A homogeneous sample of sub-damped Lyman $\alpha$ systems – III. Total gas mass $\Omega_{\text{H}I+\text{He}II}$ at $z > 2^*$

Céline Péroux,† Miroslava Dessauges-Zavadsky, Sandro D’Odorico, Tae Sun Kim and Richard G. McMahon

1European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching-bei-München, Germany
2Observatoire de Genève, 1290 Sauverny, Switzerland
3Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

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ABSTRACT
Absorbers seen in the spectrum of background quasars are a unique tool with which to select H I-rich galaxies at all redshifts. In turns, these galaxies allow us to determine the cosmological evolution of the H I gas $\Omega_{\text{H}I+\text{He}II}$, which is a possible indicator of gas consumption as star formation proceeds. The damped Lyman $\alpha$ (Ly$\alpha$) systems (DLAs with $N_{\text{H}I} \geq 2 \times 10^{20}$ 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, called ‘sub-damped Ly$\alpha$’ 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 the Very Large Telescope (VLT). This sample is composed of 21 new sub-DLAs which, together with another 10 systems from previous European Southern Observatory 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 $z \sim 3$. These results are further used to estimate the redshift evolution of the characteristic radius of these classes of absorbers, assuming a Holmberg relation and one unique underlying parent population. DLAs are found to have $R_* \sim 20 h_{100}^{-1}$ kpc, while sub-DLAs have $R_* \sim 40 h_{100}^{-1}$ kpc. The redshift evolution of the column density distribution, $f(N,z)$, down to $N_{\text{H}I} = 10^{19}$ 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 $z = 2$. Finally, the possibility that sub-DLAs are less affected by the effects of dust obscuration than classical DLAs is discussed.

Key words: galaxies: abundances – galaxies: high-redshift – quasars: absorption lines – quasars: general.

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 HI 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 Lyman $\alpha$ (Ly$\alpha$) forest have H I column densities ranging from $\lesssim 10^{12}$ to $1.6 \times 10^{17}$ atom cm$^{-2}$, the Lyman-limit systems (LLSs) with $N(\text{H}I) > 1.6 \times 10^{17}$ atom cm$^{-2}$ and the damped Ly$\alpha$ systems (DLAs) with $N(\text{H}I) > 2 \times 10^{20}$ atom 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 $\Omega_{\text{H}I+\text{He}II}$, the total amount of neutral gas expressed as a fraction of today’s critical density (Lanzetta et al.

*Based on observations collected during programme ESO 69.A-0613, ESO 71.A-0114 and ESO 73.A-0653 at the European Southern Observatory with the Ultraviolet-Visual Echelle Spectrograph on the 8.2 m Kueyen telescope operated at the Paranal Observatory, Chile.

†E-mail: cperoux@eso.org
In addition, quasar absorbers are direct indicators of element abundances over >90 per cent of the age of the Universe. The cosmological evolution of the H I column-density weighted metallicity (e.g. Kulkarni & Fall 2002) shows surprising results: contrary to virtually all chemical models (e.g. Malaney & Chaboyer 1996; Pei, Fall & Hauser 1999), the most recent observations indicate mild evolution with redshift (Khare et al. 2004; Kulkarni et al. 2005). Therefore, the results to date might give a biased or incomplete view of the global galactic chemical evolution. The ultimate goal of this project is to undertake detailed abundance and dynamical studies of an appropriate sample of sub-DLAs in order to estimate the evolution of their mean abundance with redshift.

In a first step towards this goal, we took advantage of the European Southern Observatory’s (ESO) Very Large Telescope (VLT) archive to build a sample of sub-DLAs by analysing Ultraviolet-Visual Echelle Spectrograph (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). Their chemical abundances were derived using Voigt profile fitting and photoionization models from the CLOUDY software package in order to determine the ionization correction. We find that the correction is negligible in systems with \( N(H) > 3.2 \times 10^{19} \) and lower than 0.3 dex for most elements in systems with \( 10^{19} < N(H) < 3.2 \times 10^{19} \) atom cm\(^{-2} \). These systems were used to observationally determine the shape of the column density distribution, \( f(N, z) \), down to \( N(H) = 10^{19} \) cm\(^{-2} \) (Péroux et al. 2003b), although the lack of high-redshift systems prevented us from measuring the \( f(N, z) \) redshift evolution. 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.

Here we present a new sample of 17 \( z > 4 \) quasar lines of sight observed at high resolution with UVES on the VLT. We use these newly acquired data to search for and study the statistical properties of high-redshift sub-DLAs. In Section 2 the observations and the data reduction process are given in detail, together with a description of each object. Section 3 presents the statistical characteristics of the survey and the newly built sub-DLA sample. Finally, our

### Table 1. Journal of observations of our programmes to find and analyse new high-redshift sub-DLAs in \( 17 z > 4 \) quasars.

| Quasar       | Alternative name | \( z_{em} \) | R mag | Obs Date     | UVES settings | Exp. Time (s) | Ref |
|--------------|------------------|--------------|-------|--------------|---------------|---------------|-----|
| BR J006−6208 |                  | 4.455        | 19.25 | 27 Sept 2002 | 580           | 7200          | 1   |
| PSS J0118 + 0322<sup>red</sup> |                | 4.230        | 18.66 | 2002 Sept 28 | 560           | 3600          | 6   |
| ...          |                  | ...          | ...   | ...          | ...           | ...           | ... |
| PSS J0121 + 0347<sup>red</sup> |                | 4.127        | 18.33 | 2002 Sept 28 | 540           | 3600          | 5   |
| SDSS J0124 + 0044<sup>red</sup> |              | 3.840        | 17.75 | 2002 Sept 27 | 520           | 3600          | 4   |
| ...          |                  | ...          | ...   | ...          | ...           | ...           | ... |
| PSS J0133 +0400 |                | 4.154        | 18.32 | 2002 Sept 27 | 520           | 3600          | 1.7 |
| BRI J0137−4224<sup>red</sup> | BRI B0135−4239 | 3.970        | 18.77 | 2002 Sept 27 | 520           | 3600          | 3   |
| ...          |                  | ...          | ...   | ...          | ...           | ...           | ... |
| PSS J0209+0517 |                | 4.174        | 17.76 | 2002 Sept 27 | 520           | 3600          | 2   |
| BRI J0244−0134 | BRI B0241−0146 | 4.053        | 18.18 | 2002 Sept 27 | 520           | 3600          | 1   |
| BR J0311−1722 |                  | 4.039        | 17.73 | 2002 Sept 27 | 540           | 3600          | 1   |
| BRI J0334−1612<sup>red</sup> |                | 4.363        | 17.86 | 2002 Sept 27 | 560           | 3600          | 1   |
| ...          |                  | ...          | ...   | ...          | ...           | ...           | ... |
| BR J0419−5716 |                  | 4.461        | 17.78 | 2002 Sept 28 | 560           | 1846          | 1   |
| BR J2017−4019<sup>BAL</sup> | BRLCO B2013−4028 | 4.131        | 18.60 | 2002 Sept 03 | 540           | 3600          | 1   |
| PSS J2154+0335 |                | 4.363        | 19.05 | 2002 Sept 28 | 560           | 3600          | 1   |
| BR J2215−1611<sup>red</sup> | BR B2212−1626 | 3.990        | 18.10 | 2002 Sept 28 | 540           | 3600          | 2   |
| ...          |                  | ...          | ...   | ...          | ...           | ...           | ... |
| BR J2216−6714<sup>red</sup> |                | 4.469        | 18.57 | 2002 Sept 28 | 560           | 3600          | 1   |
| ...          |                  | ...          | ...   | ...          | ...           | ...           | ... |
| BR J2239−0552 | BR B2237−0607    | 4.558        | 18.30 | 2002 Sept 27 | 580           | 3600          | 2   |
| BR J2349−3712 | BRLCO B2346−3729 | 4.208        | 18.70 | 2003 Sept 03 | 540           | 3600          | 1   |

<sup>BAL</sup>: affected by broad absorption line features.<sup>red</sup>: spectrum with complete wavelength coverage including the red of the Ly-α emission line.<sup>red</sup>: attempt to get a spectrum with complete wavelength coverage impaired by bad weather conditions (strong northern wind).

References: (1) Péroux et al. (2001); (2) Storrie-Lombardi et al. (1996a); (3) Storrie-Lombardi et al. (2001); (4) Schneider et al. 2002; (5) Stern et al. 2000; (6) from the Palomar Sky Survey, see http://www.astro.caltech.edu/~george/z4.qsos; (7) Prochaska et al. (2003).
current state of knowledge of this class of absorbers together with implications for the cosmological evolution of H I gas mass are discussed in Section 4.

2 THE Z > 2 SUB-DLA SAMPLE

2.1 Observations and data reduction

In order to complement the previous study and analyse sub-DLAs at z > 3, we started in 2002 September 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, undertaken a year later in 2003 September, aims at concentrating on the seven most promising targets that would enable detailed metallicity and dynamical studies at high redshifts. An extra set of data was obtained on 2004 August 29, 2004 September 2 and 4, in service mode in the framework of a parallel observing programme (ESO 73.A-0653; principal investigator N. Bouché). Table 1 gives the journal of the observations.

The data reduction of the observations from periods 69 and 71 is done using the version of the UVES pipeline within the MIDAS environment available at the time (version: UVES/2.0.0 FLMIDAS/1.0.0). The newest data (period 73) are reduced with the most recent version of the pipeline to accommodate the new format of the raw fits file (version: UVES/2.1.0 FLMIDAS/1.1.0). The raw wavelength frames are inspected closely to optimize the number of echelle orders to be extracted for each CCD. Master bias and flat images are constructed using calibration frames taken nearest in time to the science frames. Lamp images are taken on various occasions throughout the observing nights to be able to make accurate wavelength calibrations. In most cases, the science frames and associated stars are extracted with the ‘optimal’ option. Nevertheless, on a few frames from the second observing run (2003 September), two of the settings (540 and 800) show a periodic feature of the order of a few Angströms. These features are not present when these few frames are extracted using the ‘average’ option followed by a cosmic filtering.

For the seven objects that were observed with more than one setting, the resulting spectra are combined by using the signal-to-noise ratio (S/N) of the spectrum as a weight. The final spectra have a resolution of 7 km s⁻¹. In some cases, we notice that the parts of the spectra that are fully absorbed do not actually reach the zero flux level. This problem is known to occur when there are not enough photons in the sky area. Indeed, the optimal extraction is done to fit a Gaussian profile and the baseline of the Gaussian is the sky level. When the seeing during the observations is poor and the exposure short, it is possible that at blue wavelengths, only a few photons fall on the sky pixel. This leads to high photon-noise and might produce the under-subtraction of the sky level. The unsaturated absorption lines are unaffected by this zero-level problem. In the case of saturated

Table 2. High-redshift quasar absorber sample composed of 21 sub-DLAs and seven DLAs.

| Quasar       | $z_{em}$ | $z_{abs}$ | log $N_\text{HI}$ | Ly series | metals                                      | Note                        |
|--------------|----------|-----------|-------------------|-----------|---------------------------------------------|-----------------------------|
| BR J0006−6208 | 4.455    | 3.202     | 20.80±0.10        | Ly1       | no metals over available coverage          | DLA                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |
| PSS J1118 + 0320         | 4.230    | 4.128     | 20.02±0.15        | Ly5       | Fe II, Si II, O I, C II, Si IV, C IV        | ...                         |
| PSS J0121 + 0347         | 4.127    | 2.976     | 19.53±0.10        | Ly1       | O I, C IV, Fe II, Al II                     | ...                         |
| SDSS J1024 + 0444         | 3.840    | 2.988     | 19.18±0.10        | Ly1       | Si II, C IV, Fe II, Al II                   | ...                         |
| PSS J0133+0400         | 4.154    | 3.139     | 19.01±0.10        | Ly1       | Ni II, C II                                | ...                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |
| BRJ137 − 4224         | 3.970    | 3.101     | 19.81±0.10        | Ly4       | Si II, C IV, Fe II, Al II                   | ...                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |
| PSS J0209+0517         | 4.174    | 3.665     | 19.11±0.10        | Ly1       | Si II, O I, C II, Si IV                     | ...                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |
| BRI J044−0134        | 4.053    | 3.603     | 19.24±0.10        | Ly2       | O I, Si IV                                  | ...                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |
| BRI J0311−1722         | 4.039    | 3.734     | 19.48±0.10        | Ly7       | Si II, O I, C II                           | ...                         |
| BRI J0334 − 1612         | 4.363    | 3.557     | 21.12±0.10        | Ly1       | Si II, C IV, Fe II, Al II, Zn II            | DLA                         |
| BRI J0419−5716       | 4.461    | 3.063     | 19.17±0.10        | Ly1       | O I                                        | ...                         |
| BRI J2017 − 4010BAL      | 4.131    | 3.101     | 19.24±0.10        | Ly2       | O I, Si IV                                  | ...                         |
| BRI J2154+0335         | 4.363    | 3.177     | 19.23±0.15        | Ly1       | no metals over available coverage          | ...                         |
| BRI J2215 − 1611         | 3.990    | 3.656     | 19.01±0.15        | Ly3       | Ni II, C II, Zn II                         | ...                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |
| BRI J2216 − 6714        | 4.469    | 3.368     | 19.80±0.10        | Ly1       | O I, Si IV, C IV, Fe II, Al II             | ...                         |
| BRI J2239−0552         | 4.558    | 4.079     | 20.55±0.10        | Ly3       | C II, C IV, Al II                          | ...                         |
| BRI J2349−3712         | 4.208    | 3.581     | 19.12±0.10        | Ly2       | no metals over available coverage          | ...                         |
| ...          | ...      | ...       | ...               | ...       | ...                                         | ...                         |

BAL: affected by broad absorption line features. red: spectrum with complete wavelength coverage including to the red of the Lyα emission line. red: attempt to get a spectrum with complete wavelength coverage impaired by bad weather conditions (strong northern wind).
lines, we correct the spectrum by subtracting a few per cent from the continuum level value. The spectra are then normalized using a spline function to join the part of the continuum that is free of absorption lines.

### 2.2 Identification and column density measurements of absorbers

The method of searching for sub-DLAs in the spectra described above very much follows the method used in our previous studies (Dessauges-Zavadsky et al. 2003). We first use an automated detection algorithm supplemented further by visual searches independently undertaken by three of us (CP, MD-Z and T-SK). Although the forest of the quasars at these redshifts is considerably absorbed by foreground structures, the presence of damping wings down to the Ly2, and occasionally to higher lines of the series, provides an unambiguous signature of damped absorbers. We also report the detection of metal lines in the associated redshifts, although this is not used as a criterion for sub-DLA selection. Table 2 summarizes this information together with the redshifts, H I column densities and the references of the seven DLAs and 21 sub-DLAs found in our new high-redshift quasar sample. The latter systems span a range of H I column densities from $10^{19.00}$ to $10^{20.21}$ cm$^{-2}$ with $z_{\text{abs}} = 2.976$ to 4.145.

The H I column-density measurements are determined by fitting a Voigt profile to the absorption line. The fits were performed using the $\chi^2$ minimization routine FITLYMAN in MIDAS (Fontana & Ballester 1995). The Doppler parameter $b$-value was usually fixed at 20 km s$^{-1}$ or left as a free parameter, since in that high column-density regime, the sub-DLA systems $N_{\text{HI}}$ are independent of the $b$-value. The fit is performed using the higher members of the Lyman series where these are available. The typical resulting error bar in $\log N_{\text{HI}}$ measurements is 0.10 and never exceeds 0.15, but does not include errors in the continuum placement which we expect would not exceed 10 per cent.

### 2.3 Notes on individual objects

In this section, we provide details on each of the identified absorbers. Whenever the spectral coverage is available, we search for metals associated with the Ly lines among the 20 transitions most frequently detected in high column-density quasar absorbers.

(i) BR J0006–6208 ($z_{\text{em}} = 4.455$). Péroux et al. (2001) have reported four candidate absorbers at $z_{\text{abs}} = 2.97, 3.20, 3.78$ and 4.14 in the medium-resolution spectrum of this quasar. The blue end of the spectrum presented here is of fairly poor quality and therefore the minimum redshift above which quasar absorbers are searched for is set to $z_{\text{min}} = 3.083$, so the lowest DLA cannot be taken into consideration upon. We confirm the presence of the $z_{\text{abs}} = 3.202$ system and measure $\log N_{\text{HI}} = 20.80 \pm 0.10$ in agreement with medium-resolution estimates. The third system, $z_{\text{abs}} = 3.78$, falls in the UVES setting gap. The last absorber is confirmed as a sub-DLA with $\log N_{\text{HI}} = 19.37 \pm 0.15$. No associated metal lines are detected over the limited wavelength coverage of our spectrum. Fig. 1 shows the best Voigt profile-fitting solutions for these two systems.

(ii) PSS J0118+0320 ($z_{\text{em}} = 4.230$). This quasar was discovered as part of the Palomar Sky Survey and to our knowledge, there are no medium-resolution spectra published. We discovered an unambiguous sub-DLA at $z_{\text{abs}} = 4.128$ and measure $\log N_{\text{HI}} = 20.02 \pm 0.15$ down to the Lyman 5. Several associated metals are also observed in the red part of the spectrum. Fig. 2 shows our best fit of the H I lines.

(iii) PSS J0121+0347 ($z_{\text{em}} = 4.127$). No absorbers have been previously reported in this quasar, also from the Palomar Sky Survey. We report here for the first time a sub-DLA with $\log N_{\text{HI}} = 19.53 \pm 0.10$ at $z_{\text{abs}} = 2.976$. Metal lines at this redshift are also observed in the red part of the spectrum. Fig. 3 shows our best fit of the H I line.

(iv) SDSS J0124+0044 ($z_{\text{em}} = 3.840$). One absorber has been previously reported in this quasar from the Sloan Digital Sky Survey (Bouché & Lowenthal 2004). We report here for the first time the column density of the two sub-DLAs with $\log N_{\text{HI}} = 19.18 \pm 0.10$ at $z_{\text{abs}} = 2.988$ and $\log N_{\text{HI}} = 20.21 \pm 0.10$ at $z_{\text{abs}} = 3.078$. Metal lines at these redshifts are also observed in the red part of the spectrum. Fig. 4 shows our best fit of the H I lines.

(v) PSS J0133+0400 ($z_{\text{em}} = 4.154$). Péroux et al. (2001) report two DLAs in this quasar which were further confirmed by observations made by Prochaska et al. (2003) using the Echelle Spectrograph and Imager (ESI) on the Keck II telescope. Here, we measure $\log N_{\text{HI}} = 20.68 \pm 0.15$ at $z_{\text{abs}} = 3.692$ and $\log N_{\text{HI}} = 20.42 \pm 0.10$ at $z_{\text{abs}} = 3.773$ (Prochaska et al. measure $\log N_{\text{HI}} = 20.70^{+0.15}_{-0.10}$ and $\log N_{\text{HI}} = 20.55^{+0.10}_{-0.15}$ respectively). We also note that these two

![Figure 1. The two absorbers detected towards BR J0006–6208 at $z_{\text{abs}} = 3.202 (\log N_{\text{HI}} = 20.80 \pm 0.10)$ and $z_{\text{abs}} = 4.145 (\log N_{\text{HI}} = 19.37 \pm 0.15)$.](https://academic.oup.com/mnras/article-abstract/363/2/479/1125511)
systems are close by each other: they are separated by ∼5170 km s$^{-1}$
with an additional log $N_{\text{HI}} < 19.0$ in between them (see second
panel of Fig. 5, below). This group constitutes almost a multiple
DLA (Lopez et al. 2001; Ellison & Lopez 2001; Lopez & Ellison
2003). In addition, we report the discovery of a further four
sub-DLAs along the same line of sight. We measure log $N_{\text{HI}} = 19.01 \pm 0.10$ at $z_{\text{abs}} = 3.139$, log $N_{\text{HI}} = 19.94 \pm 0.15$ at $z_{\text{abs}} = 3.995$, log $N_{\text{HI}} = 19.16 \pm 0.15$ at $z_{\text{abs}} = 3.999$ and log $N_{\text{HI}} = 19.09 \pm 0.15$ at $z_{\text{abs}} = 4.021$. Again, two of these are very close to one another, $z_{\text{abs}} = 3.995$ and 3.999 corresponding to 250 km s$^{-1}$. There are fitted together using Ly2 and Ly4 since those provide better constraints than Ly1. The Lyman series down to Ly4 is also available for

the last three sub-DLAs. The various Lyman-series absorption lines
along this rich line of sight are displayed in Fig. 5. Given the limited
wavelength coverage of our spectrum, only metals associated with the
lowest and the highest system are detected.

(vi) BRI J0137−4224 ($z_{\text{em}} = 3.970$). Storrie-Lombardi et al.
(2001) do not find any DLA in the spectrum of this quasar. We
confirm that there are none of the highest H I column densities, but
we find two sub-DLAs. The first system is at $z_{\text{abs}} = 3.101$ and has an H I column density log $N_{\text{HI}} = 19.81 \pm 0.10$, while the second
is at $z_{\text{abs}} = 3.665$ and has log $N_{\text{HI}} = 19.11 \pm 0.10$. Both of these
systems have metals associated with them. The Lyman series down
to Ly11 is also visible for the second system. Fig. 6 shows the best
Voigt profile-fitting solutions for these two systems.

(vii) PSS J0209+0517 ($z_{\text{em}} = 4.174$). Péroux et al. (2001) report
two DLAs in this quasar which were further confirmed by ESI/Keck
II observations of Prochaska et al. (2003). Here, we measure
log $N_{\text{HI}} = 20.47 \pm 0.10$ at $z_{\text{abs}} = 3.666$ and log $N_{\text{HI}} = 20.45 \pm 0.15$ at $z_{\text{abs}} = 3.863$ (Prochaska et al. measure log $N_{\text{HI}} = 20.55 \pm 0.10$ and log $N_{\text{HI}} = 20.55 \pm 0.10$ respectively). We also find a sub-
DLA at $z_{\text{abs}} = 3.707$. We measure log $N_{\text{HI}} = 19.24 \pm 0.10$ for that
system. All these absorbers have metals associated with them. Fig. 7
shows our best fit of these H I lines.

(viii) BR J0244−0134 ($z_{\text{em}} = 4.053$). This quasar was observed
by Storrie-Lombardi, McMahon & Irwin (1996b) who did not re-
port any DLA. The high-resolution spectrum that we have ac-
quired shows that no sub-DLA is found either along this line of
sight.

(ix) BR J0311−1722 ($z_{\text{em}} = 4.039$). Péroux et al. (2001) report
an absorber with column density below the classical definition along
this line of sight from medium-resolution spectroscopy. Here, we
confirm that the system has log $N_{\text{HI}} = 19.48 \pm 0.10$ at $z_{\text{abs}} = 3.734$
observable down to Ly7 as shown in Fig. 8. Most of the constraints
in this system come from Ly3 and Ly5. The lower members of the
series were therefore merely used as a check for the solution. We
Figure 5. The rich line of sight towards PSS J0133+0400 is composed of systems with the following redshifts: $z_{\text{abs}} = 3.139$ ($\log N_{\text{HI}} = 19.01 \pm 0.10$), $z_{\text{abs}} = 3.692$ ($\log N_{\text{HI}} = 20.68 \pm 0.15$), $z_{\text{abs}} = 3.773$ ($\log N_{\text{HI}} = 20.42 \pm 0.10$), $z_{\text{abs}} = 3.995$ ($\log N_{\text{HI}} = 19.94 \pm 0.15$) together with $z_{\text{abs}} = 3.999$ ($\log N_{\text{HI}} = 19.16 \pm 0.15$) and finally $z_{\text{abs}} = 4.021$ ($\log N_{\text{HI}} = 19.09 \pm 0.15$).
Figure 6. These are the two absorbers detected towards BRI J0137–4224 at $z_{\text{abs}} = 3.101$ (log $N_{\text{H}I} = 19.81 \pm 0.10$) and $z_{\text{abs}} = 3.665$ (log $N_{\text{H}I} = 19.11 \pm 0.10$). The latter system is detected down to Ly11, but for display purposes only the first seven members of the series are shown.

Figure 7. The absorbers detected towards PSS J0209+0517 at $z_{\text{abs}} = 3.666$ (log $N_{\text{H}I} = 20.47 \pm 0.10$), $z_{\text{abs}} = 3.707$ (log $N_{\text{H}I} = 20.55 \pm 0.10$) and $z_{\text{abs}} = 3.863$ (log $N_{\text{H}I} = 20.45 \pm 0.15$).
Figure 8. The absorber detected towards BR J0311−1722 at \( z_{\text{abs}} = 3.734 \) (\( \log N_{\text{H I}} = 19.48 \pm 0.10 \)).

Figure 9. The DLA absorber detected towards BR J0334−1612 with \( z_{\text{abs}} = 3.557 \) (\( \log N_{\text{H I}} = 21.12 \pm 0.15 \)). We note the asymmetry in the shape of the profile, a possible signature of multi-component absorbers.

Figure 10. The sub-DLA absorber detected towards BR J0419−5716 at \( z_{\text{abs}} = 3.063 \) (\( \log N_{\text{H I}} = 19.17 \pm 0.10 \)).

Note that using only Ly\( \alpha \) to fit this system would mistakenly derive a much higher H\( \alpha \) (>20.0). Metals are found at the same redshift.

(x) BR J0334−1612 (\( z_{\text{em}} = 4.363 \)). A DLA at \( z_{\text{abs}} = 3.56 \) was reported by Péroux et al. (2001) from medium-resolution spectroscopy. They derive \( \log N_{\text{H I}} = 21.0 \) in excellent agreement with the measurement made here from higher resolution spectroscopy. Several metal lines are detected at these redshifts, with \( \log N_{\text{H I}} = 21.0 \pm 0.10 \) as well as one metal transition. Fig. 10 shows our best fit of this H\( \alpha \) line.

(xii) BR J0419−5716 (\( z_{\text{em}} = 4.461 \)). This quasar was observed by Péroux et al. (2001) who did not detect any sub-DLA in its medium resolution spectrum. Using higher-resolution data, we detect a sub-DLA with \( z_{\text{abs}} = 3.063 \) with \( \log N_{\text{H I}} = 19.17 \pm 0.10 \) as well as one metal transition. Fig. 10 shows our best fit of this H\( \alpha \) line.

(xiii) PSS J2154+0335 (\( z_{\text{em}} = 4.363 \)). This quasar was observed by Péroux et al. (2001) who report a DLA at \( z_{\text{abs}} = 3.61 \). This system falls in the setting gap of our UVES spectra. On the other hand, we discover a new sub-DLA at \( z_{\text{abs}} = 3.177 \) with \( \log N_{\text{H I}} = 19.23 \pm 0.15 \). No metals were found associated with system over the limited wavelength range of our spectrum. Fig. 11 shows our best fit of this H\( \alpha \) line.

(xiv) BR J2215−1611 (\( z_{\text{em}} = 3.990 \)). This quasar was observed by Storrie-Lombardi et al. (1996b) who did not find any DLA in the spectrum. Here we report on two new sub-DLAs with \( \log N_{\text{H I}} = 19.01 \pm 0.15 \) and \( 20.05 \pm 0.15 \) at \( z_{\text{abs}} = 3.656 \) and 3.662 respectively. The two are separated by just \( \sim 320 \) km s\(^{-1}\). The Lyman series is detected down to Ly\( \beta \), where the division into two distinct systems is unambiguous. Several metal lines are detected at these redshifts.
redshifts too. Fig. 12 shows our best fit of these H I lines. We also note O vi λλ 1032 and 1037 features at z_{abs} = 3.9785 along this quasar line of sight.

(xv) BR J2216−6714 (z_{em} = 4.469). This quasar was observed by Péroux et al. (2001) who do not report an absorber but do mention a possible sub-DLA candidate at z_{abs} = 3.37. We now confirm that system and derive log N_{H I} = 19.80 ± 0.10 at z_{abs} = 3.368. Several metal lines are also observed at this redshift. Fig. 13 shows our best fit of this H I line.

(xvi) BR J2239−0552 (z_{em} = 4.558). This quasar was observed by Storrie-Lombardi et al. (1996b) who report a DLA at z_{abs} = 4.08. We now confirm that system and derive log N_{H I} = 20.55 ± 0.10 at z_{abs} = 4.079 in good agreement with estimates from medium-resolution spectroscopy. The absorber is detected down to the Ly3 level and has associated metal lines. Fig. 14 shows our best fit of these H I lines.

(xvii) BR J2349−3712 (z_{em} = 4.208). This quasar was observed by Péroux et al. (2001) at medium resolution. They do not find any DLA along its line of sight. Here, we report on the discovery of three sub-DLAs, two of which are blended. The first system has log N_{H I} = 19.12 ± 0.10 at z_{abs} = 3.581 while the two others have log N_{H I} = 19.79 ± 0.15 at z_{abs} = 3.690 and log N_{H I} = 19.78 ± 0.10 at z_{abs} = 3.696 (i.e. Δν ∼ 380 km s^{-1}). The subdivision of these is unambiguous in Ly2. For all the systems the Lyman series is available down to Ly3. No associated metal lines are detected over the limited wavelength coverage of our spectrum. Fig. 15 shows our best fit of these H I lines.
2.4 Medium/high-resolution $N_{\text{H I}}$ comparison

Seven of the quasar absorbers described above are classical DLAs with $\log N_{\text{H I}} > 20.3$. In Table 3, the $N_{\text{H I}}$ column density estimates from medium-resolution spectroscopy of these DLAs is compared with the new high-resolution measurements presented here. The last two systems (toward BR J0334−1612 and BR J2239−0552) were also observed by Storrie-Lombardi & Wolfe (2000) who found $N_{\text{H I}}$ values in very good agreement with ours. The comparison shows that previous $N_{\text{H I}}$ estimates from 5-Å resolution quasar spectra are reliable. In fact, it is also known that systems with high column density from echelle data might be affected by the difficulty of tracing the correct continuum over a different echelle order. In the sub-DLA regime however, high-resolution spectra are definitely required in order to accurately measure $N_{\text{H I}}$.

Table 3. This table compiles the DLA column density and redshift estimates from 5 Å (full width at half maximum), S/N per pixel ~20 (Péroux et al. 2001, except BR J2239−0552 which is from Storrie-Lombardi et al. 1996b) and 2 Å, S/N per pixel ~25 quasar spectra from the present study.

| Quasar              | medium resolution | high resolution | $\Delta N_{\text{H I}}$ (med-high) |
|---------------------|-------------------|-----------------|-----------------------------------|
| BR J0006−6208       | $z_{\text{abs}}$ | $N_{\text{H I}}$ | $z_{\text{abs}}$ | $N_{\text{H I}}$ | $z_{\text{abs}}$ | $N_{\text{H I}}$ |
|                     | 3.20              | 20.9            | 3.202             | 20.80             | +0.10             |
| PSS J0133+0400      | 3.69              | 20.4            | 3.692             | 20.68             | +0.28             |
| ...                 | 3.77              | 20.5            | 3.773             | 20.42             | −0.08             |
| PSS J0209+0517      | 3.66              | 20.3            | 3.666             | 20.47             | +0.17             |
| ...                 | 3.86              | 20.6            | 3.863             | 20.43             | −0.17             |
| BR J0334−1612       | 3.56              | 21.0            | 3.557             | 21.12             | +0.12             |
| BR J2239−0552       | 4.08              | 20.4            | 4.079             | 20.55             | +0.15             |
| mean                | 3.69              | 20.58           | 3.689             | 20.64             | +0.08             |
| min value           | 3.20              | 20.30           | 3.202             | 20.42             | −0.17             |
| max value           | 4.08              | 21.00           | 4.079             | 21.12             | +0.28             |

3 ANALYSIS

3.1 Properties of the survey

3.1.1 Survey sensitivity

Table 4 lists the minimum ($z_{\text{min}}$) and maximum ($z_{\text{max}}$) redshifts along which a sub-DLA could be detected along each quasar line-of-sight. $z_{\text{min}}$ corresponds to the point below which the S/N is too low to find absorption features at the sub-DLA threshold of $W_{\text{rest}} = 2.5$ Å, and $z_{\text{max}}$ is 3000 km s$^{-1}$ blueward of the Lyα emission of the quasar. We took care to exclude the DLA regions and the gaps in the spectrum due to non-overlapping UVES settings when computing the redshift path surveyed.

Fig. 16 shows the cumulative number of lines of sight along which a sub-DLA could have been detected at the 5σ confidence level. This survey sensitivity, $g(z)$, is defined by:

$$g(z) = \sum_i H(z_{\text{max}} - z_i) H(z - z_{\text{min}})$$

where $H$ is the Heaviside step function. In Fig. 16, it is compared with those of the previous sub-DLA survey (Péroux et al. 2003b). It shows that our new observations probe a higher redshift interval than did the first archive-based work and that the combination of the two provides more homogeneous survey coverage in the range $z = 1.5$ to 4.5.

3.1.2 Redshift distribution

The sub-DLA sample described in Section 2 leads to 21 sub-DLAs along 17 quasar lines of sight, whilst we had 10 sub-DLAs making up our ‘statistical sample’ toward 22 lower redshift quasars in our previous archival study (Dessauges-Zavadsky et al. 2003). We also confirm the presence of seven DLAs along the same lines of sight. The histograms showing the redshift distribution of these homogeneous sub-DLA samples are shown in Fig. 17.

3.2 Sub-DLAs statistical properties

3.2.1 Redshift number density

The number of quasar absorbers per unit redshift, $n(z)$, is a direct observable. This quantity, however, can be used to constrain the evolution or lack of it only when deconvolved from the effect of cosmology.
Table 4. Redshift path surveyed. \(z_{\text{min}}\) corresponds to the point below which no flux is observed and \(z_{\text{max}}\) is 3000 km s\(^{-1}\) bluewards of the Ly\(\alpha\) emission line. Gap in non-overlapping settings and known DLAs are taken into account.

| Quasar        | \(z_{\text{em}}\) | \(z_{\text{min}}\) | \(z_{\text{max}}\) |
|---------------|-------------------|-------------------|-------------------|
| BR J006–6208  | 4.455             | 3.083             | 3.188             |
| ...           | ...               | ...               | ...               |
| PSS J0118+0520| 4.230             | 2.767             | 4.225             |
| PSS J0121+0547| 4.127             | 2.739             | 3.410             |
| ...           | ...               | 3.474             | 4.122             |
| SDSS J0124+0044| 3.840             | 2.414             | 3.835             |
| PSS J0133+0400| 4.154             | 2.414             | 3.247             |
| ...           | ...               | 3.305             | 3.676             |
| ...           | ...               | 3.070             | 3.765             |
| ...           | ...               | 3.786             | 4.149             |
| PSS J0209+0515| 4.174             | 2.767             | 3.658             |
| ...           | ...               | 3.675             | 3.855             |
| BR J017–4019  | 4.131             | 2.607             | 2.994             |
| ...           | ...               | 3.022             | 3.407             |
| ...           | ...               | 3.473             | 4.126             |
| PSS J2154+0335| 4.363             | 2.748             | 3.572             |
| ...           | ...               | 3.369             | 4.358             |
| BR J2215–1611 | 3.990             | 2.315             | 3.408             |
| ...           | ...               | 3.473             | 3.985             |
| BR J2216–6714 | 4.469             | 2.748             | 4.464             |
| BR J2239–0552 | 4.558             | 2.894             | 3.735             |
| ...           | ...               | 3.801             | 4.070             |
| ...           | ...               | 4.096             | 4.552             |
| BR J2349–3712 | 4.208             | 2.601             | 3.407             |
| ...           | ...               | 3.473             | 4.203             |

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. 18, where the number density for DLAs (Péroux et al. 2003a; Rao, Turnshek & Nestor, in preparation), sub-DLAs (both predictions from Péroux et al. 2003a, computation and new direct measurements from the present work) and LLS are presented (also from Péroux et al. 2003a). It can already be seen that the predictions overestimated the number density for DLAs (Péroux et al. 2003a; Rao, Turnshek & Nestor, in preparation), sub-DLAs (both predictions from Péroux et al. 2003a, computation and new direct measurements from the present work) and LLS are presented (also from Péroux et al. 2003a). It can already be seen that the predictions overestimated the number density for DLAs (Péroux et al. 2003a; Rao, Turnshek & Nestor, in preparation), sub-DLAs (both predictions from Péroux et al. 2003a, computation and new direct measurements from the present work) and LLS are presented (also from Péroux et al. 2003a).

where \(\Omega_M\) is the matter density and \(\Omega_{\Lambda}\) is the contribution of the cosmological constant. The following values have been used: \(\Omega_M = 0.3,\ \Omega_{\Lambda} = 0.7\) and \(H_0 = 65\text{ km s}^{-1}\text{Mpc}^{-1}\). These ‘no-evolution curves’ are shown for each class of quasar absorbers in Fig. 18 where \(n(z) = n_0(1+z)^2\left(\frac{H(z)}{H_0}\right)^{-1}\) (2)

with \(\frac{H(z)}{H_0} = \left(\frac{\Omega_M(z+1)^2 - \Omega_{\Lambda}[\zeta(z+2)] + (1+z)^2}{\Omega_M + \Omega_{\Lambda}[\zeta(z+2)] + (1+z)^2}\right)^{1/2}\) (3)
with the assumption that all classes of absorbers (i.e. DLAs, sub-DLAs and LLS) and all members of a given class are arising from the same underlying parent population, one can estimate the cross-section radius of spherical absorbers, $\sigma$, from the observed redshift number density $n(z)$. Following Tytler (1981) and using a non-zero $\Lambda$-cosmology, we find:

$$n(z) = \frac{c}{H_0} \left(1 + z\right)^2 \left[ \frac{H(z)}{H_0} \right] \int_0^\infty \epsilon \Phi(L) \kappa \pi R^2(L) \, dL,$$

where $R(L)$ is the average $\text{H} \text{I}$ absorption cross-section radius of a spherical galaxy with luminosity $L$, and $\epsilon$ is the fraction of galaxies which have gaseous absorbing envelopes with filling factor $\kappa$. $\Phi(L)$ is estimated from the Schechter (1976) galaxy luminosity function:

$$\Phi \left( \frac{L}{L_*} \right) = \Phi_* \left( \frac{L}{L_*} \right)^{−\alpha} \exp \left( \frac{L}{L_*} \right).$$

If we further assume that a Holmberg (1975) relation between optical radius and luminosity holds at all redshifts

$$\frac{R}{R_*} = \left( \frac{L}{L_*} \right)^{−\alpha},$$

we obtain the following relation for the radius:

$$R_*^2 = \frac{c}{H_0} \left(1 + z\right)^2 \left[ \frac{H(z)}{H_0} \right] \left[ \frac{H(z)}{H_0} \right] \epsilon \Phi_* \kappa \pi \Gamma(1 + 2t - s),$$

where $\Gamma(z)$ is the Gamma function. We take $\epsilon = 1$, $\kappa = 1$ and $t = 0.4$ (derived from Peterson, Strom & Strom 1979). Two different sets of parameters are used for the luminosity function: $\Phi_* = 0.0149 \pm 0.04 \, h^3 \, \text{Mpc}^{-3}$ and $s = 1.05 \pm 0.01$ for $z < 0.75$ from the Sloan measurements of Blanton et al. (2003) and $\Phi_* = 0.0142 \pm 0.014 \, h^3 \, \text{Mpc}^{-3}$ and $s = 0.50^{+0.06}_{-0.06}$ for $z > 0.75$ from infrared selected galaxies of Chen et al. (2002). These yield an $\text{H} \text{I}$ gas radius of

$$R_* = \frac{A h^{-1}}{100} \left( \frac{H(z)}{H_0} \right)^{1/2} \left[ \frac{H(z)}{H_0} \right]^{1/2},$$

where $A = 76$ for $z < 0.75$ and $A = 91$ for $z > 0.75$. The redshift evolution of the characteristic radius of DLAs, sub-DLAs and LLS are plotted in Fig. 19. All classes of absorbers have their characteristic radius, $R_*$, decreasing with decreasing redshift, and this effect is stronger at lower column densities. For comparison, the impact parameters of spectroscopically confirmed $z < 1$ DLAs (see Boissier, Péroux & Pettini 2003, for a compilation) and MgII-selected galaxies (Steidel et al., 2002), a proxy for LLS, are also plotted. Given the number of assumptions made in the calculation, the few available observations are in relatively good agreement with our results.

### 3.2.3 Column density distribution

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

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**Table 5.** This table summarizes the observed number density of quasar absorbers for different column-density ranges together with the predicted number density of sub-DLAs (from Péroux et al. 2003a and Rao et al., in preparation, except for the sub-DLA number density which is from the present work). The empty entries are regions of redshift/column-density parameter space as yet unobserved. Column headings are as follows: # number of absorption systems, 19.0$^{+0.0}_{-0.0}$: number of absorption systems and corresponding $dz$ refer to systems with $19.0 < \log N_{\text{H} \text{I}} < 20.3$, whilst $n(z)$ is for all systems with $\log N_{\text{H} \text{I}} > 19.0$.

| log $N_{\text{H} \text{I}}$ range | # | (z) | $dz$ | $n(z)$ | # | (z) | $dz$ | $n(z)$ | # | (z) | $dz$ | $n(z)$ |
|-------------------------|---|------|-----|--------|---|------|-----|--------|---|------|-----|--------|
| 0.01−1.78 | 7 | 0.64 | 10.9 | 0.64±0.24 | . | ... | ... | ... | ... | ... | ... | ... |
| 1.78−2.50 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2.50−3.00 | 17 | 2.82 | 10.2 | 1.67±0.07 | 5 | 2.74 | 9.1 | 0.73±0.25 | 0.46 | 15 | 2.73 | 84.5 | 0.18±0.05 |
| 3.00−3.50 | 11 | 3.14 | 4.3 | 2.57±0.47 | 5 | 3.15 | 9.4 | 1.01±0.28 | 0.67 | 15 | 3.27 | 75.0 | 0.26±0.07 |
| 3.50−4.00 | 9 | 3.84 | 2.3 | 3.89±1.30 | 12 | 3.74 | 9.6 | 1.62±0.36 | 1.52 | 16 | 3.77 | 42.4 | 0.38±0.09 |
| 4.00−5.00 | 26 | 4.29 | 7.2 | 3.63±0.71 | 4 | 4.13 | 5.1 | 1.28±0.40 | 2.00 | 9 | 4.19 | 18.5 | 0.49±0.16 |
| total | 71 | ... | 34.9 | ... | 31 | ... | 42.0 | ... | ... | 100 | ... | 514.8 | ... |

n/a: ‘not applicable’ refers to low-redshift MgII-selected systems and so the number of absorption systems and corresponding $dz$ are not directly comparable to higher-redshift statistics.

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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 \( \log N_{\text{HI}} = 19.0 \). The column density distribution has often been fitted with a simple power law (i.e., Prochaska & Herbert-Fort 2004), but there has been recent work showing that a Schechter-type of function is more appropriate (Pei & Fall 1995; Storrie-Lombardi et al. 1996b; Péroux et al. 2003a). In any case, it should be noted that neither of these two functions is physically motivated; rather, they 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 ionized by incident UV flux. We note once more the paucity of very high column-density DLAs at high redshift. All the data are summarized in Table 6.

3.3 \( \Omega_{\text{HI}+\text{He II}} \) gas mass

3.3.1 Cumulative number of absorbers

In Fig. 21, the number of quasar absorbers per unit comoving distance interval is plotted as a function of \( \log N_{\text{HI}} \). The new observations increase, by one dex, the \( N_{\text{HI}} \) column-density parameter space probed and therefore provide a much better handle on the true shape of the distribution. This, in turn, is crucial for constraining the total HI gas content which is a function of both column densities and redshifts. In our surveys, the DLA and sub-DLA samples (and associated redshift paths) are totally independent (Fig. 21) in the sense that the quasars used to make up the samples are different in both cases given that higher resolution is required for the study of sub-DLAs. Therefore, the shapes of both sections of the curves are unrelated and the fact that the function in the sub-DLA regime is a smooth continuation of the DLA part is a result of the observations.

3.3.2 \( \Omega_{\text{HI}+\text{He II}} \)

The gas mass density, \( \Omega_{\text{HI}+\text{He II}} \), observed in high-redshift quasar absorbers is classically expressed as a fraction of today’s critical
Table 6. This table summarizes the observed column-density distribution of quasar absorbers down to the sub-DLA column density. The empty entry in the highest column density bin at the highest redshift range reflects the lack of systems with log $N_{\text{HI}} > 21.35$ at $z > 3.5$.

| $z$ range | log $N_{\text{HI}}$ range | # | log $f(N, z)$ | log $f_{\text{min}}(N, z)$ | log $f_{\text{max}}(N, z)$ |
|----------|--------------------------|---|--------------|------------------|------------------|
| 19.00–19.50 | 1.78–3.5 | 6 | 19.23 | -20.5 | -20.8 |
| 19.50–20.30 | 1.78–3.5 | 9 | 19.94 | -21.2 | -21.4 |
| 20.30–20.65 | 1.78–3.5 | 33 | 20.45 | -21.9 | -22.0 |
| 20.65–21.00 | 1.78–3.5 | 20 | 20.81 | -22.5 | -22.6 |
| 21.00–21.35 | 1.78–3.5 | 13 | 21.08 | -23.0 | -23.2 |
| 21.35–21.70 | 1.78–3.5 | 5 | 21.42 | -23.8 | -24.1 |
| 3.5–5.0 | | | | | |

Figure 21. Cumulative number of quasar absorbers as a function of column density for two redshift intervals. The discontinuity at log $N_{\text{HI}} = 20.3$ illustrates that the DLA and sub-DLA samples (and associated redshift paths) are made of different quasar spectra and are therefore totally independent. The observations show that the incidence of low column-density absorbers is bigger at high redshift, as predicted by Péroux et al. (2003a).

4 DISCUSSION

4.1 On the ionized fraction of sub-DLAs

The extension of the classical DLA definition to log $N_{\text{HI}} > 19$ proposed by Péroux et al. (2003a) has triggered concerns about the ionized fraction in these sub-DLAs. This issue is not relevant when quasar absorbers are included in the total $H_1$ gas mass of the Universe, $\Omega_{\text{HI}}$. Indeed, it is the sheer number of sub-DLAs which makes them add up to the classical DLA contribution, and this does not depend on the amount of gas ionized in these systems. On the contrary, the quasar absorbers which have a high ionization fraction should not be included when measuring the neutral gas mass, as these absorbers indicate hotter gas. Nevertheless, the evolution of neutral gas mass is most probably the result of several phenomena including star formation, galactic feedback, ionization of neutral gas and formation of molecular $H_2$ gas (which will in turn lead to the formation of stars). Which of these may be the dominant processes is still unclear.

3.4 Clustering properties

As already noted in Péroux et al. (2003b), quite a few of the 21 sub-DLAs which make up the new sample are close in redshift. The notes in the last column of Table 2 emphasize in particular those systems less than $\sim 400$ km s$^{-1}$ apart, which in practice means that they needed to be fitted together: $z_{\text{abs}} = 3.995$ and $3.999$ toward PSS J0133+0400 ($\Delta v = 240$ km s$^{-1}$), $z_{\text{abs}} = 3.656$ and $3.662$ toward BR J2215−1611 ($\Delta v = 380$ km s$^{-1}$) and $z_{\text{abs}} = 3.690$ and $3.696$ toward BR J2349−3712 (also have $\Delta v = 380$ km s$^{-1}$). Another example is the two $z_{\text{abs}} = 3.692$ and $3.773$ DLAs along PSS J0133+0400 ($\Delta v = 5100$ km s$^{-1}$), with (between them) a $z_{\text{abs}} = 3.760$ quasar absorber just below the sub-DLA definition log $N_{\text{HI}} < 19.0$. In fact, the line of sight toward PSS J0133+0400 is particularly rich, containing a total of six DLAs/sub-DLAs, all except one of which are separated by no more than $\Delta v = 15000$ km s$^{-1}$. This complex group of systems appears to be similar to the multiple DLAs (MDLAs) studied in Lopez & Ellison (2003), which are found to have abundance patterns distinctly different from those of classical DLAs. In the present data, we do not cover the red part of the spectrum which would allow us to test the hypothesis from Lopez & Ellison (2003). Acquiring a spectrum covering the red part of this quasar would allow us to test further the hypothesis about the possibly truncated star formation of these MDLAs.
shown that relative or absolute abundances estimated from $X^+/{H}^e$ measurements are a good approximation of, e.g., $X_{\text{tot}}/\text{Fe tot}$ or $X_{\text{mg}}/\text{H tot}$. Therefore, using the metals commonly detected in sub-DLAs for a measure of the metallicity of the H I gas in the Universe does not introduce a systematic bias, even though the ionization fraction of the systems is not small.

### 4.2 On the nature of sub-DLAs

By assuming that both DLAs and sub-DLAs indicate the same underlying parent population, a natural explanation for the nature of sub-DLAs could be that they are the outermost part of galaxies (Péroux et al. 2003b). This is illustrated by the calculations of absorber sizes presented here, where the characteristic radius of sub-DLAs is around 40 $h^{-1}_{100}$ kpc and that of DLAs is 20 $h^{-1}_{100}$ kpc.

The metallicity of sub-DLAs also seems to differ from that of classical DLAs. Smoothed particle hydrodynamics simulations (Nagamine, Springel & Hernquist 2004a, b) indicate that DLAs should be 1/3 of solar metallicity at $z = 2.5$, and even more metal-rich toward lower redshifts. Indeed, there are lines of evidence pointing toward lower column-density quasar absorbers like sub-DLAs being more metal rich at $z < 2$ (Péroux et al. 2003b). This could be explained by classical DLAs being dustier than their sub-DLA counterparts. The high dust content of DLAs could act against their selection by dimming background quasars in the first place. Recent computations have shown that even current radio-selected quasar samples (Ellison et al. 2001) are not in disagreement with such a scenario (Vladilo & Péroux 2005). In fact, from figure 9a of Vladilo & Péroux (2005), it can be appreciated that in the decade $z = 20–21$, from 10–50 per cent of the DLAs might be missed as a result of dust obscuration. Extrapolations of these mathematical formulations to the log $N_{\text{H I}} = 19–20$ decade suggest that only a little under 10 per cent of the sub-DLAs might be missed by dust obscuration.

If confirmed, this can be explained by the fact that in sub-DLAs, the Zn column-density threshold does not combine with the H I threshold log $N_{\text{H I}} > 20.3$ that prevents the detection of sub-DLAs.

### 4.3 Cosmological evolution of the mass densities

Fig. 23 shows the cosmological evolution of some of the observable baryons in the Universe. In recent years, new observations have considerably changed the global picture with respect to previous studies (Lanzetta et al. 1991; Wolfe et al. 1995; Storrie-Lombardi et al.)
Fall & Pei (1993) calculations, taking into account the most recent fraction of the quasar absorbers is missed because their background content of the quasar absorbers we know of today and (b) what et al. 2005; Murphy & Liske 2004). It should be emphasized, how-ever (Pettini et al. 1997; Ledoux, Petitjean & Srianand 2003; Kulkarni et al. 2005; Blanton M. R. et al., 2003, ApJ, 592, 819 observations, addresses both these issues: Vladilo & Péroux (2005) show that whilst the dust content of the DLAs in the current sample is not too high, the missing fraction is possibly quite important, ranging from 30–50 per cent at \( z = 1.8–3.0 \).

Concerning points (ii) and (iii), the number of quasar absorbers observed at \( z > 2 \) is now reaching the hundreds. The mild fluctuations in the redshift evolution in the range \( z = 5 \) to \( z = 2 \) is within the small error estimates. Therefore the cosmological evolution of the total gas mass, \( \Omega_{\text{HI+HeII}} \), can be approximated to constant in that redshift range. Yet, radio observations of very large numbers of local \( \text{H} I \) galaxies such as the \( \text{H} I \) Parkes All-Sky Survey (Zwaan et al. 2005a) indicate a low value of \( \Omega_{\text{HI+HeII}} \) at \( z = 0 \). This would imply a fast evolution of the gas mass between \( z \sim 0.61 \) (Rao et al., in preparation) and \( z = 0 \).

The last point illustrates how challenging it still is to find and study quasar absorbers at intermediate redshifts. Warnings about \( \Omega_{\text{HI+HeII}} \) measurements based on small number statistics have already been issued (Péroux et al. 2004b) and unfortunately future developments in that direction appear limited given the presently restricted availability of UV optimized instruments.

### 5 Conclusion

We have presented a new sample of high-redshift sub-DLAs (\( N_{\text{HI}} > 10^{19} \text{ cm}^{-2} \)) found in the spectra of 17 \( z > 4 \) quasar spectra observed with the Ultraviolet-Visual Echelle Spectrograph 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 and sub-DLAs and compare it with that of LLSs taken from the literature. 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 \( N_{\text{HI}} = 10^{19} \text{ cm}^{-2} \) is also presented. A departure from the usually fitted power law is observed in the sub-DLA regime. \( f(N,z) \) is further used to determine the total \( \text{HI} \) 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 \( \Omega_{\text{HI+HeII}} \) is \( \sim 20 \) per cent or more if compared with the Sloan results (Prochaska & Herbert-Fort 2004). Finally, we discuss the possibility that sub-DLAs are less affected by the effects of dust obscuration than classical DLAs.

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### References

Blanton M. R. et al., 2003, ApJ, 592, 819
Boissier S., Péroux C., Pettini M., 2003, MNRAS, 338, 131
Bouché N., Lowenthal J. D., 2004, ApJ, 609, 513

\( \Omega_{\text{HI+HeII}} = \Omega_1 \) at high redshift \( \sim \)

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**Figure 23.** Observable baryons in the Universe as a function of time. The curve represents the mass density in stars from Rudnick et al. (2003) integrated from the Star Formation Rate measured by Cole et al. (2001). The uncertainties in that measurement are estimated to be around 15 per cent but are also a strong function of the chosen initial mass function. The error bars represent the mass density in those quasar absorbers deconvolved from the local critical density. A direct comparison of these two quantities illustrates the puzzling current situation concerning the baryon content of the Universe.
Total gas mass $\Omega_{\text{HI-He II}}$ at $z > 2$