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Stellar Abundances in Local Group Galaxies

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Abstract. Here we describe some of our latest results from measuring detailed abundances in Local Group dwarf galaxies with the VLT. Combining spectroscopic abundances with Color-Magnitude diagrams allows the effective *measurement* of detailed chemical evolution with time in these galaxies. Although there are not yet significant numbers of individual stars observed in local group dwarf galaxies, the uniformity of the abundance patterns of the majority of stars in galaxies with very different star formation histories must hint at general properties of all star formation in these small systems.

1. The Fossil Record of the Early Universe

Low mass stars, such as those found on the Red Giant Branch (RGB), have long lifetimes, often comparable to the age of the Universe, and they have retained much of their original chemical composition in their atmospheres. These stars are thus very useful because they are fossils containing a direct measure of abundances and their evolution since the earliest times. This is what Freeman & Bland-Hawthorn (2002) have neatly termed *Chemical Tagging.*

The spectroscopic abundance measurements of individual stars on the RGB by definition break the age-metallicity degeneracy in determining the star formation histories of galaxies from Color-Magnitude Diagrams (CMDs). High resolution spectra give a much more accurate measure of the metallicity than can be obtained from CMD analysis alone. If we believe that theoretical stellar evolution tracks are reasonably accurate, then we can determine ages for all the stars for which we have measured a metallicity. These ages range from the earliest star formation in the Universe to 1−2 Gyr from the present day. Thus they enable a measurement of the chemical evolution variations within dwarf galaxies over almost the entire age of the (star-forming) Universe. With a large enough sample of stars we can determine the influence of gas and metal infall and outflow in the galaxy. We can determine the relative importance of different enrichment processes over time (e.g., Supernovae Ia and II, AGB stars, stellar winds and the like). We can re-examine our understanding of the nucleosynthesis of the elements, especially those that have many possible formation sites, *e.g.,* Ti, Mg/Ca, Cu/Fe, Zn/Fe, Y/Ba, Ba/Eu, Mg/Eu.

It is also possible to measure accurate abundances of relatively young stars in nearby galaxies to determine how the ongoing star formation we observe di-

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rectly today in dwarf galaxies relates to past star formation. Dwarf galaxies can have extremely low metallicities and therefore enable us to study star formation in a regime which is more common at high-redshift.

As well as allowing us a better understanding of star formation and the effects it has on individual systems, spectroscopic abundances allow a comparison between the chemical signatures of stars found in dwarf galaxies with stars found in other environments, such as our Galaxy. This allows us to examine the theory that larger galaxies like our own were built up from small, dwarf galaxy sized clumps. It is clear from direct observations of the Universe at all redshifts that galaxies frequently merge with each other. Looking at the differences in properties of stars in small and large galaxies provides additional constraints on the likelihood and time scale of these merger events.

Dwarf galaxy size objects are believed to be the first structures to form in the early universe and thus they are potentially the sites of the formation of the first stars. Of course we have no guarantee that these first structures *were* actually dwarf galaxies that have survived until today but there is no evidence against this either. All dwarf galaxies for which sufficiently detailed observations exist have ancient stellar populations, which are most directly observed by the presence of a blue Horizontal branch in their CMD and/or an RR Lyr variable star population. There are a number of scenarios as to how the first stars may have formed, each with a distinct chemical signature for which we can test.

2. Measuring Chemical Evolution

There are several different approaches to measuring stellar abundances in nearby galaxies. Each has their own regime of validity and interest, and all contain the inherent assumption that the stellar abundances we observe are representative of the abundance of the gas out of which the stars were initially formed.

For the nearest dwarf galaxies, out to about 200 kpc from us, we can obtain high resolution spectra of individual RGB stars. This provides the most direct information about the chemical evolution of the host galaxy over the longest time baseline. These types of observations have been made with UVES (e.g., Shetrone et al. 2003; Tolstoy et al. 2003; Hill et al. 2000) and also at Keck with HIRES (e.g., Shetrone et al. 2001). High resolution spectra allow the determination of the abundance of a wealth of different chemical elements often from more than one spectral line. In each UVES spectrum, for example, there are around 100 lines of iron (Fe I and Fe II), there are also lines from α-elements (e.g., O, Ca, Mg, Ti), Fe-peak elements (V, Cr, Mn), and neutron capture elements (e.g., Y, Ba, La, Eu). Several of these elements are also frequently observed in high resolution absorption spectra of high-redshift damped Lyman-alpha (DLA) systems (e.g., Zn, Cr, Mn). Direct comparison can also be made with extensive spectroscopic surveys of stars in the Milky Way (e.g., Edvardsson et al. 1993; McWilliam et al. 1995; Fulbright 2002).

It is also possible to take lower resolution spectra of more simple metallicity indicators. For example the Ca II triplet at $\lambda\lambda$8500, 8544, 8665 Å is a well calibrated [Fe/H] indicator (e.g., Cole et al. 2000, 2003) which allows us to trace [Fe/H] with time using RGB stars. This has been successfully applied to several nearby galaxies, and allows us to survey galaxies out 1.5 Mpc, or almost

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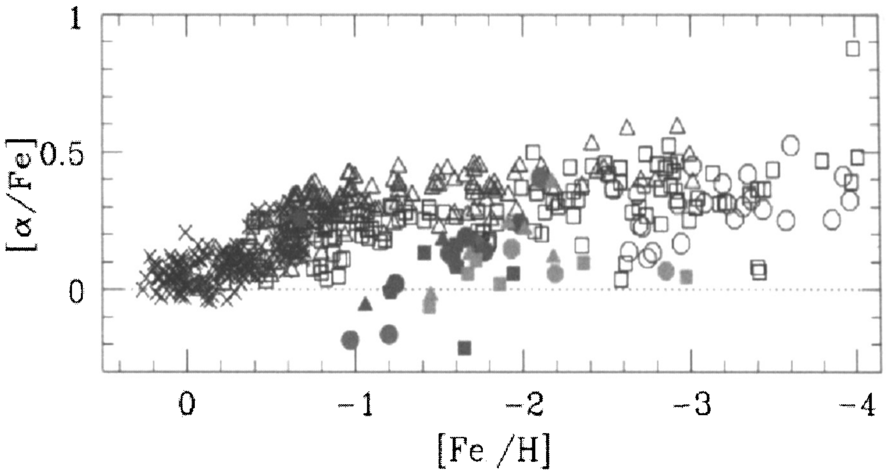

Figure 1. α-Element abundances from Shetrone et al. (2001) and Tolstoy et al. (2003) plotted versus [Fe/H] as filled symbols which represent the individual stars observed in Carina, Leo I, Sculptor, Fornax, Draco, Ursa Minor and Sextans dSphs. The crosses are Galactic disk star measurements from Edvardsson et al. (1993); the open squares are halo data from McWilliam et al. (1995) and the open circles and triangles are Galactic stars from Ryan et al. (1996) and Fulbright (2002). This plot highlights the differences between the α-element abundances observed in our Milky Way and in dwarf galaxies.

the entire volume of the Local Group (e.g., M31: Reitzel & Guhathakurta 2002; LMC: Olszewski et al. 1991, Cole et al. 2000; Fornax, Sculptor & NGC 6822: Tolstoy et al. 2001). Although this abundance measurement is quite basic (only providing information on Fe) many measurements can efficiently be made and this method can benefit greatly from multi-object instruments (e.g., VIMOS and FORS on VLT and DEMOS on Keck). In fact the wavelength range of the Ca II triplet is < 200Å, so a narrow band filter can enhance the multiplexing power of slit mask instruments many fold.

It is also possible to observe Blue Supergiants (BSGs) at high resolution to obtain more detailed abundance information for young stars in galaxies out to 1.5 Mpc distance. BSGs are much brighter than RGB stars, but they are also much younger. This means that they provide us with an accurate measurement of the *present day* metallicity in the galaxies where they are observed but they do not provide a *direct* measurement of chemical evolution, although they are of course the end product of galaxy evolution. Long observations with UVES at VLT (or HIRES on Keck) are typically required for these abundance studies. There have been several galaxies studied to date (e.g., M31, NGC 6822, WLM: Venn et al. 2000, 2001, 2003; Sextans A: Kaufer et al. 2004). These measurements can, of course, only be made in galaxies with recent star formation, i.e. dwarf irregulars rather than dwarf spheroidals where most of the detailed RGB abundances have been measured. Dwarf Irregulars are typically somewhat more massive than dSph and have arguably had an evolution less disturbed by close proximity to our Galaxy. These abundances can also be compared to H II

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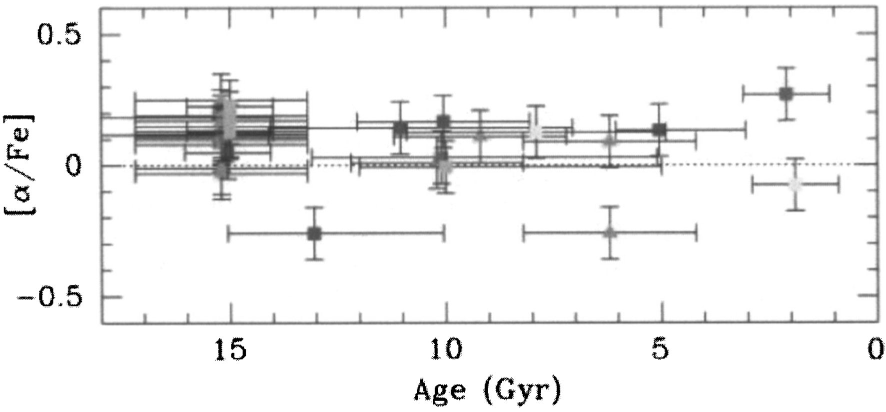

Figure 2. α-element abundance plotted against time. The age of each star is determined from an isochrone of the measured metallicity at the best fitting age. The objects plotted here are stars from the same galaxies listed in Figure 1. There is no obvious trend with age.

region metallicities, determined from emission line analysis of ionized gas. Both measures of current chemical enrichment in a galaxy are generally in agreement with each other, although some enigma remain (e.g., Venn et al. 2003).

3. Interpreting the Abundance Patterns

One of the, perhaps, most surprising results of the measurement of abundance ratios in RGB in dwarf spheroidal galaxies is that the α elements are typically found to be around solar and there is no apparent correlation between age and star formation history and α-abundance (see Figures 1 & 2). If we were to take the Milky Way as a template (e.g., Gilmore & Wyse 1991), for their [Fe/H] and especially for the oldest stars in each system we would expect dwarf spheroidals to have higher [α/Fe] than the average trend which is observed in Figure 1.

Although the number of stars with high resolution abundances in any given dwarf spheroidal to date is on average very small (around 5), the [α/Fe] measured is consistently low for all dSph despite widely varying ages, [Fe/H] and star formation histories. This suggests that for dSph the Galaxy is probably not the best template to interpret the observed abundances. It seems that low α-abundance need not mean stars which have been made from material which was enriched by SNIa explosion. It is possible for a low-α enrichment pattern to exist from very early on in the star formation history of a galaxy *before there has been any time for SNIa enrichment* (Tolstoy et al. 2003), unless we have significantly overestimated the SNIa time scale at low metallicities (not impossible). It is also possible to invoke AGB wind enrichment, as another mechanism to diminish [α/Fe], and account for the over-abundance of s-process elements (e.g., Ba, Y). However, the time scale for this to occur is also thought to be at least a giga-year after the onset of star formation and so this would have

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to occur more rapidly than current predictions suggest (also not impossible) to fully explain our observations.

It is also possible that the dwarf galaxies we observed may have an *effectively* truncated Initial Mass Function, in the sense of a lack of very high mass stars. This is not too hard to envisage as these dwarf galaxies are small systems with extremely low star formation rates throughout their history. They may not typically form very high mass molecular clouds, and thus the probability that a galaxy will form many (or even any) high mass stars is statistically low. This could explain the abundance patterns seen. In addition to the low α-element abundances observed, the enhanced abundance of the r-process element Eu, for example, is consistent with the scenario of predominantly low mass SNII in a slow evolving environment.

It is also possible that blow-out has played a significant role in the chemical evolution of these galaxies going back to the earliest times. But it would have to be quite selective (predominantly expelling α-elements for example), and consistent over a range of different galaxy masses (and types). Blowing up a small galaxy is "easy" in theory, (e.g., Mori, Ferrara & Madau 2002) but it is not so easy to find direct evidence of blow-out in a small galaxy with the confidence that the gas currently seen flowing out will never return (e.g., Martin et al. 2002). Determining if gas and/or metals will leave a galaxy for good is very sensitive to the structure of the ISM in a galaxy and whether or not it contains a significant gaseous halo, and how high the star formation rate can be at any given time.

It is also interesting to note that $[\alpha/\mathrm{Fe}]$ measured in massive (young) BSG stars in dIrr galaxies is also low and thus unlike the Milky Way at the same [Fe/H] (e.g., Venn et al. 2001, 2003; Kaufer et al. 2003). Another class of object with low α-abundance measurements are damped Lyman-alpha systems (e.g., Nissen et al. 2003, submitted). That is not to say that they are necessarily dwarf galaxies but it appears that their chemical evolution has been similar to that of dwarf galaxies in the Local Group.

Looking at Figure 1 it is rather clear that significant numbers of stars from dwarf galaxies cannot be included in a merging formation scenario for our Galaxy *at any epoch.* Thus, dwarf galaxies *are not obvious hierarchical fragments.* The only way this aspect of standard hierarchical galaxy formation scenario can be retained is if the dwarf galaxies merged to form larger objects like the Milky Way *very* early in the Universe, before the majority of their stars were formed, while they were still gas rich.

4. In Summary

The results of our observations of high resolution abundances of a handful of individual stars in nearby dwarf galaxies suggest that the evolution of [Fe/H] with time is consistent with a closed box chemical evolution scenario, although the evidence is not very definitive with the current small samples. The role of outflows remains unclear. We note that, despite wide variations in star formation histories and [Fe/H] in dwarf galaxies, the $[\alpha/\mathrm{Fe}]$ abundances are very similar and typically Galactic-disk-like solar values for the majority of the stars we observe. The iron peak elements observed are similar to the Galactic halo,

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but occur at *higher* [Fe/H]. Dwarf galaxies are thus not obvious hierarchical fragments. Their slow evolution apparently leads to distinctly different abundance patterns from those seen in the Milky Way.

To put our tentative results on a firmer basis requires spectra of many more stars in dwarf galaxies. We have in VLT/FLAMES the ideal instrument for this kind of study. We have put together a programme with the Dwarf Abundance Radial-velocity Team (DART, http::/www.astro.rug.nl/~dart) to use FLAMES to make detailed observations at high resolution of abundances of more than a hundred stars in each of three nearby dwarf spheroidal galaxies (Sculptor, Fornax and Sextans). This promises dramatic new data sets in the near future to answer many of the unresolved issues discussed here.

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