On the two high-metallicity DLAs at $z = 2.412$ and 2.583 towards Q 0918+1636

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ABSTRACT

The quasar Q0918+1636 ($z = 3.07$) has two intervening high-metallicity Damped Lyman $\alpha$ Absorbers (DLAs) along the line of sight, at redshifts of $z = 2.412$ and 2.583. The $z = 2.583$ DLA is located at a large impact parameter of 16.2 kpc, and despite this large impact parameter it has a very high metallicity (consistent with solar), a substantial fraction of $H_2$ molecules and it is dusty as inferred from the reddened spectrum of the background QSO. The $z = 2.412$ DLA has a metallicity of $[M/H] = -0.6$ (based on Zn II and Si II). In this paper we present new observations of this interesting sightline consisting of deep multiband imaging and further VLT spectroscopy. By fitting stellar population synthesis models to the photometric Spectral Energy Distribution we constrain the physical properties of the $z = 2.583$ DLA galaxy, and we infer its morphology by fitting a Sérsic model to its surface brightness profile. We find it to be a relatively massive ($M_\star \approx 10^{10} M_\odot$), strongly star-forming (SFR $\approx 30 M_\odot$ yr$^{-1}$), dusty ($E(B-V) = 0.4$) galaxy with a disc-like morphology. We detect strong emission lines from the $z = 2.583$ DLA ([O III] $\lambda 3727$, [O III] $\lambda\lambda 4960, 5007$, H$\beta$ and H$\alpha$, albeit at low signal-to-noise ratio except for the [O III] $\lambda 5007$ line). The metallicity derived from the emission lines is consistent with the absorption metallicity ($12 + \log (O/H) = 8.8 \pm 0.2$). We also detect [O III] $\lambda 5007$ emission from the galaxy counterpart of the $z = 2.412$ DLA at a small impact parameter ($< 2$ kpc). Overall our findings are consistent with the emerging picture that high-metallicity DLAs are associated with relatively luminous and massive galaxy counterparts, compared to typical DLAs.

Key words: galaxies: formation – galaxies: high-redshift – galaxies: ISM – quasars: absorption lines – quasars: individual: SDSS J 091826.16+163609.0 – cosmology: observations.

* Based on observations carried out under programme IDs 084.A-0303 and 089.A-0087 with the X-Shooter spectrograph installed at the Cassegrain focus of the Very Large Telescope (VLT), Unit 2 – Kueyen, operated by the European Southern Observatory (ESO) on Cerro Paranal, Chile. Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with programme 12553. Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.
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1 INTRODUCTION

For a long time the only available method for studying galaxies at redshifts $z > 1$ (barring QSO host galaxies) was to look at them in absorption against the light of background QSOs (e.g. Weymann, Carswell & Smith 1981; Wolfe, Gawiser & Prochaska 2005). Then, from the second half of the 1990’s, the study of high-$z$ galaxies in emission went through a breakthrough that is still unfolding (e.g. Giavalisco 2002; Shapley 2011). However, combining the information from absorption and emission lines is still a poorly developed field. Although more than 10 000 of the so-called Damped Lyman α Absorbers (DLAs) have been found so far (Noterdaeme et al. 2012b), and despite some progress (e.g. Möller et al. 2002) in finding their galaxy counterparts, we still have less than a dozen examples of such absorption selected galaxies (Krogager et al. 2012, see also Rauch et al. 2008; Rauch & Haehnelt 2011; Schulze et al. 2012).

Expanding the sample is of great interest as we in this manner obtain unique information about the kinematics and chemical composition of gas surrounding the central ~1 kpc, which are typically studied in emission. This information is vital for probing current ideas about the role of processes like inflow of pristine gas and outflow of enriched gas in galaxy formation and evolution (e.g. Dekel et al. 2009; Bouché et al. 2010; Fumagalli et al. 2011; Crighton, Hennawi & Prochaska 2013; Dekel & Krumholz 2013, and references therein).

The $z = 3.07$ quasar SDSS J 091826.16+163609.0 was selected in the survey for high-metallicity DLAs described in Fynbo et al. (2010, 2011). It was selected due to the presence of a DLA at $z = 2.412$ with strong Fe II lines. After obtaining deep X-Shooter spectroscopy of the QSO, Fynbo et al. (2011) serendipitously discovered a second DLA at $z = 2.583$ along the line of sight with even stronger metal lines. Fynbo et al. (2011) detected the forbidden [O II] and [O III] emission lines of the galaxy counterpart of this second DLA. The galaxy is located at an impact parameter of 2 arcsec, corresponding to ~16 kpc at $z = 2.583$. The $z = 2.412$ DLA was not detected in emission in that study.

In this paper, we present new results based on new observations of this sightline obtained with the Hubble Space Telescope (HST), European Southern Observatory (ESO) Very Large Telescope (VLT) and Nordic Optical Telescope (NOT). In Section 2 we give an overview of the observations and data reduction, and describe the data analysis and the results in Sections 3 and 4. Finally, Section 5 contains a discussion of our findings and their implications for the field.

Throughout this paper, we use a flat Λ cold dark matter cosmology with $Ω_Λ = 0.728$, $Ω_m = 0.272$ and a Hubble constant of $H_0 = 70.4$ km s$^{-1}$ Mpc$^{-1}$ (Komatsu et al. 2011). All magnitudes are given in the AB system.

2 OBSERVATIONS AND DATA REDUCTION

2.1 HST imaging

The field of Q 0918+1636 was observed with the Wide Field Camera 3 (WFC3) on the HST on two epochs in 2011 November [with the near-infrared (NIR) detector in the F105W and F160W filters] and on 2012 April 18 (with the UVIS detector in the F606W filter). The roll angle of the telescope was set such that the $z = 2.583$ DLA galaxy falls between the diffraction spikes of the point spread function (PSF) of the QSO. The two observations with the NIR detector were taken using the WFC3-IR-DITHER-BOX-MIN pattern providing an optimal 4-point sampling of the PSF. The UVIS observation was taken using the WFC3-UVIS-DITHER-BOX pattern.

We have reduced and combined the images using the software package MULTIDRIZZLE provided by the STScI. By shifting and combining the images taken with subpixel offsets one achieves a better sampling of the PSF, which in the case of the infrared (IR) observations is crucial as the PSF is poorly sampled in the native 0.13 arcsec px$^{-1}$ images. For this work we have set the parameter $\text{pixfrac}$ to 0.7 in all reductions and used a final pixel scale of 0.06 arcsec px$^{-1}$ for IR and 0.024 arcsec px$^{-1}$ for UVIS. For a detailed description of the parameters in the software we refer to the MULTIDRIZZLE user manual.

2.2 NOT imaging

On the nights of 2012 January 25−26 and March 3 Q 0918+1636 was observed with the Andalucia Faint Object Spectrograph and Camera (ALFOSC) and with the Nordic Optical Telescope near-infrared Camera and spectograph (NOTCam) at the NOT. A total of 8400, 11 500 and 7830 s of exposure time was obtained in the $g$, $u$ and $K_s$ band, respectively (see Table 1). Observing conditions were clear, with an average seeing full width at half maximum (FWHM) of ~1 arcsec in the 2012 January nights, and clear and subarcsec seeing on 2012 March 3. The optical images were reduced using IRAF$^1$ standard procedures. The NOTCam images were reduced with custom IDL scripts, using a running median for sky subtraction, and an object mask for 2nd pass sky subtraction. The NOTCam distortion correction was applied using the IRAF$^1$/geomtran task.

2.3 VLT/X-Shooter spectroscopy

Q 0918+1636 was observed with VLT/X-Shooter on 2012 April 15. Both a stare observation at a position angle of 162° east of north and a nodding observation at a position angle of −66° east of north were obtained. The observation at position angle −66° east of north was a mistake: it should have been at 66° east of north with the purpose of covering the $z = 2.583$ DLA galaxy and the QSO. In a stare observation the target is kept at a fixed position on the slit throughout the observation, whereas in a nodding observation an observing block consists of four exposures between $\text{Band}$ | $\text{Obs. Date}$ | $\text{Exp. time (s)}$
|---|---|---|
| $\text{HST/WFC3/F105W}$ | 2011 Nov 9 | 2612 |
| $\text{HST/WFC3/F160W}$ | 2011 Nov 9 | 2612 |
| $\text{HST/WFC3/F606W}$ | 2011 Apr 9 | 2523 |
| NOT/ALFOSC$^c$/g | 2012 Jan 25–26 | 8400 |
| NOT/ALFOSC$^c$/u | 2012 Jan 25–26 | 11500 |
| NOT/NOTCam/Ks | 2012 Mar 3 | 7830 |
| VLT/X-Shooter$^e$ stare PA = 0° | 2010 Feb 16 | 3600 |
| VLT/X-Shooter$^e$ stare PA = 60° | 2010 Feb 16 | 3600 |
| VLT/X-Shooter$^e$ stare PA = −60° | 2010 Feb 16 | 3600 |
| VLT/X-Shooter nod PA = −66° | 2012 Apr 15 | 2920 |
| VLT/X-Shooter stare PA = 162° | 2012 Apr 15 | 6400 |
| VLT/X-Shooter nod PA = 66° | 2013 Mar 15–16 | 10800 |

$^a$Already published in Fynbo et al. (2011).

$^{1}$IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation.
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3 THE $z = 2.583$ DLA GALAXY

3.1 HST imaging

Based on the high-resolution HST imaging we can now improve the relative astrometry over that presented in Fynbo et al. (2011). We find that the DLA galaxy is located at an impact parameter of 1.98 ± 0.02 arcsec from the QSO at a position angle of −115° east of north, consistent with the earlier measurements. This impact parameter corresponds to a proper distance of 16.2 kpc at $z = 2.583$.

We used the GALFIT tool (Peng et al. 2002; Peng 2010) to fit 2D Sérsic models, convolved with the PSF, to the HST images of the DLA galaxy. The PSFs for the HST images were simulated using the software TINYTIM. We chose to simulate the PSFs instead of using an empirical PSF as the model PSF has higher signal-to-noise (S/N) ratio in the outer parts, where the PSFs from the data have high noise due to the background. We did the PSF simulation by first creating models using TINYTIM for each position of the target in the four-point dither pattern, assuming a QSO spectrum for the wavelength dependent PSF modelling, and taking into account the aberrations of the telescope as specified in the auxiliary data files.

The models were resampled by a factor of 5 compared to the native pixel scale of the detectors in order to position the model PSF more accurately. We then re-sampled the model PSF images to the native sampling and convolved them with the appropriate filter-specific charge diffusion kernel. The four ‘raw’ PSF images were then combined by the pipeline task multidrizzle in IRAF using the same parameters as for the data reduction. This allows us to mimic the effects of the reduction procedures. The results from GALFIT are the best-fitting values for the effective half-light radius $r_{\text{eff}}$, the Sérsic index $n$ and the axis ratio $\sqrt{b/a}$, which quantify the structure of the galaxy. The circularized radius is calculated as $r_c = r_{\text{eff}} \times \sqrt{2\pi n}$.

GALFIT also delivered photometry in all three bands, summarized in Table 2. Galactic extinction corrections are taken from the Schlafly & Finkbeiner (2011) maps.

The $z = 2.583$ DLA galaxy has a disc-like morphology with a Sérsic index consistent with 1. The galaxy is compact with a circularized radius of only 0.11 arcsec corresponding to 0.9 kpc.

3.2 NOT/ALFOSC imaging

We use $mag_{\text{auto}}$ in SEXTRACTOR (Bertin & Arnouts 1996) to measure the total fluxes of Sloan Digital Sky Survey stars in the $u$- and g-band images of the field of Q 0918+1636, which we use to

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2 Provided by http://ned.ipac.caltech.edu/
derive the zero-points. In order to do photometry of the DLA galaxy counterpart we first did PSF subtraction using the same procedure as in similar previous studies (e.g. Møller & Warren 1993; Fynbo, Møller & Warren 1999; Fynbo, Burud & Møller 2000). Magnitudes were measured in circular apertures. Again, Galactic extinction corrections are taken from the Schlafly & Finkbeiner (2011) maps. In the g band we measure an AB magnitude of 25.9 ± 0.3 and in the u band we do not detect the DLA galaxy down to a 3σ detection limit of 26.5 (in a 2 arcsec diameter aperture).

3.3 NOT/NOTCam imaging

For the NOTCam/Ks band we determined the zero-point with stars from the 2MASS catalogue (Skrutskie et al. 2006). On the combined image in the Ks band we again subtracted the PSF of the QSO using a PSF determined from stars in the field. The residual image does not contain significant emission at the position of the z = 2.583 DLA galaxy. There is residual flux at the expected position at the 2σ significance level, but we conservatively report a 3σ detection limit of 23.3 (on the AB system) measured in a 2 arcsec diameter aperture.

3.4 SED fitting

We fit stellar population synthesis models to the six broad-band photometric points from the HST and NOT imaging listed in Table 2, to derive the stellar mass, age and star formation rate (SFR) with the same procedure as in Krogager et al. (2013). In summary the fitting code uses the stellar population templates from Bruzual & Charlot (2003) convolved with a large Monte Carlo library of star formation histories (SFHs; exponential plus random bursts) assuming a Chabrier (2003) initial mass function (IMF). Dust is added following the two-component model of Charlot & Fall (2000), with the parameters being the total optical depth, τ_v, and the fraction of dust contributed by the interstellar medium, μ. The metallicity is restricted to solar as inferred from the absorption analysis, but we find consistent results when using the full range of the models between 20 per cent and 2.5 times solar. We then adopt a Bayesian approach by comparing the observed magnitudes to the ones predicted by all the models in the library, and we construct the probability density functions of stellar mass, mean luminosity-weighted stellar age and SFR. Fortunately, none of the filters contains any of the strong emission line and hence we do not include emission lines in the fits. The results of the Spectral Energy

Table 2. Results from the GALFIT fits and NOT photometry, b/a is the ratio of the minor and major axis radii and n is the Sérsic index. The magnitudes in the HST filters were computed by GALFIT, whereas aperture photometry was done on the NOT images.

| Band   | Mag (AB) | r_eff (kpc) | PA (degree) | b/a | n  | r_e (kpc) |
|--------|----------|-------------|-------------|-----|----|-----------|
| F606W  | 25.46 ± 0.13 | 1.2 ± 0.2   | -37 ± 6     | 0.4 ± 0.1 | 0.8 ± 0.4 | 0.73      |
| F105W  | 24.61 ± 0.09 | 1.3 ± 0.3   | -44 ± 9     | 0.3 ± 0.2 | 0.1 ± 0.7 | 0.69      |
| F160W  | 23.68 ± 0.06 | 1.4 ± 0.1   | -47 ± 6     | 0.4 ± 0.1 | 1.1 ± 0.4 | 0.93      |
| u      | > 26.5(3σ) |             |             |     |    |           |
| g      | 25.9 ± 0.3  |             |             |     |    |           |
| Ks     | > 23.3(3σ) |             |             |     |    |           |

Table 3. Results from the SED fitting.

| Parameter     | Value       |
|---------------|-------------|
| Age (Myr)     | 233 ± 268   |
| E(B − V) (mag)| 0.38 ± 0.16 |
| A_V (mag)     | 1.54 ± 0.56 |
| M_*(10^9M_⊙)| 12.6 ± 6.1  |
| SFR (M⊙yr⁻¹)² | 27 ± 9      |

²Averaged over 1 Gyr, but averaged over a shorter timescale of 10 Myr we get a similar value within the errors.

Figure 2. The broad-band SED of the z = 2.583 DLA galaxy, comprising of the ALFOSC u and g bands, HST/WFC3 F606W, F105W and F160W bands and the NOTCam Ks band, is shown as black points. The best-fitting model is shown with a full-drawn line.

Distribution (SED) fits are provided in Table 3 and illustrated in Fig. 2.

3.5 VLT/X-Shooter spectroscopy

The galaxy which is responsible for the z = 2.583 DLA is located at a projected distance of 1.98 arcsec from the QSO, which corresponds to 10 pixels on the spatial axis of the 2D spectrum. Given the good seeing of 0.8 arcsec the two objects are well separated. Thus, we do not need to subtract the continuum of the QSO. At the spatial position where the DLA galaxy is located, there is very little continuum flux, but the [O ii] λ5007 emission line of the z = 2.583 DLA galaxy is clearly visible. The [O ii] λ5007 line is typically the line detected at highest S/N ratio for galaxies at similar redshifts (e.g. Fynbo et al. 2011). We then extract a 1D spectrum of the z = 2.583 DLA galaxy similarly as for the QSO spectrum, but this time using a Gaussian PSFSF with a FWHM of 0.8 arcsec, as there is not enough continuum signal to determine the PSFSF. The [O ii] λ5007 emission line is clearly located in wavelength regions without sky-line residuals. For this line the flux is determined by summing up the flux in the 1D spectrum. In Fig. 3 we show the [O ii] λ5007 line in 1 and 2 dimensions. The redshift determined from the [O ii] λ5007 line is z = 2.582 ± 0.000 ± 10, which is 36 ± 20 km s⁻¹ (where the uncertainty also includes the uncertainty on the absorption redshift) blueshifted compared to the centre of the low-ionization absorption lines (Fynbo et al. 2011).

To search for emission at lower impact parameter we subtract the QSO continuum following the procedure described in Fynbo et al.
is very high. We use the emission-line ratio $R_{23}$ (originally defined by Pagel et al. 1979) to derive the oxygen abundance for the system. The index is defined as the ratio of [O ii] $\lambda$3727 and [O iii] $\lambda\lambda$ 4959, 5007 to H$\beta$. The $R_{23}$ metallicity indicator is double valued. Moreover, the calibration of the line ratio depends on the ionization parameter, which also depends on metallicity. We therefore solve the problem iteratively by use of the line ratio $O_{23}$ as an indicator of the ionization parameter. By using the calibration of Kobulnicky & Kewley (2004) to infer the metallicity, we obtain the following two values: the upper branch solution is $12 + \log (\text{O/H}) = 8.8 \pm 0.2$, and the lower branch solution is $12 + \log (\text{O/H}) = 8.2 \pm 0.2$. We consider the upper branch solution most likely in this case given the other properties of the system (absorption metallicity, luminosity, mass), but we cannot establish this on the basis of the emission lines alone.

For the H$\alpha$ emission line the observed line flux corresponds to a luminosity of $L_{H\alpha} = 1.5 \pm 0.5 \times 10^{42} \text{ erg s}^{-1}$. Converting the luminosity into SFR using Kennicutt (1998) gives $\text{SFR}_{\odot} = 13 \pm 5 M_\odot \text{ yr}^{-1}$. Converting to the assumed Chabrier IMF (Treyer et al. 2007) we find $\text{SFR}_{\odot} = 8 \pm 3 M_\odot \text{ yr}^{-1}$. Correcting for the extinction inferred from the SED fitting this corresponds to $22 \pm 7 M_\odot \text{ yr}^{-1}$ for the Chabrier IMF, consistent with the SFR derived from the SED fitting in Table 3.

Due to the increased S/N ratio of the spectrum of Q0918+1636 we are also able to detect much weaker absorption lines than in Fynbo et al. (2011). An example is Ti $\Pi \lambda$1910 for which we measure an observed equivalent width of $0.102 \pm 0.014 \text{ Å}$ corresponding to a metallicity of $-0.98 \pm 0.05$ implying that Titanium is depleted by close to 1 dex. This is consistent with observations of Titanium in the Local Group where Titanium is found to be highly depleted on to dust grains (e.g. Welty & Crowther 2010). It is also consistent with the large depletion of Fe, Mn and Cr (Fynbo et al. 2011).

4 THE $z = 2.412$ DLA GALAXY

4.1 Absorption line analysis

The original reason for targeting this QSO was the presence of a metal-strong DLA at $z = 2.412$. To characterize the absorption line properties of the $z = 2.412$ DLA we performed Voigt-profile fitting of the H i and metal absorption lines. For the DLA we derive an H i column density of $\log N/\text{cm}^{-2} = 21.26 \pm 0.06$ (Fig. 5).

![Figure 3](https://example.com/f3.png)

**Figure 3.** The [O ii] $\lambda$5007 emission line of the $z = 2.583$ DLA galaxy. The top panel shows the 2D spectrum and the bottom panel shows the 1D spectrum. The vertical dashed line indicates the predicted position of the line based on the absorption line redshift of the DLA. The observed line has a centroid that is blue shifted by 36 km s$^{-1}$ relative to the absorption redshift. The FWHM of the line based on a Gaussian fit is $256 \pm 23$ km s$^{-1}$ (uncorrected for the spectroscopic resolution of 45 km s$^{-1}$).

![Figure 4](https://example.com/f4.png)

**Figure 4.** A wider region around the [O ii] $\lambda$5007 line of the $z = 2.583$ DLA galaxy after subtraction of the QSO SPSF (the boundaries of where the QSO continuum has been subtracted can be seen at each end of the figure). As seen here, there is no evidence for [O ii] $\lambda$5007 emission at small impact parameter. A [O ii] $\lambda$5007 line three times fainter than the detected line would have been detected even if superposed on the QSO trace.

| Transition | Wavelength$^a$ | Flux$^b$ | FWHM$^c$ |
|------------|----------------|---------|---------|
| $z = 2.412$ DLA | [O ii] 5006.84 | 4.1 ± 1.1 | 50 ± 12 |
| $z = 2.583$ DLA | [O ii] 3726.03, 3728.82 | 25 ± 4 | |
| [O iii] 4958.92 | 11 ± 3 | |
| [O iii] 5006.84 | 25 ± 3 | 252 ± 23 |
| H$\beta$ | 4861.325 | 13 ± 3 | |
| H$\alpha$ | 6562.80 | 27 ± 10 | |

$^a$Transition rest frame wavelength in Å.

$^b$Flux in units of $10^{-18}$ erg s$^{-1}$ cm$^{-2}$.

$^c$Line width at FWHM in units of km s$^{-1}$ corrected for the instrumental resolution of 45 km s$^{-1}$.

(2010). In Fig. 4 we show a wider region around the [O ii] $\lambda$5007 line from the $z = 2.583$ DLA galaxy after subtraction of the SPSF of the QSO. There is no evidence for emission at smaller impact parameters.

The H$\alpha$, H$\beta$, [O ii] $\lambda$4960 and [O ii] $\lambda$3727 lines are visible but detected at lower S/N ratio. We derive fluxes for these lines by fixing the redshift and width from the [O ii] $\lambda$5007 line. The resulting line fluxes are provided in Table 4. In particular H$\alpha$ is very uncertain as it is located far in the red end of the K band where the sky background is very high. We use the emission-line ratio $R_{23}$ (originally defined by Pagel et al. 1979) to derive the oxygen abundance for the system. The index is defined as the ratio of [O ii] $\lambda$3727 and [O iii] $\lambda\lambda$ 4959, 5007 to H$\beta$. The $R_{23}$ metallicity indicator is double valued. Moreover, the calibration of the line ratio depends on the ionization parameter, which also depends on metallicity. We therefore solve the problem iteratively by use of the line ratio $O_{23}$ as an indicator of the ionization parameter. By using the calibration of Kobulnicky & Kewley (2004) to infer the metallicity, we obtain the following two values: the upper branch solution is $12 + \log (\text{O/H}) = 8.8 \pm 0.2$, and the lower branch solution is $12 + \log (\text{O/H}) = 8.2 \pm 0.2$. We consider the upper branch solution most likely in this case given the other properties of the system (absorption metallicity, luminosity, mass), but we cannot establish this on the basis of the emission lines alone.

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![Figure 5](https://example.com/f5.png)

**Figure 5.** Voigt-profile fits to the two DLA lines. For the $z = 2.583$ DLA at $\lambda = 4355$ Å the fit is from Fynbo et al. (2011). The derived column density for the $z = 2.412$ DLA is $\log N/\text{cm}^{-2} = 21.26 \pm 0.06$. 

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Figure 6. Voigt-profile fits to metal lines from the $z = 2.412$ DLA. The zero-point for the velocity scale is defined from the centroid of the [OIII] 5007 emission line. Data are shown in black and the model fits in red. In the left-hand column we list a weak and a strong low-ionization line (Si II and Fe II) and a medium- and high-ionization line (Al III and C IV) to illustrate the very different ionization states of the different subcomponents. The vertical dotted lines mark the velocities for the subcomponents in the fit to the low-ionization lines. In the right-hand column we show the low-ionization lines from Zn II, Cr II, Fe II and Mg I. The zero-point for the velocity scale is defined by the centroid (first moment) of the Si I 1808 line.

Voigt profiles were fitted to several metal lines using the vpfit software, assuming turbulence-dominated internal motion in the system. The redshift measured from the low-ionization (Si II, Fe II, Zn II, Cr II, Mn II) absorption lines is $z = 2.4121 \pm 0.0002$. Redshifts and velocity dispersions were tied for each of the individual components of the low-ionization lines. High-ionization lines were fitted independently. The low-ionization absorption was found to be best fitted by six distinct components. A plot of the fit results is shown in Fig. 6, and inferred column densities are shown in Table 5. Integrated metallicities [M/H] based on low-ionization absorption are $-0.6 \pm 0.2, -0.6 \pm 0.2, -1.2 \pm 0.2, -1.2 \pm 0.2$ and $-1.3 \pm 0.2$ for Zn II, Si II, Cr II, Fe II and Mn II, respectively. In Fig. 6 we also show the intermediate- and high-ionization lines from Al III and C IV. These lines are fitted independently and in this case only five subcomponents suffice. It is striking that the $v < 0$ km s$^{-1}$ absorption is strongest for Al III and C IV whereas the strongest low-ionization absorption is at $v > 0$ km s$^{-1}$.

The resolution of X-Shooter is, as discussed in several earlier works, not ideal for robust Voigt-profile fitting (e.g. Fynbo et al. 2010; Noterdaeme et al. 2012a; Krühler et al. 2013), but for our purposes of establishing that the system is metal rich and for inferring the velocity width of the absorption, the data are sufficient.

We also determine the velocity width of the low-ionization absorption following the prescription of Ledoux et al. (2006). Here we find $\Delta v = 349$ and 352 km s$^{-1}$ for Fe II 2260 and Si II $\lambda$1808, respectively.

In conclusion, the metallicity of the system is well above our target selection criterion of 0.1 Z$_\odot$ and there is evidence for substantial depletion of refractory elements on dust grains.

Table 5. Ionic column densities in the six individual line components of the DLA system at $z_{\text{abs}} = 2.412$.

| Ion    | Transition lines used | $\log N \pm \sigma_{\log N}$ | $b \pm \sigma_b$ (km s$^{-1}$) |
|--------|------------------------|-------------------------------|---------------------------------|
| Mg I   | 2026, 2852             | 12.60 $\pm$ 0.05             | 38 $\pm$ 1                      |
| Si II  | 1808                   | 15.40 $\pm$ 0.05             | 38 $\pm$ 1                      |
| Mn II  | 2576, 2594, 2606       | 12.79 $\pm$ 0.05             | 38 $\pm$ 1                      |
| Fe II  | 1608, 1611, 2249, 2260 | 14.70 $\pm$ 0.05             | 38 $\pm$ 1                      |
| Zn II  | 2026, 2062             | 12.77 $\pm$ 0.05             | 38 $\pm$ 1                      |
| Cr II  | 2056, 2062, 2066       | 12.80 $\pm$ 0.10             | 38 $\pm$ 1                      |
| Mg I   | 2026, 2852             | 12.34 $\pm$ 0.07             | 20 $\pm$ 3                      |
| Si II  | 1808                   | 15.01 $\pm$ 0.01             | 20 $\pm$ 3                      |
| Mn II  | 2576, 2594, 2606       | 11.9 $\pm$ 0.2               | 20 $\pm$ 3                      |
| Fe II  | 1608, 1611, 2249, 2260 | 14.29 $\pm$ 0.08             | 20 $\pm$ 3                      |
| Zn II  | 2026, 2062             | 12.3 $\pm$ 0.1               | 20 $\pm$ 3                      |
| Cr II  | 2056, 2062, 2066       | 12.3 $\pm$ 0.1               | 20 $\pm$ 3                      |

Further details on the analysis of this system can be found in Thorsen (2011).

4 http://www.ast.cam.ac.uk/~rfc/vpfit.html

4.2 The galaxy counterpart

In Fynbo et al. (2011) no emission was found from the galaxy counterpart of this absorber. From the spectrum taken with the slit at the position angle of 162° east of north we find that the galaxy seen at the bottom of Fig. 1 is at a lower redshift of $z = 0.987$ based on the detection of the [OIII] $\lambda$3727 doublet and the [OII] $\lambda$5007 line. In Fig. 7 there is no obvious other source at smaller impact parameters except the counterpart of the $z = 2.583$ DLA. One possibility is that the source is a faint galaxy at a small impact parameter. In the lower-left subpanel of the upper panel in Fig. 7 there is a hint of a source at
Figure 7. Top 9 panels: $5 \times 5$ arcsec$^2$ sections centred on the QSO in $F_{606W}$, $F_{105W}$ and $F_{160W}$ (from left to right). The DLA galaxy is seen southwest of the QSO at an impact parameter of 2 arcsec. The top row shows the science images, the middle row shows the GALFIT model and the bottom row shows the residuals after subtracting the model (QSO PSF and galaxy models) from the science images. The field size is $5 \times 5$ arcsec$^2$ and the images are oriented with north up and east to the left. The arrow in the lower-left panel indicates the possible signature of the $z = 2.412$ DLA galaxy. The tail extending below the QSO is a result of charge transfer inefficiency. Bottom panel: $19 \times 19$ arcsec$^2$ sections centred on the QSO in the $u$, $g$ and $K_s$ bands after PSF subtraction. Also shown to the right is the HST/$F_{160W}$ band image on the same scale for comparison. The position of the $z = 2.583$ DLA galaxy is marked with a dotted circle. Again the images are oriented with north up and east to the left.
We do not detect other lines, but \([\text{O} \text{iii}] \lambda 5007\) is the line expected to be detected at highest significance at these redshifts (e.g. Fynbo et al. 2010; Krühler et al. 2012, 2013) and the non-detection of the other lines is expected on S/N grounds.

The impact parameter is consistent with 0 and a conservative upper limit is 0.25 arcsec corresponding to 2.0 kpc.

5 DISCUSSION

In this paper we have presented new observations of the two DLAs towards Q 0918+1636 and their galaxy counterparts. The galaxy counterpart of the \(z = 2.583\) DLA was discovered previously (Fynbo et al. 2011), whereas the discovery of the counterpart of the \(z = 2.412\) DLA is first reported here.

5.1 The \(z = 2.583\) DLA Galaxy

For the \(z = 2.583\) DLA Galaxy we have the largest amount of information: detection of several strong emission lines and a clear detection of the galaxy in the HST images. We can use our information about the size of the galaxy and the kinematics, as probed by the \([\text{O} \text{iii}] \lambda 5007\) emission line of the \(z = 2.583\) DLA galaxy to get an estimate of the dynamical mass of the system. As in Krogager et al. (2013) we follow the method described in Rhoads et al. (2013) to estimate the dynamical mass given the measured size and velocity dispersion:

\[
M_{\text{dyn}} \approx \frac{4 \sigma^2 r_{\text{eff}}}{G \sin^2(i)},
\]

where \(i\) denotes the inclination of the system with \(i = 90^\circ\) being edge-on and \(G\) is the gravitational constant. In order to estimate the velocity dispersion of the system we use the FWHM of the emission lines as a probe of the integrated gas kinematics of the system. We then use the width of the \([\text{O} \text{iii}] \lambda 5007\) line to estimate the velocity dispersion to be \(\sigma = 107 \pm 10\) km s\(^{-1}\), and we adopt the size from the GALFIT analysis: \(r_{\text{eff}} = 1.4\) kpc (see Table 2).

From the GALFIT analysis we infer a (projected) axis ratio of the galaxy of \(b/a = 0.43\). The system may be described as disc-like, given the elongated shape, and the fact that we see a value of Sérsic \(n\) close to 1. We thus adopt a value of \(\sin(i) = 0.5\) and use the fitted half-light semimajor axis for our estimate of the dynamical mass of the system: \(M_{\text{dyn}} \approx 6.0 \pm 1.3 \times 10^{10} M_\odot\). This estimate should only be considered a rough approximation given the assumptions.

From our SED fit to the broad-band imaging data, we obtain a stellar mass of \(M_\star \gtrsim 10^{10} M_\odot\). We can use this measurement to test the mass–metallicity relation for DLA systems (Ledoux et al. 2006; Möller et al. 2013). Using the relation in Möller et al. (2013, their equation 6) using as input solar metallicity (i.e. assuming that \(C_{[\text{M/H}]} = 0\)) we predict a stellar mass of \(M_\star = 3 \times 10^{10} M_\odot\). Given the substantial (~0.38 dex) scatter in their relation, the agreement between the prediction and our best fit stellar mass from the SED fit is good.

5.2 The nature of DLA galaxies

The two DLA systems studied here are, as other systems in our survey (Fynbo et al. 2010, 2011; Krogager et al. 2012), drawn from the extreme high-metallicity end of the distribution and hence should not be considered typical examples of DLA galaxies. In Table 6 we compare the two systems and include also DLA galaxies from the literature for comparison (Weatherley et al. 2005; Fynbo et al. 2010, 2011; Bouché et al. 2012; Noterdaeme et al. 2012a; Krogager...
et al. 2013). For consistency we re-calculate the velocity shifts for N-14-1C and N-14-2C using the centroids of the low-ionization lines corresponding to $z_{\text{abs}} = 2.085$. The galaxy counterpart of the $z = 2.412$ DLA is the system with the highest velocity extent of the low-ionization absorption. However, the FWHM of its [O III] emission is the lowest in the sample. This indicates that additional influences than mass must be important in determining the velocity width of the low-ionization absorption. One such possible influence is of course outflows. Another important reason for this may be the low impact parameter, which implies that a larger fraction of the gravitational potential is probed by the line of sight. We also observe here, as in Krogager et al. (2012), that the systems with the highest H i column densities have the smallest impact parameters. It would be interesting to carry out detailed comparisons of the quantities in Table 6 with simulations, e.g. similar to the works of Pontzen et al. (2008) and Rakic et al. (2013).

For the galaxy counterpart of the $z = 2.583$ we can establish further properties: it is a compact ($r_{\text{eff}} = 1 \text{ kpc}$), strongly star-forming galaxy with a centroid 16.2 kpc away from the line of sight to the background QSO. The galaxy photometry is well fitted by galaxy templates with ages up to several 100 Myr. The ratio between the H i gas scalelength of this DLA galaxy, as measured by its impact parameter, and the light scalelength, as measured by its half-light radius, is of the order of 10 as seen in previous cases of DLA galaxy counterparts (Møller et al. 2002; Krogager et al. 2013). This is very different from the situation in local galaxies, where the gas only extends up to a few times the extension of the light (Bosma 1981). Our data are deep, but the $(1 + z)^4$ dimming of surface brightness with redshift is a very strong effect. Hence, an important question is whether the measured compact morphology is only due to central high surface brightness regions embedded in lower surface brightness regions with extension more similar to the H i gas, but below the surface brightness detection limit of our data. Such H i central high surface brightness regions are also seen in local spiral galaxies (e.g. Carollo et al. 1997). The issue of morphology of star-forming galaxies at these redshifts as inferred from WFC3/IR data has been studied intensively by Law et al. (2012a,b) who find that these systems are not rotationally supported disc galaxies. Rather, they appear to be predominantly unstable, dispersion dominated, systems fuelled by rapid gas accretion which presumably later form extended rotationally supported discs. They also argue that all these galaxies drive strong outflows with more massive galaxies driving less highly ionized outflows. Compared to their sample the $z = 2.583$ DLA galaxy is in the upper third of the mass distribution. For the $z = 2.583$ galaxy the distances and ages are also consistent with a wind scenario: for an age of 233 Myr a mean speed of $\sim 70$ km s$^{-1}$ is required to reach 16 kpc. Such winds speeds are well below what is seen in nearby (more modest) winds (e.g. Melioli, de Gouveia Dal Pino & Geraissate 2013).

Bouché et al. (2013) argue for a similar system of a galaxy counterpart to a DLA at an even larger impact parameter (DLA2243-60 in Table 6) that the gas causing the DLA absorption is in a cold inflow. In their case the DLA metallicity is $-0.72$, which is too high to be pristine gas. Hence, also in this case, an outflow must have been important for determining the properties of the system.

Rafelski, Wolfe & Chen (2011) use statistical arguments to show that most DLA galaxies must probe atomic gas with very low star formation efficiencies. This would be consistent with a picture where metals in this gas originate from a wind rather than having been formed in situ.

The large impact parameter of the $z = 2.583$ galaxy could also be related to other processes like tidal stripping similar to what is seen in the Magellanic stream (Misawa et al. 2009). As DLAs are H i cross-section selected such systems will have a higher probability of being selected (see also Rauch et al. 2011, 2013). However, we note that the correlation between metallicity and impact parameter found by Krogager et al. (2012) would not obviously result from such a scenario and we do not see evidence for a nearby galaxy that could have caused tidal stripping.

We note that none of the two galaxies have Lyα in emission. This may help explain the many non-detections resulting from searches for DLA galaxies in the previous few decades (Lowenthal et al. 1995; Møller, Fynbo & Fall 2004; Fynbo et al. 2010, and references therein).

A coherent picture of DLAs and their relation to emission selected galaxies could be the following: DLAs originate from the outskirts of galaxies with properties (i.e. sizes, luminosities, stellar masses, metallicities) within the range of star-forming Lyman-break galaxies at similar redshift, but due to their cross-section selection they are more likely to be drawn from the fainter end of the luminosity function than emission selected galaxies (Fynbo et al. 1999; Møller et al. 2002; Fynbo et al. 2008; Rauch et al. 2008; Rauch & Haehnelt 2011). There is evidence that DLA galaxies fulfil a metallicity–luminosity relation (Møller et al. 2004; Ledoux et al. 2006; Fynbo et al. 2008; Møller et al. 2013) and therefore high-metallicity DLAs are expected to have galaxy counterparts more similar to typical emission-selected galaxies (i.e. Lyman-break galaxies seen in ground-based surveys) than DLAs in general which probably have.

| DLA galaxy         | $z_{\text{abs}}$ | log N/cm$^{-2}$ | [M/H] | b (kpc) | FWHM([O III]) | $\Delta v_{90}$ | $\Delta v$([O III]) | Ref. |
|--------------------|------------------|----------------|--------|---------|----------------|----------------|---------------------|------|
| DLA0918+1636-1     | 2.412            | 21.26          | -0.6   | <2      | 50             | 350            | -38 ± 25            | (1)  |
| DLA0918+1636-2     | 2.583            | 20.96          | 0.0    | 16.2    | 252            | 295            | -36 ± 20            | (1)  |
| DLN135-0010        | 2.207            | 22.10          | -1.1   | 0.9     | 120            | 186            | 9 ± 10              | (2)  |
| DL2222-0946        | 2.353            | 20.65          | -0.5   | 6.2     | 115            | 185            | 25 ± 20             | (3)  |
| N-14-1C            | 1.920            | 20.67          | -0.4   | 10.6    | 180            | 136            | 80 ± 9              | (4)  |
| N-14-2C            | 1.920            | 20.67          | -0.7   | 22.9    | 320            | 173            | 200 ± 20            | (5)  |
| DLA2243-60         | 2.350            | 20.65          | -0.7   | 22.9    | 320            | 173            | 200 ± 20            |      |

(1) This work, Fynbo et al. (2011); (2) Noterdaeme et al. (2012a); (3) Fynbo et al. (2010); Krogager et al. (2013); (4) Weatherley et al. (2005); Ledoux et al. (2006); (5) Bouché et al. (2012); Ledoux et al. (2006); Bouché et al. (2013); Noterdaeme (private communication).

$^1$Recalculated from the values in the original references to be consistent with the assumed cosmology.
extreme galaxy counterparts (Fynbo et al. 1999; Haehnelt, Steinmetz & Rauch 2000; Rauch et al. 2008). The galaxy counterparts of the two DLAs towards Q0918+1636 are consistent with this picture.

### 5.3 Outlook

Thanks to new sensitive NIR spectrographs the study of galaxy counterparts of $z > 2$ DLAs has now opened (Weatherley et al. 2005; Fynbo et al. 2010, 2011; Bouché et al. 2012; Noterdaeme et al. 2012a; Kroger et al. 2013). The identification of intervening DLAs towards transient sources like gamma-ray burst afterglows have also led to the detection of a galaxy counterpart and this approach hence also appears promising for the future (Schulze et al. 2012). At the moment observations like these are limited to the bright counterparts of the highest metallicity DLAs. With the advent of extremely large telescopes equipped with advanced adaptive optics in the next decade, however, such studies can be extended to the galaxy counterparts of more typical DLAs and hence a more complete unification of absorption and emission studies of high-$z$ galaxies is within reach.

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