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Galaxy counterparts of metal-rich damped Ly$\alpha$ absorbers: the case of J205922.4−052842

O. E. Hartoog, J. P. U. Fynbo, L. Kaper, A. De Cia and J. Bagdonaite

ABSTRACT

We present observations of three new sources in the European Southern Observatory VLT/X-shooter survey dedicated to the detection of the emitting counterparts of damped Ly$\alpha$ (DLA) systems towards bright quasars (QSOs). The aim is to bridge the observational gap between absorption (i.e. DLAs) and emission-selected galaxies at $z \sim 2.2$–2.5, in order to get a more complete picture of (proto)galaxies around this epoch. The hypothesis is that because DLA galaxies fulfill metallicity–velocity width and luminosity–metallicity relations, high-metallicity DLAs are more likely to be detected in emission. The region around each QSO is covered with slits (1.3 arcsec × 11 arcsec) at three different position angles. In the DLA towards QSO J205922.4−052842 ($\zeta_{\text{DLA}} = 2.210$, [S/H] = −0.91 ± 0.06), Ly\$\alpha$ emission is detected at $3\sigma$ confidence limit at an impact parameter of <6.3 kpc, and indicates a star formation rate >0.40 $M_{\odot}$ yr$^{-1}$ for the associated DLA galaxy. We do not detect the associated emission of two other DLAs in the spectra of QSOs J003034.4−512946 ($\zeta_{\text{DLA}} = 2.452$, [Zn/H] = −1.48 ± 0.34) and J105744.5+062914 ($\zeta_{\text{DLA}} = 2.499$, [Zn/H] = −0.24 ± 0.11, [S/H] = −0.15 ± 0.06). We conclude that focusing on metal-rich DLAs is a good way to find counterparts, but the non-detections at high metallicity (e.g. that of the DLA in J105744.5+062914) show that there is not a one-to-one relationship, and cautions us to not naively apply the properties of the DLA counterparts to all metal-rich DLAs.

Key words: galaxies: abundances – galaxies: ISM – quasars: absorption lines – quasars: individual: J205922.4-052842 – quasars: individual: J105744.5+062914 – quasars: individual: J003034.4-512946.

1 INTRODUCTION

Damped Ly$\alpha$ (DLA) systems are absorbers in the line of sight towards bright background sources, typically quasars (QSOs), with a neutral hydrogen column density $\log(N(\text{H}I)/\text{cm}^{-2}) \geq 20.3$ (see e.g. Wolfe, Gawiser & Prochaska 2005, for a review). Furthermore, in gamma-ray burst (GRB) afterglow spectra, the host galaxy is often seen as a DLA. The term DLA can refer to both the characteristic damping wings, and the astronomical object that gives rise to the absorption, also referred to as DLA galaxy or DLA counterpart. It appears that DLAs are not just a scaled-up version of Ly$\alpha$ forest absorbers ($\log(N(\text{H}I)/\text{cm}^{-2}) < 17.0$ and Lyman limit systems ($17.0 < \log(N(\text{H}I)/\text{cm}^{-2}) < 20.3$), using arbitrary distinctions for the column density. Rather, the distinctions are physical and associated with the ionization state of the gas. The H$\text{I}$ column densities of DLAs are so high that they, contrary to other classes of QSO absorbers, are mostly neutral. DLAs are thought to be the dominant reservoirs of neutral gas in the Universe in the interval $z = 0$–5; and this neutral gas is where a significant fraction of the stellar mass in present-day galaxies finds its origin (Storrie-Lombardi & Wolfe 2000; Wolfe et al. 2005).

Thanks to the Sloan Digital Sky Survey (SDSS), over 10,000 $z > 2$ DLAs are identified in the spectra of QSOs (Prochaska, Herbert-Fort & Wolfe 2005; Noterdaeme et al. 2009, 2012b; Prochaska & Wolfe 2009). Their absorption spectra have been extensively studied yielding their metal abundances (e.g. Dessauges-Zavadsky et al. 2006; Rafelski et al. 2012; Jorgenson, Murphy & Thompson 2013), dust

*Based on observations obtained with ESO telescopes at the Paranal Observatory under programmes 084.A-0524(A) and 088.A-0601(A).

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content (e.g. Ledoux, Bergeron & Petitjean 2002) and kinematical structure (e.g. Ledoux et al. 2006a; Prochaska et al. 2008; Möller et al. 2013; Neeleman et al. 2013). This information is strongly complementary to the properties we can infer from the light emitted by galaxies, such as star formation rates (SFRs), luminosities, colours, stellar masses, morphology and sizes (e.g. Kauffmann et al. 2003; Shen et al. 2003; Tremonti et al. 2004; Smolčić et al. 2006; Weinmann et al. 2006; Fukugita et al. 2007). It is therefore very useful to be able to combine the information of galaxies inferred from both emission and absorption properties. However, it is difficult to connect observational samples that are selected with fundamentally different methods, and very different selection biases. There seems to be hardly any overlap between emission and absorption selected galaxy samples at intermediate to high redshifts (Fynbo, Möller & Warren 1999; Colbert & Malkan 2002; Möller et al. 2002; Kulkarni et al. 2006). DLA galaxies are selected by their cross-section areas, because their detection rate depends on the probability that a QSO sight line intersects them. The cross-section area of a galaxy is known to scale locally with its luminosity to a given power (Wolfe et al. 1986; Zwaan et al. 2005). On the assumption that a similar relation was at play at higher redshifts, and combining this with the faint end slope of the luminosity function (Schechter 1976), one can conclude that DLA galaxies are mostly selected from this faint end. On the other hand, emission selected galaxies will naturally be drawn mostly from the bright end. Fynbo et al. (2008) show that QSO-DLAs as well as GRB host galaxies, which are referred to as GRB-DLAs when observed in absorption, are consistent with being drawn from the same population as Lyman-break galaxies (LBGs), which are UV-selected star-forming galaxies.

Progress in the field of connecting absorption and emission selected galaxies has been slow for many years, but recently some developments have been reported. With modern observing facilities, it has been possible to study emission-selected galaxies to much deeper rest-frame flux limits (e.g. Sawicki & Thompson 2006; Gronwall et al. 2007; Ouchi et al. 2008; Rauch et al. 2008; Grove et al. 2009; Reddy & Steidel 2009; Cassata et al. 2011; Trinario & Steidel 2012; Alavi et al. 2014). Dedicated campaigns to detect emitting counterparts of DLAs have been carried out: using long-slit spectroscopy (e.g. Hunstead, Pettini & Fletcher 1990; Noterdaeme et al. 2012a), (narrow-band) imaging (e.g. Smith, Cohen & Bradley 1986; Möller & Warren 1993; Kulkarni et al. 2001; Fumagalli et al. 2014) and integral field spectroscopy (e.g. Christensen et al. 2007; Péroux et al. 2011; Bouché et al. 2012; Jorgensen & Wolfe 2014). Despite the much larger number of systems being observed, between 1986 and 2010 the galaxy counterparts of only two bona fide DLAs were identified (Möller, Fynbo & Fall 2004; but see also Kroghager et al. 2012; Christensen et al. 2014). At lower redshift ($z = 0–1$) emitting counterparts of DLAs and lower column density line-of-sight objects are naturally detected more frequently (see e.g. Chen & Lanzetta 2003; Rao et al. 2011).

This study reports on an ongoing observational survey with the X-shooter spectrograph on the European Southern Observatory (ESO) Very Large Telescope (VLT) with the aim to identify and study DLA counterparts by their emission lines, and also to test observationally the hypothesis in Fynbo et al. (2008) that DLAs and LBGs are drawn from the same parent population. Earlier successes within this campaign are presented in Fynbo et al. (2010, 2011, 2013), and are summarized in Section 5 together with detections of DLA-associated emission from other campaigns. The selection of candidates in our survey is based on the hypothesis that DLA galaxies obey luminosity–metallicity and metallicity–velocity width relations (Möller et al. 2004; Ledoux et al. 2006a; Möller et al. 2013; Neeleman et al. 2013) and that therefore the probability to detect the associated emission is higher for a more metal-rich and thus more massive and luminous galaxy. We selected DLAs with a rest-frame equivalent width (EW_{Hα}) of the Si II λ1526 larger than 1 Å in the SDSS spectrum (Noterdaeme et al. 2009). This is an indication that the metallicity of the DLA is likely to be at least 10 per cent solar (e.g. Prochaska et al. 2008, their fig. 6). From these, candidates were selected that also show strong Fe II λλ2344, 2374 and 2382 lines. We selected DLAs with redshifts such that the strongest emission lines should fall in spectral windows that are observable from the ground and covered by X-shooter (i.e. $z \sim 2.2–2.5$), so that we do not have to rely on Lyα emission alone.

In this paper we report a positive detection of Lyα in emission associated with the DLA towards QSO J205922.4–052842 ($z = 2.210$, hereafter DLA-2059), and two non-detections for the DLAs towards J105744.5+062914 ($z = 2.499$, DLA-1057) and J003034.4–512946 ($z = 2.452$, DLA-0030). While DLA-2059 and DLA-1057 are bona fide high-metallicity DLAs obeying the criteria listed above, DLA-0030 was a southern backup target that does meet the line strength criteria and does not have a high metallicity.

The paper is structured as follows. In Section 2 the strategy and details of the observations and data reduction are described. In Section 3.1 we report the Lyα emission in DLA-2059. In Section 3.2 the absorption properties of DLA-2059 are analysed. In Section 4 we report the emission limits and the absorption properties of DLA-1057 and DLA-0030. The implications of our results are discussed in Section 5, and we conclude in Section 6.

Throughout the paper we adopt a standard Λ-cold-dark-matter cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, Ω_m = 0.27, Ω_Λ = 0.73 from the Wilkinson Microwave Anisotropy Probe seven-year data (Komatsu et al. 2011). For metallicities and other abundance ratios we issue the standard definition $[X/Y] \equiv \log (N(X)/N(Y)) – \log (n(X)/n(Y))_{⊙}$, with $N(X)$ the column density of element $X$ and $(n(X)/n(Y))_{⊙}$ the particle number ratio of elements $X$ and $Y$ in the solar reference environment. We use solar reference values from Asplund et al. (2009), following the recommendations by Lodders, Palme & Gail (2009) to use photospheric values for the volatile elements, meteoric values for the less refractory elements, or the average between them (for details see also De Cia et al. 2012). Errors and limits are 1σ unless explicitly specified otherwise.

### 2 STRATEGY AND OBSERVATIONS

With the ESO VLT/X-shooter spectrograph (D’Odoorio et al. 2006; Vernet et al. 2011) we observed three QSO-DLAs that belong to the survey described in Section 1: DLA-1057 in guaranteed time observations (GTO) programme 084.A-0524(A) (PI Kaper), and DLA-2059 and DLA-0030 in GTO programme 088.A-0101(A) (PI Kaper). See Table 1 for details on the sources. We followed the same observing strategy as for the other candidates in this sample (Fynbo et al. 2010). Each target is observed at three different position angles (PAs): 0°, −60° and 60° (east of north, referred to as PA1, PA2 and PA3, respectively), for 1 h per source and position, using a slit width of 1.3 arcsec for the ultraviolet-blue (UVB) arm and 1.2 arcsec for both the visual (VIS) and near-infrared (NIR) arms (see Fig. 1). We observed in staring mode, with 1 × 2 binning and 100 kHz / high-gain readout in the UVB and VIS arms. The choice for this triangulation strategy is based on the model described in Fynbo et al. (2008), and is aimed at optimizing the probability to detect the emission of the galaxy that is producing the DLA. According to this model, a DLA with a metallicity of >0.1 solar at $z \sim 2.2$ has an ~90 per cent probability to be detected in at least one of the slits.
A weighed average of the spectra is constructed with help of the vacuum wavelength scale and a barycentric correction is applied. For the NIR spectrum, which is afterwards scaled to the level indicated in the SDSS data base. Telluric standard stars HD 112504 (P84) and Hip105164 (P88) are observed with the same settings as the DLA counterpart due to a too large impact parameter. Furthermore, counts at the edge of the slit can easily be due to artefacts introduced by the reduction process. We caution, however, that the proximity of these artefacts to our detections at the centre of the slit may affect the significance of the detections.

We define nine square apertures (see Fig. 2) for measuring the Lyα flux in the three PAs; apertures 3 and 4 correspond to where we detect the emission in the stacked spectrum. Taking the same apertures for the different PAs is valid because of the small impact parameter seen in the stacked spectrum. In Table 2 we list the fluxes in the apertures where a significant signal is measured. The flux is obtained by the counts within the aperture in the flux-calibrated 2D spectrum multiplied with the spectral bin size (0.2 Å). The 1σ error on this number is based on the pixel variance in the same 2D spectrum multiplied with the spectral bin size (0.2 Å). Taking into account a wavelength-dependent seeing (λ\(^{-1}\)) and a different slit width (see Fynbo et al. 2011, for details). The resolving powers we find for UVB, VIS and NIR are 4800, 8200 and 6300 for DLA-1057, 5100, 8800 and 6700 for DLA-2059 and 5000, 8500 and 6500 for DLA-0030 (see Table 1).

### 3 ANALYSIS AND RESULTS

#### 3.1 Emission properties of the DLA counterpart in DLA-2059

We detect the emission counterpart of DLA-2059 in Lyα in all three PAs at 2.5–3.4σ confidence level. In Fig. 2 (top panel) we show the stacked and smoothed (15 pixel) 2D spectrum around the DLA where we find two emission ‘blobs’ between −1 and +2 arcsec on the spatial scale (vertical). We see also enhanced flux at the top (between +4 and +5 arcsec) of the stacked spectrum and in all three individual frames, which we do not consider signal from the DLA counterpart due to a too large impact parameter. Furthermore, the expected resolving power for the used slit widths is \( R = 4000, 6700 \) and 4300 for UVB, VIS and NIR, respectively. These values are confirmed by the width of sky emission lines, which is always fully set by the slit width. Due to a seeing smaller than the slit width, the spectral resolution of the point source is higher. To calculate this, we measure the width of telluric absorption lines in the VIS spectra. For UVB and NIR, we apply a correction factor derived from that in the VIS, taking into account a wavelength-dependent seeing (λ\(^{-1}\)) and a different slit width (see Fynbo et al. 2011, for details). The resolving powers we find for UVB, VIS and NIR are 4800, 8200 and 6300 for DLA-1057, 5100, 8800 and 6700 for DLA-2059 and 5000, 8500 and 6500 for DLA-0030 (see Table 1).
Figure 2. 2D spectrum (negative) around Lyα from DLA-2059, for all three PAs and a stacked and smoothed (15 pixel) version (top), which clearly shows the detected emission at low impact parameter. The emission at 4 arcsec is displayed (bottom panel we show the normalized and combined 1D spectrum at the central part of the DLA together with the Lyα absorption fit, on the same wavelength scale. The emission cannot be seen here.

Table 2. Flux measured in the apertures in DLA-2059 (see Fig. 2), where it is significant. The error on the flux is based on the variance of the spectrum in the same aperture. The significance is the flux divided by the standard deviation of the fluxes in all apertures, except 3 and 4 collectively for all PAs (σbg).

<table>
<thead>
<tr>
<th>Position angle</th>
<th>Aperture</th>
<th>Lyα flux (10^{-18} erg s^{-1} cm^{-2})</th>
<th>Significance (σbg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA1 = 0°</td>
<td>3</td>
<td>4.97 ± 1.12</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.41 ± 1.21</td>
<td>2.5</td>
</tr>
<tr>
<td>PA2 = -60°</td>
<td>3</td>
<td>5.93 ± 1.17</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.26 ± 1.19</td>
<td>2.4</td>
</tr>
<tr>
<td>PA3 = 60°</td>
<td>3</td>
<td>4.82 ± 1.12</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Notes. Aperture 4 in PA3 contains a cosmic ray hit residual, hampering a reliable measurement of the flux.
being the observed wavelength of a Lyman break at $z_{\text{QSO}}$. However, the strong absorption line at 4312 Å ($E_{\text{W,obs}} = 1.20 \pm 0.02$ Å), just redwards of the centre of the broad Ly$\alpha$ emission line of the QSO, might be due to inflowing neutral hydrogen gas to the QSO, because the line cannot be associated with any strong absorption line other than Ly$\alpha$. Assuming that this is a Ly$\alpha$ line, we find $z = 2.547336 \pm 0.000007$, $\log(N/(H)) = 13.941 \pm 0.005$ and Doppler parameter $b = 57.7 \pm 0.9$. The inflow velocity would then be of the order $v_{\text{in}} \sim 800$ km s$^{-1}$. The small width of the line (FWHM $\sim 120$ km s$^{-1}$) would imply a cold or very confined flow. No strong metal absorption lines (e.g. C IV, Si IV, Mg II) are detected at this velocity.

### 3.2.1 Metallicity and dust depletion

To obtain metal densities for the DLA we use the Voigt profile fitting program VPFIT version 10.0.2 In general, we tie the redshift $z$ and Doppler parameter $b$ of the different components for ions that are likely to reside in the same absorbing clouds, such as the singly ionized metals. We assume $b$ to be purely due to turbulent broadening and neglect the thermal contribution, which is a valid assumption for DLAs, given their low level of ionization. Many lines are saturated: Mg II $\lambda \lambda 2796, 2803$, Al II $\lambda 1670$, Si II $\lambda \lambda 1190, 1193, 1526$, Fe II $\lambda \lambda 2344, 2586, 2600$, Si II and Fe II have weaker lines present as well, so the saturated ones are included in the fit. This helps to constrain $b$ of the strong component and the column density of the small component. Mg II and Al II do not have weak lines, so for these ions only lower limits are given. We take care of intrinsically blended lines (e.g. Cr II $\lambda 2062$ and Zn II $\lambda 2062$) by including uncontaminated lines from the same ions. Blends with lines at other redshifts and with strong telluric lines are avoided as much as possible. Table 3 gives the $b$ and the $z$ values that result from fitting the ensemble of metal lines. Here we also give the ionic column densities of each component resulting from the fit, the total ionic column density and the metal abundances with respect to hydrogen of this line. The resulting fit profiles are shown in Fig. 3. We assume that the majority of the gas in the DLA is in its singly ionized state (e.g. Wolfe et al. 2005) and thus no ionization corrections are needed to derive the metallicity. Our metal column densities are in reasonable agreement with the column densities of Si and Zn reported in Herbert-Fort et al. (2006) based on the SDSS spectrum. We measure a 0.2 dex higher $N_{\text{H},\text{tot}}$.

The metallicity derived from the less refractory elements [S/H] = $-0.91 \pm 0.06$ and [Zn/H] = $-0.96 \pm 0.06$ (Table 3) are in agreement with each other ($Z \sim 0.11 Z_{\odot}$). Si is expected to be slightly lower due to dust depletion, but the abundance [Si/H] = $-0.99 \pm 0.05$ is of the same level as S and Zn. The degree of dust depletion probed by [Zn/Fe] = $0.45 \pm 0.05$ as compared to the metallicity, is within the scatter for samples of QSO-DLAs (see e.g. Noterdaeme et al. 2008; Rafelski et al. 2012). This value of [Zn/Fe] corresponds to a dust-to-metals ratio DTM = 0.86 ± 0.06, expressed as a fraction of the Galactic value, following the method by De Cia et al. (2013). The full set of metal abundances in the DLA can be compared to observed Galactic depletion patterns (e.g. Savage & Sembach 1996), in order to not only identify the amount of dust, but also the type of environment (see e.g. Savaglio 2001; Savaglio, Fall & Fiore 2003; Savaglio & Fall 2004; De Cia et al. 2013) Savage & Sembach (1996) report the depletion pattern for four different sight lines: Halo, Warm Disc, Warm Disc & Halo and Cold Disc. The depletion pattern in the observed DLA resembles the Halo environment pattern best, with a $\chi^2$/dof = 2.94 (see Fig. 4). However, we note that the Halo is the only Galactic environment where Mn is more heavily depleted than Cr. This is also what we observe for this DLA. From this analysis follows DTM = 0.87 ± 0.02, in agreement with the value based on [Zn/Fe] alone. This value is typical for DLAs of this metallicity (De Cia et al. 2013).

### 3.2.2 Kinematic structure of absorption lines

The velocity width $\Delta V$ of optically thin absorption lines is sensitive to the mass of the galaxy that gives rise to the DLA. A correlation between $\Delta V$ and the metallicity is observed in DLAs (Ledoux et al. 2006a; Møller et al. 2013; Neeleman et al. 2013) and can be used as a proxy for testing the mass–metallicity relation (Christensen et al. 2014). Si II $\lambda 1808$ is considered to be a suitable line to measure $\Delta V$. Using the definition by Prochaska &

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Table 3. Ionic column densities for DLA-2059. The lines are found to have two components, of which we obtained $z$ and $b$ from a fit to the ensemble of Fe II lines only. In the cases of Si II and Ni II the left weak component is rejected by the fitting program as not being significant. In the last column, the abundance with respect to hydrogen is given for the two components together.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transitions used in the fit</th>
<th>$z = 2.208622 \pm 0.000005$</th>
<th>$z = 2.210166 \pm 0.0000003$</th>
<th>$\log(N)$ (cm$^{-2}$)</th>
<th>$\log(N)$ (cm$^{-2}$)</th>
<th>$\log(N_{\text{H},\text{tot}})$ (cm$^{-2}$)</th>
<th>$[X/H]_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H I</td>
<td>Lyα, Lyβ</td>
<td>1.81 ± 0.06</td>
<td>12.81 ± 0.01</td>
<td>12.86 ± 0.01</td>
<td>21.00 ± 0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg II</td>
<td>$\lambda \lambda 1668, 1707, 1827, 2026, 2852$</td>
<td>14.60 ± 0.13</td>
<td>$&gt;15.00$</td>
<td>$&gt;15.11$</td>
<td>$&gt;-1.55$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al II</td>
<td>$\lambda 1670$</td>
<td>12.60 ± 0.08</td>
<td>$&gt;13.90$</td>
<td>$&gt;13.92$</td>
<td>$&gt;-1.57$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si II</td>
<td>$\lambda \lambda 1190, 1193, 1526, 1808$</td>
<td>13.73 ± 0.04</td>
<td>15.52 ± 0.02</td>
<td>15.52 ± 0.02</td>
<td>$-0.99 ± 0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S II</td>
<td>$\lambda 1255$</td>
<td>comp. rejected</td>
<td>15.23 ± 0.03</td>
<td>15.23 ± 0.03</td>
<td>$-0.91 ± 0.06$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr II</td>
<td>$\lambda \lambda 2056, 2062, 2066$</td>
<td>12.48 ± 0.25</td>
<td>13.42 ± 0.02</td>
<td>13.45 ± 0.03</td>
<td>$-1.19 ± 0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn II</td>
<td>$\lambda \lambda 2576, 2594, 2606$</td>
<td>11.32 ± 0.41</td>
<td>12.85 ± 0.02</td>
<td>12.87 ± 0.03</td>
<td>$-1.61 ± 0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe II</td>
<td>$\lambda \lambda 1611, 2249, 2260, 2344, 2586, 2600$</td>
<td>13.42 ± 0.02</td>
<td>15.05 ± 0.01</td>
<td>15.06 ± 0.01</td>
<td>$-1.41 ± 0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni II</td>
<td>$\lambda \lambda 1317, 1370, 1454, 1467, 1703, 1709, 1741, 1751$</td>
<td>comp. rejected</td>
<td>13.81 ± 0.01</td>
<td>13.81 ± 0.01</td>
<td>$-1.40 ± 0.05$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn II</td>
<td>$\lambda \lambda 2026, 2062$</td>
<td>11.72 ± 0.22</td>
<td>12.61 ± 0.04</td>
<td>12.67 ± 0.05</td>
<td>$-0.96 ± 0.06$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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2 http://www.ast.cam.ac.uk/rfc/vpfit.html
Figure 3. The low-ionization lines belonging to DLA-2059 on a velocity scale with respect to the largest component. The obtained parameters for the Voigt profile fits shown in red are given in Table 3. The orange line shows a higher-resolution atmospheric transmission spectrum, indicating the locations of contamination by telluric absorption lines.

Wolfe (1997, the width in velocity space containing 90 per cent of the total optical depth of the line), we find $\Delta V = 124 \text{ km s}^{-1}$ for this line (see Fig. 5). None of the other lines fulfils the criteria in Ledoux et al. (2006a). According to the $[\text{M}/\text{H}] - \Delta V$ trend by Møller et al. (2013), the metallicity of this DLA agrees with its mass within errors, and well within the scatter in their sample of DLAs (0.38 dex in $[\text{M}/\text{H}]$).

4 NON-DETECTIONS OF EMITTING COUNTERPARTS

Two more QSO-DLAs have been observed with the same observational setup as described in Section 2 (see Fig. 1): DLA-1057 and DLA-0030 (see Table 1). DLA-1057 is observed in the SDSS survey (Noterdaeme et al. 2009) and meets the target selection...
The depletion pattern of the metal column densities of DLA-2059 (diamonds). The red curve shows the average observed pattern in the Milky Way halo, which can be fit to the data by varying the DTM and the metallicity. This pattern fits with a $\chi^2$/dof = 2.94.

Optical depth distribution for Si II $\lambda$1808 in DLA-2059, with in the upper panel the cumulative distribution. Dashed boundaries indicated with $\lambda_1$ and $\lambda_2$ show the range that is measured, the solid horizontal bar with ‘hats’ shows the range that contains 90 per cent of the total optical depth of the line. This is the definition for $\Delta V$ by Prochaska & Wolfe (1997). For this line we find $\Delta V = 124$ km s$^{-1}$.

Figure 5. Optical depth distribution for Si II $\lambda$1808 in DLA-2059, with in the upper panel the cumulative distribution. Dashed boundaries indicated with $\lambda_1$ and $\lambda_2$ show the range that is measured, the solid horizontal bar with ‘hats’ shows the range that contains 90 per cent of the total optical depth of the line. This is the definition for $\Delta V$ by Prochaska & Wolfe (1997). For this line we find $\Delta V = 124$ km s$^{-1}$.

4.1 DLA-1057

DLA-1057 ($z_{QSO} \sim 3.154$) has log(N(H I)/cm$^{-2}$) = 20.51 ± 0.03 and shows multicomponent metal lines at a central redshift of $z_{DLA} \sim 2.499$. The strongest metal lines show five components (see Fig. 8), of which we list the redshifts and Doppler parameters in Table 4. We also report the total column densities and relative abundances. This system has a very high metallicity for a DLA at this redshift: [Zn/H] = −0.24 ± 0.11 ($Z \sim 0.58^{+0.17}_{-0.13} Z_{\odot}$). Zn is in agreement with S: [S/H] = −0.15 ± 0.06 ($Z \sim 0.71^{+0.10}_{-0.013} Z_{\odot}$). [Si/H] = −0.37 ± 0.05 provides a more precise measurement, being based on more than one transition, but at a metallicity this high, the gas-phase column density of this element will be significantly lower due to dust depletion. This picture is in agreement with the much lower gas-phase abundances of Mn, Fe and Ni. Strong identified intervening absorbers other than this DLA are listed in Table B1. Although the multicomponent structure and high metallicity of this DLA could be due to (metal-rich) in- or outflows, it could also imply that the DLA galaxy is massive and luminous. However, we did...
Figure 8. Line profile fits for DLA-1057; see also Table 4. The orange line shows a higher-resolution atmospheric transmission spectrum, indicating the locations of contamination by telluric absorption lines.

not detect the emission associated with this DLA (Fig. 6). The Ly$\alpha$ flux is below $9 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (3$\sigma$) based on the standard deviation of the noise measured in nine apertures in the DLA trough similar in size as used in DLA-2059. The [O III] $\lambda$5008 emission line is not detected to a limit of $<2.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (1$\sigma$). It is, however, possible that we have missed the emitting counterpart in all three slit positions.

Despite the high metallicity and dust content, there is no indication for the presence of diffuse interstellar bands or the 2175 Å feature.
Table 4. Kinematical structure, column densities and derived metallicities of the absorption lines belonging to DLA-1057 and DLA-0030.

<table>
<thead>
<tr>
<th></th>
<th>DLA-1057</th>
<th></th>
<th>DLA-0030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$z_{\text{QSO}} \sim 3.154$</td>
<td></td>
<td>$z_{\text{QSO}} \sim 4.175$</td>
</tr>
<tr>
<td>$z$</td>
<td>$b$ (km s$^{-1}$)</td>
<td>$z$</td>
<td>$b$ (km s$^{-1}$)</td>
</tr>
<tr>
<td>2.496400 ± 0.000006</td>
<td>25 ± 1</td>
<td>2.45175 ± 0.000003</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>2.497262 ± 0.000004</td>
<td>25 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.498633 ± 0.000003</td>
<td>23 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.499930 ± 0.000008</td>
<td>17 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.501115 ± 0.000008</td>
<td>12 ± 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.1 Molecular hydrogen in DLA-1057

The molecular hydrogen ($H_2$) detection probability is higher for DLAs with a higher metal and dust content since such an environment is suitable for $H_2$ to form and stay shielded from ambient UV flux that can dissociate the molecule (e.g. Petitjean et al. 2006). Because DLA-1057 is metal rich for a DLA at this redshift, we have explicitly searched for the presence of $H_2$, traced by spectral features of the rovibronic Lyman-band transitions. These spectral features are in the rest-frame UV ($\lambda_0 \lesssim 1100\AA$), and are thus located in the Ly$\alpha$ forest.

$H_2$ absorption associated with DLAs is typically observed in one or two clumps whose redshifts correspond to those of the strongest metal velocity components. However, $H_2$ velocity components usually have narrower widths of typically $\sim 3$ km s$^{-1}$ if compared to metal-line widths of $\sim 15$ km s$^{-1}$ (Noterdaeme et al. 2008). For the analysis of the $H_2$ content of DLA-1057, which will yield an upper limit, we will assume $b = 3$ km s$^{-1}$.

We proceed as follows. First, we create a model including $H_2$ transitions from ground rotational level $J = 0$ which is always highly populated at low temperatures. The redshift is varied based on the metal-line widths of $J$ transitions from ground rotational level $b = 3$ km s$^{-1}$ convolved with an instrumental profile of FWHM = 3 km s$^{-1}$. The redshift is varied based on the metal-line widths of $J$ transitions from ground rotational level $b = 3$ km s$^{-1}$ convolved with an instrumental profile of FWHM = 3 km s$^{-1}$.

$$N_J = N_{J=0} \times \frac{g_J}{g_{J=0}} \times e^{-E_{J-1}/kT}$$

where $g_J$ is the nuclear spin statistical weight that has the value $g_J = 1$ for even values of $J$ and $g_J = 3$ for odd values, and $E_{J-1}$ is the energy interval between a rotational level $J$ and the ground level. We assume a temperature of $T = 100$ K which is a typical value measured in other studies of high-redshift $H_2$ systems (see e.g. Ledoux, Petitjean & Srianand 2006b). This results in log ($N(J)/cm^{-2}$) values of 17.1, 15.5 13.9 and 10.7 for $J = 1, 2, 3$ and 4, respectively. Convolving this $H_2$ model with the rest of identified $H_1$ and metal absorbers in the Ly$\alpha$ forest (see Fig. 9) gives satisfactory results with the total model still being above the spectrum (including its error) at all wavelengths. As can be seen in Fig. 9, there are many unidentified features in the Ly$\alpha$ forest. Although the $H_2$ model is consistent with the spectrum, all features could still be different intervening (Ly$\alpha$) absorbers. Therefore the reported $H_2$ level populations are upper limits, for the total yielding log ($N(H_2, \text{tot})/cm^{-2}$) $< 17.4$.

4.2 DLA-0030

In DLA-0030, the redshift of the QSO is $z_{\text{QSO}} \sim 4.175$, which is so high that many of the metal lines at the DLA redshift $z_{\text{DLA}} = 2.45174 \pm 0.00003$ fall in the Ly$\alpha$ forest (i.e. intergalactic medium between Z$_{\text{DLA}}$ and Z$_{\text{QSO}}$; see also Fig. A1). Furthermore, the Ly$\alpha$ absorption itself is in a region where the QSO flux level is very low, due to the combined effect of the forest, and being located bluewards of the Lyman break of an additional intervening absorber at $z = 3.78175 \pm 0.00003$. This and other unidentified intervening absorbers are listed in Table B1.

For the DLA we estimate log ($N(H_1)/cm^{-2}$) $= 20.8 \pm 0.2$, the uncertainty mainly due to the placement of the continuum. This is in perfect agreement with the earlier measurement by Péroux et al. (2001), who report log ($N(H_1)/cm^{-2}$) $= 20.8$. The metal lines can be fitted with a single component with $b = 15 \pm 1$ km s$^{-1}$; see Fig. 10 for the line fits. In Table 4 we summarize the gas-phase metal abundances. The metallicity of this DLA is low compared to the other two DLAs with $[\text{Zn/H}] = -1.48 \pm 0.34$ (Z $\sim 0.03 Z_\odot$), but common for DLAs in general at this redshift (e.g. Rafelski et al. 2012).
favour a metallicity–velocity width relation (Ledoux et al. 2006a) and a luminosity–metallicity relation (Møller et al. 2004, 2013; Fynbo et al. 2008; Neeleman et al. 2013) and therefore high-metallicity DLAs are expected to have more luminous galaxy counterparts than DLAs in general. The results of the study presented in this paper are in overall agreement with this picture. We detect the galaxy counterpart of the relatively metal-rich DLA-2059 and do not detect the counterpart of the metal-poor DLA-0030. The non-detection of the counterpart of the very metal-rich DLA-1057 reinforces the idea that while most detected counterparts are associated with metal-rich DLAs, the opposite does not have to be true (see e.g. Péroux et al. 2012; Fumagalli et al. 2014). The simple model we assume predicts a large scatter in the luminosities of the DLA galaxies at a given metallicity (see, e.g. fig. 3 in Fynbo et al. 2008). Another possibility is that this system is bright, but falls outside the region covered by our three slit positions. Hence it would be very interesting to carry out deep imaging of this field to search for a continuum source which consequently is expected to be relatively free from the glare of the bright background QSO. If such an exercise would still yield a non-detection in deep imaging (down to an R-band magnitude of \( \sim 24 \)), according to Fynbo et al. (2008), the case of DLA-1057 might be an indication that the picture is more complex than the one we sketch.

In Table 5 we list the DLAs reported in literature that have an associated emission counterpart, and that are similar to DLA-2059: they (1) are bona fide DLAs with \( \log(N(H\text{I})/\text{cm}^{-2}) \geq 20.3 \), (2) are at \( z \geq 2 \), (3) have a well-constrained metallicity and (4) have a constrained impact parameter. We note that there are more identified absorption–emission pairs reported that are at lower redshift and at lower column density (see e.g. Chen & Lanzetta 2003; Rao et al. 2011; Christensen et al. 2014); these are not included here. The metallicity and impact parameter of DLA-2059 are very similar to the other values in the sample; DLA-1057 would be among the most metal-rich ones in this already biased sample. Krogager et al. (2012) performed a more in-depth analysis of the relationships within this sample between column density, impact parameter and metallicity. From the good agreement with numerical simulations by Pontzen et al. (2008), they conclude that the observations support a scenario in which the size–metallicity relation is driven by feedback mechanisms that control the outflow of enriched gas and the star formation efficiency.

5 DISCUSSION

The emerging picture on the nature of DLAs we have seen developing over the previous decade is the following: DLAs originate from the outskirts of galaxies with properties within the range of star-forming LBGs at similar redshift, but due to their cross-section selection they are predominantly drawn from the faint end of the luminosity function (Fynbo et al. 1999; Møller et al. 2002; Fynbo et al. 2008; Rauch et al. 2008; Rauch & Huchmelt 2011). DLA galaxies fulfil a metallicity–velocity width relation (Ledoux et al. 2006a) and a luminosity–metallicity relation (Møller et al. 2004, 2013; Fynbo et al. 2008; Neeleman et al. 2013) and therefore high-metallicity DLAs are expected to have more luminous galaxy counterparts than DLAs in general. The results of the study presented in this paper are in overall agreement with this picture. We detect the galaxy counterpart of the relatively metal-rich DLA-2059 and do not detect the counterpart of the metal-poor DLA-0030. The non-detection of the counterpart of the very metal-rich DLA-1057 reinforces the idea that while most detected counterparts are associated with metal-rich DLAs, the opposite does not have to be true (see e.g. Péroux et al. 2012; Fumagalli et al. 2014). The simple model we assume predicts a large scatter in the luminosities of the DLA galaxies at a given metallicity (see, e.g. fig. 3 in Fynbo et al. 2008). Another possibility is that this system is bright, but falls outside the region covered by our three slit positions. Hence it would be very interesting to carry out deep imaging of this field to search for a continuum source which consequently is expected to be relatively free from the glare of the bright background QSO. If such an exercise would still yield a non-detection in deep imaging (down to an R-band magnitude of \( \sim 24 \)), according to Fynbo et al. (2008), the case of DLA-1057 might be an indication that the picture is more complex than the one we sketch.

In Table 5 we list the DLAs reported in literature that have an associated emission counterpart, and that are similar to DLA-2059: they (1) are bona fide DLAs with \( \log(N(H\text{I})/\text{cm}^{-2}) \geq 20.3 \), (2) are at \( z \geq 2 \), (3) have a well-constrained metallicity and (4) have a constrained impact parameter. We note that there are more identified absorption–emission pairs reported that are at lower redshift and at lower column density (see e.g. Chen & Lanzetta 2003; Rao et al. 2011; Christensen et al. 2014); these are not included here. The metallicity and impact parameter of DLA-2059 are very similar to the other values in the sample; DLA-1057 would be among the most metal-rich ones in this already biased sample. Krogager et al. (2012) performed a more in-depth analysis of the relationships within this sample between column density, impact parameter and metallicity. From the good agreement with numerical simulations by Pontzen et al. (2008), they conclude that the observations support a scenario in which the size–metallicity relation is driven by feedback mechanisms that control the outflow of enriched gas and the star formation efficiency.

5.1 The mass of the DLAs

We can estimate the stellar mass of the DLAs using the mass–metallicity relation for DLAs described in Møller et al. (2013), with the assumption that the difference between predicted and directly measured stellar mass is due to a metallicity gradient (Christensen et al. 2014). For the latter, the impact parameter directly measured stellar mass is due to a metallicity gradient with the assumption that the difference between predicted and metallicity relation for DLAs described in Møller et al. (2013),

\[
\frac{M_{\text{DLA}}}{M_{\odot}} \leq 6.3 \text{ kpc},
\]

resulting in a stellar mass \( 1.4 \times 10^{9} \leq M_{\text{DLA}}/M_{\odot} \leq 1.6 \times 10^{9} \), given the uncertainty of 0.41 in \( \log M_{\text{DLA}} \) in the relation by Christensen et al. (2014). This is in good agreement with the stellar mass that is predicted from the neutral hydrogen column density and impact parameter by simulations from Rahmati & Schaye (2014). This is rather massive for a DLA, but in emission-selected samples which are biased towards the most luminous and thus heavier galaxies, on average much higher stellar masses are found (see e.g. Kauffmann et al. 2003). Therefore, this galaxy is typically one of the systems in the small overlapping part between absorption and emission-selected galaxies.

Figure 9. Shown is an excerpt from the Lyα forest spectrum towards J105744.5+062914. The error spectrum is shown with a dotted line. In blue a model that includes all identified transitions from the DLA and other known intervening absorbers (see Table B1), found in the full spectrum; in red the same model with addition of the \( \text{H}_2 \) model described in Section 4.1.1.

The low level of dust depletion indicated by [Zn/Fe] = 0.07 ± 0.27 is typical for this metallicity (Noterdaeme et al. 2008). The Lyα flux is below \( <8 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \) (3σ) based on the standard deviation of the noise measured in nine apertures in the DLA trough similar in size as used in DLA-2059. The flux upper limit on the [O iii] 25008 emission line is \( <2.5 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \) (1σ). The emission could be only partly covered, but even if we covered the full emitting region, this limit would be consistent with the low metallicity of the DLA according to our hypothesis.
The emitting counterpart of DLA-1057 is not detected, therefore we do not know \( b_{\text{imp}} \). As explained above, it is possible that the counterpart is luminous, but missed by all three slit positions (i.e. \( b_{\text{imp}} \gtrsim 9.8 \) kpc, see also Fig. 1). From Table 5 we see that such an impact parameter would not be abnormally high. If this would be the physical situation, a lower limit for the stellar mass of the DLA can be derived. With the relation from Christensen et al. (2014) and using \( [M/H] = -0.24 \), \( z_{\text{DLA}} = 2.50 \) and \( b_{\text{imp}} \gtrsim 9.8 \) kpc (assuming that we missed the emission), we find \( M_{\text{DLA}}^* \gtrsim 9 \times 10^9 \) \( M_\odot \). We stress that this is a model-dependent quantity, not a direct result of our measurements. The fact that some of the metal absorption lines in DLA-1057 have five components spanning a velocity range of \( \sim 600 \) km s\(^{-1}\) reflects that the virial mass of this DLA could also be high, which is in line with this stellar mass. Another explanation for the observed metal-line profiles is in- and outflowing gas. For a \( \log(N(\text{H}I)/\text{cm}^{-2}) = 20.51 \) DLA at this impact parameter, Rahmati & Schaye (2014) predict \( M_{\text{DLA}}^* \sim 10^{8.5-9} \) \( M_\odot \), which is slightly lower than the value we derive.

5.2 Star formation and molecular hydrogen in DLA galaxies

DLAs are thought to be the neutral gas reservoirs fuelling star formation over most of the Universe’s history. There is much evidence for star formation in DLAs. First, the neutrality of the DLA gas content is a prerequisite, since stars form in cold, neutral gas with potentially a high molecular fraction. Secondly, DLA metallicities, typically 1/30th solar, are much higher than in the intergalactic medium (i.e. the Ly\( \alpha \) forest) and therefore indicate previous star formation. Thirdly, high SFRs are inferred from the detection of the \( \text{C} \, \text{n} \, \lambda 1335.7 \) \( \AA \) absorption line in DLAs (Wolfe, Gawiser & Prochaska 2003). However, despite this evidence for star formation, actual molecules like \( \text{H}_2 \), a precursor for star formation, have been detected in relatively few DLAs, and by highly biased targeting strategies. Ledoux, Petitjean & Srianand (2003) found \( \text{H}_2 \) in 8 out of 33 DLAs observed with VLT/UVES, and only a few more by-chance detections have been reported. Noterdaeme et al. (2008) reported the detection of \( \text{H}_2 \) in only 12 out of 68 DLAs (13 out of 77 if also some sub-DLA systems are included). Other molecules,
like HD (Noterdaeme et al. 2008; Malec et al. 2010) and CO (Srianand et al. 2008) have so far been detected in only one or two high-redshift systems.

In the most metal-rich DLA discussed in this paper (DLA-1057), H2 is not detected and we obtain an upper limit of \( \log (N(H_2)/\text{cm}^{-2}) < 17.4 \). We also do not detect it in DLA-2059 and DLA-0030. These non-detections are not surprising given the low detection rate even in samples of metal-rich and star-forming DLAs. Although H2 is expected to be the primary molecular coolant, radiating away the energy created by stellar gravitational collapse, there does not necessarily have to be a detectable amount of it to be able for the DLA to be star forming.

### 6 CONCLUSIONS

In the VLT/X-shooter survey with the aim to detect the emitting counterpart of relatively metal-rich DLAs towards QSOs, we present three new observations, among which one detection of the associated Lyα emission. With both absorption- and emission-inferred properties, as well as model-dependent quantities, we sketch an as complete as possible picture of the DLA galaxies (see Table 6).

DLA-2059 is with \([\text{Zn}/\text{H}] = -0.96 \pm 0.06\) and \([\text{S}/\text{H}] = -0.91 \pm 0.06\) relatively metal rich for a DLA at redshift \((z = 2.210)\). The dust depletion pattern resembles that of the Milky Way halo, with DTM = 0.87 ± 0.02 as a fraction of the Galactic value. The Lyα emission line is detected at an impact parameter of \(\sim 6.3\) kpc, and its flux yields \(\text{SFR} > 0.40 \, \odot \, \text{yr}^{-1}\). Together with results from Péroux et al. (2012), we constrain \(\leq 0.40 < \text{SFR} < 1.3 \, \odot \, \text{yr}^{-1}\). Following Christensen et al. (2014), where a metallicity gradient is assumed, we obtain a model-dependent stellar mass of the DLA galaxy of \(M^{\text{DLA}} \sim 0.14-1.6 \times 10^9 \, \odot\), in agreement with simulations of Rahmati & Schaye (2014).

DLA-1057 \((z = 2.499)\) is very metal rich for a DLA \((\text{Zn}/\text{H}) = -0.24 \pm 0.11, [\text{S}/\text{H}] = -0.15 \pm 0.06, [\text{Si}/\text{H}] = -0.37 \pm 0.04)\) and DLA-0030 \((z = 2.452)\) has an average metallicity for a DLA \((\text{Zn}/\text{H}) = -1.48 \pm 0.34\). The emitting counterparts of these two DLAs are not detected in any strong emission line: flux \(f ([\text{O} \text{iii}] \lambda 5008) < 2.5 \times 10^{-17} \, \text{erg s}^{-1} \, \text{cm}^{-2} (1\sigma)\) for both sources.

Based on our findings within the context of earlier observational studies, we conclude that focusing on metal-rich DLAs is a good way to find counterparts in emission. We stress, however, that metal-rich DLAs do not necessarily have bright counterparts.

### ACKNOWLEDGEMENTS

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### REFERENCES


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**Table 5.** Overview of \(z \geq 2\) DLAs for which the emitting counterpart is detected, the impact parameter could be constrained and the metallicity is known. Column densities are on a log scale in \(\text{cm}^{-2}\). Table based on Krogager et al. (2012).

<table>
<thead>
<tr>
<th>QSO-DLA</th>
<th>(z_{\text{abs}})</th>
<th>(N(\text{H} I))</th>
<th>([\text{M}/\text{H}])</th>
<th>(b_{\text{imp}}) (kpc)</th>
<th>(N(\text{H}_2))</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2206−1958 N-14-1C</td>
<td>1.92</td>
<td>20.65 ± 0.05</td>
<td>-0.42 ± 0.07</td>
<td>9.7 ± 0.4</td>
<td>unknown</td>
<td>[1,2,3,4]</td>
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<tr>
<td>Q2206−1958 N-14-2C</td>
<td>1.92</td>
<td>20.65 ± 0.05</td>
<td>-0.42 ± 0.07</td>
<td>11.5 ± 0.5</td>
<td>unknown</td>
<td>[1,2,3,4,5]</td>
</tr>
<tr>
<td>PKS 0458−02</td>
<td>2.04</td>
<td>21.65 ± 0.09</td>
<td>-1.19 ± 0.10</td>
<td>2.62 ± 0.34</td>
<td>unknown</td>
<td>[4,6]</td>
</tr>
<tr>
<td>Q1135−0010</td>
<td>2.21</td>
<td>22.10 ± 0.05</td>
<td>-1.10 ± 0.08</td>
<td>0.84 ± 0.08</td>
<td>not detected</td>
<td>[7]</td>
</tr>
<tr>
<td>J20522.4−052842</td>
<td>2.21</td>
<td>21.00 ± 0.05</td>
<td>-0.96 ± 0.06</td>
<td>&lt;6.3</td>
<td>not detected</td>
<td>this work</td>
</tr>
<tr>
<td>Q0338+0005</td>
<td>2.22</td>
<td>21.05 ± 0.05</td>
<td>-1.25 ± 0.10</td>
<td>4.10 ± 1.00</td>
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<td>[6]</td>
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<td>Q2243+60</td>
<td>2.33</td>
<td>20.67 ± 0.05</td>
<td>-0.72 ± 0.05</td>
<td>23.2 ± 1.7</td>
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<td>Q2222−0946</td>
<td>2.35</td>
<td>20.65 ± 0.05</td>
<td>-0.46 ± 0.07</td>
<td>6.6 ± 0.8</td>
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<td>[9,10]</td>
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<tr>
<td>Q0918+1636-1</td>
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<td>[6,11,12]</td>
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<td>Q0918+1636-2</td>
<td>2.58</td>
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<td>16.3 ± 0.8</td>
<td>16.15−19.05</td>
<td>[6,11]</td>
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<td>Q0139−0824</td>
<td>2.67</td>
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<td>PKS 0528−250</td>
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<td>9.09 ± 0.40</td>
<td>18.2</td>
<td>[14,15,16]</td>
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<td>Q0953+47</td>
<td>3.40</td>
<td>21.15 ± 0.15</td>
<td>-1.80 ± 0.30</td>
<td>2.56 ± 0.75</td>
<td>unknown</td>
<td>[6,17]</td>
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</table>

APPENDIX A: SPECTRA

In Fig. A1 we show the UVB and VIS spectra of all three targets.

Figure A1. One-dimensional spectra of the three QSO-DLAs discussed in this paper (see Table 1). Shown are UVB and VIS, not NIR, because the absorption line analysis is mostly done in this spectral range. The solid line shows the average spectrum, the dotted line is the average error spectrum. In grey, we indicate the atmospheric transmission (scaled to the upper and lower boundaries of the windows). The absolute flux level is scaled to match that of the SDSS spectrum, if available (for DLA-2059 and DLA-1057, see Section 1). We indicate the DLA in each spectrum with an arrow.
APPENDIX B: INTERVENING ABSORBERS IN J205922.4−052842, J105744.5+062914, AND J003034.4−512946

In Table B1 we list the additional intervening absorbers that are identified in the QSOs.

APPENDIX C: AN EXTRA COMPONENT IN THE METAL LINES OF DLA-2059

The spectral resolution of VLT/X-shooter is insufficient when we want to distinguish between different velocity components within broad metal lines. The largest component in the metal lines of DLA-2059 is fitted with a \( b = 45 \text{ km s}^{-1} \). This is a very high value for the Doppler parameter for DLA metal lines. It is likely that what we measure is a blend of several components, with smaller individual \( b \) parameters, although this is not visible from the shape of the line profiles. To estimate the significance of the error we introduce by assuming it is single, we have fit a model to the line profiles where the largest component is double. This results in two components of comparable strength at \( z = 2.20986 \pm 0.00001 \) and \( 2.21035 \pm 0.00002 \) with, respectively, \( b = 32 \) and \( 34 \text{ km s}^{-1} \). The resulting total column densities are equal within the errors when compared to the single component model in the main analysis. The same holds for a total number of four velocity components, but in that case, the reddest component still converges to a large \( b \). If we force the two components within the large component to have \( b = 20 \text{ km s}^{-1} \), and leave the \( z \) and \( N \) free to vary, the resulting fit does not reproduce the observed profiles, especially not in the weak lines. From this we conclude that the error that is introduced by the fact that the spectral resolution is too low to distinguish different velocity components is likely minor.

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