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Neutral Gas and Metals From z = 4 to z = 0.5

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Abstract. A complementary method to the emission selection of high-redshift galaxies consists in the observation of absorbers along the line of sight toward a background quasar. This selection technique has a constant sensitivity at all redshifts up to $z = 6$ (i.e. no redshift desert) and allow to select all types of galaxies regardless of their luminosity or star formation rate. The highest column density absorbers, the Damped Lyman-α (DLAs) systems, in particular, can be used to determine the cosmic evolution of HI gas in the Universe, $\Omega_{\rm HI}$, and the global metallicity in the gas phase. Since stars are known to form from HI gas, $\Omega_{\rm HI}$ provides an indirect tracer of the history of star formation. Recent results from several parallel VLT programmes aiming at determining the cosmological evolution of the metallicity in the neutral gas phase are presented.

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A direct consequence of the star formation history is the production of heavy elements, known as metals. However, at high-redshift, our knowledge of the cosmic metal budget is still highly incomplete. In fact, the amount of metals observed in high-redshift galaxies (e.g. Lyman Break Galaxies) and the intergalactic medium, is roughly a factor of 5 below the expected amount of metals produced on the cosmic star formation history. This is dubbed as the "missing metals problem". An alternative technique of studying high-redshift galaxies is provided by observing quasar absorbers seen in the spectra of background quasars. Although, we can accurately measure the metallicities of DLAs up to high-redshifts, they are not found to be a major contributor to the metal budget. However, the dust contained in these systems might introduce biases into current surveys.

On the other hand, new lines of evidence are pointing toward lower $N_{\rm HI}$ quasar absorbers being more metal-rich. Sub-Damped Lyman-α Absorbers (sub-DLAs), in particular, which were first coined by Péroux *et al.* (2003) as quasar absorbers with H I column density $19.0 < \log N_{\rm HI} < 20.3$ atoms cm^{-2}, show higher metallicity than classically DLAs. Indeed, the dust bias, if real, is likely to be less severe for metal-rich sub-DLAs as compared to the metal-rich DLAs due to the lower gas and therefore dust content in the former, for a constant dust-to-gas ratio. Thus, the obscuration bias will affect the DLAs at a lower dust-to-gas ratio as compared to the sub-DLAs. In fact, Vladilo and Péroux (2005) have shown that lower H I column densities are expected to be less affected by the dust bias with the predicted obscuration fraction decreasing dramatically with $N_{\rm HI}$.

Figure 1 shows the $N_{\rm HI}$ column density weighted-metallicity relation, $[\langle {\rm Zn/H_{DLA}} \rangle]$, for both DLAs and sub-DLAs separately and including the metal-rich sub-DLAs recently discovered (Péroux *et al.* 2006a; Péroux *et al.* 2006b; Prochaska *et al.* 2006). Clearly, sub-DLAs show a stronger evolution than classical DLAs, and their metallicity at low redshift is higher. Indeed,it might be expected that these systems are less prone to the biasing effect of dust and thus represent the only tool currently available to detect the most metal-rich galaxies seen in absorption. Such metal-rich systems would then be the

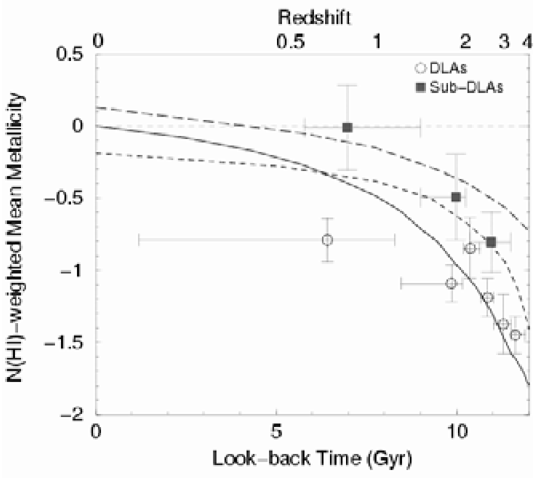

Figure 1. N(H I)-weighted mean Zn abundance relative to solar abundance vs. look-back time relation. The solid, short-dashed and long-dashed curves show models.

"tip of the iceberg" population which has remained so far un-noticed. Another possibility suggested by Khare *et al.* (2006) and based on the observed mass-metallicity relationship for galaxies (e.g. Tremonti *et al.* 2004; Savaglio *et al.* 2005), is that sub-DLAs may arise in massive galaxies and DLAs in less massive galaxies.

In this context, it is interesting to quantify the contribution of the possibly metal-rich sub-DLAs to the metal budget. At z ~2.5, the co-moving density of H I gas in DLAs and sub-DLAs is measured to be $\Omega_{\rm H\,I} = 0.85 \times 10^{-3}$ and 0.18×10^{-3}, respectively (Péroux *et al.* 2005). At the same redshifts, the mean global metallicity of the sub-DLAs is $[\langle Zn/H \rangle] = -0.8$ (Figure 1). Therefore, the co-moving mass density of metals in sub-DLAs, in units of $\Omega(Z_\odot)$ $(= \Omega_{\rm baryons} \times Z_\odot = 5.5 \times 10^{-4}$; $Z_\odot$=0.0126 by mass), is: $\Omega_Z^{sub-DLA} = f \times 10^{-0.8} \times Z_\odot \times 0.18 \times 10^{-3}/\Omega(Z_\odot) = f \times\ 6.5 \times 10^{-4}$ where f (>1) accounts for the ionised fraction of the gas. For sub-DLAs with low $N_{\rm HI}$, the ionised fraction may be important. The exact value of f is yet to be determined and will depend on detailed photo-ionisation calculations (Péroux *et al.* 2007). Thus, sub-DLAs contribute at least 25% of what DLAs contribute to the metal census $[\Omega_Z^{DLA} = 2.6 \times 10^{-3}$], and the contribution could be higher depending on the value of f.

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