On the selection of damped Lyman $\alpha$ systems using Mg $\text{II}$ absorption at $2 < z_{\text{abs}} < 4$

T. A. M. Berg,1⋆ S. L. Ellison,1 J. X. Prochaska,2 R. Sánchez-Ramírez,3,4,5 S. Lopez,6 V. D’Odorico,7 G. Becker,8,9 L. Christensen,10 G. Cupani,7 K. Denney11 and G. Worseck12

1Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada
2Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
3Unidad Asociada Grupo Ciencias Planetarias (UPV/EHU, IAA-CSIC), Departamento de Física Aplicada I, E.T.S. Ingeniería, Universidad del País Vasco (UPV/EHU), Alameda de Urquijo s/n, E-48013 Bilbao, Spain
4Ikerbasque, Basque Foundation for Science, Alameda de Urquijo 36-5, E-48008 Bilbao, Spain
5Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain
6Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
7INAF-Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34143 Trieste, Italy
8Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
9Institute of Astronomy and Kavli Institute of Cosmology, Madingley Road, Cambridge CB3 0HA, UK
10Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark
11Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
12Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

ABSTRACT

The XQ-100 survey provides optical and near-infrared coverage of 36 blindly selected, intervening damped Lyman $\alpha$ systems (DLAs) at $2 < z_{\text{abs}} < 4$, simultaneously covering the Mg $\text{II}$ doublet at $\lambda\lambda 2796, 2803$Å, and the Ly $\alpha$ transition. Using the XQ-100 DLA sample, we investigate the completeness of selecting DLA absorbers based on their Mg $\text{II}$ rest-frame equivalent width ($W_{0}^{2796}$) at these redshifts. Of the 29 DLAs with clean Mg $\text{II}$ profiles, we find that six (20 per cent of DLAs) have $W_{0}^{2796} < 0.6$ Å. The DLA incidence rate of $W_{0}^{2796} < 0.6$ Å absorbers is a factor of $\sim 5$ higher than what is seen in $z \sim 1$ samples, indicating a potential evolution in the Mg $\text{II}$ properties of DLAs with redshift. All of the $W_{0}^{2796} < 0.6$ Å DLAs have low metallicities ($-2.5 < [M/H] < -1.7$), small velocity widths ($\sigma_{90} < 50$ km s$^{-1}$), and tend to have relatively low $N$(H$\text{I}$). We demonstrate that the exclusion of these low $W_{0}^{2796}$ DLAs results in a higher mean $N$(H$\text{I}$) which in turn leads to an $\sim 7$ per cent increase in the cosmological gas density of H$\text{I}$ of DLAs at $2 < z_{\text{abs}} < 4$; and that this exclusion has a minimal effect on the H$\text{I}$-weighted mean metallicity.

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

1 INTRODUCTION

Quasar (QSO) absorption line systems provide an excellent probe of the evolution of the H$\text{I}$ gas content over cosmic time. Of the many classes of QSO absorption line systems, damped Lyman $\alpha$ systems (DLAs) are the highest H$\text{I}$ column density absorbers, defined as having $N$(H$\text{I}$) $\geq 20.3$ (Wolfe et al. 1986; Wolfe, Gavaiser & Prochaska 2005). Although fewer in number compared to lower $N$(H$\text{I}$) counterparts (such as subDLAs; $19.0 < \log N$(H$\text{I}$) $< 20.3$), DLAs dominate the H$\text{I}$ column density distribution from $z_{\text{abs}} \sim 5$ to the present epoch and are used to trace the cosmological gas density of H$\text{I}$ ($\Omega_{\text{HI}}$), eventually fueling future generations of star formation (Lanzetta, Wolfe & Turnshek 1995; Rao & Turnshek 2000; Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003; Prochaska, Herbert-Fort & Wolfe 2005; Rao, Turnshek & Nestor 2006; Prochaska & Wolfe 2009; Noterdaeme et al. 2012; Zafar et al. 2013; Crighton et al. 2015; Neeleman et al. 2016; Sánchez-Ramírez et al. 2016). At absorption redshifts where the H$\text{I}$ is observed in optical bands ($z_{\text{abs}} \gtrsim 1.5$), $\Omega_{\text{HI}}$ remains relatively constant with redshift (for the most recent results at these redshifts, see Crighton et al. 2015; Sánchez-Ramírez et al. 2016). As $z \sim 0$, $\Omega_{\text{HI}}$ is currently best

*E-mail: trystynb@uvic.ca
measured from 21 cm emission line surveys of galaxies (Zwaan et al. 2005; Martin et al. 2010). Between these $z \sim 0$ measurements and $\Omega_M$, measured in DLAs at $z \sim 1.5$, the gas content of galaxies has only evolved by a factor of $\sim 2$ (Zwaan et al. 2005; Sánchez-Ramírez et al. 2016).

Despite well-constrained estimates of $\Omega_M$ at $z \sim 0$ and at $z > 2$, studying the nature of the evolution between $0.3 \lesssim z_{\rm abs} \lesssim 1.5$ is challenging, as the Ly$\alpha$ transition shifts into the ultraviolet, requiring expensive space-based observations; and 21 cm emission becomes extremely difficult to detect (Rhee et al. 2016).

In an effort to improve the efficiency of space telescope observations, it has become common practice to pre-select candidate DLAs based on the rest-frame equivalent widths (EWs) of the associated Mg $\textsc{ii} \lambda\lambda 2796, 2803\AA$ absorption observed in the optical (Rao & Turnshek 2000; Rao et al. 2006, hereafter referred to as R00 and R06, respectively). With the inclusion of absorbers satisfying an Mg $\textsc{ii} \lambda 2796 \text{ Å} \text{ EW} \geq 0.3 \text{ Å} (\text{R00})$, the final statistical sample compiled in R06 contains no DLAs at $z_{\text{abs}} \sim 1$ with $W_{2796} < 0.6 \text{ Å}$.\(^1\)

$\Omega_{\text{HI}}$ derived from $z_{\text{abs}} \sim 1$ DLA samples pre-selected from Mg $\textsc{ii}$ ($\Omega_{\text{HI}} \sim 7.5 \times 10^{-5}$) are consistent with the $z_{\text{abs}} \gtrsim 2$ value, implying strong evolution at the lowest redshifts (R06). However, a recent ‘blind’ archival survey of DLAs at $z \sim 1$ derived a value of $\Omega_{\text{HI}}$, a factor of 3 lower than R06 ($< 2.5 \times 10^{-5}$), and consistent with 21 cm results at $z \sim 0$ (Neelam et al. 2016). This tension in $\Omega_{\text{HI}}$ has led to suggestions that Mg $\textsc{ii}$ DLA pre-selection may be biased, possibly leading to high $\Omega_{\text{HI}}$ (Péroux et al. 2004; Dessauges-Zavadsky, Ellison & Murphy 2009; Neelam et al. 2016).

In this Letter, we investigate the nature of Mg $\textsc{ii}$ selection of 36 DLAs at $2 < z_{\text{abs}} < 4$ from the XQ-100 Legacy Survey (PI: S. Lopez). The blind nature of the XQ-100 DLA sample combined with simultaneous observations of Ly$\alpha$ and Mg $\textsc{ii} \lambda 2796$ provides an excellent test of the effectiveness of the Mg $\textsc{ii}$ selection technique for comparison with low redshift statistics.

2 DATA

The XQ-100 Legacy Survey observed 100 QSOs with the X-Shooter spectrograph on the Very Large Telescope, providing simultaneous wavelength coverage from 3150 Å–25000 Å at a full width at half-maximum (FWHM) resolution $R \sim 5000$–9000. For more details on the observations, see López et al. (2016). We emphasize that the 100 QSO targets were not pre-selected to contain DLAs, thus providing a ‘blind’ sample of DLAs along the lines of sight.

Sánchez-Ramírez et al. (2016) identified 41 DLAs by their Lyman series absorption in the XQ-100 spectra. However, five of these DLAs are within 5000 km s$^{-1}$ of the rest frame of the QSO. These proximate absorbers likely trace a different population of systems compared to their intervening counterparts (Ellison et al. 2002, 2010; Berg et al. 2016) and are typically ignored when computing $\Omega_{\text{HI}}$. We therefore restrict the DLA sample used in this Letter only to intervening DLAs.

Table 1 contains a summary of the intervening DLAs, including the measured rest-frame EW for the Mg $\textsc{ii} \lambda 2796$ and 2803 Å lines, as well as the Fe $\textsc{ii} \lambda 2600$ line (with EW $W_{2600}$). The redshift, metallicity, and $v_{\text{vir}}$ measurements are taken from Sánchez-Ramírez et al. (2016) and Berg et al. (2016). Absorption line profiles of the Mg $\textsc{ii}$ lines are provided in Berg et al. (2016). Additionally, we tabulated the D-index defined in Ellison (2006) and Ellison, Murphy & Dessauges-Zavadsky (2009). For the rest of this Letter, only the 29 DLAs with EWs that are not blended (i.e. are not upper limits in Table 1) are used in the analysis.

3 RESULTS AND DISCUSSION

The vast majority of DLAs identified at $z_{\text{abs}} \sim 1$ have $W_{2796} \geq 0.6 \text{ Å}$ (R00; R06). For example, in a recent compilation of 369 Mg $\textsc{ii}$ systems (Rao et al., in preparation), there are 70 Mg $\textsc{ii}$ absorbers with $0.3 \leq W_{2796} < 0.6 \text{ Å}$, but only one of these is a DLA (S. Rao private communication). As a result, many works have typically used $W_{2796} \geq 0.6 \text{ Å}$ to pre-select potential DLA systems (R00; R06). Moreover, R06 used the EW of Fe $\textsc{ii} \lambda 2600$ ($W_{2600}$) to aid in identifying DLAs, and found that their DLA sample is confined to $W_{2796}/W_{2600} < 2$, whereas their subDLAs span a larger range of $W_{2796}/W_{2600}$

Fig. 1 shows how the XQ-100 measurements of $W_{2796}$ (left-hand panel), the ratio $W_{2796}/W_{2600}$ (middle panel), and D-index (right-hand panel) vary with log($N$($\text{H}$)). Starting with the left-hand panel of Fig. 1, we find that six\(^2\) (20 per cent of the sample) of the XQ-100 DLAs with measured $W_{2796}$ have $W_{2796} < 0.6 \text{ Å}$ (dashed line). However, all DLAs pass the $W_{2796} > 0.3 \text{ Å}$ cut. The middle panel of Fig. 1 shows the $W_{2796}/W_{2600}$ ratio for the XQ-100 and R06 samples, and demonstrates that 30 per cent of the XQ-100 DLAs with Fe $\textsc{ii} \lambda 2600$ measurements have $W_{2796}/W_{2600} > 2$ (DLAs above dashed line). Only one DLA (J0034+1639, $z_{\text{abs}} = 3.69$) does not

\(^1\) Although some DLAs with $W_{2796} < 0.6 \text{ Å}$ have been previously identified (e.g. Péroux et al. 2004; R06).

\(^2\) $v_{\text{vir}}$ measures the velocity width corresponding to 90 per cent of the integrated optical depth using one low-ion transition (Prochaska & Wolfe 1997).

\(^3\) Two of these six DLAs with $W_{2796} < 0.6 \text{ Å}$ have previously been observed in the literature (DLAs towards J1108+1209 and J0134+0400), but previous observations have not covered the Mg $\alpha$ absorption. We also note that one of the excluded proximate DLAs (J0034+1639 at $z_{\text{abs}} = 4.25$) does not satisfy the $W_{2796} > 0.6 \text{ Å}$ cut. This DLA is metal-poor ([M/H] = −2.40) and has an equivalent width $W_{2796} = 0.344 \pm 0.013 \text{ Å}$.
not satisfy both $W_{\lambda 2796}^0 \geq 0.6$ Å and $W_{\lambda 2796}^0/W_{\lambda 2600}^0 \leq 2$ restrictions. Lastly, the right-hand panel of Fig. 1 shows the D-index (i.e. $W_{\lambda 2796}^0$ normalized by the velocity width of the line $\Delta V$) for the XQ-100 DLAs as a function of log $N$(H\textsc{i}). The minimum D-index cuts required for absorbers to be DLA candidates are derived from Ellison (2006, their table 2), and are tabulated in Table 1. The D-index cuts are based on the resolution of the X-Shooter spectrum at each Mg \textsc{ii} line (assuming an FWHM resolution of $R=5300$). We note that the D-index of the XQ-100 DLAs does recover all the DLAs (i.e. points are above the grey band in the right-hand panel of Fig. 1).

Figure 1. Left-hand panel: the rest-frame $W_{\lambda 2796}^0$ as a function of log $N$(H\textsc{i}) for the XQ-100 DLAs (large circles; colours indicate metallicity) and R06 data (black squares). For reference, the $W_{\lambda 2796}^0$ cuts ($W_{\lambda 2796}^0 \geq 0.3$ Å and $W_{\lambda 2796}^0 \geq 0.6$ Å) are shown as horizontal lines (dotted and dashed; respectively). Six of the 29 XQ-100 DLAs show $W_{\lambda 2796}^0 < 0.6$ Å. Middle panel: the ratio $W_{\lambda 2796}^0/W_{\lambda 2600}^0$ as a function of log $N$(H\textsc{i}) for the XQ-100 sample and R06 data. The region below the dashed line at $W_{\lambda 2796}^0/W_{\lambda 2600}^0 \geq 2.0$ characterizes the Mg \textsc{ii}-selected DLAs in the R06 sample, while the dotted line divides subDLAs from DLAs. 30 per cent of the XQ-100 DLAs do not exhibit $W_{\lambda 2796}^0/W_{\lambda 2600}^0 < 2$. Right-hand panel: the D-index ($W_{\lambda 2796}^0/\Delta V$) as a function of log $N$(H\textsc{i}) for the XQ-100 DLA sample. The grey horizontal band represents the range of possible D-index cuts for the XQ-100 data. All XQ-100 DLAs pass their respective D-index cuts.

Are the properties of $W_{\lambda 2796}^0 < 0.6$ Å DLAs different to the higher EW systems?

The colour bar in Fig. 1 indicates the metallicity of each DLA in the XQ-100 sample (Berg et al. 2016). Interestingly, the DLAs whose $W_{\lambda 2796}^0 < 0.6$ Å all have low metallicities, below [M/H] $< -1.7$. The mean metallicity of the XQ-100 DLAs subsample with $W_{\lambda 2796}^0 \geq 0.6$ Å is [M/H] $= -1.42 \pm 0.03$, whereas the entire sample has a mean metallicity of $[M/H] = -1.60 \pm 0.02$. However, the H\textsc{i} weighted metallicity that is generally used to trace the evolution of DLA metallicity with cosmic time (e.g. Pettini et al. 1999; Rafelski et al. 2012) is negligibly affected, increasing from [M/H] $= -1.47 \pm 0.03$ for the full sample to [M/H] $= -1.43 \pm 0.03$ when $W_{\lambda 2796}^0 < 0.6$ Å absorbers are excluded.

In addition to the metallicity, we checked for other DLA properties dependent on $W_{\lambda 2796}^0 \geq 0.6$ Å selection. Fig. 2 shows the distributions of [M/H], $v_{\text{abs}}$, (which has been suggested as a proxy for mass, e.g. Prochaska & Wolfe 1997; Haehnelt, Steinmetz & Rauch 1998), $z_{\text{abs}}$, and log $N$(H\textsc{i}) for the XQ-100 DLAs for a selection cut of $W_{\lambda 2796}^0 \geq 0.6$ Å. DLAs passing the EW selection cut are shown as the shaded region, whilst DLAs that fail the selection cut are shown as the red line. DLAs with $W_{\lambda 2796}^0 < 0.6$ Å tend to show low metallicities, low log $N$(H\textsc{i}), and low $v_{\text{abs}}$ widths with respect to DLAs with $W_{\lambda 2796}^0 \geq 0.6$ Å. These properties are consistent with a ‘mass–metallicity’ relationship seen in DLAs (Lodewig et al. 2006; Jorgenson, Wolfe & Prochaska 2010; Møller et al. 2013; Neeleman et al. 2013; Christensen et al. 2014), where narrower metal lines are typically found in lower metallicity systems. The dependence of $W_{\lambda 2796}^0$ on velocity width has been previously identified in other works (Nestor et al. 2003; Ellison 2006; R06; Murphy et al. 2007).

The D-index defined in Ellison (2006) potentially corrects for this bias towards low $v_{\text{abs}}$, as the EW is normalized by the velocity width of the line. As demonstrated by the right-hand panel of Fig. 1, the D-index provides a more complete DLA sample relative to a fixed Mg \textsc{ii} EW cut by including those absorbers with low metallicity and $v_{\text{abs}}$.

What are the implications for the cosmological context of DLAs at $2 \leq z_{\text{abs}} \leq 4$?

The typical approach to calculating $\Omega_{\text{HI}}$, at high redshifts is to sum the total $N$(H\textsc{i}) observed over the total redshift path (X) for all QSOs observed, i.e.

$$\Omega_{\text{HI}} = \frac{H_0 \mu_{\text{HI}} \sum N$(H\textsc{i})}{c \rho_{\text{crit}}} \sum X.$$

If DLAs are missed from a Mg \textsc{ii}-selected sample, the computed $\Omega_{\text{HI}}$ from equation (1) would be underestimated, as the sum of $N$(H\textsc{i}) would exclude the low Mg \textsc{ii} EW DLAs while $\sum X$ remains unaffected. For the entire XQ-100 DLA sample, $\Omega_{\text{HI}}$ would be underestimated by $\sim 5$ per cent if $W_{\lambda 2796}^0 < 0.6$ Å DLAs were excluded.

However, R06 used a different approach to compute $\Omega_{\text{HI}}$, that combines the number density of DLAs ($n_{\text{DLA}}$; observed along Mg \textsc{ii} absorber sightlines in R06) and the average $N$(H\textsc{i}) of DLAs ($\langle N$(H\textsc{i})$\rangle$),

$$\Omega_{\text{HI}}(z) = \frac{H_0 \mu_{\text{HI}} E(z)}{c \rho_{\text{crit}}} \langle 1 + z \rangle^2 n_{\text{DLA}}(z) \langle N$(H\textsc{i})$\rangle).$$

4 All errors for mean quantities are derived using a bootstrap technique with one million iterations. The errors on individual measurements were assumed to be Gaussian.
With the R06 formalism, the calculation of $\Omega_{\text{HI}}$, depends on two measured quantities: the frequency of absorbers and their mean $N(\text{HI})$. As shown in Fig. 2, in the XQ-100 sample, DLAs with $W_{0}^{2796} < 0.6$ Å tend to have lower $N(\text{HI})$ than higher EW absorbers. If the low EW systems were not included in the XQ-100 sample statistics then $\Omega_{\text{HI}}$ would be overestimated. However, this effect in our sample is minimal: the mean log($N(\text{HI})$) of the XQ-100 sample increases minimally from 20.98 ± 0.03 to 21.01 ± 0.03 (7 per cent) upon exclusion of the DLAs with $W_{0}^{2796} < 0.6$ Å. Therefore, for a constant $n_{\text{DLA}}$, $\Omega_{\text{HI}}$, would be overestimated by 7 per cent when low EW systems are excluded.

**Comparison with the properties of Mg II in DLAs at $z_{abs} \leq 1.5$.**

In the latest compilation of 369 $z_{abs}$~1 Mg II absorbers (Rao et al., in preparation) only 1 out of 70 (1.4+1.2 per cent) systems with $0.3 < W_{0}^{2796} < 0.6$ Å is confirmed to be a DLA (S. Rao, private communication). In contrast, $\sim 7\%$ per cent of $0.3 < W_{0}^{2600} < 0.6$ Å systems are DLAs\(^5\) (Lopez et al., in preparation). The DLA incidence for the low $W_{0}^{2796}$ regime is a factor of $\sim 5$ higher at $z_{abs} \sim 3$ than at $z_{abs} \sim 1$. These incidence rates indicate a potential evolution in the Mg II properties of DLAs as a function of redshift. Whereas DLAs at low $z_{abs}$ are almost uniquely associated with $W_{0}^{2796} \geq 0.6$ Å, at high redshift a significant fraction of DLAs (20 per cent in our sample) can have lower values. The known relationship between $W_{0}^{2796}$ and velocity spread (e.g. Ellison 2006), as well as the relatively low values of measured $v_{90}$ and low metallicity of the $W_{0}^{2796} < 0.6$ Å DLAs in the XQ-100 sample indicate that low $W_{0}^{2796}$ absorbers may preferentially be probing low-mass galaxies, which are less prevalent at low redshift. This is consistent with the lack of low metallicity DLAs at low redshift (Rafelski et al. 2014; Berg et al. 2015). What is currently unknown is whether, despite their rarity, low Mg II EW DLAs at low $z_{abs}$ show the same distribution of properties (metallicities, $v_{90}$, $N(\text{HI})$) as high $z_{abs}$ DLAs of the same $W_{0}^{2796}$. Based on our high $z_{abs}$ results, we caution that DLAs that have been selected based on a high Mg II EW cut have the potential to be biased against low-metallicity systems. Indeed, Kulkarni et al. (2007) have argued that Mg II pre-selection could select against DLAs with $[M/H] < -2.5$. None the less, the low frequency of such systems at low redshifts (and their tendency towards lower $N(\text{HI})$) means that $z_{abs}$, and the $\text{H}i$-weighted metallicity is unlikely to be significantly affected.

### 4 SUMMARY

Using the unbiased sample of 29 DLAs from the XQ-100 sample ($2 < z_{abs} < 4$), we have investigated the Mg II properties of 2 $\leq z_{abs} \leq 4$ absorbers. In summary:

(i) The XQ-100 DLAs span a larger range of $W_{0}^{2796}$ and $W_{0}^{2796}/W_{0}^{2600}$ than previously seen in low-redshift samples. 20 percent of the XQ-100 DLAs have $W_{0}^{2796} < 0.6$ Å. We note that both the $D$-index presented in Ellison (2006) and the $W_{0}^{2796}$ $0.3$ Å cut (R06) identify all the DLAs in the XQ-100 sample.

(ii) Using $W_{0}^{2796}/W_{0}^{2600} < 2.0$ only selected 70 per cent of the XQ-100 DLAs, and would not aid in pre-selecting DLAs from Mg II absorbers at high redshifts.

(iii) The XQ-100 DLAs with $W_{0}^{2796} < 0.6$ Å tend to have lower metallicities, low $v_{90}$ and lower $N(\text{HI})$ compared to DLAs with high Mg II EW, suggesting that DLAs at $z_{abs} > 2.0$ with $W_{0}^{2796} < 0.6$ Å may preferentially select lower mass galaxies.

(iv) The $\text{H}i$-weighted metallicity of our complete XQ-100 DLA sample is $[M/H] = -1.47 \pm 0.03$, compared with $[M/H] = -1.43 \pm 0.03$ for only DLAs with $W_{0}^{2796} \geq 0.6$ Å.

(v) The mean $N(\text{HI})$, and hence $\Omega_{\text{HI}}$, of DLAs may be overestimated solely using $W_{0}^{2796} > 0.6$ Å systems. This is due to both a bias against low $N(\text{HI})$ absorbers and a possible over-representation of high $N(\text{HI})$ absorbers for the $W_{0}^{2796} > 0.6$ Å DLAs. If the cosmic $\text{H}i$ gas density is computed based on the summation of $N(\text{HI})$ in the DLA sample (equation 1), the exclusion of $W_{0}^{2796} < 0.6$ Å absorbers leads to a reduction in $\Omega_{HI}$ by 5 per cent. However, since DLAs associated with $W_{0}^{2796} < 0.6$ Å absorbers tend to have lower

---

\(^5\) The subscript and superscript represent the Poisson 1σ confidence limits derived from tables 1 and 2 in Gehrels (1986).

\(^6\) We note that the DLA incidence rate for $W_{0}^{2796} > 0.6$ Å absorbers in the XQ-100 sample is $\sim 14.1^\pm 2.3$ per cent (compared to the $\sim 22$ per cent seen at $z_{abs} \sim 1$; R06).
H\textsc{i} column densities, using the mean N(H\textsc{i}) to compute the cosmic H\textsc{i} gas density (e.g. equation 2) results in a 7 percent increase in $\Omega_{\text{HI}}$, if $W_{2796}^0 < 0.6$ Å absorbers are excluded, relative to the full DLA sample.

(vi) There is a factor of ~5 more DLAs with $W_{2796}^0 < 0.6$ Å at high redshifts ($z_{\text{abs}} > 3$) compared to lower redshifts ($z_{\text{abs}} < 1$), suggestive of an evolution in the Mg\textsc{ii} properties of DLAs as a function of redshift. This evolution would be consistent with the deficit of low-metallicity systems observed at low redshifts.

ACKNOWLEDGEMENTS

We are very grateful to Sandhya Rao for her useful comments on an earlier edition of this manuscript, and sharing her results of a new Mg\textsc{ii} survey prior to publication. We also thank the referee (Michael Murphy) for his comments for improving the manuscript. SLE acknowledges the receipt of an NSERC Discovery Grant which supported this research. JXP is supported by NSF grant AST-1109447. SL has been supported by FONDECYT grant number 1140838 and partially by PFB-06 CATA. KDD is supported by an NSF AAPF fellowship awarded under NSF grant AST-1302093.

REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this Letter:
Table 1. DLA properties and equivalent widths.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the Letter.

This paper has been typeset from a T\textsc{eX} file prepared by the author.