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Metal-poor Damped Lyα systems: high-redshift analogues of Local Group dwarf galaxies?

Max Pettini[1] & Ryan J. Cooke[2]

[1] Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK
e-mail: pettini@ast.cam.ac.uk
[2] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA

Abstract. Measurements of element abundances in damped Lyα systems at redshifts $z \simeq 2$–4 offer clues to nucleosynthesis in the metal-poor regime that are complementary to those provided by analogous studies of old stellar populations in Local Group galaxies. We briefly review some of the main results from our survey of the most metal-poor DLAs, with [Fe/H] ≤ -2, particularly concerning the behaviours of oxygen and carbon with decreasing metallicity. Links with Local Group dwarf spheroidal galaxies are suggested by similarities in the metallicity, in the relative abundances of α-capture and Fe-peak elements, and in the quiescent gas kinematics exhibited by the most metal-poor DLAs. While evidence of any evolutionary link is still largely circumstantial, there is clearly a strong incentive to pursue such lines of inquiry in the years ahead.

Key words. Galaxies: abundances – Galaxies: evolution – Quasars: absorption lines

1. Introduction

As the title of this symposium emphasises, galaxies in the Local Group are increasingly being used as templates to investigate the galaxy formation process in general and to guide us in the interpretation of data on galaxies at high redshifts, observed when the Universe was a great deal younger than today. "Galactic Archaeology" has become a buzzword: we look to the oldest stars in the Milky Way and its companions for clues to understand the nature of the first stars that ended the cosmic dark ages at redshifts $z > 10$. Similarly, we examine the stellar populations and the physical properties of the faintest galaxies in the Local Group motivated in part by an inkling that such systems may be local analogues of what, in the distant past, were the building blocks of today's massive galaxies.

In the spirit of the symposium, which aims to bring together astronomers from different fields, I am here to describe a complementary approach to these stellar studies which my colleagues and I have been pursuing for a number of years. The idea is simple: can we find pockets of gas at high redshift that have the characteristics of the interstellar clouds from which the most metal-poor stars in Local Group galaxies formed a long time ago? Such clouds of gas cannot be imaged directly, but their presence can be surmised by the absorption lines they produce in the spectra of background light sources, such as QSOs and gamma-ray bursts.

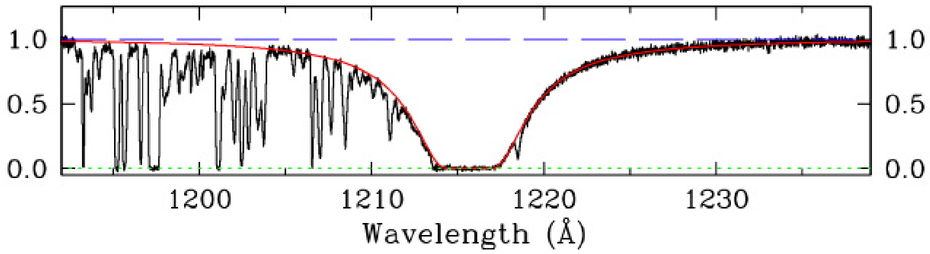

Fig. 1. Damped Lyα line in the $z_{\rm abs} = 3.04984$ DLA in the spectrum of the QSO SDSS J1419+0829 (reproduced from Pettini & Cooke 2012). The black histogram is the data, while the red continuous line shows the theoretical absorption Lyα profile produced by a neutral hydrogen column density $\log N(\text{H}\,\textsc{i})/\text{cm}^{-2} = 20.40$. The strong damped Lyα line is easily distinguished from the multitude of weaker Lyα lines produced by diffuse gas in the intergalactic medium. The y-axis is residual intensity.

Measuring element abundances in metal-poor gas at high redshift complements very effectively analogous studies using old stars. Each approach has its strengths and weaknesses. In a nutshell, interstellar gas is a far simpler astrophysical environment than stellar atmospheres. Consequently, interpreting interstellar absorption spectra to deduce element abundances does not suffer from many of the complications that can affect the analysis of stellar spectra, such as taking into account the three-dimensional structure of a star, whether a spectral feature is formed under local thermodynamical equilibrium or not (LTE vs NLTE), and whether the photospheric composition reflects that of the gas from which the star formed, or has been subsequently altered by convection, rotation or mass transfer from a companion. Furthermore, high redshift studies offer a less 'parochial' view of the early stages of galactic chemical enrichment than can ever be obtained from Local Group galaxies alone.

2. Metal-poor damped Lyman alpha systems

Among the many classes of QSO absorption line systems, the so-called damped Lyα systems—or DLAs for short—are best suited for precise measures of element abundances. DLAs are the 'heavyweights' of the QSO absorption line family; with neutral hydrogen column densities $N(\text{H}\,\textsc{i}) \geq 2 \times 10^{20}\,\text{cm}^{-2}$, they dominate the census of neutral gas at all redshifts. For this reason, DLAs have been the focus of sustained attention over the last 25 years—see Wolfe, Gawiser, & Prochaska 2005 for a review of their most important properties. Figure 1 shows an example.

Hydrodynamical simulations of galaxy formation (e.g. Pontzen et al. 2008) suggest that a wide range of galaxies can give rise to DLAs, but that most of the cross-section for absorption at $z \sim 3$ is likely to be provided by galaxies with small stellar masses, in the range $M_* \simeq 10^7$–$10^9\,\text{M}_\odot$. In accord with this 'prediction', most DLAs are metal-poor: the metallicity distribution peaks at $Z_{\rm DLA} \simeq 1/30 Z_\odot$ (e.g. Rafelski et al. 2012). The number of known DLAs has increased by more than one order of magnitude in recent years thanks to wide-field surveys of the sky, particularly the Sloan Digital Sky Survey (SDSS). Such improved statistics have given us access to the metal-poor tail of the DLA metallicity distribution which now extends to $[\text{Fe/H}] < -3$; these are the absorbers which may still retain the nucleosynthetic signatures of the first few generations of stars to form in our Universe.

A recently published (Cooke et al. 2011, 2013, 2014) survey of 22+ DLAs with $[\text{Fe/H}] < -2$ has provided us with the first detailed data on some of the most important physical properties of metal-poor gas at redshifts $z \simeq 2$–3. In particular, it has uncovered new clues on the nucleosynthesis of C, N, O and

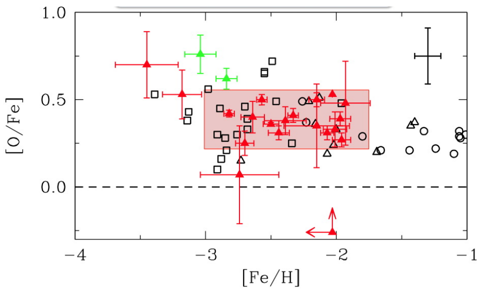

Fig. 2. [O/Fe] vs. [Fe/H] in metal-poor Galactic stars (open symbols) and damped Lyα systems (filled triangles). The typical error applicable to the stellar abundances is shown in the top right corner. For all the stars shown here, the oxygen abundance was deduced from the weak [O I] λ6300 line; see Cooke et al. (2011) for references to the original works.

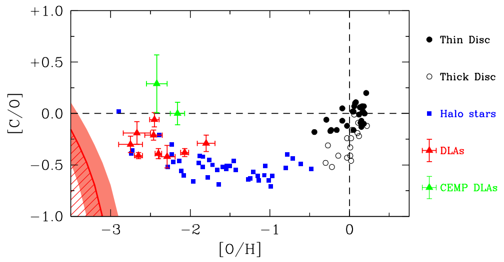

Fig. 3. [C/O] vs. [O/H] in Galactic stars (circles and squares) and damped Lyα systems (filled triangles). The red hatched region indicates the transition between Population III and Population II star formation according to Frebel, Johnson & Bromm (2007). See Cooke et al. (2011) for references to the stellar abundance measurements.

Fe-peak elements in this regime. Here we mention just two highlights from this work, and refer the interested reader to the above papers for more comprehensive discussions.

3. Oxygen and carbon at low metallicities

3.1. Oxygen

High redshift DLAs and Galactic halo stars concur in showing only a modest enhancement in the abundance of oxygen relative to iron, $[\langle \mathrm{O/Fe} \rangle]_{\mathrm{DLA}} = +0.35 \pm 0.09$ when the 'metallicity' is between 1/100 and 1/1000 of solar ($-3 \leq$ [Fe/H] ≤ -2; see Figure 2). This is only the case, however, if the stellar oxygen abundance is deduced from the weak, forbidden [O I] λ6300 line after applying small 3D corrections. Other O spectral features which have been resorted to when [O I] λ6300 becomes vanishingly small, appear to suffer from significantly larger NLTE and 3D corrections which, unless properly accounted for, can lead to spurious conclusions concerning the degree of α-enhancement at the lowest metallicities. It remains to be established with future observations whether the plateau in [O/Fe] continues below [Fe/H] = -3, or whether more metal-poor stars and DLAs exhibit significantly higher values of [O/Fe].

The good agreement between the local and distant universe, as well as the uniformity in the degree of α-enhancement between different high redshift galaxies, has far-reaching consequences. It points to a universality not only of the initial mass function, but also of the physical processes that drive core collapse supernovae and determine the stellar mass range responsible for the release of oxygen into the interstellar medium (see the recent discussion of this point by Brown & Woosley 2013).

3.2. Carbon

Turning to Figure 3, DLAs confirm the trend of *increasing* C/O ratio with *decreasing* oxygen abundance below [O/H] $\simeq -1.5$ in Galactic stars reported by Akerman et al. (2004) and more recently by Fabbian et al. (2009), and allay reservations that such a trend may be due to unaccounted NLTE and 3D corrections. An appealing explanation for such a rise is that it represents the dilution (with increasing O/H) of large amounts of carbon synthesised by metal-free stars. This interpretation is supported by the marked carbon enhancement exhibited by the most metal-poor stars known—see Tim Beers' contribution to these conference proceedings.

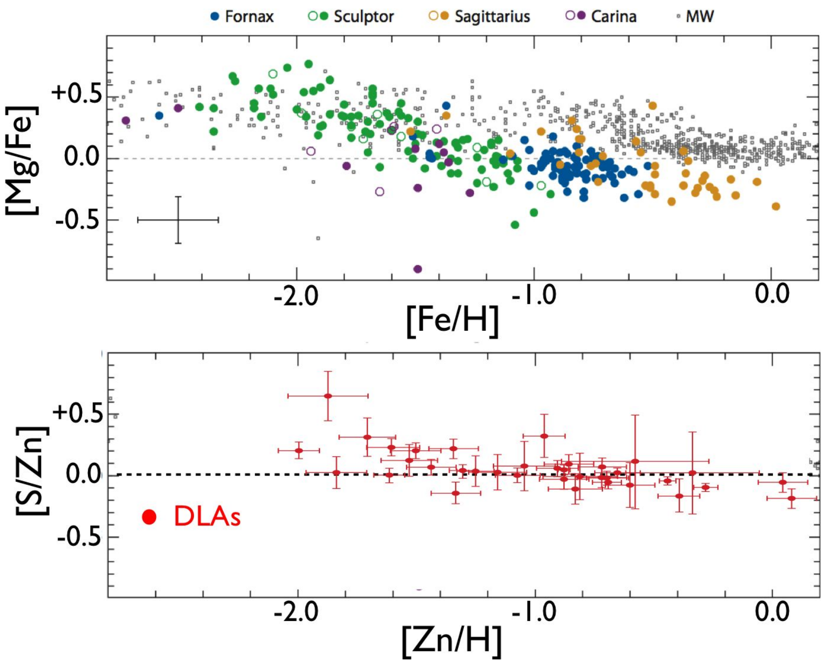

Fig. 4. α/Fe-peak vs. Fe-peak abundance in Local Group stars (upper panel, reproduced from Tolstoy, Hill & Tosi 2009) and in damped Lyα systems at redshifts $z = 2$ to 4 (lower panel, reproduced from Rafelski et al. 2012). The Mg abundance is not readily measured in DLAs; in its place, S is the most reliable proxy for the abundance of α-capture elements. Similarly, in order to measure the true abundance of Fe in DLAs it is necessary to account for the uncertain fraction of Fe hidden in dust grains; the undepleted Fe-peak element Zn avoids such difficulties. If these 'substitutions' are valid (Nissen et al. 2007), the chemical evolution of the DLA population evidently resembles more closely those of Local Group dwarfs than that of the Milky Way, exhibiting no marked α-enhancement down to [Zn/H] $\simeq -1.5$.

4. Metal-poor DLAs: analogues of Local Group dwarfs?

4.1. Chemistry

Can we draw some parallels between metal-poor DLAs and Local Group dwarfs that can help us understand better how they both fit into the broader picture of galaxy formation and evolution? The first thing to realise here is that we are very unlikely to make such a connection *directly* in the near future; imaging the integrated stellar light of dwarf galaxies at $z = 2-3$ is a goal beyond current observational capabilities. Thus, such comparisons are of necessity based on indirect arguments.

Differences in the behaviour of the α-capture elements as a function of metallicity have been used to argue that the Milky Way and its satellite dwarf spheroidal galaxies (dSph) followed different chemical evolutionary paths (e.g. Tolstoy, Hill & Tosi 2009). Figure 4 suggests that, as a whole, the DLA population experienced chemical enrichment more in line with those of the Milky Way companions than the Galaxy itself. In DLAs the enhancement of α-capture elements relative to Fe-peak elements is only evident when [Fe/H] ≤ -2, whereas in stars of the Milky Way disk (thick and thin) such an enhancement persists from the lowest metallicities to [Fe/H] > -1 (e.g. Bensby, Feltzing & Oey 2014). If the metallicity at which [α/Fe] begins to decrease towards the solar value is an indication of the rate at which gas has been

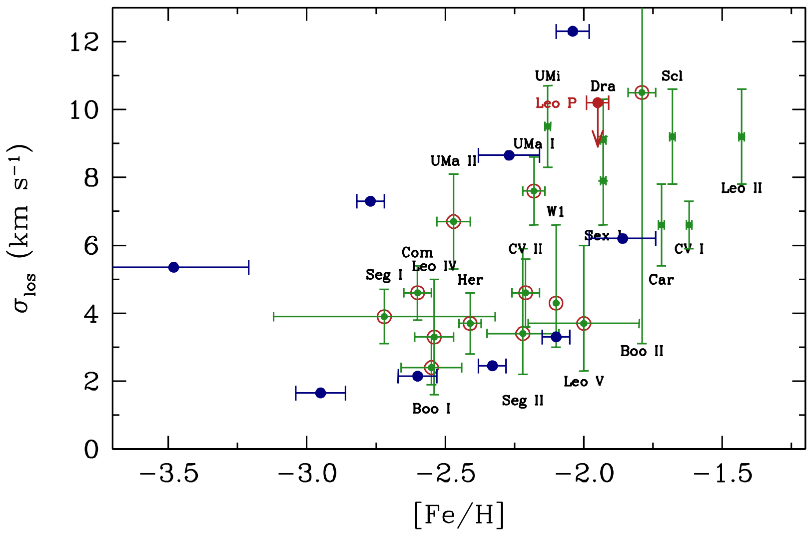

Fig. 5. Projected line-of-sight velocity dispersions of metal-poor DLAs (blue filled dots) and dwarf spheroidal galaxies in the vicinity of the Milky Way (labelled green symbols, from McConnachie 2012). Green symbols with red circles denote ultra-faint dwarf galaxies, with total luminosities $L \leq 10^5$ $L_\odot$. (Figure reproduced from Cooke et al. 2014).

cycled through stars, then one would conclude that the star formation histories of high-z DLAs are more akin to those of Local Group dSph than massive galaxies like the Milky Way.

It is important to sound (at least!) two cautionary notes regarding this conclusion. First, it is clear from deep imaging searches (e.g. Péroux et al. 2012) that the DLA hosts cover a wide range of galaxy luminosities and star formation rates; thus, it is inherently dangerous to draw general conclusions for the entire DLA population. Second, as explained in Figure 4, it is difficult to measure the same elements in stars and DLAs over the full range of metallicities of interest, and one often has to resort to ‘proxies’, such as Zn for Fe and S for α-capture elements. The work by Asa Skuladottir et al. (in prep.) aims to remedy this situation by measuring Zn and S abundances in stars in Local Group dSph.

4.2. Kinematics

It is plausible to conjecture that the most metal-poor DLAs may be the closest high-redshift counterparts of dwarf galaxies in the local Universe. In accord with the now well-established relationship between DLA metallicity and velocity extent of the absorption lines (e.g. Prochaska et al. 2008), the most metal-poor DLAs exhibit the simplest kinematics, with the absorption lines generally breaking up into very few components, distributed over a velocity interval $\Delta v \sim$ 10–20 km s^{-1} and with internal velocity dispersions of only a few km s^{-1}.

The 1σ line-of-sight velocity dispersion of the gas in metal-poor DLAs is approximately half of the velocity interval that accounts for the innermost 68% of the total optical depth in absorption lines by neutral gas (after correcting for thermal and instrumental broadening). Figure 5 compares such measurements in the best determined cases with values of the stellar velocity dispersion of Milky Way dwarf spheroidals. While it remains to be established whether the velocity dispersion measured in the absorbing gas reflects the full gravitational potential of the DLA host, it is hard to escape the conclusion that the host galaxies of the most metal-poor DLAs are low mass objects. For comparison, the dSph galaxies in Figure 5 have stellar masses $M_* \leq 10^6\,M_\odot$.

5. Conclusions

More than fifteen years since the discovery of 'normal' galaxies at redshifts $z = 2$–3 (Steidel et al. 1996), we are still struggling to make the connection between these objects and today's galaxy population. Clear evolutionary links are even more difficult to establish for 'galaxies' seen in absorption, such as the DLAs, for which imaging and morphological studies are particularly challenging. With the results I have presented here, we are only beginning to take the first steps, using chemical and kinematical clues, towards the ultimate goal of understanding how galaxies evolved over the cosmic ages. A logical next step is to try and image the environments of the most metal-poor DLAs: are they found in the outskirts of more massive galaxies, in analogy with Local Group dwarfs, or do they occur preferentially in voids? This and other questions will undoubtedly be answered in the next decade, thanks to powerful new facilities now on the horizon, such as *JWST* and 30-40 m-class telescopes. We look forward to such developments with great anticipation.

One of us (MP) would like to thanks the organisers of this fruitful and engaging meeting for all their efforts which made it a real success.

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