Early Galaxy Evolution: Report on UVES Studies of a New Class of Quasar Absorbers

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Distant galaxies can be studied using the imprints that their gaseous structures leave in the spectrum of a background quasar. These "quasar absorbers" provide a measure of both the neutral gas and metallicity content of the Universe back to early cosmic times. A newly defined class of quasar absorbers, the sub-Damped Lyman-α Systems, have been studied for the first time using both the ESO archives and new UVES/VLT data. This review presents results from four years of research on these systems and emphasises the scientific role played by the ever-growing ESO science archive.

Tracing the rate at which stars form over cosmological scales still remains a challenging observational task. An indirect way to measure the assembly of galaxies is to probe the rate at which they convert their gas into stars. The neutral H I mass in particular can be estimated from observations of absorbers seen in the spectrum of background quasars. The most remarkable property of these systems is that their detection threshold is essentially redshift independent and only relies on the properties of random luminous background sources (quasars or Gamma-Ray Bursts) observed up to early cosmological times ($z > 6$). Thus, unlike other high-redshift galaxies (such as Ly-α emitters or Lyman Break Galaxies), these objects are selected regardless of their morphologies or intrinsic luminosities but solely on their H I cross-sections (see Figure 1). Therefore, they provide unbiased samples to measure the redshift evolution of $\Omega_{\rm H\,I}$, the total amount of neutral gas expressed as a fraction of today's critical density.

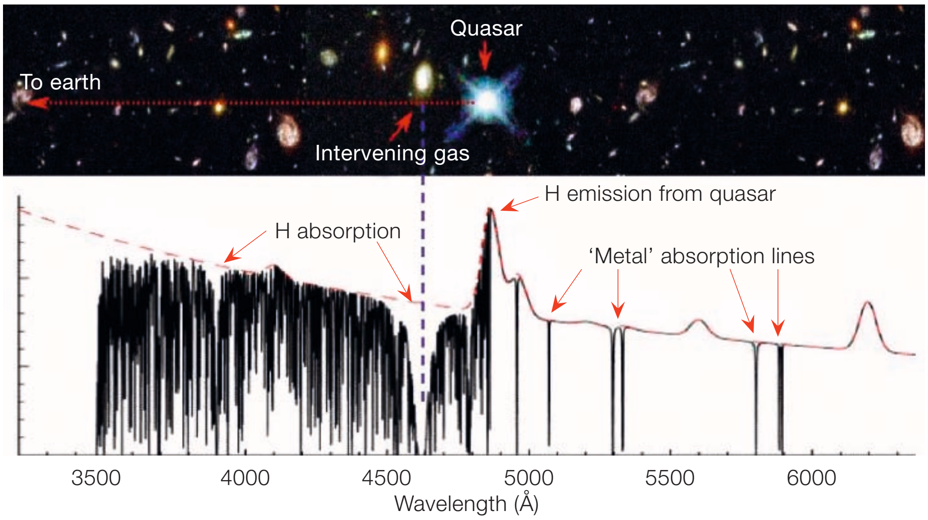


Figure 1: Cartoon illustrating a quasar line of sight along which various objects give rise to absorption features seen in the spectrum of the background quasar. The panel presents a typical quasar spectrum, showing the quasar continuum, emission lines, and the absorption lines produced by galaxies and intergalactic material that lie between the quasar and the observer. The strongest $N_{\rm H\,I}$ absorption at $\lambda_{\rm obs} \sim 4600$ Å is due to a Damped Lyman-α Absorber at $z \sim 2.79$ (Figure courtesy of John Webb).

Quasar absorbers are also an excellent tool for measuring the abundances of a wide variety of elements over >90 % of the age of the Universe. In addition to providing information on individual objects, they can be used statistically to provide measures of the cosmological evolution of metals in the neutral gas phase. The so-called H I-column density weighted metallicity shows surprising results: contrary to virtually all chemical models, the most recent observations indicate only mild evolution with redshift. Nevertheless, it is wellknown that such analyses are dominated by the main contributors to the H I mass. Therefore, it is important that all the quasar absorbers containing a significant fraction of H I gas are included to get a global metallicity estimate.

A new class of quasar absorbers

Quasar absorbers are sub-divided into classes according to their column density, the number of hydrogen atoms per unit area along the line of sight between the observer and the quasar (commonly expressed in atoms cm^{-2}). Therefore a low column density cloud could either be a small cloud with high density or a large cloud with low density. They are thus believed to probe a variety of physical conditions including halos and discs of both dwarf and normal (proto)galaxies. Damped Lyman-α systems (hereafter DLAs) have $N_{\rm H\,I} > 2 \times 10^{20}$ atoms cm^{-2} and are the major contributors to the neutral gas $\Omega_{\rm H\,I}$. Nevertheless, based on a new sample of $z > 4$ quasars (Péroux et al. 2001), we have suggested that some fraction of the H I lies in systems below the traditional DLA definition. We proposed to extend the definition to $N_{\rm H\,I} > 10^{19}$ atoms cm^{-2} and introduced the terminology " sub-Damped Lyman-α systems" (sub-DLAs) in Péroux et al. 2003a. Such high column density systems are reportedly good tracers of galaxies: looking out through the Milky Way, many lines of sight have $10^{19} < N_{\rm H\,I} < 2 \times 10^{20}$ atoms cm^{-2}, reminding us that we actually live in a sub-DLA!

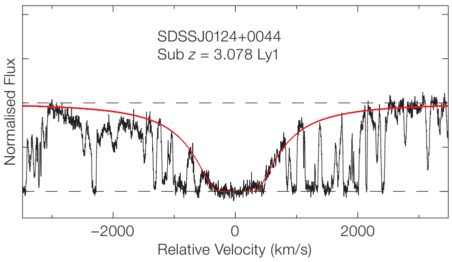
The study of sub-DLAs has been made possible only thanks to the advancement of 8–10-m-class telescope related technologies. Indeed high-resolution spectroscopy is required to study sub-DLAs. The Ultraviolet-Visual Echelle Spectrograph UVES (D'Odorico et al. 2000) mounted on UT2 has played a key role in recent developments of our understanding of quasar absorbers, and sub-DLAs in particular. In 2001, we initiated a programme aimed at building and studying a homogeneous sample of sub-DLAs. The overall goal of this ongoing project is to identify what can be learned about the early stages of galaxy evolution from the study of the systems detected in absorption.

Global metallicity evolution

In a first step towards this aim, we took advantage of the ESO VLT archive to build a sample of sub-DLAs by reducing and analysing UVES archival Echelle quasar spectra available to us on July 2001. This represented a sample of 35 quasars, 22 of which were unbiased for our study. This work led to the discovery of 12 sub-DLAs (Dessauges-Zavadsky et al. 2003). Their chemical abundances were derived using Voigt profile fitting (see Figure 2 for an example) and photoionisation models from the CLOUDY software package in order to determine the ionisation correction. We find that the correction is negligible in systems with $N_{\rm H\,I} > 3.2 \times 10^{19}$ and lower than 0.3 dex for most elements in systems with $10^{19} < N_{\rm H\,I} < 3.2 \times 10^{19}$ atoms $\rm cm^{-2}$. The abundances observed in this sample of sub-DLAs were further used to determine the global metallicity of H I gas in both DLAs and sub-DLAs. We found that the metallicity redshift evo-lu-tion of absorbers as traced by [Fe/H] shows a slightly more pronounced slope for sub-DLAs ($\alpha = -0.40 \pm 0.22$) than for DLAs ($\alpha = -0.18 \pm 0.12$). In addition, the H I-weighted mean metallicity was computed for DLAs and sub-DLAs. The evolution of [⟨Fe/$\rm H_{DLA}$⟩] might be stronger for sub-DLAs than for DLAs, and absorbers with $N_{\rm H\,I} > 10^{21}$ atoms $\rm cm^{-2}$ appear to be the less evolved (Figure 3). Observational evidence supports the hypothesis that this different behaviour is not due to the hidden effect of dust (Péroux et al. 2003b).

A study of the metallicity evolution with metal line profile ionisation showed hints of a correlation, whereby higher [Fe/H] ratios are associated with systems with larger widths (Figure 4). This correlation could indicate either a recent activity of star formation (and hence more enrichment) or a higher mass (higher rotational velocity being proportional to the mass of the system). Abundance ratios for [Si/Fe], [O/Fe], [C/Fe] and [Al/Fe] were determined and compared with two different sets of models of the chemical evolution of galaxies. Overall, these appear to resemble

Figure 2: Example of a normalised UVES/VLT spectrum of a high-redshift quasar. This velocity scale plot is centred at the sub-DLA position corresponding to $z_{\rm abs} = 3.078$. The red line represents the Voigt profile model used to determine the quasar absorber column density: $N_{\rm H\,I} = 1.62 \times 10^{20}$ atoms $\rm cm^{-2}$ (Figure from Péroux et al. 2005).



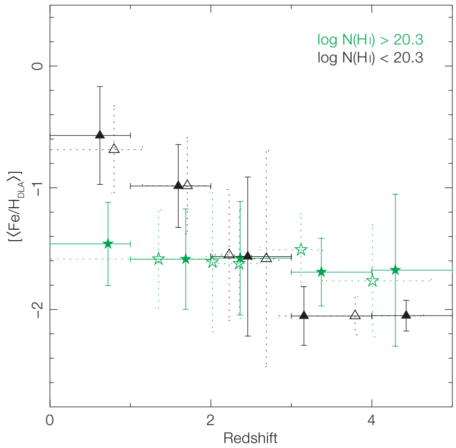


Figure 3: $N_{\rm H\,I}$ column density-weighted mean metallicities for DLAs (green) and sub-DLAs (black). The dotted bins are for constant $N_{\rm H\,I}$ intervals and the solid bins are for constant redshift intervals. The evolution of [⟨Fe/$\rm H_{DLA}$⟩] is possibly more pronounced for sub-DLAs than for DLAs (Figure from Péroux et al. 2003b).

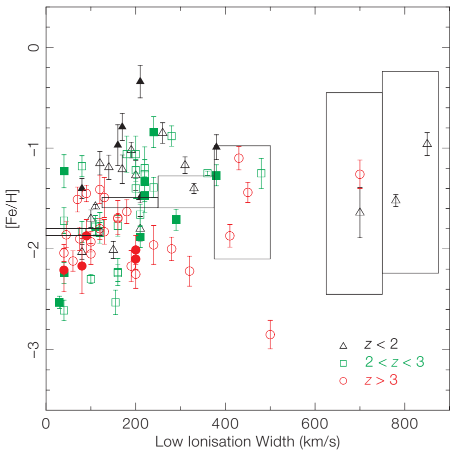


Figure 4: [Fe/H] as a function of the velocity width of the low-ionisation transition. The colours of the symbol depict different redshift ranges. The open sym-bols are for DLAs and the filled symbols are for sub-DLAs. The boxes represent the mean in a given velocity interval with *rms* errors and suggest an increase of metallicity towards larger widths of the low ionisation species. (Figure from Péroux et al. 2003b).

abundance ratios observed in DLAs. The first comprehensive sets of measurements of O I and C II in high $N_{\rm H\,I}$ column density systems were given. Indeed, another advantage is that these elements are well-defined in sub-DLAs while they are almost always saturated in DLAs. These species, unaffected by dust depletion, provide direct indicators of the abundances in quasar absorbers.

Cosmological evolution of H I gas mass

In order to study the early stages of galaxy evolution, we selected a sample of 17 $z > 4$ quasar lines of sight observed with UVES/VLT (Péroux et al. 2005). The statistical properties of the resulting sample of 21 new sub-DLAs were analysed in combination with the sub-DLAs from the previous ESO archive study. This homogeneous sample allowed us to determine the redshift evolution of the number density of DLAs and sub-DLAs. All these systems seem to be evolving in the redshift range from $z = 5$ to $z \sim 3$. Assuming that all the classes of absorbers arose from the same parent population, estimates of the characteristic radii were provided. R_* increases with decreasing column density, and decreases with cosmological time for all systems. The sub-DLA downsizing runs from $R_* = 40\ h^{-1}_{100}$ kpc at $z = 4$ to $R_* = 30\ h^{-1}_{100}$ kpc at $z = 2$. The redshift evolution of the column density distribution, $f(N,z)$, down to $N_{\rm H\,I} = 10^{19}\ \rm cm^{-2}$ was also presented for two different redshift ranges (Figure 5). A departure from the usual power law is observed in the sub-DLA regime.

$f(N,z)$ was further used to determine the total H I gas mass in the Universe at $z > 2$ (Figure 6). The complete sample of sub-DLAs shows that they are important at all redshifts from $z = 5$ to $z = 2$ and that their contribution to the total gas mass $\Omega_{\rm H\,I}$ is ~ 20 % (or more if compared with the latest Sloan results). It appears that $\Omega_{\rm H\,I}$ observed in both DLAs and sub-DLAs at high redshift ($z > 2$) is low compared with the mass density observed in stars today, Ω_*. The possibility that large numbers of quasar absorbers are missing in optically selected quasar surveys is still hotly debated. While radio surveys looking for DLAs in quasar samples without optical limiting magnitudes (Ellison et al.

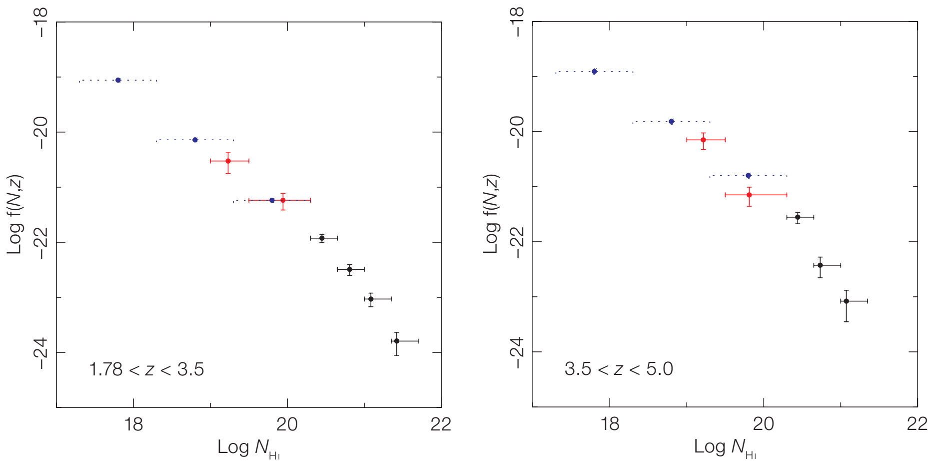


Figure 5: Column density distributions for two redshift ranges down to the sub-DLA definition. The horizontal error bars are the bin sizes and the vertical error bars represent the uncertainties. The blue dotted bins are predictions from Péroux et al. (2003a), while the red bins at $10^{19} < N_{HI} < 2 \times 10^{20}$ atoms cm^{-2} correspond to the direct observations from the sample of sub-DLAs. The black bins represent DLAs (Figure from Péroux et al. 2005).

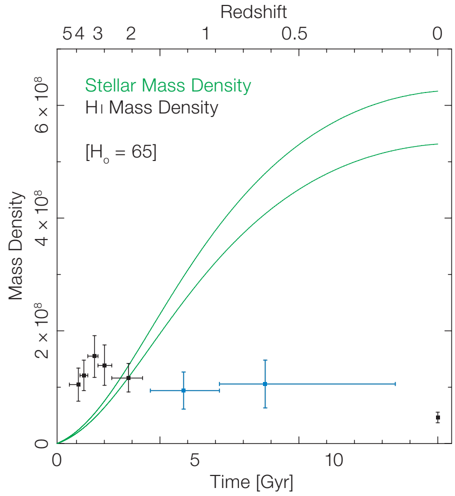


Figure 6: Observable baryons in the Universe as a function of time. The green curve represents the mass density in stars integrated from the Star Formation Rate (SFR). The error bars represent the mass density in HI gas as derived from quasar absorbers deconvolved from the local critical density (Figure from Péroux et al. 2005).

2003) show that there are not a large number of DLAs missing, our expectations are that high-redshift galaxies should be dusty. It should be emphasised however that there are two separate issues: i) what is the dust content of the quasar absorbers we know of today and ii) what fraction of the quasar absorbers are missed because their background quasar is not selected in the first place.

On the nature of sub-DLAs

By assuming that both DLAs and sub-DLAs trace the same underlying parent population, a natural explanation for the nature of sub-DLAs could be that they are the outermost parts of galaxies. This is illustrated by the absorber size calculations where the characteristic radius of sub-DLAs is around 40 h^{-1}_{100} kpc and the one from DLAs is 20 h^{-1}_{100} kpc.

The metallicity of sub-DLAs also seem to differ from the one of classical DLAs. Smoothed particle Hydrodynamics simulations indicate that DLAs have one third solar metallicity at $z = 2.5$ and should be even more metal-rich towards lower redshifts. Indeed there are lines of evidence pointing towards lower column density quasar absorbers like sub-DLAs being more metal-rich at $z < 2$ (Figure 3). This could be explained by classical DLAs being dustier than their sub-DLAs counterparts, hence preventing the selection of their background quasar. If confirmed, this can be explained by the fact that in sub-DLAs, the Zn column density threshold does not combine with the N_{HI} threshold $N_{HI} > 2 \times 10^{20}$ atoms cm^{-2} that prevents their detection. We therefore propose that sub-DLAs might be associated with the external parts of galaxies which better traces the overall chemical evolution of the Universe.

Future prospects

In order to investigate further this hypothesis, we are currently investigating the metallicity of sub-DLAs at $z > 3$, using 10 of the 17 high-resolution UVES $z > 4$ quasar spectra from our sample for which we have spectral coverage at wavelengths red-wards of the quasar emission lines. These systems will also be modelled with CLOUDY in order to determine the ionisation fraction of the gas.

In parallel, one of us (CP) is working on the UVES ESO VLT archive data with the aim to provide the user community with a uniform data set of pipeline-reduced products. The results will be made available to the public with the hope that it will encourage and facilitate the ESO archive usage. This new data set could be used to search for new sub-DLAs already observed with ESO facilities but so far unstudied. This type of research illustrates the role that the ever-growing ESO archive plays for science.

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