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

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ABSTRACT

The XQ-100 survey provides optical and near-infrared coverage of 36 blindly selected, intervening damped Lyman α systems (DLAs) at $2 < z_{\rm abs} < 4$, simultaneously covering the Mg II doublet at $\lambda\lambda$2796, 2803Å, and the Ly α transition. Using the XQ-100 DLA sample, we investigate the completeness of selecting DLA absorbers based on their Mg II rest-frame equivalent width (W_0^{2796}) at these redshifts. Of the 29 DLAs with clean Mg 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 II properties of DLAs with redshift. All of the $W_0^{2796} < 0.6$ Å DLAs have low metallicities ($-2.5 < [M/{\rm H}] < -1.7$), small velocity widths ($v_{90} < 50\,{\rm km\,s^{-1}}$), and tend to have relatively low N(H I). We demonstrate that the exclusion of these low W_0^{2796} DLAs results in a higher mean N(H I) which in turn leads to an $\sim$7 per cent increase in the cosmological gas density of H I of DLAs at $2 < z_{\rm abs} < 4$; and that this exclusion has a minimal effect on the H 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 I gas content over cosmic time. Of the many classes of QSO absorption line systems, damped Lyman α systems (DLAs) are the highest H I column density absorbers, defined as having log N(H I) $\geq$ 20.3 (Wolfe et al. 1986; Wolfe, Gawiser & Prochaska 2005). Although fewer in number compared to lower N(H I) counterparts (such as subDLAs; 19.0 < log N(H I) < 20.3), DLAs dominate the H I column density distribution from $z_{\rm abs}\sim5$ to the present epoch and are used to trace the cosmological gas density of H I ($\Omega_{\rm H\,I}$), eventually fuelling 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 I is observed in optical bands ($z_{\rm abs} \gtrsim 1.5$), $\Omega_{\rm H\,I}$ remains relatively constant with redshift (for the most recent results at these redshifts, see Crighton et al. 2015; Sánchez-Ramírez et al. 2016). At $z \sim 0$, $\Omega_{\rm H\,I}$ is currently best

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Table 1. DLA properties and equivalent widths. Full table is available in online version.

QSO	$z_{\rm em}$	$z_{\rm abs}$	log N(H I)	W_0^{2796} Å	W_0^{2803} Å	W_0^{2600} Å	[M/H] (elem)	v_{90} km s^{-1}	D-index (cut^a)
J0003−2603	4.12	3.3900	21.40 ± 0.10	1.393 ± 0.010	1.147 ± 0.009	–	−1.93 ± 0.12 (Zn II)	21	5.6 (3.8)
J0006−6208	4.44	3.2030	20.90 ± 0.15	0.553 ± 0.027	<0.537	0.383 ± 0.088	−2.31 ± 0.15 (Fe II)	43	5.8 (3.8)
J0006−6208	4.44	3.7750	21.00 ± 0.20	1.196 ± 0.023	0.963 ± 0.026	0.724 ± 0.034	−0.94 ± 0.20 (Zn II)	54	7.0 (3.8)
J0034+1639	4.29	3.7525	20.40 ± 0.15	0.518 ± 0.013	0.510 ± 0.022	0.369 ± 0.015	−1.88 ± 0.16 (Fe II)	32	5.4 (3.8)
J0113−2803	4.31	3.1060	21.20 ± 0.10	4.377 ± 0.047	3.620 ± 0.040	2.326 ± 0.035	−1.11 ± 0.10 (Si II)	164	8.9 (3.9)

Notes. ^{a}The cut is obtained from table 2 in Ellison (2006), and is based on the resolution at the Mg II 2796 Å line (assuming $R = 5300$). An absorber with a D-index larger than the cut value would be considered a DLA candidate.

measured from 21 cm emission line surveys of galaxies (Zwaan et al. 2005; Martin et al. 2010). Between these $z \sim 0$ measurements and $\Omega_{\rm H\,I}$ measured in DLAs at $z \sim 1.5$, the gas content of galaxies has only evolved by a factor of ∼2 (Zwaan et al. 2005; Sánchez-Ramírez et al. 2016).

Despite well-constrained estimates of $\Omega_{\rm H\,I}$ at $z \sim 0$ and at $z > 2$, studying the nature of the $\Omega_{\rm H\,I}$ evolution between $0.3 \lesssim z_{\rm abs} \lesssim 1.5$ is challenging, as the Ly α 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 II $\lambda\lambda$ 2796, 2803Å 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 II 2796 Å EW cut of $W_0^{2796} \geq 0.3$ Å (R00), the final statistical sample compiled in R06 contains *no* DLAs at $z_{\rm abs} \sim 1$ with $W_0^{2796} < 0.6$ Å.[1]

$\Omega_{\rm H\,I}$ derived from $z_{\rm abs}$∼1 DLA samples pre-selected from Mg II ($\Omega_{\rm H\,I}$∼7.5 × 10^{-3}) are consistent with the $z_{\rm abs} \gtrsim 2$ 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 $\Omega_{\rm H\,I}$ a factor of 3 lower than R06 (∼2.5 × 10^{-3}), and consistent with 21 cm results at $z \sim 0$ (Neeleman et al. 2016). This tension in $\Omega_{\rm H\,I}$ has led to suggestions that Mg II DLA pre-selection may be biased, possibly leading to high $\Omega_{\rm H\,I}$ (Péroux et al. 2004; Dessauges-Zavadsky, Ellison & Murphy 2009; Neeleman et al. 2016).

In this Letter, we investigate the nature of Mg II selection of 36 DLAs at $2 < z_{\rm abs} < 4$ from the XQ-100 Legacy Survey (P.I. S. Lopez). The blind nature of the XQ-100 DLA sample combined with simultaneous observations of Ly α and Mg II λ 2796 Å provide an excellent test of the effectiveness of the Mg 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∼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 $\Omega_{\rm H\,I}$. 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 II 2796 Å and 2803 Å lines, as well as the Fe II 2600 Å line (with EW W_0^{2600}). The redshift, metallicity, and v_{90}[2] measurements are taken from Sánchez-Ramírez et al. (2016) and Berg et al. (2016). Absorption line profiles of the Mg 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 $z_{\rm abs}$∼1 have $W_0^{2796} \geq 0.6$ Å (R00; R06). For example, in a recent compilation of 369 Mg II systems (Rao et al., in preparation), there are 70 Mg II absorbers with $0.3 \leq W_0^{2796} < 0.6$ Å, but only one of these is a DLA (S. Rao private communication). As a result, many works have typically used $W_0^{2796} \geq 0.6$ Å to pre-select potential DLA systems (R00; R06). Moreover, R06 used the EW of Fe II 2600 Å (W_0^{2600}) to aid in identifying DLAs, and found that their DLA sample is confined to $W_0^{2796}/W_0^{2600} < 2$, whereas their subDLAs span a larger range of W_0^{2796}/W_0^{2600}.

Fig. 1 shows how the XQ-100 measurements of W_0^{2796} (left-hand panel), the ratio W_0^{2796}/W_0^{2600} (middle panel), and D-index (right-hand panel) vary with log N(H I). Starting with the left-hand panel of Fig. 1, we find that six[3] (20 per cent of the sample) of the XQ-100 DLAs with measured W_0^{2796} have W_0^{2796} <0.6 Å (dashed line). However, *all DLAs pass the* $W_0^{2796} \geq 0.3$ *Å cut*. The middle panel of Fig. 1 shows the W_0^{2796}/W_0^{2600} ratio for the XQ-100 and R06 samples, and demonstrates that 30 per cent of the XQ-100 DLAs with Fe II 2600 Å measurements have $W_0^{2796}/W_0^{2600} > 2.0$ (DLAs above dashed line). Only one DLA (J0034+1639, $z_{\rm abs}$=3.69) does

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[1] Although some DLAs with $W_0^{2796} < 0.6$ Å have been previously identified (e.g. Péroux et al. 2004; R06).

[2] v_{90} 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 $W_0^{2796} < 0.6$ Å have previously been observed in the literature (DLAs towards J1108+1209 and J0134+0400), but previous observations have not covered the Mg II absorption. We also note that one of the excluded proximate DLAs (J0034+1639 at $z_{\rm abs} = 4.25$) does not satisfy the $W_0^{2796} \geq 0.6$ Å cut. This DLA is metal-poor ([M/H] = −2.40) and has an equivalent width $W_0^{2796} = 0.344 \pm 0.013$ Å.

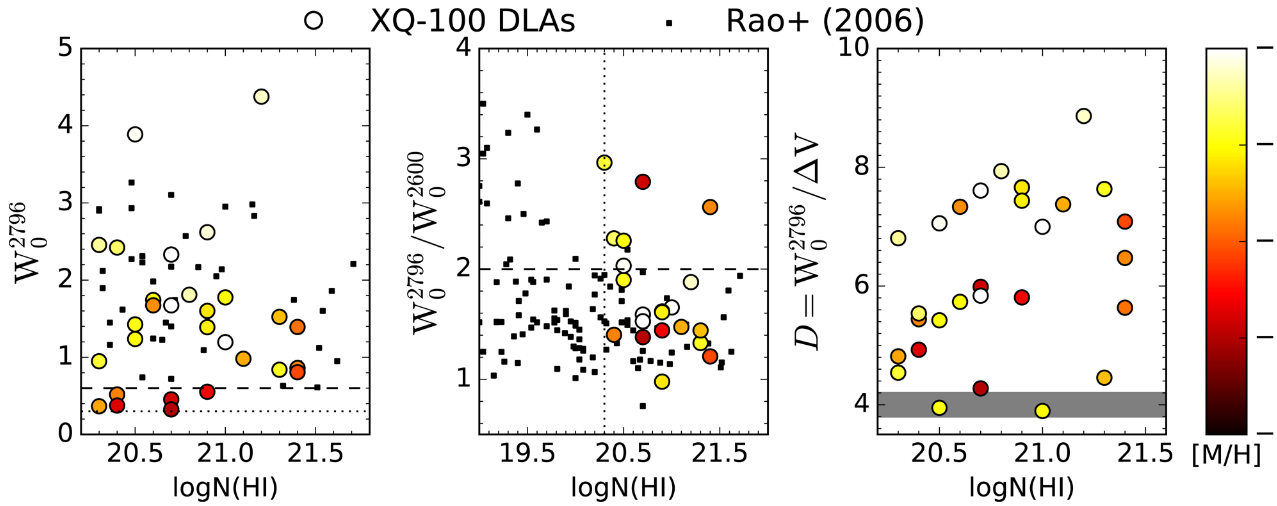

Figure 1. Left-hand panel: the rest-frame W_0^{2796} as a function of log N(H I) for the XQ-100 DLAs (large circles; colours indicate metallicity) and R06 data (black squares). For reference, the W_0^{2796} cuts ($W_0^{2796} \geq 0.3$ Å and $W_0^{2796} \geq 0.6$ Å) are shown as horizontal lines (dotted and dashed; respectively). Six of the 29 XQ-100 DLAs show $W_0^{2796} < 0.6$ Å. Middle panel: the ratio W_0^{2796}/W_0^{2600} as a function of log N(H I) for the XQ-100 sample and R06 data. The region below the dashed line at $W_0^{2796}/W_0^{2600} \leq 2.0$ characterizes the Mg 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 $W_0^{2796}/W_0^{2600} < 2$. Right-hand panel: the D-index (W_0^{2796}/ΔV) as a function of log N(H 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.

not satisfy both $W_0^{2796} \geq 0.6$ Å and $W_0^{2796}/W_0^{2600} < 2$ restrictions. Lastly, the right-hand panel of Fig. 1 shows the D-index (i.e. W_0^{2796} normalized by the velocity width of the line ΔV; from Ellison 2006) for the XQ-100 DLAs as a function of log N(H 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 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).

Are the properties of $W_0^{2796} < 0.6$ 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 $W_0^{2796} < 0.6$ Å all have low metallicities, below [M/H] < −1.7. The mean metallicity of the XQ-100 DLAs subsample with $W_0^{2796} \geq 0.6$ Å is [M/H] = −1.42 ± 0.03,[4] whereas the entire sample has a mean metallicity of [M/H] = −1.60 ± 0.02. However, the H 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 ± 0.03 for the full sample to [M/H] = −1.43 ± 0.03 whenxbrk $W_0^{2796} < 0.6$ Å absorbers are excluded.

In addition to the metallicity, we checked for other DLA properties dependent on $W_0^{2796} \geq 0.6$ Å selection. Fig. 2 shows the distributions of [M/H], v_{90} (which has been suggested as a proxy for mass, e.g. Prochaska & Wolfe 1997; Haehnelt, Steinmetz & Rauch 1998), $z_{\rm abs}$, and log N(H I) for the XQ-100 DLAs for a selection cut of $W_0^{2796} \geq 0.6$ 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 $W_0^{2796} < 0.6$ Å tend to show low metallicities, low log N(H I), and low v_{90} widths with respect to DLAs with $W_0^{2796} \geq 0.6$ Å. These properties are consistent with a 'mass–metallicity' relationship seen in DLAs (Ledoux 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_0^{2796} 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_{90}, 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 II EW cut by including those absorbers with low metallicity and v_{90}.

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

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

$$\Omega_{\rm H\,I} = \frac{H_0 \mu m_{\rm H}}{c \rho_{\rm crit}} \frac{\sum N({\rm H\,I})}{\sum X}. \quad (1)$$

If DLAs are missed from a Mg II-selected sample, the computed $\Omega_{\rm H\,I}$ from equation (1) would be underestimated, as the sum of N(H I) would exclude the low Mg II EW DLAs while $\sum X$ remains unaffected. For the entire XQ-100 DLA sample, $\Omega_{\rm H\,I}$ would be *underestimated* by ∼5 per cent if $W_0^{2796} < 0.6$ Å DLAs were excluded.

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

$$\Omega_{\rm H\,I}(z) = \frac{H_0 \mu m_{\rm H}}{c \rho_{\rm crit}} \frac{E(z)}{(1+z)^2} n_{\rm DLA}(z) \langle N({\rm H\,I})\rangle. \quad (2)$$

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[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.

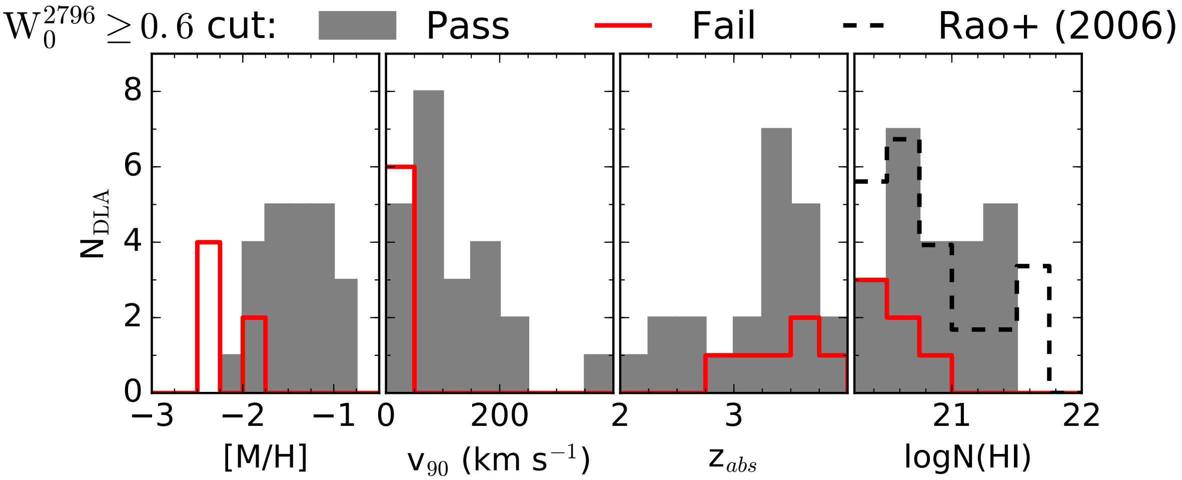

Figure 2. XQ-100 DLA distribution of metallicity ([*M*/H]), v_{90}, $z_{\rm abs}$, and log *N*(H I from left to right). Different histograms are shown for DLAs that pass (shaded grey region) or fail (red line) the equivalent width cut $W_0^{2796} \geq 0.6$ Å. The simple $W_0^{2796} \geq 0.6$ Å cut clearly misses low-metallicity systems, with small log *N*(H I) and v_{90}. For reference, the H I distribution of the R06 DLAs is shown as the dashed line. For visual purposes the R06 distribution is scaled down by a factor of ∼1.8 to match the number of DLAs in the shaded region.

With the R06 formalism, the calculation of $\Omega_{\rm H\,I}$ depends on two measured variables: the frequency of absorbers and their mean *N*(H I). As shown in Fig. 2, in the XQ-100 sample, DLAs with $W_0^{2796} < 0.6$ Å tend to have lower *N*(H I) than higher EW absorbers. If the low EW systems were not included in the XQ-100 sample statistics then ⟨*N*(H I)⟩ and thus $\Omega_{\rm H\,I}$ would be overestimated. However, this effect in our sample is minimal: the mean log(⟨*N*(H I)⟩) 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 $n_{\rm DLA}$, $\Omega_{\rm H\,I}$ would be *overestimated* by ∼7 per cent when low EW systems are excluded.

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

In the latest compilation of 369 $z_{\rm abs}$∼1 Mg II absorbers (Rao et al., in preparation) only 1 out of 70 ($1.4^{+3.3}_{-1.2}$ per cent[5]) systems with $0.3 \leq W_0^{2796} < 0.6$ Å is confirmed to be a DLA (S. Rao, private communication). In contrast, $\sim 7^{+4}_{-2}$ per cent of $0.3 \leq W_0^{2796} < 0.6$ Å systems are DLAs[6] (Lopez et al., in preparation). The DLA incidence for the low W_0^{2796} regime is a factor of ∼5 higher at $z_{\rm abs}$∼3 than at $z_{\rm abs}$∼1. These incidence rates indicate a potential evolution in the Mg II properties of DLAs as a function of redshift. Whereas DLAs at low $z_{\rm abs}$ 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 $z_{\rm abs}$ show the same distribution of properties (metallicities, v_{90}, *N*(H I)) as high $z_{\rm abs}$ DLAs of the same W_0^{2796}. Based on our high $z_{\rm abs}$ 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*(H I)) means that $\Omega_{\rm H\,I}$ and the H I-weighted metallicity is unlikely to be significantly affected.

4 SUMMARY

Using the unbiased sample of 29 DLAs from the XQ-100 sample ($2 < z_{\rm abs} < 4$), we have investigated the Mg II properties of $2 \leq z_{\rm abs} \leq 4$ 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 per cent 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 $W_0^{2796} \geq 0.3$ Å cut (R00) 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*(H I) compared to DLAs with high Mg II EW, suggesting that DLAs at $z_{\rm abs} \gtrsim 2.0$ with $W_0^{2796} < 0.6$ Å may preferentially select lower mass galaxies.

(iv) The H I-weighted metallicity of our complete XQ-100 DLA sample is [*M*/H] = −1.47 ± 0.03, compared with [*M*/H] = −1.43 ± 0.03 for only DLAs with $W_0^{2796} \geq 0.6$ Å.

(v) The mean *N*(H I), and hence $\Omega_{\rm H\,I}$, of DLAs may be overestimated solely using $W_0^{2796} \geq 0.6$ Å systems. This is due to both a bias against low *N*(H I) absorbers and a possible over-representation of high *N*(H I) absorbers for the $W_0^{2796} \geq 0.6$ Å DLAs. If the cosmic H I gas density is computed based on the summation of *N*(H I) in the DLA sample (equation 1), the exclusion of $W_0^{2796} < 0.6$ Å absorbers leads to a reduction in $\Omega_{\rm H\,I}$ by 5 per cent. However, since DLAs associated with $W_0^{2796} < 0.6$ Å absorbers tend to have lower

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[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 $\sim 14^{+4}_{-3}$ per cent (compared to the ∼22 per cent seen at $z_{\rm abs}$∼1; R06).

H I column densities, using the mean N(H I) to compute the cosmic H I gas density (e.g. equation 2) results in a 7 per cent increase in $\Omega_{\rm H\,I}$ if $W_0^{2796} < 0.6$ Å absorbers are excluded, relative to the full DLA sample.

(vi) There is a factor of ~5 more DLAs with $W_0^{2796} < 0.6$ Å at high redshifts ($z_{\rm abs}$~3) compared to lower redshifts ($z_{\rm abs}$~1), suggestive of an evolution in the Mg 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.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this Letter:

Table 1. DLA properties and equivalent widths. (http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/slw185/-/DC1).

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