Classical and Mg II-selected damped Lyman α absorbers: impact on $\Omega_{H_I}$ at $z < 1.7$

Céline Péroux,1⋆ Jean-Michel Deharveng,2 Vincent Le Brun2 and Stefano Cristiani1

1 Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy
2 Laboratoire d’Astrophysique de Marseille, Traverse du Siphon, Les trois Lacs BP 8, 13376 Marseille Cedex 12, France

ABSTRACT
The damped Lyα systems (DLAs), seen in absorption in the spectrum of background quasars, are believed to contain a large fraction of the neutral gas in the Universe. Paradoxically, these systems are more difficult to observe at $z_{\text{abs}} < 1.7$, since they are rare and their H I feature then falls in UV spectra, thus requiring the use of space-borne facilities. In order to overcome this observational difficulty, Rao & Turnshek pioneered a method based on Mg II-selected DLAs; that is, absorbers discovered thanks to our knowledge of their Mg II feature in optical spectra. In the present work, we use new observations undertaken at the TNG as well as a careful literature and archival search to build samples of low-redshift absorbers classified according to the technique used for their discovery. We successfully recover $N_{H_I}$ and equivalent widths of $\text{Fe II } 2600$, $\text{Mg II } 2796$, $\text{Mg II } 2803$ and $\text{MgI } 2852$ for a sample of 36 absorbers, 21 of which are Mg II-selected. We find that the Mg II-selected sample contains a marginally larger fraction of absorbers with log $N_{H_I} > 21.0$ than seen otherwise at low redshift. If confirmed, this property will in turn affect estimates of $\Omega_{H_I}$, which is dominated by the highest H I column densities. We investigate the source of the potential discrepancy and find that log $N_{H_I}$ does not correlate significantly with metal equivalent widths. Similarly, we find no evidence that gravitational lensing, the fraction of associated systems or redshift evolution affect the absorber samples in a different way. We conclude that the hint of discrepancies in $N_{H_I}$ distributions between the Mg II-selected DLAs and the others probably arises from small-number statistics. Therefore, further observations based on both H I and Mg II selection techniques are required in order to clarify the impact on estimates of $\Omega_{H_I}$ at low redshifts.

Key words: galaxies: evolution – galaxies: formation – intergalactic medium – quasars: absorption lines – cosmology: observations – large-scale structure of Universe.

1 INTRODUCTION
Absorption systems in the line of sight towards distant quasars allow direct observation of the distribution of gaseous matter from the epoch of initial galaxy formation to the present day (Lanzetta et al. 1991; Wolfe et al. 1995). In particular, these absorbers provide important ways of measuring the neutral gas and metallicity content of the Universe at high redshifts (Vladilo et al. 2000; Savaglio 2001; Kulkarni & Fall 2002; Prochaska et al. 2003; Péroux et al. 2003a). The high column density end of this population is composed of the damped Lyα systems (DLAs), which have H I column densities log $N_{H_I} > 20.3$ cm$^{-2}$, and the sub-damped Lyα systems (sub-DLAs), with 19.0 < log $N_{H_I} < 20.3$ cm$^{-2}$. These two are found to contain a large fraction of the neutral gas in the Universe (Péroux et al. 2003b). Therefore, these systems can be used to compute the ratio of H I density to the critical density of the Universe, $\Omega_\text{b}$, which in turn provides information on the gas consumption and star formation over time.

This cosmological mass density is fairly well constrained at high redshift (Storrie-Lombardi, McMahon & Irwin 1996; Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003b). In contrast, measurements of $\Omega_{H_I}$ at $z < 1.7$ are more difficult for several reasons: the observed absorber wavelengths are shifted to the ultraviolet, requiring space observations, and the geometry of the Universe combined with the paucity of DLA systems requires the observation of many quasar lines of sight. Nevertheless, this redshift range is of particular importance since it comprises ~70 per cent of the look-back time ($\Omega_\text{M} = 0.3; \Omega_\Lambda = 0.7$ cosmology).

Lanzetta, Wolfe & Turnshek (1995) were the first to derive $\Omega_{H_I}$ at low redshift using the International Ultraviolet Explorer (IUE) satellite. Rao, Turnshek & Briggs (1995) proposed a new method...
based on the observational evidence which indicates that DLAs are always associated with a Mg II system, while the reverse is not true. From successful HST observations of a sample of Mg II-selected systems (Rao & Turnshek 2000), they estimate DLA statistics by correcting for the observationally known incidence of Mg II systems in a random quasar sample. They then compute the mass of neutral gas using their ‘derived’ sample of low-redshift DLAs. Using the same technique, Churchill (2001) discovered new DLAs at very low redshifts: $z \sim 0.05$. These observations imply a rather flat distribution of the cosmological mass density of neutral hydrogen down to low redshifts, at odds with current ideas and models of cosmic star formation (Pei & Fall 1995; Nagamine, Springer & Hernquist 2004). Moreover, local estimates of $H_I$ mass measured by Zwaan et al. (1997), and recently confirmed by Zwaan et al. (2003), are difficult to reconcile with such high values of $\Omega_{HI}$ in low-redshift quasar absorbers.

In the present work, we compare the observed properties of Mg II-selected absorbers with more ‘classical’ DLAs/sub-DLAs. The goal is to identify whether the two observational methods sample the column density parameter space, and whether the calculation of the cosmological mass density at low redshifts is affected or not. In Section 2, we present the data samples, which are from both a targeted observational programme and a dedicated literature and archival search. We describe the data reduction process as well as the method used to make the measurements of $\log N(H_I)$, and metal equivalent widths (hereafter EWs). Constructing well-defined samples is challenging since the data have been taken at various epochs by different authors having distinct scientific goals in mind. Nevertheless, we have been extremely conservative in selecting the systems and, for the purpose of our analysis, we have also split the non-Mg II-selected samples into two subsamples, which allows for comparison of the various discovery techniques. Details on this matter are given in Sections 3 and 4, where we also compare the properties of the samples of classical and Mg II-selected quasar absorbers.

2 THE DATA

2.1 Mg II measurements

In order to build the so-called ‘classical’ sample, we have acquired optical spectra covering the Fe II 2600, Mg II 2796, Mg II 2803 and Mg I 28522 features of known DLAs/sub-DLAs with well-constrained $N_{HI}$ column densities. The observations were carried out in service mode with the DOLORES spectrograph at the 3.58-m Telescopio Nazionale Galileo (TNG) located at Roque de Los Muchachos Observatory in the Canary Islands. High signal-to-noise optical spectrophotometry was obtained covering the appropriate wavelength range so as to study the Mg II and other associated metal lines in $z_{abs} < 1.7$ quasar absorbers, the exact range depending on the grism used for the observations. A journal of the observations is presented in Table 1.

13 quasars were observed between 2003 February and April. The integrating times are all of a total of 1800 s, regardless of the brightness of the object. Only in one case (Q1354+3139/Q1351+318) were the weather conditions poor, with the resulting spectrum thus suffering from a low signal-to-noise ratio. A combination of high- and low-resolution modes of the DOLORES spectrograph was used. The camera is equipped with a Loral thinned and back-illuminated CCD with 2048 $\times$ 2048, 15-$\mu$m pixels. Grisms 1, 5, 6 and 7 (LR $\sim$ B, HR $\sim$ V and HR $\sim$ R respectively) were used for the observations. Therefore the dispersion of the spectra ranges from 0.8 to 2.8 $\AA$ pixel$^{-1}$. All the observations were taken with a slit width of 1.0–1.5 arcsec.

The data reduction is done using the IRAF$^1$ software package. The bias frames are so similar over successive nights that a master ‘zero’ frame for each month is created using the IMCOMBINE routine. After trimming, the data are zero-corrected using CCDPROC. Similarly, a single flat-field frame is produced by taking the median of the flats. The overall background variation across this frame is removed using IMSURFIT to produce an image to correct for the pixel-to-pixel sensitivity variation of the data. The task APALL is used to extract 1-D multispectra from the 2-D frames of the quasars and spectrophotometric standard stars, while a cut through the 2-D frames of the Arc serves as an extraction procedure. The APALL routine estimates the sky level by model fitting over specified regions on either side of the spectrum. In the case for which the object is faint on the 2-D frame (i.e. for Q0238$+1636$/Q0235+164), different exposures are IMCOMBINED before extraction with APALL. The spectra are then wavelength-calibrated using Ar, Ne or He arcs according to the grism used. We pay particular attention to this step of the data processing, since it is crucial for the later measurements of the metal equivalent widths. Given that the objects have magnitudes ranging from 15 to 19 but identical exposure times, the signal-to-noise ratios of the resulting spectra vary from one object to another.

In addition to these new data, we thoroughly checked published literature and public data sets for any other spectra of sufficient quality for us to be able to estimate equivalent widths of metal features. Fe II 2600, Mg II 2796, Mg II 2803 and Mg I 2852 lines found in such a way are only retained if they are of comparable quality to those obtained with our own TNG survey. Only two spectra met those criteria: the UVES commissioning spectrum of Q1106$-1821$/HE1104$-1805$; and the HST/STIS spectra of QO238$+1636$/Q235+164 taken as part of programme 7294 (PI: Cohen). In order to obtain a uniform set of data we degrade the UVES spectrum of Q1106$-1821$/HE1104$-1805$ to the TNG data resolution before undertaking the equivalent width measurements.

The Fe II 2600, Mg II 2796, Mg II 2803 and Mg I 2852 absorption features of all 15 absorbers are shown in Fig. 1. We compute the

\begin{table}
\centering
\caption{Journal of the TNG observations for metal equivalent width measurements.}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Coordinate Name & Alternative Name & $z_{em}$ & Mag & Obs. Date & Exp. Time (s) \\
\hline
Q0217+0144 & Q0215+015 & 1.715 & 18.3 & 19 Feb 2003 & 1800 \times 2 \\
Q0456+0040 & Q0454+039 & 1.345 & 16.5 & 18 Feb 2003 & 1800 \times 2 \\
Q0813+4813 & 3C196 & 0.871 & 17.8 & 18 Feb 2003 & 1800 \times 2 \\
Q0938+4129 & Q0935+417 & 1.980 & 16.2 & 18 Feb 2003 & 1800 \times 2 \\
Q1001+5553 & Q0957+561 & 1.414 & 16.7 & 19 Feb 2003 & 1800 \times 2 \\
Q1124+1705 & HE1122$-1649$ & 2.400 & 16.5 & 19 Feb 2003 & 1800 \times 2 \\
Q1211+1030 & Q1209+107 & 2.187 & 17.6 & 19 Feb 2003 & 1800 \times 2 \\
Q1232$-0224$ & PKS1229$-021$ & 1.045 & 17.6 & 21 Feb 2003 & 1800 \times 2 \\
Q1250+2631 & Q1247+267 & 2.038 & 15.8 & 19 Feb 2003 & 1800 \times 1 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
Q1331+3030 & Q1328+307 & 0.849 & 17.2 & 22 Mar 2003 & 1800 \times 2 \\
Q1354+3139 & Q1351+318 & 1.326 & 17.4 & 26 Mar 2003 & 1800 \times 2 \\
Q1624+2345 & Q1622+238 & 0.927 & 17.5 & 10 Apr 2003 & 1800 \times 2 \\
Q1631+1156 & Q1629+120 & 1.795 & 18.5 & 10 Apr 2003 & 1800 \times 1 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\hline
\end{tabular}
\end{table}

\footnote{Quasar with Broad Absorption Lines (BAL).}
Classical and $\text{Mg}^{\text{II}}$-selected DLAs: impact on $\Omega_{\text{H}_1}$ at $z < 1.7$

Figure 1. $\text{Fe}^{\text{II}}, \text{Mg}^{\text{II}}$ and $\text{Mg}^{\text{I}}$ measured as part of our survey. 13 of these systems were observed at the TNG, while two additional absorptions were measured in an archival $HST$ spectrum (Q0238+1636/0235+164), and in the commissioning ESO/UVES spectrum, degraded to the TNG resolution (Q1106−1821/HE1104−1805).
equivalent widths of the metal lines for the 15 spectra at our disposal. One object in our TNG sample (Q1001+5555/Q0957+561) does not cover the Fe II 2600 line, while on several occasions Fe II 2600 and/or Mg II 2852 are not detected at the redshift expected for the absorber. It can be seen from Fig. 1 that the Mg II doublet is resolved in all the spectra used for this study.

2.2 \(N_{\text{HI}}\) measurements

In addition to using the systems presented in the section above, we searched the literature for suitable \(\log N_{\text{HI}}\) measurements. In order to gather a significant sample, we looked for any absorber down to the sub-DLA definition (\(\log N_{\text{HI}} > 19.0\)) with \(z_{\text{abs}} < 1.7\). We only include \(N_{\text{HI}}\) measurements derived from high signal-to-noise \(HST\) (STIS or FOS) spectra. We therefore exclude measurements based on \(IUE\) spectra or \(N_{\text{HI}}\) estimates from 21-cm observations or other even more indirect methods. Furthermore, we thoroughly checked ESO and \(HST\) archives for any available spectra for which the relevant measurements were not available in the literature. 11 \(N_{\text{HI}}\) measurements are possible thanks to \(HST/FOS\) spectra recovered from the \(HST/ESO\) archives. The UVES commissioning spectrum of Q1106−1821/HE1104−1805 provides a further measurement of \(N_{\text{HI}}\). In particular, we extend the Rao & Turnshek (2000) sample by including seven sub-DLAs that were Mg II-selected, but that these authors rejected because they had \(\log N_{\text{HI}} < 20.3\). We also include the two Mg II-selected absorbers mentioned by Churchill (2001) and for which the \(N_{\text{HI}}\) measurements could be made (Q1429+4747/PK1127+480 and Q0441−4333/PKS0439−4333).

In order to measure \(N_{\text{HI}}\) column densities of the 11 absorbers available to us, we normalize the spectra in the region of interest using spline functions. We then fit Voigt profiles using the FITLYMAN package within MIDAS (Fontana & Ballester 1995). We note that, for several \(HST/FOS\) spectra, the absorbing feature does not reach the zero flux level in its centre, even if the line is clearly saturated. We use a convolution of the Voigt profile together with the instrumental line spread function to estimate whether this effect is real or not. Only in a few cases do we find it to be an artefact, and we correct the spectrum by subtracting a few per cent from the continuum level, as is standard practice (Boissé et al. 1998; Rao & Turnshek 2000). The typical resulting error bar in \(\log N_{\text{HI}}\) measurements is 0.10 and never exceeds 0.15, but does not include error in the continuum placement. The resulting fits are shown in Fig. 2 for the 11 systems, while information on the observing details is provided in Table 2.

3 DISTRIBUTIONS OF MG II EQUIVALENT WIDTHS

In this section, we study the distribution of the equivalent widths of metals in Mg II-selected absorbers compared with that of more classical DLAs/sub-DLAs. The latter sample is further divided into two subsamples: on one hand absorbers selected by their H I feature and on the other hand systems selected at 21 cm, or, in one case, because a galaxy was known and later turns out to be a DLA.

3.1 Samples definition

The method developed by Rao & Turnshek (2000) makes use of the empirical fact that all DLAs studied are found to have a matching Mg II metal-like absorption (Rao 1994; Rao et al. 1995). In their study, the authors selected a sample of 243 \(z_{\text{abs}} < 1.65\), EW Mg II (2796) > 0.3 Å Mg II absorbers taken from various sources in the literature. A fraction of these absorbers (87) already had a spectrum in the \(HST\) archives (48 absorbers), while others were observed as part of their own \(HST\) observing programme (39 Mg II doublets). Using these data, they measured whether a DLA is present or not at the expected absorbing redshift.

In the present study, the emphasis is on constructing well-defined DLAs/sub-DLA samples: one where the absorbers are Mg II-selected, and another for the remaining systems, discovered predominantly, but not only, by their H I feature. Therefore the latter also includes absorbers selected at 21 cm or a known galaxy which is further found to produce a DLA signature in a quasar spectrum. Moreover, we extend the work of Rao & Turnshek (2000) (as well as our literature search for ‘classical’ systems) down to the sub-DLA definition in order to obtain a more statistically significant sample of absorbers. This is done by measuring the H I column densities of Rao & Turnshek’s (2000) \(HST\) programme for which Mg II absorbers were detected.

The resulting Mg II-selected sample in the present study is thus larger than the original work from Rao & Turnshek (2000). It is composed of 21 systems defined as follows.

(i) 7 DLAs newly discovered in Rao & Turnshek (2000).
(ii) 7 sub-DLAs in the same observing programme and fitted by us.
(iii) 1 of the 4 very low-redshift systems of Churchill (2001) for which \(\log N_{\text{HI}}\) is reported in the literature (Q0441−4313/PKS0439−4333), and 1 other for which \(\log N_{\text{HI}}\) is determined by us (Q1429+4747/PK1127+480).
(iv) 1 sub-DLA (Q0100+0211/Q0058+019PHL938) selected by Rao & Turnshek (2000) and 1 other DLA found by the same group with their new \(HST\) programme (Q1631+1156/Q1629+120).
(v) 2 systems (Q0456+0400/Q0454+039 and Q1211+1030/Q1209+107) observed during \(HST\) programme 5351 (PI: Bergeron) based on their metal features in optical spectra (see Boissé et al. 1998).
(vi) 1 DLA (Q1624+2345/Q1622+238/3C336) selected thanks to its Mg II signature and observed during \(HST\) programme 5304 (PI: Steidel).

It should be noted that most of the quasar spectra with DLAs in the \(HST\) archives are clearly taken because the observer expects the absorber to be present. As an example, for the system along (Q0304−2211/EX−PKS0302−223), the \(HST\) proposal abstract (ID: 6224; PI: Burbidge) states that, ‘This data set will yield high quality absorption line data for studies of the damped Lyman alpha absorption system’. Therefore, such absorbers were initially not selected on the basis of their Mg II feature and we do not include them in our Mg II-selected sample, even if they were ‘re-discovered’ in the archive search of Rao & Turnshek (2000). Rather, we define the Mg II-selected sample as all systems that have been newly discovered based on their metal signature in optical quasar spectra.

The remaining systems form the classical sample, which can be defined as follows.

(i) 10 DLAs/sub-DLAs discovered directly thanks to their H I signature. These systems also form the so-called H I-selected sample (see Section 4).
(ii) 4 absorbers selected at 21 cm and with \(N_{\text{HI}}\) measured in UV spectra (Q0238+1636/Q0235+164; Q0813+4813/Q0809+483/3C196; Q1232−0224/PKS1229−021; Q1331+3030/Q1328+307/3C286).
(iii) 1 system for which the quasar–galaxy association was known prior to the \(HST\) observations (Q1215+3309/TON1480).

© 2004 RAS, MNRAS 352, 1291–1301

Downloaded from https://academic.oup.com/mnras/article-abstract/352/4/1291/1076102 by guest on 28 July 2018
Figure 2. Voigt profile fits of $N\text{H}_1$ retrieved from public archives. 10 of these spectra were recovered from the HST/ESO archive, while the remaining system was measured in the commissioning ESO/UVES spectrum (Q1106−1821/HE1104−1805).

Altogether, the number of systems studied here is 36. A summary of the resulting sample is shown in Table 3, together with the properties of both the quasar itself and its absorbers. It should be emphasized once more that we only include systems for which both $N\text{H}_1$ and metal equivalent widths can be securely recovered.

Hence, while during the course of our literature search we came across as many as 93 DLAs/sub-DLAs with $z_{\text{abs}} < 1.7$, our criterion reduces the sample to 36 absorbers, 21 of which are Mg II-selected.
In particular, we choose not to include the two Mg II-selected DLAs \( \log N_{\text{HI}} = 21.16 \) and \( \log N_{\text{HI}} = 21.41 \) recently reported by Turnshek et al. (2004), since these initial results might not be representative of the most recent HST UV spectroscopic survey undertaken by their group.

3.2 Metal equivalent widths

We compare the Mg II/Fe II EW distribution of Mg II-selected and classical systems. A simple picture would have Mg II EWs correlating with the column densities. Indeed, Churchill et al. (2000)
### Table 2. Observing details for the spectra retrieved from public archives and used for $N_{\text{HI}}$ measurements.

| Coordinate Name | Alternative Name | $z_{\text{abs}}$ | $\lambda_{\text{abs}}$ | $\log N_{\text{HI}}$ | $HST$/ESO | Inst. | Gratings | Selection Method |
|-----------------|------------------|------------------|------------------|-----------------|-----------|-------|----------|------------------|
| Q0424+0204      | PKSO421+019      | 1.638            | 3207             | 19.01±0.15      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q0427-1302      | PKSO424-13       | 1.408            | 2927             | 19.43±0.15      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q0427-1302      | PKSO424-13       | 1.562            | 3114             | 19.35±0.10      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q0826-2230      | PKSO823-22       | 0.910            | 2322             | 19.38±0.10      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q0938+1129      | Q0935+147        | 0.373            | 2885             | 20.45±0.10      | 6237 (Beaver) | FOS   | 270      | H i              |
| Q1106-1821 ¹    | HE1104-1805      | 1.662            | 3236             | 20.75±0.10      | 60-A-9022  | UVES   | ...      | H i              |
| Q1325+6515      | 4C65.15          | 1.610            | 3173             | 19.76±0.10      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q1331+1410      | PG1329+412       | 1.282            | 2774             | 19.86±0.10      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q1331+1410      | PG1329+412       | 1.601            | 3162             | 19.33±0.15      | 6577 (Rao) | FOS   | 270      | Mg II            |
| Q1429+4747      | PG1427+480       | 0.221            | 1484             | 19.73±0.10      | 6781 (Wills) | FOS   | 130      | Mg II            |
| Q2131-1207      | Q2128-123/HPL1598| 0.430            | 1738             | 19.55±0.10      | 4581 (Bahcall) | FOS   | 190      | H i              |

¹UVES commissioning spectrum used for both $\log N_{\text{HI}}$ and Mg II measurements.

### Table 3. Summary of the properties of the 36 $z_{\text{abs}} < 1.7$ absorbers (21 of which are Mg II-selected) making up our complete sample.

| Coordinate Name | Alternative Name | $z_{\text{em}}$ | Mag | $z_{\text{abs}}$ | $\log N_{\text{HI}}$ | EW rest (Fe II) | EW rest (Mg II) | Selection Method |
|-----------------|------------------|-----------------|-----|-----------------|----------------------|-----------------|-----------------|------------------|
| Q0100+0211      | Q0058+019/HPL938 | 1.954           | 172 | 0.613           | 20.08               | (3) 1.39        | 1.70            | 0.51            |
| Q0217+0144      | Q0215+015       | 1.715           | 183 | 1.345           | 19.57               | (4) 2.06        | 2.57            | 1.63            |
| Q0238+1636      | Q0235+164       | 0.940           | 190 | 0.524           | 21.70               | (3) 2.13        | 2.42            | 3.28            |
| Q0251+4315      | Q0248+430       | 1.310           | 174 | 0.394           | 21.56               | (5) 1.03        | 1.86            | 1.42            |
| Q0304-2211      | EX/PKSO302-223  | 1.400           | 160 | 1.009           | 20.36               | (12) 0.63       | 1.16            | 0.96            |
| Q0424-0204      | PKSO424-019     | 2.055           | 170 | 1.638           | 19.01               | (5) <0.4        | 0.35            | 0.28            |
| Q0427-1302      | PKSO424-13      | 2.166           | 175 | 1.408           | 19.43               | (1) 0.44        | 0.55            | 0.35            |
| Q1106-1821 ¹    | HE1104-1805     | 1.662           | 3236 | 20.75±0.10      | 60-A-9022  | UVES   | ...      | H i              |
| Q1429+4747      | PG1427+480      | 0.221            | 1484             | 19.73±0.10      | 6781 (Wills) | FOS   | 130      | Mg II            |

¹Quasar with Broad Absorption Lines (BAL).

²Gravitationally lensed quasar.

References:
(1) This work; (2) Pettini et al. (1999); (3) Chen & Lanzetta (2003); (4) Ledoux, Bergeron & Petitjean (2002); (5) Rao & Turnshek (2000); (6) Churchill (2001); (7) Boisse et al. (1998); (8) Boisse & Boulade (1990); (9) Lanzetta et al. (1997); (10) Zuo et al. (1997); (11) Miller, Knezeck & Bregan (1999); (12) Turnshek, Rao & Nestor (2002).
observe that at $z < 1.6$ the MgII equivalent widths are dominated by
kinematic spreads. They propose that these could be directly corre-
lated to column density, implying in turn a correlation between EW
and $N_{\text{HI}}$.

In order to address this issue we plot, in Fig. 3, MgII 2796
top panel) and FeII 2600 (bottom panel) EWs for each of
the 36 systems. Upper limits and non-detections are plotted at
zero.

In their work, Rao & Turnshek (2000) look for DLAs only when
MgII 2796 has a rest EW > 0.3 Å. This is illustrated in the top
panel of Fig. 3 by the vertical dotted line. It can be seen that such a
criterion is indeed appropriate for selecting DLAs with $\log N_{\text{HI}} >$
20.3 cm$^{-2}$ (which is precisely the aim of these authors), while any
higher MgII EW threshold will miss a fraction of the absorbers. This

![Figure 3. Top panel: log $N_{\text{HI}}$ as a function of the MgII 2796 Å rest equivalent widths. The dashed horizontal line corresponds to log $N_{\text{HI}} = 21.0$, while the dotted horizontal line corresponds to log $N_{\text{HI}} = 20.3$. The dotted vertical line is the MgII rest equivalent width lower limit that Rao & Turnshek (2000) use as a criterion for their DLA search. Bottom panel: as top, for FeII 2600.](image1)

![Figure 4. Top panel: log $N_{\text{HI}}$ as a function of the ratio EW_{MgII(2796)}/ EW_{MgII(2803)}. Bottom panel: log $N_{\text{HI}}$ as a function of the ratio EW_{MgII(2796)}/ EW_{FeII(2600)}.](image2)

DLA definition is represented by the horizontal dotted line. In the
present work, we extended both classical and MgII-selected samples
to the sub-DLA definition in order to obtain larger samples. We note
that, even down to lower column densities, the rest EW threshold set
by Rao & Turnshek (2000) is still a good tracer of quasar absorbers.

Nevertheless, it is puzzling that the majority of absorbers with
$\log N_{\text{HI}} > 21.0$ (horizontal dashed line) are MgII-selected, while
fewer of the MgII-selected systems have $20.3 < \log N_{\text{HI}} < 21.0$.
Conversely, in general classical absorbers do not have such high
column densities, and this regardless of the way they have been
selected (direct HI selection, 21 cm or known galaxy).

In Fig. 4, we plot the log $N_{\text{HI}}$ column density as a function of
metal EW ratios. The top panel shows EW_{MgII(2796)}/ EW_{MgII(2803)}
while the bottom panel displays EW_{MgII(2796)}/ EW_{FeII(2600)}. We find
again that both classical and MgII-selected absorbers span a similar
parameter range for both these quantities.
4 \( N_{\text{HI}} \) DISTRIBUTIONS

4.1 Comparison of the two samples

In this section, we analyse the normalized cumulative \( N_{\text{HI}} \) distributions of the Mg II-selected sample and compare it with a purely HI-selected sample. This distribution directly impacts measurements of the cosmological mass density, \( \Omega_{\text{HI}} \). Here, the Mg II-selected sample presented in Section 3.1 is compared with the sample of DLAs/sub-DLAs selected only on their HI. The latter sample does not include absorbers selected at 21 cm or otherwise, but solely HI-selected systems. Therefore the total sample is now composed of 31 absorbers, 21 of which are Mg II-selected. Fig. 5 shows the normalized cumulative \( N_{\text{HI}} \) distributions for these. The Mg II-selected curve is different from the other at the high \( N_{\text{HI}} \) column density end. In particular, there are systems with log \( N_{\text{HI}} > 21.0 \) in the Mg II-selected sample, while HI-selected systems are never found to have \( N_{\text{HI}} > 20.8 \). This cannot be due to a bias in the HI-selected sample, since that selection method should in principle favour high \( N_{\text{HI}} \) column densities. A Kolmogorov–Smirnov (KS) test shows that the two distributions are consistent at a 0.56 level of probability, but clearly we are dealing with small-number statistics. In any case, the fraction of high-column-density systems will in turn affect the determination of \( \Omega_{\text{HI}} \), computed directly from the integration of the \( N_{\text{HI}} \) distribution function.

Furthermore, we find that, by comparing systems with log \( N_{\text{HI}} > 20.3 \) only, none of the HI-selected DLAs have log \( N_{\text{HI}} > 21 \) (out of four), while 50 per cent (five out of 10) of the Mg II-selected DLAs have log \( N_{\text{HI}} > 21 \) (see Fig. 3). Assuming a Poisson distribution, the probability of obtaining zero HI-selected DLAs at log \( N_{\text{HI}} > 21 \) when expecting two (i.e. half of four) is 13.5 per cent. Therefore the absence of HI-selected log \( N_{\text{HI}} > 21 \) systems might also be due to statistical fluctuation. When all classical DLAs are taken into account, only 25 per cent (two out of eight) have \( N_{\text{HI}} > 21 \), even though these have been selected using different techniques. Rao & Turnshek (2000) have already noted that the comparison of a sample of local gas-rich galaxies studied in 21-cm emission (\( \langle z \rangle = 0 \)) with Mg II-selected low-redshift DLAs (\( \langle z \rangle = 0.5 \)) shows an unexpectedly high rate of occurrence of very large column densities. This could be due to redshift evolution or the selection methods or a combination of both.

Therefore, the Mg II-selected sample has a higher fraction of log \( N_{\text{HI}} > 21 \) systems, but only marginally. Given the impact of this on \( \Omega_{\text{HI}} \), we try to identify what the origin of such a discrepancy could by testing various scenarios in the following sections.

4.2 Gravitational lensing

Another effect possibly at play could be the gravitational lensing of the background quasar by the absorber itself. This could amplify the luminosity of the quasars and therefore cause them to be preferentially selected as they would be easier targets to observe. In order to check whether gravitational lensing affects the two samples of absorbers differently, we plot the apparent magnitude of quasars for the samples of classical and Mg II-selected DLAs/sub-DLAs. Looking at the top panel of Fig. 6, we find no evidence that the two populations are composed of quasars with different magnitude ranges. There might be hints of a trend where higher column density absorbers are found in fainter quasars, probably a signature of
extinction by dust (Boissé et al. 1998), but this result is not currently statistically significant.

In order to test further the strong lensing hypothesis, we perform another test. It is known from gravitational lensing theory that the magnification effects are maximized when the lensing object is midway between the source and the observer in physical space. In our given cosmology, the physical distances can be expressed as

\[ X(z) = \int_0^z (1+z)^2(1+z)^2(1+0.3z) - 0.7z(2+z)^{-1/2} \, dz. \]  

In the bottom panel of Fig. 6, we plot the ratio of the distance to the absorber over the distance to the quasar. The configuration that would most favour the occurrence of gravitational lensing would have this ratio equal to 0.5. In our study, the two samples of absorbers do not show any significant difference. Therefore, gravitational lensing does not appear to be a viable explanation for the observed discrepancy in log \( N_{\text{HI}} \) distributions of the classical and Mg II-selected DLAs/sub-DLAs. This finding is further supported by the results of Le Brun et al. (2000), who used the DLA sample of Le Brun et al. (1997) to show that the amplification due to the presence of an absorber along the quasar line of sight does not exceed 0.3 mag.

4.3 Associated systems and evolutionary effects

Another scenario would have the absorbers associated with the quasar rather than being truly intervening systems. In order to test this hypothesis, we compute the velocity difference between the absorbers and the quasars themselves on the basis that the former are actually associated systems. The \( z_{\text{em}} - z_{\text{abs}} \) in km s\(^{-1}\) can be expressed as

\[ \frac{(z_{\text{em}} - z_{\text{abs}})c}{(1+z_{\text{em}})}, \]  

where \( c \) is the speed of light in km s\(^{-1}\). The result is shown in Fig. 7. Interestingly, there seems to be a hint of a correlation between log \( N_{\text{HI}} \) and \( (z_{\text{em}} - z_{\text{abs}}) \) for the Mg II-selected population, while this is not true for the classical DLAs/sub-DLAs. In any case, we see no differences between the two samples that could possibly explain their apparent discrepancy in terms of \( N_{\text{HI}} \) distributions.

Finally, we test for potential evolutionary effects by analysing log \( N_{\text{HI}} \) as a function of quasar emission redshift \( z_{\text{em}} \) (top panel of Fig. 8) and absorber redshift (bottom panel of Fig. 8). Again, we find no obvious trend, and the two populations of quasar absorbers appear to sample the same parameter space.

5 DISCUSSION AND CONCLUSION

In this study, we compare the properties of the complete samples of Mg II-selected absorbers and more ‘classical’ DLAs at \( z_{\text{abs}} < 1.7 \). Constructing well-defined samples has proved a challenging task, given the difficulties of building a homogeneous \( \text{H} \text{I} \)-selected sample. Nevertheless, we find that the metal EW criterion used by Rao & Turnshek (2000) to select DLAs traces the population of these systems well down to log \( N_{\text{HI}} = 19.0 \). Moreover, we find that the Mg II-selected sample presented has a marginally larger fraction of absorbers with log \( N_{\text{HI}} > 21.0 \) than seen otherwise at low redshift.
This property might in turn affect our estimates of \( \Omega_{HI} \), which is dominated by the highest H I column densities.

We investigate the origin of the potential discrepancy and find that \( \log N_{HI} \) does not correlate in a significant way with either metal equivalent widths or ratios of combination of equivalent widths, quasar magnitude, quasar emission redshift, absorber redshift, velocity distance from the absorber to the quasar, or position of the absorber with respect to the quasar in physical space (a test for the gravitational lensing hypothesis). We conclude that the marginal discrepancy in \( N_{HI} \) distributions between the MgII-selected absorbers and those discovered with other techniques probably arises from small-number statistics.

We note that, regardless of the physical reason for selecting high-column-density systems, these absorbers will directly affect calculation of \( \Omega_{HI} \) at low redshifts. In particular, comparison of \( \Omega_{HI} \) calculations dominated by MgII-selected absorbers at \( z_{abs} < 1.7 \) with high-redshift systems selected solely on H I might not be appropriate if the two methods are not consistent. Furthermore, if there is a discrepancy between classical and MgII-selected absorption systems, and if it holds at high redshift, this would imply that H I-selected surveys for DLAs/sub-DLAs at \( z > 2 \) have been missing a large fraction of the neutral gas.

Since the MgII method has proved an extremely efficient technique to find low-redshift absorbers, we anticipate that forthcoming observations will help extend and refine the current results. Therefore, larger samples are required in order to better constrain \( \Omega_{HI} \) at \( z < 1.7 \) and enable comparison with high-redshift results.

ACKNOWLEDGMENTS

We thank Alberto Buzzoni for performing the TNG observations in service mode, Marisa Girardi and Piercarlo Bonifacio for hints on blue-wavelength calibration, and Jean-Claude Bouret for help with MAST. We are grateful to the referee, Sandhya Rao, for openly providing objective and expert suggestions which improved our study. CP is supported by a Marie Curie fellowship. The work is based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

REFERENCES

Boissé P., Boulade O., 1990, A&A, 236, 291
Boissé P., Le Brun V., Bergeron J., Deharveng J.-M., 1998, A&A, 333, 841
Chen H.-W., Lanzetta K., 2003, ApJ, 597, 706
Churchill C. W., 2001, ApJ, 560, 92
Churchill C. W., Mellon R. R., Charlton J. C., Jannuzi B. T., Kirhakos S., Steidel C. C., Schneider D. P., 2000, ApJ, 543, 577
Fontana A., Ballester P., 1995, Messenger, 80, 37
Kulkarni V. P., Fall S. M., 2002, ApJ, 580, 732
Lanzetta K., McMahon R. G., Wolfe A., Turnshek D., Hazard C., Lu L., 1991, ApJ, 77, 1
Lanzetta K. M., Wolfe A. M., Turnshek D. A., 1995, ApJ, 440, 435
Lanzetta K. M. et al., 1997, AJ, 114, 1337
Le Brun V., Bergeron J., Boissé P., Deharveng J.-M., 1997, A&A, 321, 733
Le Brun V., Smette A., Surdej J., Claeskens J.-F., 2000, A&A, 363, 837
Ledoux C., Bergeron J., Petitjean P., 2002, A&A, 385, 802
Miller E., Knezek P., Bregman J., 1999, ApJ, 510, 95
Nagamine K., Springer V., Hernquist L., 2004, MNRAS, 348, 421
Pei Y., Fall M., 1995, ApJ, 454, 69
Péroux C., Dessauges-Zavadsky M., D’Odorico S., Kim T. S., McMahon R. G., 2003a, MNRAS, 345, 480
Péroux C., McMahon R. G., Storrie-Lombardi L. J., Irwin M., 2003b, MNRAS, 346, 1103
Pettini M., Ellison S. L., Steidel C. C., Bowen D. V., 1999, ApJ, 510, 576
Prochaska J. X., Gawiser E., Wolfe A. M., Castro S., Djorgovski S. G., 2003, ApJ, 595, L9
Rao S. M., 1994, PhD thesis, Univ. Pittsburgh
Rao S. M., Turnshek D. A., 2000, ApJS, 130, 1
Rao S. M., Turnshek D. A., Briggs F., 1995, ApJ, 449, 488
Savaglio S., in Harwit M., ed., Proc. IAU Symp. 204, The Extragalactic Infrared Background and its Cosmological Implications. Astron. Soc. Pac., San Francisco, p. 307
Storrie-Lombardi L. J., Wolfe A. M., 2000, ApJ, 543, 552
Storrie-Lombardi L. J., McMahon R. G., Irwin M., 1996, MNRAS, 283, L79
Turnshek D. A., Rao S. M., Nestor D. B., 2002, in Mulchaey J. S., Stocke J., eds, ASP Conf. Proc. Vol. 254, Extragalactic gas at low redshift. Astron. Soc. Pac., San Francisco, p. 42
Turnshek D. A., Rao S. M., Nestor D. B., Vanden Berk D., Belfort M., Monier E. M., 2004, ApJL, in press (astro-ph/0404609)
Vladilo G., Bonifacio P., Centurión M., Molaro P., 2000, ApJ, 543, 24
Wolfe A., Lanzetta K. M., Foltz C. B., Chaffee F. H., 1995, ApJ, 454, 698
Zuo L., Beaver E., Burbidge M., Cohen R., Junkkarinen V., Lyons R., 1997, ApJ, 477, 568
Zwaan M. A., Sprayberry D., Sorar E., 2002, MNRAS, 332, 484
Zwaan M. A. et al., 2003, AJ, 125, 2842

This paper has been typeset from a TeX file prepared by the author.