Galaxy Counterparts of metal-rich Damped Lyman-α Absorbers - I: The case of the $z = 2.35$ DLA towards Q 2222–0946

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ABSTRACT

We have initiated a survey using the newly commissioned X-shooter spectrograph to target candidate relatively metal-rich damped Lyman-α absorbers (DLAs). Our rationale is that high-metallicity DLAs due to the luminosity-metallicity relation likely will have the most luminous galaxy counterparts. In addition, the spectral coverage of X-shooter allows us to search for not only Lyman-α (Lyα) emission, but also rest-frame optical emission lines. We have chosen DLAs where the strongest rest-frame optical lines ([OII], [OIII], Hβ) fall in the NIR atmospheric transmission bands. In this first paper resulting from the survey, we report on the discovery of the galaxy counterpart of this DLA is amongst the most metal-rich ($z > 2$) DLAs studied so far at comparable redshifts and there is evidence for substantial depletion of refractory elements onto dust grains. We measure metallicities from ZnII, SiII, NiII, MnII and FeII of $-0.46 \pm 0.07$, $-0.51 \pm 0.06$, $-0.85 \pm 0.06$, $-1.23 \pm 0.06$, and $-0.99 \pm 0.06$, respectively. The galaxy is detected in the Lyα, [OIII] $\lambda\lambda$4959, 5007 and Hα emission lines at an impact parameter of about 0.8 arcsec (6 kpc at $z_{abs} = 2.354$). Based on the Hα line, we infer a star-formation rate of $10 M_\odot$ yr$^{-1}$, which is a lower limit due to the possibility of slit-loss. Compared to the recently determined Hα luminosity function for $z = 2.2$ galaxies the DLA-galaxy counterpart has a luminosity of $L_\alpha \sim 0.1 L_\alpha^{\ast}$. The emission-line ratios are 4.0 (Lyα/Hα) and 1.2 ([OIII]/Hα). In particular, the Lyα line shows clear evidence for resonant scattering effects, namely an asymmetric, redshifted (relative to the systemic redshift) component and a much weaker blueshifted component. The fact that the blueshifted component is relatively weak indicates the presence of a galactic wind.

The properties of the galaxy counterpart of this DLA is consistent with the prediction that metal-rich DLAs are associated with the most luminous of the DLA-galaxy counterparts.

Key words: galaxies: formation, galaxies: high-redshift, galaxies: ISM, quasars: absorption lines, cosmology: observations

1 INTRODUCTION

A central aspect of the history of the Universe is the formation and evolution of galaxies, and in particular their gradual build-up of metallicity (Pei & Fall 1995; Cen & Ostriker 1999; Pettini 2006; Sommer-Larsen & Fynbo 2008). While the study of galaxies in the...
early universe has seen great progress through the identification of large samples of \( z \gtrsim 3 \) Lyman-Break Galaxies (LBGs) and other emission-selected galaxies (e.g., Steidel et al. 1996, 2004; Bouwens et al. 2009), the study of the metals at the same cosmic epoch has seen equally large progress but mostly based on the study of \( z \gtrsim 2 \) DLAs in the sightlines towards bright quasars (e.g., Wolfe et al. 2005; Pontzen & Pettini 2009). Thanks to the SDSS the sample of high-redshift DLAs is now larger than 1000 (Prochaska et al. 2005; Noterdaeme et al. 2009). In order to be able to form a complete picture of galaxy evolution one must find a way to combine the information inferred from high-redshift galaxies studied in emission and absorption, and it is a perplexing fact that there is almost no observational overlap between the two samples (e.g., Fynbo et al. 1999; Möller et al. 2002).

It is not obvious how one may combine the two samples because they have very different selection biases. LBG samples are all flux-limited, and therefore they carry information only about objects at the bright end of the luminosity function. DLAs are selected based on the probability that a random sightline passes through it, and they are therefore selected with a weight proportional to the absorption cross-section (area) they span on the sky. This area is known, locally, to scale with the luminosity to a given power (the so-called Holmberg and Bosma relations; Wolfe et al. 1986 and references therein; see also Zwaan et al. 2005). On the reasonable assumption that similar relations were in place at \( z = 3 \), and combining this with the slope of the faint end of the UV luminosity function, one finds that most DLAs are selected from the faint end of the luminosity function (Fynbo et al. 1999, 2008; Haehnelt et al. 2000; Schaye 2001; Pontzen et al. 2008). Hence, the plausible connection between DLAs and LBGs is that they are drawn from the same overall population of high-z galaxies but that in the mean they are picked from two opposite ends of the high-z galaxy UV luminosity function.

To better establish the validity of this picture, more detections of DLAs in emission are required. Detection of emission from DLAs has been vigorously pursued for more than 20 years (e.g., Smith et al. 1989), but with limited success. Since 1993 only two bona-fide high-redshift DLAs have been detected in emission (Möller et al. 2002, 2004; Heinmüller et al. 2006). In addition, counterparts of either \( z_{\text{abs}} \approx z_{\text{em}} \) DLAs or sub-DLAs have been published (Möller & Warren 1993, 1998; Warren & Möller 1996; Djorgovski et al. 1996; Leibundgut & Robertson 1999; Fynbo et al. 1999; Adelberger et al. 2006). At least ten times more systems have been searched for in emission with no detection (e.g., Charlot & Fall 1991 and references therein; Lowenthal et al. 1995; Colbert & Malkan 2002; Kulkarni et al. 2006). In addition to published nondetections many non-detections have not been published, e.g., nondetections in the survey conducted with FORS1 at the VLT 1999–2000 (PI Möller), and the FLAMES/IFU survey also conducted at the VLT 2003–2005 (PIs Leibundgut and Zwaan). More recently, tentative detections based on integral-field unit spectrographs have been reported (Christensen et al. 2007) and one of these has been confirmed with long-slit spectroscopy (Christensen, private communication). The low success rate has been thought to be the result of attenuation of Ly\( \alpha \) photons by dust grains (Charlot & Fall 1991), but as discussed above it is also plausibly explained in terms of the prediction that DLA galaxies must in the mean be drawn from the faint end of the luminosity function.

Möller et al. (2004) and Ledoux et al. (2006) provide evidence that DLA galaxies obey luminosity-metallicity and velocity-metallicity relations with similar slopes as in the local Universe. Moreover, the DLA galaxies that have been detected in emission (both Ly\( \alpha \), broad band, and for those with redshifts in a range allowing observations in NIR atmospheric windows, also in [OII] emission) are amongst the most metal-rich DLAs (Möller et al. 2004; Weatherley et al. 2005). Fynbo et al. (2008) describe a model that reconciles the known properties of DLAs, LBGs and also Gamma-Ray Burst host galaxies based on scaling relations known from the local Universe (Luminosity Function, Holmberg/Bosma relation, luminosity-metallicity relation and metallicity gradients). There is no doubt that reality is more complex than this simple picture (see, e.g., Zwaan et al. 2008 and Tescari et al. 2009 for a discussion of the likely importance of galactic winds for the kinematical properties of DLAs). Nevertheless, the basic ingredients in this picture have been found also in hydrodynamical simulations of DLAs at \( z \approx 3 \) (Pontzen et al. 2008).

To test this picture, we have embarked on a survey targeting high-metallicity DLAs in order to search for the galaxy counterparts. The project is carried out using our guaranteed time on the newly commissioned X-shooter spectrograph on the European Southern Observatory (ESO) Very Large Telescope (VLT) on Cerro Paranal in Chile. X-shooter is an echelle spectrograph with three arms covering the full spectral range from the atmospheric cut-off around 2950 Å to the K-band. From the SDSS DLA sample of Noterdaeme et al. (2009), we have selected DLAs with a rest-frame equivalent width (EW) of the SiII \( \lambda 1526 \) line larger than 1 Å. This is a good indication that the metallicity is high, i.e. likely larger than 0.1 solar (e.g., Prochaska et al. 2008, their figure 6; Kaplan et al. 2010). Among these DLAs, we selected the subsample with well-detected FeII \( \lambda 2344, \lambda 2374, \) and \( \lambda 2382 \) lines. For local starburst galaxies, the strength of the Ly\( \alpha \) emission line is controlled by a complex interplay between geometry, kinematical properties of the gas and dust content (see, e.g., Atek et al. 2009 and references therein). For this reason, we only include DLAs with redshifts close to 2.4 which places the H\( \beta \), [OII], [OIII] and/or H\( \alpha \) emission lines from the intervening DLA in the NIR transmission windows. At these redshifts, the spectral range covered by X-shooter extends from the Lyman-limit to H\( \alpha \) and we are not relying on Ly\( \alpha \) alone for detecting the galaxy counterpart. In this paper, we report on the first target observed in the program, namely SDSS J222256.11–094636.2 (Q 2222–0946 in the following), which has an intervening DLA at a redshift of \( z_{\text{abs}} = 2.354 \) (Noterdaeme et al. 2009).

Throughout this paper, we assume a flat cosmology with \( \Omega_L = 0.70, \Omega_m = 0.30 \), and a Hubble constant of \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\).

### 2 STRATEGY AND OBSERVATIONS

Q 2222–0946 was observed on October 21 2009 with X-shooter. Our strategy was to observe the QSO at the position angles (PAs) 60°, −60°, and 0° (all East of North), 1 hr each, using a 1.3 arcsec slit in the UBV arm and 1.2 arcsec slits in the VIS and NIR arms. The resulting resolving powers are 4700 (UVB), 6700 (VIS), and 4400 (NIR) respectively (as measured from sky lines in the spectra). With this strategy, we cover the field of view close to the QSO and will be able to determine the impact parameter and position angle of galaxy counterparts using triangulation (see Möller et al. 2004 for an example of such a triangulation). Based on the model by Fynbo et al. (2008) mentioned above, we predict that less than 10% of the galaxy counterparts will fall outside all three slits (see Fig. 1). With a full-drawn rectangle, we illustrate the field covered by the X-shooter IFU. With a single IFU pointing centred on the...
QSO, 30% of the DLA-galaxy centres will be lost. We prefer to use long slits as this strategy provides superior data for the QSO itself and the data analysis is more robust.

Due to an error in the execution of our Observing Blocks at the telescope, the object was observed twice at PA = 0° and once at PA = −60°. Hence, we did not get a spectrum at PA = 60°. The observing conditions were variable with a seeing degrading from 0.8 to 1.6 arcsec (as measured in the B-band). The airmass ranged from 1.0 to 1.2 and there were no clouds.

We processed the spectra using a preliminary version of the X-shooter data reduction pipeline (Goldoni et al. 2006). The pipeline performs the following actions. First, the raw frames are corrected for the bias level (UVB and VIS) and dark current (NIR). Then, after background subtraction, cosmic ray hits are detected and corrected using the method developed by van Dokkum (2001) and sky emission lines are subtracted using the Kelson (2003) method. After division by the flat field, the orders are extracted and rectified in wavelength space using a wavelength solution previously obtained from calibration frames. The orders are then merged and in the overlapping regions the merging is weighted by the errors which are being propagated in the process. From the resulting 2D merged spectrum, a one-dimensional spectrum is extracted at the source’s position. The one-dimensional spectrum with the corresponding error file and bad-pixel map is the final product of the reduction. Intermediate products such as the sky spectrum and individual echelle orders (with errors and bad-pixel maps) are also produced.

To perform flux calibration, we extracted with the same procedures a spectrum of the flux standard BD +17° 4708 (Bohlin & Gilliland 2004). This spectrum was divided by the flux table of the same star from the CALSPEC HST database (Bohlin 2001) to produce the response function. The response was then interpolated where needed in the atmospheric absorption bands in the VIS and NIR spectra and applied to the spectrum of the source. No telluric correction was applied. We compare our flux calibration to the flux calibrated spectrum from the Sloan survey (Adelman-McCarthy et al. 2009) and find that our calibration gives 30% larger fluxes compared to the Sloan calibration, but the shapes of the two spectra match very well. We have chosen to rescale our spectrum so that is matches the Sloan spectrum.

3 RESULTS

3.1 Emission properties of the DLA-galaxy counterpart

We clearly detect Lyα emission in the DLA trough in all three individual spectra. The strongest component of the Lyα emission in the two PA = 0° spectra is clearly asymmetric and redshifted by ∼200 km s$^{-1}$ relative to the redshift of low-ionisation absorption lines (see below). There is also a weak, but significantly detected, component blueshifted by a similar amount (see Fig. 7 below). The impact parameter in these spectra is 0.57 ± 0.03 arcsec. From the PA = −60° spectrum, which has been taken under the worst seeing, we measure a redshift which is consistent with the measurement from the PA = 0° spectra. The maximum velocity shift we can expect with a dispersion of 0.25 Å per pixel and a slit width of 9 pixels is about 2.3 Å, which at the wavelength of Lyα would correspond to 170 km s$^{-1}$. The impact parameter in the PA = −60° spectrum is −0.20 ± 0.10 arcsec. From just two position angles

We match the Sloan spectrum. The strongest component of the Lyα emission in the trough is indicated with an arrow. Note that in this one-dimensional spectrum the Lyα emission is not entirely recovered as the spectrum is extracted from the combined QSO spectrum along the QSO trace and the Lyα emission is spatially offset from the QSO trace.

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Figure 3. The \([\text{OIII}]\ \lambda 5007\) emission line from the DLA-galaxy counterpart. The upper three figures show the two-dimensional spectra after SPSF subtraction of the QSO continuum. The position of the QSO trace (which has been subtracted) is marked by a horizontal dashed line. In the bottom panel, we plot the one-dimensional spectrum from each of the above three spectra with dotted, full-drawn and dot-dashed lines. The vertical dashed line shows the predicted position of the \([\text{OIII}]\) line from the redshift determined from low-ionisation absorption lines. The horizontal dashed line indicates the zero-flux level. The spectra have been rescaled to have the same peak count-level.

Figure 4. The \(\text{H}\alpha\) emission line from the DLA-galaxy counterpart. As in Fig. 3, the upper three figures show the two-dimensional spectra after SPSF subtraction of the QSO continuum. In the bottom panel, we plot the corresponding one-dimensional spectra. The vertical dashed line shows the predicted position of the \(\text{H}\alpha\) line from the redshift determined from low-ionisation absorption lines. The horizontal dashed line indicates the zero-flux level. The shift in the peak position of the \(\text{H}\alpha\) line relative to the position expected from the redshift of low-ionisation absorption lines is 25 km s\(^{-1}\). The origin of this apparently significant shift is unclear. The spectra have been rescaled to have the same peak count-level.
it is not always possible to uniquely triangulate the position of the galaxy counterpart. However, in this case we can obtain a fairly secure position (see right panel of Fig. 1). The DLA galaxy must be located at an impact parameter of $\sim 0.8$ arcsec and at a position angle of $\sim 40^\circ$. As the seeing (as measured around the wavelength of the redshift Ly$\alpha$ line) degraded substantially from the first (0.8 arcsec) to the last spectrum (1.6 arcsec) we cannot get an additional constraint from comparing the counts in the line to the QSO continuum (this ratio is close to constant in all three spectra).

Integrating over the line profile, we derive a flux of $f = 10.0 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ in the best of our three spectra (see Table 1). This constitutes a lower limit to the total flux due to slit-loss. The corresponding Ly$\alpha$ luminosity is $L = 4.3 \times 10^{42}$ erg s$^{-1}$. Converting this to a star-formation rate (SFR) using standard case-B recombination theory and the relation between H$\alpha$ luminosity and SFR from Kennicutt (1998) gives SFR $= 4 \, M_{\odot}$ yr$^{-1}$.

To search for rest-frame optical emission lines, we carried out Spectral Point Spread Function (SPSF) subtraction of the QSO light (see Møller 2000). We do this by locating spectral regions free of sky emission lines on each side of the expected positions of the rest-frame optical emission lines. Over these regions, we calculate the average SPSF. We then subtract the SPSF over the spectral region covering the emission line by assuming that the QSO spectrum can be fitted by a linear function across the position of the emission line. The [OIII] $\lambda 4959$, $\lambda 5007$, and H$\alpha$ emission lines are located in regions free of sky lines in the H- and K-bands. After SPSF subtraction, we clearly detect the [OIII] $\lambda 5007$ line in both $PA = 0^\circ$ spectra and in the $PA = -60^\circ$ spectrum (see Fig. 3). The redshift of the [OIII] $\lambda 5007$ line is $z_{abs} = 2.35406$. This is consistent with the redshift of low-ionisation absorption lines (see below) within the error, which is $\pm 5$ km s$^{-1}$. The Full Width at Half Maximum (FWHM) of the [OIII] emission line is 105 km s$^{-1}$, which means that the line is reasonably well resolved. Correcting for the instrumental resolution, the intrinsic width of the line is $\sim 80$ km s$^{-1}$. The impact parameters measured from the [OIII] lines are consistent within about 10% with what is measured from the Ly$\alpha$ line.

For the flux of the [OIII] $\lambda 5007$ line, we measure $f = 3.1 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ in the best of our three spectra (see Table 1), which corresponds to a luminosity of $L = 1.3 \times 10^{42}$ erg s$^{-1}$ similar to the luminosities of the other two DLAs detected in [OIII] (Weatherley et al. 2005). We also clearly detect the [OIII] $\lambda 4959$ emission line, but as expected at lower significance.

The H$\alpha$ line is detected in the K-band in all three spectra, but at significantly lower S/N ratio than the [OIII] line. In Fig. 4 we show the line in each of our three spectra. For the H$\alpha$ line, we measure a flux of $f = 2.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a luminosity of $L = 1.1 \times 10^{42}$ erg s$^{-1}$ and SFR $= 10 \, M_{\odot}$ yr$^{-1}$ again using the relation between SFR and H$\alpha$ luminosity from Kennicutt (1998). The ratio between the [OIII] and H$\alpha$ luminosities is 1.2, in good agreement with the estimate of Weatherley et al. (2005) based on the models of Kewley & Dopita (2002).

The ratio between the Ly$\alpha$ and H$\alpha$ luminosities is 4.0 whilst a ratio of about 8.7 is expected from case-B recombination. This suggests that about 55% of the Ly$\alpha$ photons are either destroyed by dust or that most of the Ly$\alpha$ emission is emitted in other directions due to radiative transfer effects. In general, scattering effects cause a quite anisotropic escape of Ly$\alpha$; Laursen et al. (2009b) find that Ly$\alpha$ emitters on average will be 2-4 times more luminous when viewed from the brightest direction compared to when viewed from the least luminous direction.

Unfortunately, one of the components of the [OII] doublet and the H$\beta$ line are located on top of bright sky emission lines. We place an upper limit of the [OII] doublet flux by adding to the observed spectrum a simulated [OII] doublet for which each component has the same spatial and spectral width as the [OIII] line. We then scale the flux of the line and infer the lowest flux for which we would still have detected the line after SPSF subtraction. The upper limit to the [OII] flux inferred this way is $8 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. Using the relation between [OII] luminosity and SFR from Kennicutt (1998), this limit implies an upper limit of SFR $< 4 \, M_{\odot}$ yr$^{-1}$. Hence, the non-detection is consistent with the value of SFR $= 10 \, M_{\odot}$ yr$^{-1}$ inferred from H$\alpha$.

We stress that there are substantial uncertainties in the absolute fluxes, probably at least 30%, both due to the possibility of slit-loss and due to uncertainties in the flux calibration. This error propagates also to the derived luminosities and SFRs.

### Table 1. Emission line fluxes and impact parameters derived from each of the three individual spectra.

| Line       | PA (degrees) | Flux ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | b (arcsec) |
|------------|--------------|-----------------------------------------|------------|
| Ly$\alpha$ | 0            | $10.0 \times 10^{-17}$                   | 0.57       |
| Ly$\alpha$ | 0            | $9.0 \times 10^{-17}$                   | 0.57       |
| Ly$\alpha$ | $-60$        | $8.7 \times 10^{-17}$                   | $-0.20$    |
| OIII       | 0            | $3.1 \times 10^{-17}$                   | 0.51       |
| OIII       | $-60$        | $3.1 \times 10^{-17}$                   | 0.47       |
| OIII       | $-60$        | $2.5 \times 10^{-17}$                   | 0.56       |
| H$\alpha$  | 0            | $2.4 \times 10^{-17}$                   | 0.37       |
| H$\alpha$  | $-60$        | $2.8 \times 10^{-17}$                   | $-0.23$    |

3.2 Absorption properties of the DLA

The QSO spectrum displays a rich set of absorption lines at $z = 2.354$. We detect transition lines from HI, CII, CIV*, CIV, OI, MgII, MgII, AlII, AlIII, SIIV, SI, VI, SI, MnII, FeII, NI and ZnII. CrII lines are also detected but they are blended with telluric absorption. By fitting a Voigt profile to the damped HI Ly$\alpha$ line in the spectrum of the quasar combining all three exposures, we determine a neutral hydrogen column density of $N_{HI} = 20.65 \pm 0.05$ (see Fig. 2). This is in good agreement with the value $N_{HI} = 20.57 \pm 0.28$ found in the automatic analysis of the lower resolution SDSS spectrum by Noterdaeme et al. (2009).

In order to estimate the overall metallicity of the DLA, we first use the SIIV $\lambda 1808$ transition line as it is weakly saturated and because silicon is known to deplete little onto dust grains. From the first moment of the line, we derive a precise redshift of $z_{abs} = 2.35409$. We also measure a rest-frame line EW of 0.215$^{+0.014}$ A which, based on the optically-thin line approximation, corresponds to a lower limit of $[Si/H] = -0.61 \pm 0.06$. Here we adopt the solar photosphere abundances from Asplund et al. (2009). Hence, our selection based on the SIIV $\lambda 1526$ line indeed has resulted in a metallicity well above 0.1 solar.

We next perform Voigt-profile fitting to measure accurate column densities for silicon and other elements. As seen from Fig. 3...
Table 2. Ionic column densities in individual components of the DLA system at $z_{\text{abs}} = 2.354$.

| Ion    | Transition lines used | $\log N \pm \sigma_{\log N}$ | $b \pm \sigma_b$ (km s$^{-1}$) |
|--------|-----------------------|-------------------------------|---------------------------------|
| MgII   | 2026,2652             | 12.61±0.02                    | 19.2±1.2                        |
| SiII   | 1808                  | 15.31±0.03                    | 19.2±1.2                        |
| SiII   | 1250                  | 14.83±0.10                    | 19.2±1.2                        |
| MnII   | 2576,2594,2606        | 12.52±0.04                    | 19.2±1.2                        |
| FeII   | 1608,2249,2260        | 14.83±0.03                    | 19.2±1.2                        |
| NiII   | 1454,1741,1751        | 13.69±0.05                    | 19.2±1.2                        |
| ZnII   | 2026                  | 12.43±0.06                    | 19.2±1.2                        |
| MgII   | 2026,2652             | 12.49±0.04                    | 26.1±3.6                        |
| SiII   | 1808                  | 15.30±0.04                    | 26.1±3.6                        |
| SiII   | 1250                  | 14.92±0.09                    | 26.1±3.6                        |
| MnII   | 2576,2594,2606        | 12.53±0.04                    | 26.1±3.6                        |
| FeII   | 1608,2249,2260        | 14.74±0.04                    | 26.1±3.6                        |
| NiII   | 1454,1741,1751        | 13.66±0.06                    | 26.1±3.6                        |
| ZnII   | 2026                  | 12.38±0.07                    | 26.1±3.6                        |
| MgII   | 2026,2652             | 11.53±0.20                    | 9.3±1.3                         |
| SiII   | 1808                  | 14.68±0.12                    | 9.3±1.3                         |
| SiII   | 1250                  | < 13.45$^a$                   | 9.3±1.3                         |
| MnII   | 2576,2594,2606        | 11.59±0.28                    | 9.3±1.3                         |
| FeII   | 1608,2249,2260        | 14.34±0.10                    | 9.3±1.3                         |
| NiII   | 1454,1741,1751        | 13.01±0.20                    | 9.3±1.3                         |
| ZnII   | 2026                  | 11.71±0.29                    | 9.3±1.3                         |

$^a$ 3$\sigma$ upper limit.

and Fig. 4 the metal-line profiles are well-resolved with widths of $\sim 200$ km s$^{-1}$. The instrumental resolution is 64 and 45 km s$^{-1}$ for the uvb and vis arm spectra respectively. This implies that, for a typical S/N of 50, one can constrain the broadening parameter of individual components reliably down to a factor of about five ($b \sim 6$ km s$^{-1}$) than the instrumental broadening. Therefore, as long as the fitted components have $b$ values larger than about 10 km s$^{-1}$, there is no problem of hidden saturation. Moreover, as we are considering weak absorption lines (see Fig. 4) the measured column densities depend weakly on $b$ if at all. The inclusion of one stronger transition line in the fit (FeII $\lambda 1608$) does not change the results because the FeII column densities are well-constrained by the weak $\lambda 2249$ and $\lambda 2260$ lines. Three components are needed to reach Chisq values of the order of one: two main components separated by about 93 km s$^{-1}$ (see Fig. 5) and one additional, redder and weaker component (this component is most clearly seen in SiII $\lambda 1808$, ZnII $\lambda 2026$ and FeII $\lambda 2249,2260$). In the following, we refer to the blueshifted component as 'a' and to the main redshifted component as 'b'. The fits are shown in Fig. 6 and the measured column densities are given in Table 2. The Voigt-profile fit results imply a Si metallicity only slightly higher than based on the optically-thin line approximation (see above): $[\text{Si/H}] = -0.51 \pm 0.06$. For Zn which, like Si, is little depleted onto dust grains, we find $[\text{Zn/H}] = -0.46 \pm 0.07$. For elements which are more sensitive to dust depletion (e.g., Meyer & Roth 1990; Pettini et al. 1997; Ledoux et al. 2002), we find $[\text{Fe/H}] = -0.99 \pm 0.06$, $[\text{Ni/H}] = -0.85 \pm 0.06$ and $[\text{Mn/H}] = -1.23 \pm 0.06$, implying significant dust depletion for these elements.

To compare the kinematics of the absorption line profiles with that of other DLAs, we follow the procedure of Ledoux et al. (2006) and calculate the line-profile velocity width, $\Delta v$, as $c \left[ (\lambda(95\%) - \lambda(5\%)) / \lambda_0 \right]$, where $\lambda(5\%)$ and $\lambda(95\%)$ are the wave-lengths corresponding to, respectively, the 5 and 95 percentiles of the apparent optical depth distribution, and $\lambda_0$ is the first moment (the average) of this distribution (see fig. 1 of Ledoux et al. 2006). We again choose SiII $\lambda 1808$ as it is a low-ionisation transition line and the line is weakly saturated. The apparent optical depth and the derived velocity width are shown in Fig. 5. We infer a velocity width of 185 km s$^{-1}$ in good agreement with the metallicity-metallicity relation for DLAs (Ledoux et al. 2006).

4 DISCUSSION

4.1 The DLA-galaxy counterpart

Simultaneous detection of the Ly$\alpha$, [OIII] and H$\alpha$ emission lines have not been seen for DLA galaxies before and it is rarely seen for other types of high-$z$ galaxies. The galaxy counterpart of the DLA appears to be a vigorously star-forming galaxy with a SFR of $10 M_\odot$ yr$^{-1}$ (this is a lower limit due to the possibility of slit-loss and dust absorption). Compared to the H$\alpha$ luminosity function for $z \approx 2$ galaxies determined by Hayes et al. (2010), the galaxy has an H$\alpha$ luminosity of $0.1 L_{H\alpha}^\ast$. From the impact parameter of the object of 0.8 arcsec, we can infer a length scale of at least 6 kpc for the extent of the neutral hydrogen associated with the galaxy. The metallicity of the gas is relatively high, 2/3 solar. This is a higher metallicity than any of the measured metallicities for DLAs at similar redshifts in the large compilation presented in Prochaska et al. (2003). It is consistent with the model described in Fynbo et al. (2008) to have a high metallicity despite a relative large impact parameter as the metallicity gradient in this model is shallow for the brightest galaxies (see also Boissier & Prantzos 2001). Unfortunately, the constraint on the metallicity based on the strong, rest-frame optical emission lines is too loose. Based on the measured [OIII] luminosity, the upper limit on the [OII] luminosity, and assuming a flux ratio of 2.88 between H$\alpha$ and H$\beta$ (the canonical case B ratio assuming no dust absorption), we infer a limit of...
log $R_{23} < 1.15$, which is fulfilled at all metallicities (see Kewley & Dopita 2002 for details).

The spatial profiles of both the Lyα and the [OIII] line are consistent with the SPSF so the star-forming region of the galaxy is much more compact than the extent of the neutral gas.

The line luminosities, impact parameter and metallicity of the DLA-galaxy counterpart are similar to what has been found for the few other $z \gtrsim 2$ DLAs detected in emission (Møller & Warren 1998; Møller et al. 2002, 2004). The rest-frame EW of the MgII $\lambda 2796$ absorption line is 2.7 Å, and hence the system fulfills the selection criterion of the strong $z \sim 1$ MgII absorbers studied by Bouché et al. (2007, see also Ménard et al. 2009). In that study, galaxy counterparts are detected in Hα emission for 67% of the studied systems. In terms of SFR, the galaxy counterpart of the DLA studied here falls within the range (1–20 $M_\odot$ yr$^{-1}$) found for $z \sim 1$ MgII absorbers. In terms of its emission-line luminosities and MgII EW, the DLA-galaxy counterpart is also similar to the $z = 0.4$–0.7 systems studied by Noterdaeme et al. (2010).

4.2 Kinematics

This DLA system is unique for having accurate determinations of the Lyα and [OIII] emission-line redshifts and of low- and high-ionisation absorption-line redshifts from the interstellar medium (ISM) of the absorbing galaxy. This makes it possible to infer kinematical information that is rarely available in such detail (see Fig. 7). The [OIII] emission line is thought to trace the systemic redshift of the galaxy as [OIII] photons originate from the HII regions in the galaxy and are unaffected by resonant scattering effects. The width of the [OIII] line, corrected for the instrumental resolution, is 80 km s$^{-1}$. This width must be related to the dynamical mass of the star-forming component of the galaxy, but as we do not have a size we cannot infer a mass. The line width is comparable to what has been found for bright LBGs at slightly larger redshifts (Pettini et al. 2001; see also Weatherley & Warren 2003, 2005).

The low-ionisation absorption lines are represented by the saturated FeII $\lambda 2600$ line in Fig. 7. The absorption profile is characterised by two main components separated by about 93 km s$^{-1}$. The total width of the absorption line profile is 185 km s$^{-1}$, i.e.
substantially wider than the [OIII] emission line. The difference may possibly be interpreted as the effect of a galactic wind, but the two velocity widths also probe quite different scales in the galaxy (a sightline through the neutral gas vs. the star-forming component of the galaxy). The absorption redshift is very similar to the systemic redshift, which is remarkable given the impact parameter of $\sim 6$ kpc. We note that, due to the offset within the slit between the QSO and the DLA galaxy (see Fig. 1), we expect a velocity shift. Assuming a roughly quarter slit width offset, we expect a shift of 20 km s$^{-1}$, so this is a small effect. In the few previous DLAs for which this information is available, blueshifts of several 100 km s$^{-1}$ have been found between systemic and low-ionisation absorption lines (Weatherley et al. 2005). For LBGs, low-ionisation ISM absorption lines are also typically blueshifted (Pettini et al. 2001). The small velocity shift observed in the present case may be an indication that we observe a disk-like system with a line-of-sight that is close to parallel with the rotation axis. The profile of the high-ionisation CIV line follows that of the low-ionisation lines, although component a is stronger than component b which is opposite to the relative strength of the two components for the low-ionisation lines.

4.3 The Ly$\alpha$ emission-line profile

The Ly$\alpha$ line is a resonant line, and the physical processes governing its formation are quite different from the metal lines. Due to the effects of scattering, Ly$\alpha$ photons have a complex path out of galaxies (Laursen & Sommer-Larsen 2007, and references therein). The profile of the line shown in the top panel of Fig. 1 is clearly asymmetric and remarkably the blue edge of the profile is close to the position of Ly$\alpha$ at the systemic redshift. Even more striking is the presence of a small peak on the blue side of the systemic redshift. This can be understood as a result of resonant scattering. In general, due to the high opacity of neutral hydrogen for a photon in the line centre, Ly$\alpha$ photons have to diffuse in frequency to either the blue or the red side. Thus, to first order the line should be characterised by two symmetric peaks with the central minimum indicating the redshift (Harrington 1973; Urbanik & Wolfe 1981). Although this has been observed on several occasions (e.g. Venemans et al. 2005; Tapken et al. 2007), typically observations show that the blue peak is missing, leaving only the asymmetric red part with the distinct steep rise in intensity close to the line centre and more shallow decrease farthest from the centre.

Various scenarios may explain the weakness of the blue peak. In particular, if large outflows of gas are present, as may be expected in the presence of a starburst, in the reference frame of the outflowing hydrogen atoms blue photons are shifted towards the line centre, while red photons are shifted away from resonance. Thus, the photons will escape more easily after having drifted to the red side. While no analytical solution exists for this scenario $^4$, it has been investigated numerically, both in the case of a homologous expansion (Dijkstra et al. 2006) and that of a thin, circumgalactic shell of gas (Verhamme et al. 2006). Even if outflows are not present, after the photons escape the galaxy, the redshift due to the Hubble expansion of the intergalactic medium may remove part of the blue peak. At $z \approx 2.4$, the average transmission bluewards of the Ly$\alpha$ line is 80–85% (Songaila 2004). However, since in the vicinity of the galaxy the expansion is slower than the gravitational potential of the galaxy, more absorption may occur close to the line centre. In the case of infalling gas, even the red peak of the spectrum may be affected (Dijkstra et al. 2007).

Considering the relatively high metallicity inferred for the system and the apparent depletion of refractory elements, the presence of dust is anticipated. Due to the path length of the Ly$\alpha$ radiation being increased by resonant scattering, dust may suppress the Ly$\alpha$ line more than other lines. Even for “gray” dust, the line is not affected uniformly, the wings being influenced more than the centre (Laursen et al. 2009). The reason is that the wings are comprised of photons originating in the very dense regions that have to diffuse far from the line centre in order to escape, while photons near the line centre must come from low-density regions. Since the dense regions are where most of the stars are, and hence most of the dust, these photons have a higher probability of being absorbed.

If we wish to understand the physical conditions responsible for the formation of the observed Ly$\alpha$ line, we must take all of these effects into account. An exact fit to the Ly$\alpha$ emission-line profile requires careful numerical modeling, varying a multitude of physical, and often degenerate, parameters (Verhamme et al. 2008) successfully modeled a number of Ly$\alpha$ profiles by varying the temperature, column density, expansion velocity and dust contents of a thin shell. Analytical solutions exist only for homogeneous, isothermal, and static configurations of gas, with either a central or evenly distributed source of light. In the case of a homogeneous gas, each of the two peaks are fairly symmetric about their maxima, but taking into account the full range of densities, and the correlation of Ly$\alpha$ emission with these densities, often results in significantly more skewed peaks. This is the result of different parts of the spectrum originating in physically distinct regions. A realistic scenario of galactic outflows probably lies somewhere in between that of the homologously expanding sphere and that of a thin shell. From Fig. 8 of Laursen et al. (2009), one sees that in the case of the expanding sphere with a maximum velocity $V$ of 20 km s$^{-1}$, the red peak maximum is approximately twice as high as the blue peak maximum, while for $V = 200$ km s$^{-1}$ the blue peak is missing completely. In the case of a shell, from Fig. 14 of Verhamme et al. (2006) slightly larger expansion velocities can occur while still allowing the blue peak to be seen.

Considering the above discussion on the radiative transfer of Ly$\alpha$ radiation, we find that the observed emission is consistent with originating at the same redshift as the systemic redshift, having scattered its way out of an inhomogeneous ISM of gas temperature $T \sim 10^4$ K, neutral hydrogen column density comparable to that inferred from the DLA absorption, as well as a fair amount of dust absorbing $\sim 1/2$ of the photons, expanding at a typical velocity of several tens to $\sim 100$ km s$^{-1}$, and further having reduced its blue side somewhat by the surrounding IGM.

5 CONCLUSIONS: THE RELATION BETWEEN EMISSION- AND ABSORPTION-SELECTED GALAXIES

The progress on understanding the relation between emission- and absorption-selected galaxies at high redshift has been slow. Today, more than 20 years after the onset of systematic studies of DLAs (Wolfe et al. 1986; Smith et al. 1989) and 15 years after the discovery of LBGs we still have very little empirical basis for establishing the relation between the two. Here we have presented the results from the first DLA observed in an X-shooter survey targeting metal-rich DLAs, namely the $z_{abs} = 2.354$ DLA towards Q 2222−0946. We confirm that our pre-selection of metal-
rich DLAs based on the strength of the SiII λ1526 line works: the inferred metallicity of the system is \([\text{[Zn/H]} = -0.46 \pm 0.07]\). We also clearly detect the galaxy counterpart of the DLA absorber in Lyα, [OIII] and Hα emission. The DLA-galaxy counterpart is a vigorously star-forming galaxy with a SFR of at least 10 M⊙ yr\(^{-1}\). The line-of-sight probes the neutral gas associated with this galaxy at an impact parameter of about 6 kpc. The kinematical information inferred from emission and absorption suggests that we observe the galaxy with a line-of-sight that is close to parallel with its rotation axis. From the profile of Lyα, we can infer that there most likely is a galactic wind causing the blueshifted part of the line to be absorbed.

The implication of this is that we now have both the strategy (selection of metal-rich DLAs) and the tool (the X-shooter spectrograph) that will allow us to attack the question of the nature of DLA-galaxy counterparts.

It would also be interesting to further explore the inverse experiment, namely to characterise the HI absorption due to LGBs close to the sightlines to background QSOs (or other LGBs). Adelberger et al. (2005) address this issue, but mainly focusing on metal-line absorption and at impact parameters of several hundred kpc. In a few cases, candidate LGBs have been found within a few arcsec from the background QSOs (Steidel & Hamilton 1992; Steidel et al. 1995), but only for one of these has confirming spectroscopy been published (Djorgovski et al. 1996; Weatherley et al. 2005). In the spectrum of the background QSO, this galaxy is detected as a sub-DLA.

We need a larger sample before firm conclusions can be drawn, but the detection of the galaxy counterpart of the DLA towards Q 2222−0946 with properties such as impact parameter and SFR within the predictions does give us hope that the basic picture presented in the works of Fynbo et al. (2008) and in the hydrodynamical simulations of Pontzen et al. (2008) are correct. We are hence within reach of firmly establishing the connection between high-z galaxies detected in emission and absorption.

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