Probing Galaxies through Quasar Absorption Lines
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Total gas mass $\Omega_{\rm HI+HeII}$ at $z > 2$

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Abstract. Absorbers seen in the spectrum of background quasars are a unique tool to select HI-rich galaxies at all redshifts. These allow us to determine the cosmological evolution of H I gas, $\Omega_{\rm HI+HeII}$, a possible indicator of gas consumption as star formation proceeds. The damped Lyman-α systems (DLAs with $N_{\rm HI}\geqslant 10^{20.3}$ cm^{-2}) in particular are believed to contain a large fraction of the H I gas, but there are also indications that lower column density systems, namely "sub-damped Lyman-α" systems play a role at high-redshift. Here we present the discovery of high-redshift sub-DLAs based on 17 $z > 4$ quasar spectra observed with the Ultraviolet-Visual Echelle Spectrograph (UVES) on VLT. This sample is composed of 21 new sub-DLAs which, together with another 10 systems from previous ESO archive studies, make up a homogeneous sample. The redshift evolution of the number density of several classes of absorbers is derived and shows that all systems seem to be evolving in the redshift range from $z = 5$ to $z \sim 3$. The redshift evolution of the column density distribution, $f(N, z)$, down to $N_{\rm HI}= 10^{19}$ cm^{-2} is also presented. A departure from a power law due to a flattening of $f(N, z)$ in the sub-DLA regime is present in the data. $f(N, z)$ is further used to determine the H I gas mass contained in sub-DLAs at $z > 2$. The complete sample shows that sub-DLAs are important at all redshifts from $z = 5$ to $z = 2$.

1. Introduction

Tracing the rate at which stars form over cosmological scales still remains a challenging observational task. An indirect way to probe 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. Unlike other high-redshift galaxies (such as Lyman Break Galaxies, Steidel *et al.* 2003), these objects are selected solely on their H I cross-sections regardless of their intrinsic luminosities or star formation rates. The quasar absorption systems are divided into several classes according to the number of atoms along the observed line of sight: the Lyα forest have H I column densities ranging from $\simeq 10^{12}$ to 1.6×10^{17} atoms cm^{-2}, the Lyman-limit systems (LLSs) with N(HI) $> 1.6\times10^{17}$ atoms cm^{-2}, and the damped Lyα systems (DLAs) with N(HI) $> 2\times10^{20}$ atoms cm^{-2}. These latter systems are believed to be the major contributors to the neutral gas in the Universe at high redshifts. They thus can be used to measure the redshift evolution of $\Omega_{\rm HI+HeII}$, the total amount of neutral gas expressed as a fraction of today's critical density (Lanzetta *et al.* 1991; Wolfe *et al.* 1995; Storrie-Lombardi *et al.* 1996a; Storrie-Lombardi & Wolfe 2000). We have recently suggested (Péroux *et al.* 2003a) that at $z > 3.5$, some fraction of the H I lies in systems below the traditional DLA definition, in "sub-damped Lyman-α systems" (sub-DLAs) with $19 < \log$ N(HI) < 20.3 cm^{-2}. The present paper reviews these predictions based on direct observations of a sample of sub-DLAs.

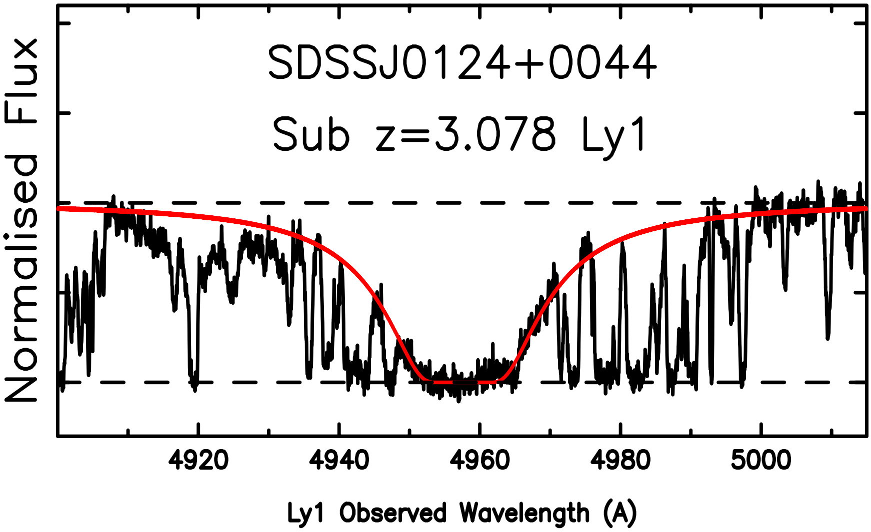

Figure 1. The absorber detected towards SDSS J0124+0044 at $z_{\rm abs}$=3.078 (log $N_{\rm HI}$=20.21±0.10).

2. The data sample

We took advantage of the ESO VLT archive to build a sample of sub-DLAs by analysing UVES archival echelle QSO spectra. This represents a sample of 35 QSOs, 22 of which were unbiased for our study. This study led to the discovery of 12 sub-DLAs (Dessauges-Zavadsky *et al.* 2003; Péroux *et al.* 2003b). In order to complement this study and analyse sub-DLAs at $z > 3$, we started in September 2002 to build a UVES sample of high redshift QSOs never observed before at high resolution. This snapshot is carefully designed to determine the redshift evolution of the statistical properties of sub-DLAs (number density and column density distribution). The second step of the observing programme undertook a year later, in September 2003, aimed at concentrating on the 7 most promising targets to enable detailed metallicity and dynamical studies at high-redshifts. An extra set of data was obtained on August 29$^{\rm th}$ 2004, September 2$^{\rm nd}$, and September 4$^{\rm th}$ 2004 in service mode in the framework of a parallel observing programme.

The methodology to search for sub-DLAs in the spectra described above is detailed in Péroux *et al.* (2005). This lead to the discovery of 7 DLAs and 21 sub-DLAs. The latter systems span a range of H I column densities from $10^{19.01}$ to $10^{20.21}$ cm^{-2} with $z_{\rm abs}$=2.976 to 4.145. The H I column density fitting is also described in details in Péroux *et al.* (2005). An example is shown in Fig. 1 where we report for the first time the sub-DLA with log $N_{\rm HI}$=20.21±0.10 at $z_{\rm abs}$=3.078. Metal lines at this redshift are also observed in the red part of the spectrum.

3. Results

3.1. *Redshift number density*

The number of quasar absorbers per unit redshift $n(z)$ is a direct observable. This quantity, however, can only be used to constrain the evolution or lack of it when deconvolved from the effects of cosmology.

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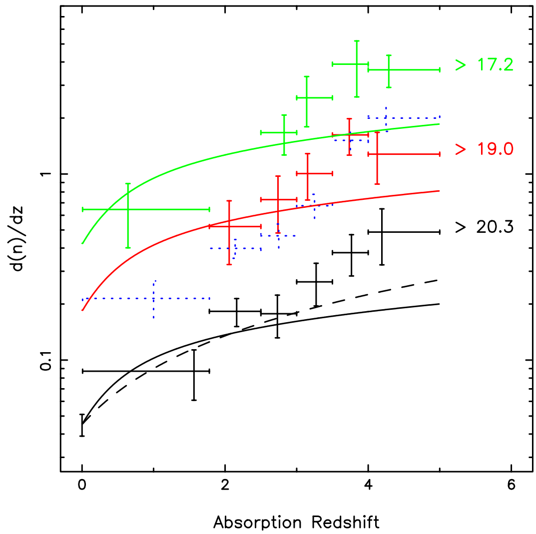

Figure 2. Number density of various classes of quasar absorbers as a function of redshift taken from Péroux *et al.* (2003a) except for sub-DLAs (this work). The horizontal error bars are the bin sizes and the vertical error bars are the 1-σ uncertainties. The dotted bins are the predictions of the number density of sub-DLAs from Péroux *et al.* (2003a), while the light grey bins at $\log N_{\rm HI}$>19.0 correspond to the observed number density presented in this paper. The DLA's $n(z=0)$ data point is from the 21-cm emission line observations of Zwaan *et al.* (2005b). The curves represent a non-evolving population for a non-zero $\Lambda-$Universe, except for the dashed line, which is for a $\Lambda = 0$, $q_0 = 0$ Universe.

The data acquired here used in combination with recent results from the literature allow us to determine this quantity for various classes of quasar absorbers. This is shown in Fig. 2 where the number density of DLAs, sub-DLAs (both predictions from the Péroux *et al.* 2003a computations, and new direct measurements from the present work), and LLS are presented. It can already be seen that the predictions overestimated the number of sub-DLAs at $z > 4$ while they underestimated the number of such systems at $z < 3.5$. The observations show that the number density of sub-DLAs is flatter than expected. Assuming no evolution in the number density Φ and gas cross-section σ, the lack of evolution in the redshift number density in a non-zero $\Lambda-$Universe can be expressed as (see for example Péroux *et al.* 2004):

$$n(z) = n_0(1+z)^2 \times \left[\frac{H(z)}{H_0}\right]^{-1}, \tag{3.1}$$

where

$$\frac{H(z)}{H_0} = \left[\Omega_M\, z(1+z)^2 - \Omega_\Lambda[z(z+2)] + (1+z)^2\right]^{1/2}. \tag{3.2}$$

These no evolution curves are shown for each class of quasar absorbers in Fig. 2 where n_0 is taken to be $n(z=0) = 0.045 \pm 0.006$ derived by Zwaan *et al.* (2005b) from high-resolution 21-cm emission line observations of the $z = 0$ analogues of DLAs. The other curves are scaled according to a factor representative of the difference in redshift number density of sub-DLAs and LLS in the redshift range $2.5 < z < 3.0$. Departure from no evolution at $z \geqslant 3$ is clear for all classes of quasar absorbers. For comparison with

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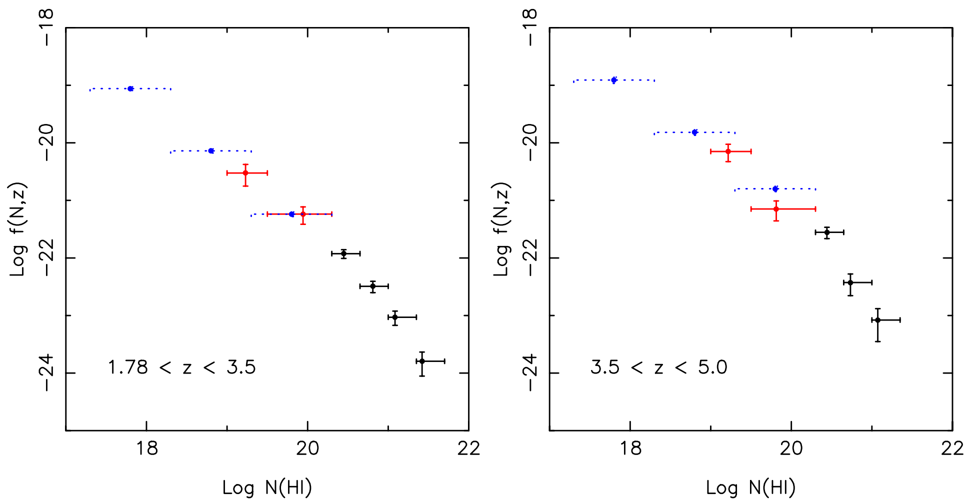

Figure 3. Column density distributions for two redshift ranges down to the sub-DLA definition. The horizontal error bars are the bin sizes and the vertical error bars represent the uncertainties. The dotted bins are the predictions from fitting a Schechter function to the expected number of LLS (Péroux *et al.* 2003a), while the two solid bins at $19.0<\log N_{\rm HI}<20.3$ correspond to the direct observations from the sample of sub-DLAs presented here.

previous work, the dashed line shows the non-evolving population for a $\Lambda = 0$, $q_0 = 0$ Universe.

3.2. *Column density distribution*

The differential column density distribution describes the evolution of quasar absorbers as a function of column density and redshift. It is defined as:

$$f(N,z)dNdX = \frac{n}{\Delta N \sum_{i=1}^{m} \Delta X_i} dNdX, \qquad (3.3)$$

where n is the number of quasar absorbers observed in a column density bin $[N, N + \Delta N]$ obtained from the observation of m quasar spectra with total absorption distance coverage $\sum_{i=1}^{m} \Delta X_i$. The column density distribution for two redshift ranges, $z < 3.5$ and $z > 3.5$ are shown in Fig. 3. These redshifts were chosen to allow a direct comparison with the work of Péroux *et al.* (2003a). In particular, the highest redshift is set to $z = 5$ to match DLA surveys even though the sub-DLA search is made only up to $z = 4.5$. Again, the observations (solid bins) are compared with the predictions from Péroux *et al.* (2003a). The new data allow us to determine $f(N, z)$ down to $\log N_{\rm HI}$=19.0. The column density distribution has often been fitted with a simple power law (i.e. Prochaska & Herbert-Fort 2004), but there have been recent work showing that a Schechter-type of function is more appropriate (Pei & Fall 1995; Storrie-Lombardi, McMahon & Irwin 1996b; Péroux *et al.* 2003a). In any case, it should be noted that *none* of these two functions is physically motivated but rather are chosen so as to best describe the data. However, as more observations are available, a clear departure from the power law is observed. This flattening of the distribution in the sub-DLA regime is indeed expected as the quasar absorbers become less self-shielded and part of their neutral gas is being ionised by incident UV flux. We note once more the paucity of very high column density DLAs at high-redshift.

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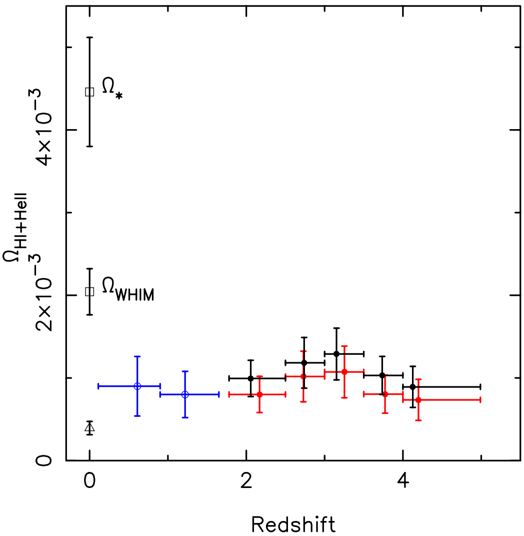

Figure 4. Redshift evolution of the gas mass density $\Omega_{\rm HI+HeII}$ expressed as a fraction of the critical density. The stellar mass density today is represented by Ω_* measured by Cole *et al.* (2001) for a Salpeter Initial Mass Function and the baryons in the hot gas are represented by $\Omega_{\rm WHIM}$ measured from the incident of OVI absorbers by Danforth & Shull (2005). The triangle at $z = 0$ corresponds to the H I mass measured with radio observations in local galaxies (Zwaan *et al.* 2005a). The two error bars at $z < 2$ are $\Omega_{\rm HI+HeII}$ from MgII-selected DLAs (Rao, these proceedings). The light grey bins at $z > 2$ are $\Omega_{\rm HI+HeII}$ in systems with log $N_{\rm HI}$>20.3, while the black bins correspond to the total H I gas, including the H I contained in sub-DLAs.

3.3. $\Omega_{\rm HI+HeII}$ *gas mass*

The gas mass density, $\Omega_{\rm HI+HeII}$, observed in high-redshift quasar absorbers is classically expressed as a fraction of today's critical density:

$$\Omega_{HI}(z) = \frac{H_o \mu m_H}{c\rho_{crit}} \frac{\sum N_i(HI)}{\Delta X}, \tag{3.4}$$

where $\mu = 1.3$ is the mean molecular weight and m_H is the hydrogen mass. The total gas mass, including H I gas in systems below the canonical DLA definition are plotted in Fig. 4 and compared with the stellar mass density today (Ω_*) and the H I mass measured with radio observations of local galaxies (triangle at $z = 0$). Measurements at $z < 2$, are $\Omega_{\rm HI+HeII}$ from MgII-selected DLAs (Rao, these proceedings). The figure decomposes the H I mass contained in both classical DLAs and in DLAs + sub-DLAs.

4. Conclusions

We have presented a new sample of high-redshift sub-DLAs ($N_{\rm HI}$> 10^{19} cm^{-2}) found in the spectra of 17 $z > 4$ quasar spectra observed with the Ultraviolet-Visual Echelle Spectrograph (UVES) on VLT. The statistical properties of this sample of 21 new sub-DLAs is analysed in combination with another 10 sub-DLAs from previous ESO archive studies. This homogeneous sample allows us to determine the redshift evolution of the number density of DLAs, sub-DLAs, and LLS. 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 arise from the same parent population, estimates of the characteristic radii are provided. R_* increases with decreasing column density, and decreases with cosmological time for all systems. The redshift evolution of the column density distribution, $f(N, z)$, down to $N_{\mathrm{HI}}= 10^{19}$ cm^{-2} is also presented. A departure from the usually fitted 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 $z > 2$. The complete sample shows that sub-DLAs are important at all redshifts from $z = 5$ to $z = 2$ and that their contribution to the total gas mass $\Omega_{\mathrm{HI+HeII}}$ is ~20% or more if compared with the latest Sloan results.

Acknowledgements

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