evolution patterns have been examined to explain this star (see Venn et al. 2012 and Koch et al. 2008), this chemical pattern would be consistent with formation in a pocket of gas enriched in SN Ia products by a factor of 5. The only stars known to have a similar abundance pattern are three outer Galactic halo stars analysed by Ivans et al. (2003), who also proposed that the degree of mixing during their formation (which was assumed to be in an accreted dwarf galaxy) must have varied from region to region. The two stars with similarly low [Mg/Fe] values as Car-612 shown in Fig. 2 may also have formed in a pocket enriched in SN Ia yields, but there is no full spectral analysis available for these stars as yet where other element abundances can be determined.

Finally, we note that Car-612 does not appear to be a part of the foreground substructure found towards Carina by Kordopatis

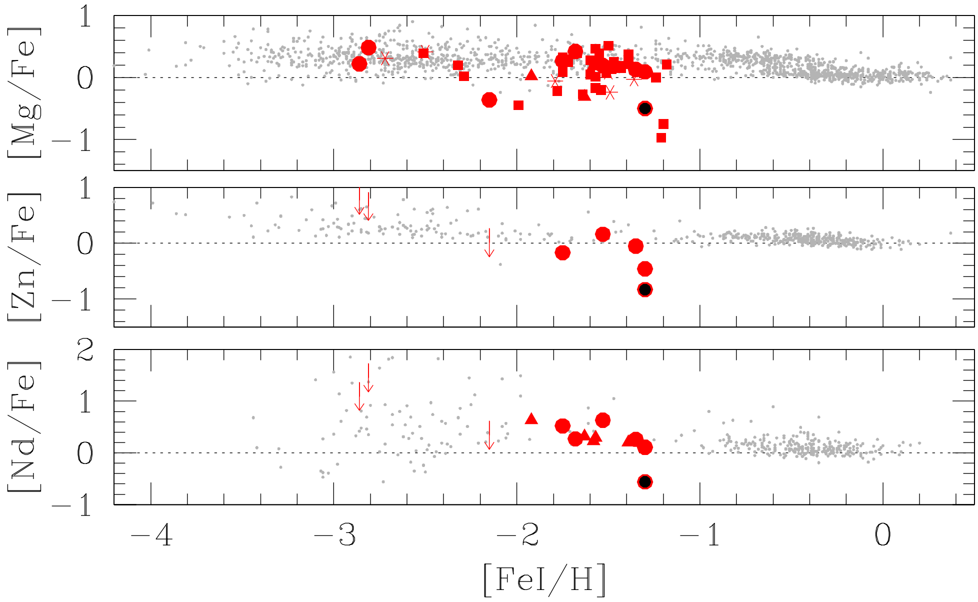

Fig. 2. The [X/Fe] ratios for stars in the Carina dwarf galaxy, to show how the star Car-612 stands out - a pattern that is repeated for nearly all elements in this one star - only Mg, Zn, and Nd shown. An usual enrichment of in SN Ia iron-products (Δ[Fe/H]~0.7) can reproduce this result, i.e., moving this star along the x-axis and down the y-axis due to increasing [Fe/H] alone.

et al. (2013), based on consideration of a log g=4.0 model.

3. Inhomogeneous mixing in models

The masses of the Carina and Draco dwarf galaxies (and also Sextans, which may show a similar behaviour, Jablonka et al. 2014, in prep.) are in a range just between the classical dwarf galaxies and the ultra faint dwarf galaxies (see Figure 11 by McConnachie 2012). Models of the chemical evolution of galaxies in this mass range do show larger abundance spreads and inhomogeneous mixing over longer timescales than more massive (classical) dwarf galaxies, according to the N-body Tree-SPH calculations by Revaz & Jablonka (2012).

Inhomogeneous mixing in the interstellar medium has been involked in several numerical models of dwarf galaxies. Governato et al. (2010) used an inhomogeneous ISM in a CDM model (rotating disk in a CDM halo) to drive higher SN losses, removing low angular momentum gas, and resulting in bulgeless dwarfs with flatter density profiles. Leaman (2012) and Oey (2003) compared the variance in the linear metallicities of dwarf galaxies and globular clusters and found they define very independent relationships. These relationships could be explained by a binomial distribution in size and enrichment level of the star forming regions, if the interstellar medium is not well mixed. Leaman (2012) further notes that this effect is only seen with linear metallicity, not the log (Fe) abundances, and the variance, not the standard deviations.

One of the more interesting numerical modelling results by Wise et al. (2012) finds that inhomogeneous mixing of the interstellar medium would be commonplace in early galaxies with intense merging rates. These models show the slow build up of metallicity in the host halo but combined with lower metal-

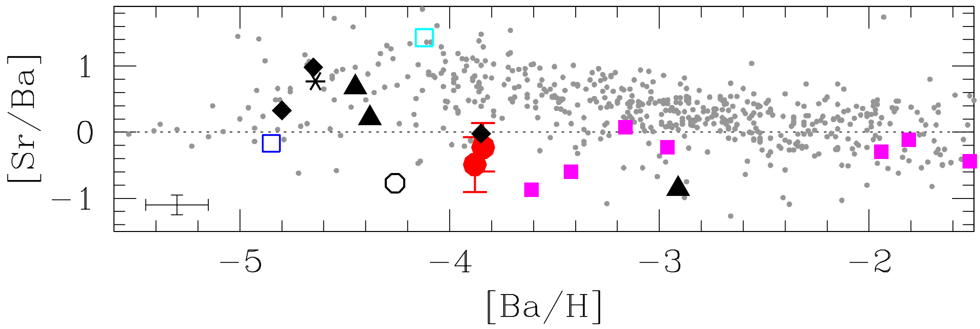

Fig. 3. The [Sr/Ba] ratios for the most metal-poor stars the Carina, Draco, and Sculptor dwarf galaxies compared with those in the ultra faint dwarf galaxies and the Milky Way (see text for references, same symbols as in Fig. 1; the one star in Fornax (cyan square) is from Tafelmeyer et al. 2010). Note that only three stars have [Fe/H] < −3.6 (the one star in each of Sculptor, Fornax, and Bootes I) which is the metallicity where Aoki et al. (2013) suggest the equation of state during the core collapse SN may affect these yields.

licity stars brought in from low mass satellites as well as forming in situ. One very interesting prediction from these models is that the *earliest* stars to form, those immediately after the first stars, could have a range in metallicities up to [Fe/H] = −2 due to variations in the size of the HI pocket that is enriched by the first stars. This is quite interesting in that it suggests that the most metal-poor stars in a low mass system are not necessarily the oldest.

Similar intense merging models of low mass halos to build the ultra faint dwarf galaxies, the classical dwarfs, and the Galactic halo by Salvadori & Ferrara (2009) are able to reproduce the observed metallicity distribution functions well (their Fig. 3). Their recent merger-tree models also show that metals ejected by supernova-driven outflows from dwarf galaxies with M < 10^9 $M_\odot$ can enrich the local Milky Way environment to [Fe/H] > −2 as early as the the end of reionization (Salvadori et al. 2014).

Wise et al. (2012) also examine the metal enrichment of a galaxy that undergoes very little merging before reionization. While the most metal-poor stars in this system tend to be the oldest stars, the in-situ star formation that occurs with metal-poor inflows from filaments at later times can also produce extremely metal-poor stars, even lower metallicities than those that formed earlier. A similar effect that very metal poor stars form in situ at later times occurs in their intense merging models, however it is more clearly seen in their quiet merging models (see their Figure 6).

4. Neutron capture ratios: [Sr/Ba]

Finally, we note that the [α/Fe] ratios are not the only elements that show a different pattern between stars in the classical dwarf galaxies and those in the Galactic halo or ultra faint dwarfs. The [Sr/Ba] ratios shown in Fig. 3 are also unusual. While the [Sr/Ba] pattern increases at low [Ba/H] in the Milky Way halo stars, it remains low in Carina and Draco, possibly Sculptor, and some of the UFDs. It is unclear if this pattern can be attributed to variations in the nucleosynthetic yields (e.g., Aoki et al. 2013, Roederer et al. 2013), or due to effects of inhomogeneous mixing in the early chemical evolution of these systems.

A different scenario is that the low [Sr/Ba] ratios in the dSphs are the result of a lack of hypernovae - either the most massive stars do not form at all or their gas is lost through SN II driven winds. Travaglio et al. (2004) and possibly Farouqi et al. (2009) suggest the excess (bump) in the Galactic stars may be attributed to hypernovae, thus if the IMF is effectively truncated in dwarf galaxies (e.g., see discussion by McWilliam et al. 2013, also Tolstoy et al. 2003) or if these systems have very high wind efficiencies at early times (e.g., Lanfranci & Matteucci 2004) then the [Sr/Ba] ratios would be lower. Note that a lack of hypernova would also predict lower sodium abundances.

Unfortunately, there is a clear lack of neutron capture element ratios in very metal poor stars in dwarf galaxies at the moment. Often these abundances are from very weak lines, or lines at blue wavelengths which were not observed. Therefore, in this case, it is true that to reduce the number of interpretations for the low [Sr/Ba] ratios in metal-poor stars in dwarf galaxies, it really will require new data.

5. Conclusions

The comparison of the elemental abundances in metal poor stars in dwarf galaxies continues to inform us on the earliest stages and environmental properties of galaxy formation. The dispersion in the [α/Fe] ratios seems to be related to galaxy merger rates and inhomogeneous mixing of the interstellar medium, while the detailed chemical composition of individual stars can further inform us on detailed properties (pockets) of the interstellar gas. Similarly, neutron capture ratios such as [Sr/Ba] in very metal-poor stars can be linked to mixing in the interstellar medium, SN II driven winds, an effectively truncated upper IMF, or possibly variations in the equation of state of the earliest SN II yields. Fortunately, more stars and more precise abundances can be used to break the degeneracies in these various interpretations - therefore, please continue to support observing programs that aim for full spectrum analyses!

Acknowledgements. I am grateful to the organizers of this workshop for the opportunity to visit Finland and talk on chemical abundances in dwarf galaxies. Also to my colleagues in the DART collaboration, without whom this work would not have been possible, and would certainly have been less fun.

References

Aoki, W., Suda, T., Boyd, R. N., et al. 2013, ApJ, 766, 13
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2007, ApJ, 654, 897
Cayrel, R., Depagne, E., Spite, M., et al. 2004, A&A, 416, 1117
Cohen, J., & Huang, W. 2009, ApJ, 701, 1053
Farouqi, K., Kratz, K.-L., Mashonkina, L. I., et al. 2009, ApJ, 694, L49
Feltzing, S., Eriksson, K., Kleyna, J., Wilkinson, M. I. 2009, A&A, 508, 1
Frebel, A. 2010, Astron. Nachr., 331, 474
Frebel, A., Simon, J. D., Geha, M., & Willman, B. 2010, ApJ, 708, 560
Frebel, A., Kirby, E., & Simon, J.D. 2010, Nature, 464, 72
Gilmore, G., & Asiri, H. M. 2012, in Assembling the Puzzle of the Milky Way, EPJ Web Conf., 19, 3001
Governato, F., Brook, C., Mayer, L., et al. 2010, Nature, 463, 203
Ibata, R.A., Gilmore, G., & Irwin, M.J. 1995, MNRAS, 277, 781
Ivans, I., Sneden, C., James, C. R., et al. 2003, ApJ, 592, 906
Koch, A., Grebel, E. K., Gilmore, G. F., et al. 2008, AJ, 135, 1580
Kordopatis, G., Hill, V., Irwin, M. et al. 2013, A&A, 555, A12
Leaman, R. 2012, AJ, 144, 183
Lemasle, B., Hill, V., Tolstoy, E., et al. 2012, A&A, 538, A100
McConnachie, A.W. 2012, AJ, 144, 4
McConnachie, A.W., Irwin, M. J., Ibata, R. A., et al. 2009, Nature, 461, 66
McWilliam, A., Wallerstein, G., Mottini, M. 2013, ApJ, 778, 149
Norris, J.E., Wyse, R. F. G., Gilmore, G., et al. 2010, ApJ, 723, 1632
Oey, M.S. 2003, MNRAS, 339, 849
Revaz, Y., & Jablonka, P. 2012, A&A, 538, 82
Roederer, I. 2013, AJ, 145, 26
Salvadori, S., Tolstoy, E., Ferrara, A., & Zaroubi, S. 2014, MNRAS, 437, L26
Salvadori, S., & Ferrara, A. 2009, MNRAS, 395, L6
Shetrone, M.D., Côté, P., & Sargent, W.L.W. 2001, ApJ, 548, 592
Shetrone, M.D., Venn, K. A., Tolstoy, E. 2003, AJ, 125, 684
Simon, J.D., et al. 2010, ApJ, 716, 446
Starkenburg, E., Hill, V., Tolstoy, E., et al. 2013, A&A, 549, 88

Tafelmeyer, M., Jablonka, P., Hill,V., et al. 2010, A&A, 524, 58

Tolstoy, E., Hill, V., Tosi, M. 2009, ARAA, 47, 371

Travaglio, C., Gallino, R., Arnone, E. 2004, ApJ, 601, 864

Venn, K. A., Irwin, M., Shetrone, M. D. 2004, AJ, 128, 1177

Venn, K. A., Shetrone, M. D., Irwin,M. J., et al. 2012, ApJ, 751, 102

Wise, J. H., et al. 2012, ApJ, 745, 50