

Cume #345

(6 Questions; 90 Points Possible; 70 Points, 77%, Guaranteed Pass)

Given September 12, 2009

Uncovering strong Mg II absorbing galaxies: imaging below the Lyman limit

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Please start each question (by number) on a new sheet of paper, write on only one side of the paper, and staple them together in order of question number when finished. It is strongly suggested that you read the abstract very carefully. I will also say that the § 1, Introduction, is very helpful.

1. [25 pts] The Lyman break and Lyman Break Technique [Hint: thinking about Figures 1 and 2 may be helpful]
 - (a) [10 pts] Consider a redshift $z = 0$ star-bursting galaxy, AGN, or quasar. Explain in your own words what a Lyman break feature in the spectrum of said galaxy, AGN, or quasar is. Include:
 - What element is involved?
 - What ionization stage of the element is involved?
 - Exactly what physical process is occurring that gives rise to the break feature?
 - At what wavelength does the break occur?
 - What overall wavelength range does the feature extend over?
 - (b) [5 pts] Draw a picture of a spectrum, observed counts versus wavelength, and include a Lyman break. Be sure that your wavelengths are labeled properly. Label the break and/or the region over which the break extends.
 - (c) [10 pts] The Lyman break technique is an imaging method used to find high redshift galaxies, AGN, or quasars. In your own words, describe how the Lyman break technique is applied in practice. That is, for example, let's say you were searching for $z = 3$ galaxies, AGN, or quasars. How would you design and carry out your experiment and what would you look for as the signature of a $z = 3$ object? Be *very* specific about the wavelength(s) you are targeting for your observations.
2. [12 pts] The authors apply a variation of the Lyman break technique; they are looking for dim high redshift galaxies that lie in projection very near to a much brighter background quasar. In §2, Observations, the authors describe their selection method.
 - (a) [6 pts] Explain, briefly, the method that the authors employ, including how this exploits the presence of the Lyman break feature, and why it is powerfully effective for searching for these dim galaxies. Include in your answer:
 - What critical role the $z \simeq 3$ damped Lyman α absorbers (DLAs) play?
 - To maximize their search, why did they require DLAs? Why not some other type of absorption system (what physical quantity is important)?
 - (b) [6 pts] Following the selection of the quasars, the author's have data that provides for them the redshifts of the galaxies they are trying to image.
 - What are these data?
 - How many galaxies are they trying to find?
 - What are the redshifts of these galaxies?

3. [24 pts] Redshifted Absorption and Velocities

- (a) [4 pts] Say you know there is a Mg II absorber at $z = 1.5$. If the rest-frame wavelength of Mg II is 2796 Å, at what wavelength would you expect to observe the Mg II $\lambda 2796$ absorption profile?
- (b) [10 pts] Let's say that the above profile has a full *rest-frame* velocity spread of 100 km/s. What is the *observed* wavelength range over which you expect to see the absorption. [HINT: careful, remember this system is at $z = 1.5$.]
- (c) [10 pts] Now reverse the question. You see an absorption line centered at wavelength 5000 Å and you identify the line as Mg II $\lambda 2796$. The *observed* wavelength spread across the profile is 5 Å. What is the *rest-frame* velocity spread of the Mg II absorbing gas.

4. [29 pts] The ΔV_{90} parameter.

- (a) [4 pts] In words, what is the ΔV_{90} parameter.
- (b) [5 pts] Let's say that you measured ΔV_{90} for a redshifted Mg II $\lambda 2796$ profile in some data you obtained. From the information given in *this* paper alone, could you estimate [M/H] for the absorbing gas? If not, which reference(s) mentioned in the paper would you need to examine in order to find the information required to make the estimate?
- (c) [20 pts] Ok, backing up one step. Let's say that you have a Mg II $\lambda 2796$ profile in some data you obtained and you want to measure ΔV_{90} . To your chagrin, this paper, nor any of the papers in the literature anywhere provide an equation or describe the method on how to compute ΔV_{90} . Thus, you need to determine how to make the calculation on your own (this scenario is common in research). Derive an expression for ΔV_{90} in terms of the cut off velocities v_+ and v_- so that you can therefore make the calculation.

[HINTS: Let's say that the word "absorption" translates to the quantity known as the flux decrement, $1 - f(v)/f_c(v)$, where $f(v)$ is the observed flux at *velocity* v , and $f_c(v)$ is the continuum (unabsorbed) flux at velocity v . You do not need to know the form of $f(v)$; you are not being asked to evaluate your relationship. Also, examine Figure 5, where the vertical dashed lines illustrate the locations of $v_+ = +40$ and $v_- = -40$ km/s. There is more than one way to write this expression. Partial credit will be given for correct mathematical ideas and written explanations.]

Uncovering strong Mg II absorbing galaxies

Imaging below the Lyman limit ^{*}

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ABSTRACT

Context. The nature of the galaxies that give rise to absorption lines, such as damped Lyman- α systems (DLAs) or strong Mg II lines, in quasar spectra is difficult to investigate in emission. These galaxies can be very faint and located close to the lines of sight of the much brighter background quasars.

Aims. Taking advantage of the total absorption of the QSO light bluewards of the Lyman limit of two DLAs at $z > 3.4$, we look for the continuum emission from intervening galaxies at $z \approx 2$ that are identified via strong metal absorption lines. The Mg II absorbers have equivalent width large enough to be potential DLA systems.

Methods. Deep images are obtained with the FOCAL Reducer and Spectrograph (FORSl) on the Very Large Telescope for the fields towards SDSS J110855+120953 and SDSS J140850+020522. These quasars have Mg II absorption lines at $z = 1.87$ ($W_r(\text{Mg II}) = 2.46 \text{ \AA}$) and $z = 1.98$ ($W_r(\text{Mg II}) = 1.89 \text{ \AA}$), respectively, and each QSO has two intervening higher redshift DLAs at $z > 3$. The *U* and *R* bands of FORSl lie blue and redwards of the Lyman limit of the background DLAs, allowing us to search for emission from the foreground galaxies directly along the lines of sight to the QSOs.

Results. No galaxies are found close to the sight line of the QSO to a point source limit of $U_{\text{AB}} \sim 28.0$. In both fields, the closest objects lie at an impact parameter of $\sim 5''$ corresponding to $\sim 40 \text{ kpc}$ in projection at $z = 2$, and have typical colours of star forming galaxies at that redshift. However, the currently available data do not allow us to confirm if the galaxies lie at the same redshifts as the absorption systems. A more extended structure is visible in the SDSS J140850+020522 field at an impact parameter of $0''.8$ or 7 kpc . If these objects are at $z \approx 2$ their luminosities are $0.03\text{--}0.04 L^*$ in both fields. The star formation rates estimated from the UV flux are $0.5\text{--}0.6 M_{\odot} \text{ yr}^{-1}$, while the SFRs are half these values if the *U* band flux is due to Ly α emission alone.

Conclusions. The non-detection of galaxies near to the line of sight is most likely explained by low metallicities and luminosities of the Mg II galaxies. Alternatively, the Mg II clouds are part of extended halos or in outflows from low-metallicity galaxies.

Key words. Cosmology: observations – Galaxies: high-redshift – Quasars: Absorption lines – Quasars: individual: SDSS J110855.46+120953.3, SDSS J140850.91+020522.7

1. Introduction

During the past decade much information has been gathered about the properties of high redshift galaxies from the surveys of Lyman break galaxies (LBGs; Steidel et al. 1995, 2003). Since their detection requires the galaxies to have relatively bright continuum emission, the Lyman break technique preferentially selects massive galaxies (Erb et al. 2006b), and follow up spectroscopy have revealed relatively metal rich galaxies ($0.4\text{--}0.8$ solar in Erb et al. 2006a). Alternatively, the spectra of high redshift quasars can reveal the existence of much fainter and more metal poor galaxies through intervening absorption lines. Strong H I absorption lines with column densities in the damped Lyman- α (DLA) regime ($\log N(\text{H I}) (\text{cm}^{-2}) \geq 20.3$) are believed to arise when the sight line toward a QSO intersects a gas rich galaxy (Wolfe et al. 1986, 2005).

Metal absorption lines indicate typical DLA metallicities between one hundredth and one tenth solar (Pettini et al. 1999; Prochaska et al. 2002). The velocity profiles of the lines (Prochaska & Wolfe 1997) can be explained by the complex dynamics of infalling clumps in a merging scenario (Haehnelt et al. 1998; Ledoux et al. 1998; Nagamine et al. 2007). Numerical simulations reproduce reasonably well the kinematics for $z = 3$ DLAs in a hierarchical model (Pontzen et al. 2008), where gas is later distributed in discs at $z = 0$. Comparisons of local H I discs with DLAs at $z > 2$ have indicated that local H I discs have different kinematics than high redshift DLAs (Zwaan et al. 2008), which may indicate that some DLAs could arise in starburst winds or debris from tidal interactions. Winds may not be solely responsible for the large velocities indicated by the absorption lines. Observations have indicated a relation between the velocity width of the metal absorption lines and DLA metallicity (Ledoux et al. 2006), which has been reproduced by numerical simulations (Pontzen et al. 2008). In one DLA towards

^{*} Based on observations collected at the European Southern Observatory, Chile, under programme IDs 380.A-0350 and 080.A-0482

Q0458-020, the velocity difference between the absorption lines and the Ly α emission line seen in the DLA trough is consistent with a rotating disc (Heinmüller et al. 2006). In most cases, no Ly α emission lines are found in the DLA trough, so whether the star formation activity and supernovae that produce the metals occur in situ (Wolfe et al. 2004) at the time of the spectroscopic observation of the DLA, still has to be verified observationally. High redshift DLA systems might also be affected by galactic winds that remove the neutral gas from the galaxies in competition with accretion from the intergalactic medium (Bond et al. 2001; Prochaska & Wolfe 2009; Tescari et al. 2009). Combining measurements of star formation rates (SFRs) and impact parameters for the galaxies with metallicities and velocities determined from the absorption lines, is needed in order to disentangle these effects.

In contrast to LBGs, the galaxy counterparts of DLAs are selected independently of their luminosities. To date ~ 1000 DLA systems are known from the SDSS spectra (Prochaska et al. 2005; Noterdaeme et al. 2009). Yet, despite intense observational efforts in the past couple of decades, only four $z > 2$ DLA galaxies have been found in emission (Møller et al. 2002, 2004). The main difficulty is detecting the galaxies against the glare of the bright background QSO, where the continuum emission from the galaxies may be 10 magnitudes fainter than the background source. High resolution images from the HST have revealed faint ($H_{AB} \sim 25$) objects typically $1-2''$ in projection from the QSOs studied (Warren et al. 2001), but without redshift information, it is not known whether these are the galaxy counterparts to the DLAs. Other techniques exploit the total absorption of the QSO emission at the wavelength of Ly α in the DLA. If the absorbing galaxies are forming stars, they should be detectable as Ly α emitters and through the UV continuum emission from their young stellar populations. Narrow band images have provided a few detections of Ly α emission (Smith et al. 1989; Wolfe et al. 1992; Møller & Warren 1993) as well as a few upper limits (Grove et al. 2009) close to the sight lines of QSOs. Some candidate Ly α emitters are found at the redshift of the DLAs with integral field spectroscopy (Christensen et al. 2007), while strong limits on the Ly α flux from DLA galaxies have been obtained with Fabry-Perot images (Kulkarni et al. 2006). DLA galaxies are fainter and have smaller SFRs than typical LBGs (Fynbo et al. 1999; Colbert & Malkan 2002; Wolfe & Chen 2006; Fynbo et al. 2008). Very deep spectroscopic observations of Ly α emission from candidate DLA galaxies gives typical SFRs of a few tenths of solar masses per year where the Ly α emission can be extended over a few tens of kpc (Rauch et al. 2008). The DLA galaxies are therefore challenging to detect even with the largest telescopes.

Another method to detect the galaxies in emission takes advantage of sight lines with multiple intervening strong absorbers. If the highest redshift absorber has a hydrogen column density much larger than 10^{17} cm^{-2} , defining a Lyman limit system (LLS), all the flux from the QSO bluewards of the Lyman break ($\lambda = 912(1+z) \text{ \AA}$) is absorbed. This idea was originally exploited in the search for high redshift galaxies towards luminous QSOs (Steidel & Hamilton 1992). If the sight line has a lower redshift absorber, the emission from its associated galaxy will be visible even directly in front of the QSO, or at a very small impact parameter. O'Meara et al. (2006) observed strong Mg II absorbers at $z \sim 2$ seen in QSO spectra which had higher redshift LLS, and found two bright L^* galaxies at projected distances of 12–16 kpc to the two QSOs. Several studies have aimed to identify the host galaxies of strong Mg II systems, mostly at lower redshifts $z \lesssim 1$. The presence of galaxies responsible for absorption lines

at impact parameters of 20–40 kpc is used to argue for starburst driven winds (Nestor et al. 2007; Bouché et al. 2007), but such winds are not necessary in a model where the extended gaseous halos follow a Holmberg relation (Steidel 1995; Kacprzak et al. 2008; Chen & Tinker 2008).

Gamma-ray burst (GRB) afterglows have recently proven to be of similar use as QSOs for the study of intervening absorption systems. GRBs have the advantage that the afterglows fade away providing a clear line of sight for the absorbing galaxies. In a several cases, galaxies which are possibly responsible for intervening strong Mg II absorption lines have been found within an impact parameter of ~ 10 kpc from the line of sight to the afterglow (Jakobsson et al. 2004; Chen et al. 2009; Pollack et al. 2009). These intervening galaxies have luminosities in the range $0.1-1 L^*$. The discrepancy between the impact parameters and luminosities found for galaxy counterparts of QSO- and GRB Mg II absorbers could suggest that bright background QSOs prevent us from detecting potentially fainter galaxies closer to their lines of sight.

In this paper we exploit the absorption of the UV light of two high redshift QSOs that have multiple intervening absorption systems in their spectra. The observations in the two fields reach an unprecedented depth with a detection limit of $0.03 L^*$ in the U band. This allows us to put strong constraints on the SFRs directly in the QSO lines of sight. Throughout the paper, we assume a flat cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Observations

2.1. Sample selection

While Lyman limit systems with H I column densities of 10^{17} cm^{-2} are optically thick bluewards of the Lyman limit, some of the background emission is transmitted, and only at higher column densities where the optical depth is sufficient ($N(\text{H I}) > 10^{19} \text{ cm}^{-2}$) will the blue wavelengths be completely absorbed. A QSO with a DLA system at $z > 3.39$ will have all its emission absorbed in the U band. An intervening galaxy with a redshift in the range $1.7 < z < 2.3$ will have a Ly α emission line in the U band provided it is forming stars. Meanwhile, the faint emission will be observable from the ground and its emission properties will be completely unaffected by the bright background QSO. This effective approach to locate the galaxies responsible for intervening strong absorption lines (including DLAs), near bright QSOs is demonstrated in O'Meara et al. (2006).

To find such configurations, we systematically searched the Sloan Digital Sky Survey spectra of about 2000 QSOs for $z > 3.5$ DLAs in the data release 5 (Schneider et al. 2007). To ensure that no flux was present from the QSO and that the Ly α emission line was well within the transmission function of the U band, the redshift criteria were chosen to be conservative. Because the QSO emission around the Ly α line of lower redshift galaxies is completely absorbed it is not possible to determine the hydrogen column density. Instead we used the strong Mg II $\lambda\lambda 2796, 2803$ doublet as a proxy for selecting DLAs. These strong lines are easy to identify in QSO spectra, and can be used to identify low redshift DLAs where only few have measured hydrogen column densities (Rao & Turnshek 2000; Rao et al. 2006). It is not known if strong Mg II absorbers are identical to DLAs; absorbers with Mg II equivalent widths larger than $0.6 \text{ \AA}$ and lines spread over more than 300 km s^{-1} only have a probability of $\sim 50\%$ of being DLAs (Ellison et al. 2009). SDSS Spectra with

at least one high redshift DLA system were investigated further to find Mg II $\lambda\lambda 2796, 2803$ absorption lines with a rest frame equivalent width (W_r) larger than $0.6 \text{ \AA}$ at $1.75 < z < 2.2$, where the redshift limits ensure that the associated Ly α emission line fall within the FORS U band. These criteria were met by two equatorial QSOs (SDSS J110855+120953 at $z = 3.671$ and SDSS J140850+020522 at $z = 4.008$) which could be observed by the VLT. Hereafter, we shall refer to these two QSOs as Q1108, and Q1408. The SDSS spectra of the two QSOs are shown in Fig. 1. By coincidence both targets had two intervening DLAs in addition to the strong Mg II system, which effectively absorb all of the QSO emission immediately bluewards of the redshifted Lyman limit break.

In each spectrum, the lower redshift absorption system is detected by several metal absorption lines in addition to the Mg II $\lambda\lambda 2796, 2803$ doublet. Table 1 lists the properties of the absorption systems. The high W_r measured for the metal lines suggest that the strong metal absorption systems are possibly DLAs. At $W_r^{\text{Mg II } \lambda 2852} > 0.6 \text{ \AA}$, combined with a criterion for the fraction $W_r^{\text{Mg II } \lambda 2796} / W_r^{\text{Fe II } \lambda 2600} < 2$, more than 50% of the systems are DLAs (Rao et al. 2006). This is consistent with the analysis of the Mg II absorption line velocity spread discussed in Sect. 5.1.

2.2. Photometry

The two fields were observed with the blue sensitive CCD on VLT/FORS1 taking advantage of the high transmission of a new U filter (U -high), which transmits almost 90% at its peak sensitivity around $3800 \text{ \AA}$. We obtained very deep observations in the U band (4.6 and 5.4 hours on target, respectively, divided into jittered exposures of 980 s), with shorter (450 s) R band observations for both fields. The R band images helped to pinpoint the exact location of the QSO with respect to the nearby galaxies. The observations were done in service mode between March 6 and 9, 2008 under photometric conditions and with seeing conditions between $0''.6$ and $1''$.

The data were reduced with standard procedures, subtracting an average bias frame, and flat fielding using twilight sky frames. The images were registered and combined to reject bad pixels and cosmic ray hits. To optimise the depth of the images in the U band, two of the 16 frames of Q1408 were rejected due to poor seeing. The $FWHM$ measured from stars in the fields is $0''.8$ and $0''.9$ in the R and U band, respectively. Both U band images do not show any residual emission from the QSOs. The full field of view of FORS1 is $6'.8 \times 6'.8$, but here we focus on the immediate regions around the QSOs, as shown in Fig. 2. The images are $30''$ on a side with orientation north up and east left.

Instrumental zero points were estimated from observations of standard stars in the field Rubin 149 obtained on the same nights as the science observations. Transformations from instrumental magnitudes to Vega magnitudes were calculated using IRAF-PHOTCAL. The transformation equations from the instrumental to Vega magnitudes included an extinction coefficient appropriate for Paranal (Patat 2003). A potential inclusion of a colour term was consistent with zero to within the uncertainties, so this term was neglected. Magnitude uncertainties were propagated through the equations. Aperture photometry showed that within a $1''$ radial aperture, the 3σ significance detection limit was $U_{\text{Vega}} = 27.3$ mag for a point source in both fields, while the 3σ significance limit in the R band was shallower: 26.4 mag and 26.5 mag (Vega) for Q1108, and Q1408, respectively. The magnitudes were corrected for Galactic extinction (Schlegel et al. 1998). Transformations from the Vega to AB magnitudes were

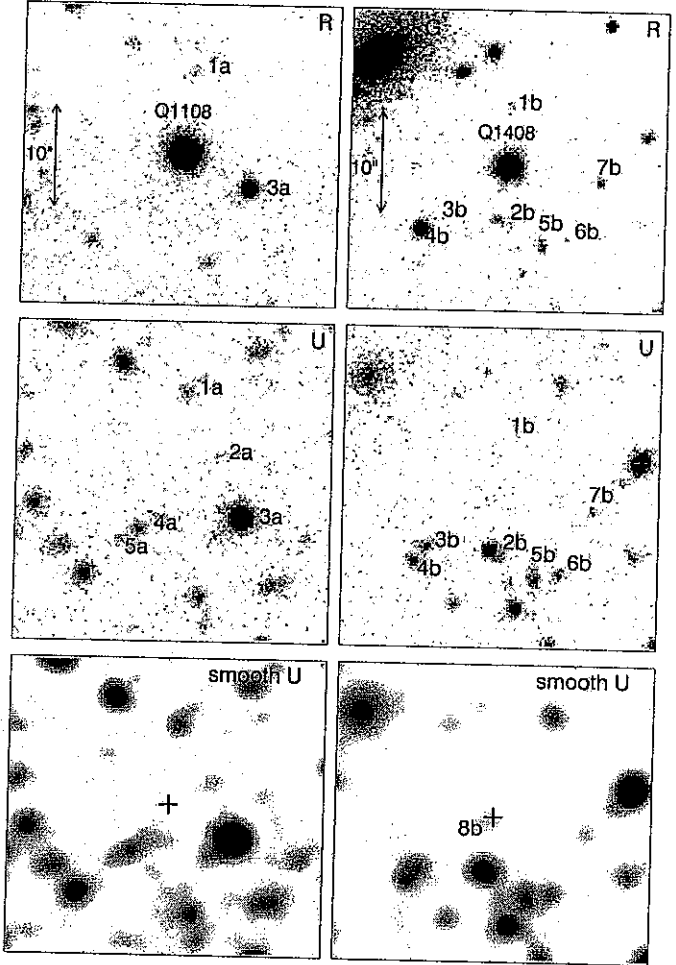


Fig. 2. R and U band images of Q1108 shown the left column, and for Q1408 in the right. In the U bands the emission from the QSOs have been completely absorbed. The images are $30''$ on a side with the orientation north up and east left. Objects within $10''$ from the QSOs lines of sight are labeled with numbers and the photometry of these is listed in Table 2. The bottom row shows smoothed version of the U band images, with a '+' sign indicating the location of the QSO. Only in the case of Q1408 do we detect an extended object close to the line of sight of the QSO, which is otherwise not detectable in the unsmoothed U band.

calculated from the filter transmission curve and the spectrum of Vega (Fukugita et al. 1995). For the FORS1 filters we calculated $U_{\text{AB}} = U_{\text{Vega}} + 0.66$ and $R_{\text{AB}} = R_{\text{Vega}} + 0.18$ mag. We use the AB magnitudes unless otherwise stated.

Since the U band images were the deepest they were used primarily to detect objects. The locations were cross checked with object detection in the R band to avoid missing any U band dropout.

2.3. High resolution spectra

In addition to the imaging data we took advantage of one 4200 s integration of Q1108 with VLT+UVES obtained as a part of another observing programme (ID 080.A-0482, PI: Sebastian Lopez). The data were used to study the velocity widths of the strong Mg II absorption lines as described in Sect. 5.1.

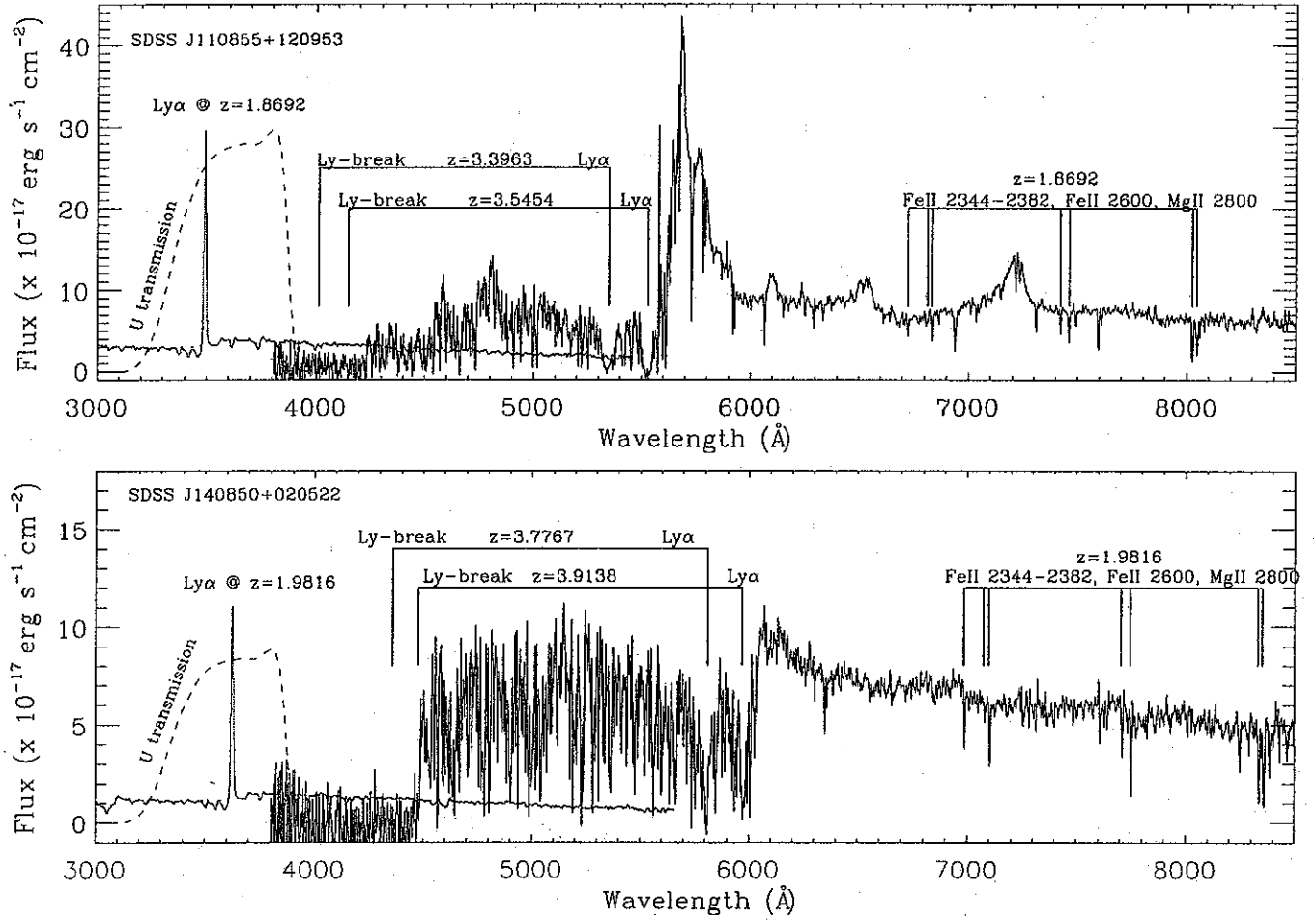


Fig. 1. Sloan spectra of the two quasars. In each quasar spectrum, two DLAs (at $z_{\text{DLA}} = 3.5454$ and 3.3963 for SDSS J110855.46+120953.3, upper panel, and $z_{\text{DLA}} = 3.9138$ and 3.7767 for SDSS J140850.91+020522.7, lower panel) completely absorb the QSO emission bluewards of $4200 \text{ \AA}$. Two lower redshift systems are identified through their strong metal absorption lines. Both panels indicate the transmission curve of the U band, which lies bluewards of the absorption cutoffs. Spectra of Lyman break galaxies with $\text{Ly}\alpha$ in emission (Shapley et al. 2003) at the redshifts of the Mg II absorption systems are indicated in the two plots. Their $\text{Ly}\alpha$ emission lines fall within the U band in both cases.

	z_{QSO}	$z_{\text{DLA},1}$	$z_{\text{DLA},2}$	$z_{\text{Mg II}}$	$W_r^{\text{Fe II } \lambda 2600}$ ($\text{\AA}$)	$W_r^{\text{Mg II } \lambda 2796}$ ($\text{\AA}$)	$W_r^{\text{Mg I } \lambda 2852}$ ($\text{\AA}$)
Q1108	3.671	3.5454	3.3963	1.8692	1.23	2.46	0.61
Q1408	4.008	3.9138	3.7767	1.9816	0.97	1.89	

Table 1. Absorption line systems in the two QSO spectra. The metal line rest frame W_r are measured for the lowest redshift systems in the SDSS spectrum for Q1408, and the UVES data for Q1108. The SDSS spectra give values consistent within the uncertainties with the UVES data. The SDSS spectrum of Q1408 is too noisy to identify the Mg I line.

Both the blue and red UVES spectrograph arms were used simultaneously with standard dichroic settings, with central wavelength of 437 and 860 nm. The resulting wavelength coverage is 305 to 1042 nm with gaps at 575–583 nm and 852–866 nm. The CCD pixels were binned by a factor of 2×2 and the slit width adjusted to $1''$. This yielded a resolving power of 48 000 under the seeing conditions of $1''$.

The data were reduced using the ESO pipeline system, which allowed for an accurate extraction of the object spectrum, while subtracting the sky spectrum and removing cosmic ray hits and CCD defects at the same time. Wavelengths were finally shifted

to the vacuum-heliocentric rest frame. The signal-to-noise ratio in the reduced spectrum was measured to be 15–20 per pixel.

3. Observational results

3.1. Nearby galaxies and colours

The goal of this study is to detect objects located directly along the QSO line of sight. In both fields the closest objects lie at a separation of $\sim 5''$ from the QSO. If either of these galaxies are responsible for the strong absorption line system seen

in the QSO spectra, the projected separation is ~ 40 kpc at the redshift of the absorbers. No other nearby objects are found at the 3σ significance level (corresponding to $0.03 L^*$). At $z = 2$ a luminous L^* galaxy has an absolute magnitude of $U_{AB}^* = -21.9$ mag (Gabasch et al. 2004), and an observed magnitude of $U_{AB} = 24.0$ mag in the adopted cosmology. The numbered objects in Fig. 2 mark all galaxies that are located within $10''$ of the QSO; most of these objects are fainter than $U = 24$ mag. The photometry of these galaxies is listed in Table 2.

We investigate whether the colours are similar to other galaxies detected in galaxy surveys. For comparison we use photometry of galaxies from the GOODS-MUSIC catalog (Grazian et al. 2006) where multiband photometry allows an accurate determination of the photometric redshift. To estimate the R_{AB} magnitude of the GOODS galaxies, we linearly interpolate the flux between the measured F606W and F775W bands to calculate the flux at $6440 \text{ \AA}$. We are mainly interested in the observed colours of galaxies around $z = 2$, where the HST bands correspond to restframes 2000 and $2580 \text{ \AA}$, respectively. Between wavelengths $1500\text{--}2800 \text{ \AA}$ galaxy spectra are mostly flat when measured in frequency units, ν (Kennicutt 1998), so a simple interpolation to calculate the R band magnitude is well justified. The transmission curves for the VIMOS U band used in the GOODS-MUSIC catalog is different from the FORS1 high transmission U filter. We calculate a transformation between the two systems: $U_{\text{FORS1}} = U_{\text{VIMOS}} + 0.04 \text{ mag}$.

A colour-magnitude diagram of ~ 1000 galaxies with photometric redshifts between 1.8 and 2.3 is shown as a grey scale image in Fig. 3. Galaxies detected in the two QSO fields with a signal-to-noise ratio > 3 are shown as small symbols, and the objects detected within $10''$ are shown as larger symbols with error bars. Due to our shallower R band observations relative to the GOODS observations, objects in the lower right hand corner are undetected in our observations. The colours of the GOODS galaxies span a narrower range than for the galaxies in the two QSO fields, where there is an excess of galaxies with colours around $U - R > 1.5$. If no photometric redshift selection is made for the GOODS galaxies, a wider range of colours are found, and the two colour distributions are consistent.

The typical colour of an irregular galaxy, calculated from template spectra (Kinney et al. 1996), and redshifted to $z = 2$ is shown as a diamond, where its U band magnitude correspond to an L^* galaxy. By creating artificial spectra of metal poor, young galaxies (Bruzual & Charlot 2003) with an additional intrinsic extinction of $A_V = 0.5$ mag, we estimate the colour and magnitude change. We also calculate the colour and magnitude change if the galaxies have strong Ly α emission with a rest frame equivalent width of $100 \text{ \AA}$. The arrows in Fig. 3 show the respective changes which are minor. More evolved galaxies have redder colours ($U - R > 3$) independently of the metallicity and the initial mass function of the galaxy templates. This implies that the entire range of colours in Fig. 3 can be obtained for high redshift galaxies. Specifically, the red colour of object no. 4b in the Q1408 field is consistent with an evolved galaxy at $z \approx 2$ with an age greater than 700 Myr for the dominant population of stars. In the Q1408 field there are several red galaxies present at impact parameters larger than $10''$ from the QSO line of sight. In the upper right hand panel of Fig. 2, the R band image of Q1408, a large and bright galaxy is partly visible (marked ‘G’) in the image. This galaxy has the morphology and colours of a low redshift elliptical, and there are several fainter galaxies with the same colours around it. It is likely that object no. 4b is part of a lower redshift group environment.

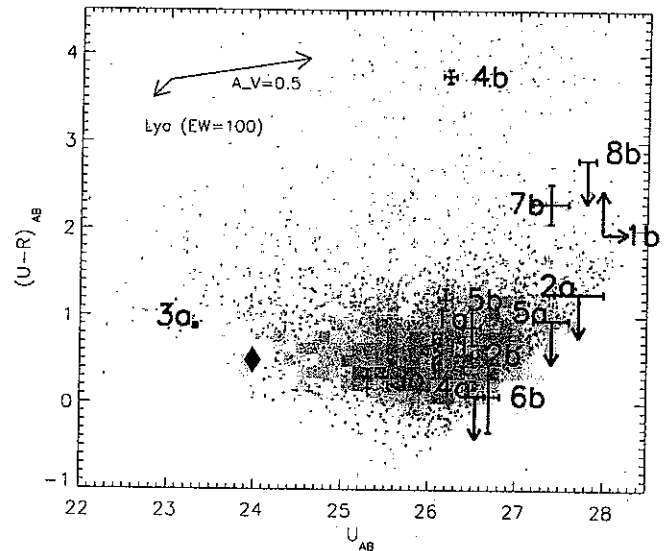


Fig. 3. Colour-magnitude diagram of the objects in the two fields (small plus signs). The grey scale image shows the distribution of ~ 1000 galaxies with photometric redshifts $1.8 < z_{\text{phot}} < 2.3$ from the GOODS-MUSIC survey. The large crosses with error bars mark the galaxies near to the QSO lines of sight and the numbers refer to those in Table 2 (red symbols for Q1408, and purple for Q1108). The large black diamond symbol shows the colour of an L^* starburst galaxy at $z = 2$. See the online edition of the journal for a colour version of this figure.

Although there are no clear correlations between the $U - R$ colour and redshift, objects with $U - R < 0.5$ are more likely to lie at $z > 0.9$. 52% of the GOODS galaxies fulfill these criteria, while only 20% of galaxies at $z < 0.9$ have such blue colours. However, the single $U - R$ colour is insufficient to make an exact redshift estimate, and not good at all to select objects at $z \sim 2$. Additional observations in the V band would be useful to apply the BM/BX colour criterion to select galaxies with $1.4 < z < 2$ (Adelberger et al. 2004).

Objects no. 2b, 3b and 6b in the Q1408 field and no. 4a in the Q1108 field have the bluest colours. Given their non-detection in the R band, several of the objects could potentially be located at higher redshifts with very blue colours.

3.2. Extended objects

To check for the presence of extended low surface brightness objects closer to the lines of sight of the QSOs, the U band images are convolved with Gaussian point spread functions with a FWHM of $1''.5$ and $2''$, respectively. While the 3σ detection limit is $U_{AB} = 28.0$ for a point source, the smoothed images have a deeper 3σ detection limit of $U_{AB} = 28.5$ within a $1''.5$ radial aperture for the two fields. No objects are detected close to the line of sight of the QSO in the field of Q1108. Objects 4a and 5a in the Q1108 field have a separation of $2''$, and appear merged into one elongated object in the smoothed image. Furthermore there is an extension of emission to the west of object no. 4a which is not directly visible in the original image. This extension reaches a minimum impact parameter of $3''.8$ directly south of the QSO with a size of $1''.5 \times 3''$ and has a magnitude of $U_{AB} = 27.4 \pm 0.1$. If the object is at $z \approx 2$, the projected distance is 31 kpc.

Object No.	offset (")		b (")	U (mag)	R (mag)	L_U/L_U^* at $z = 2$
Q1108						
1a	0.7 E	8.4 N	8.4	25.83±0.10	25.41±0.18	0.10
2a	4.1 W	2.4 N	4.7	27.06±0.28	>26.4	0.03
3a	6.4 W	3.4 S	7.2	22.66±0.01	22.23±0.02	1.87
4a	3.4 E	4.8 S	5.8	25.88±0.11	>26.4	0.10
5a	5.3 E	5.2 S	7.4	26.75±0.28	>26.4	0.03
Q1408						
1b	0.0 E	6.4 N	6.4	>27.3	25.82±0.25	<0.03
2b	1.0 W	5.4 S	5.5	24.64±0.04	24.81±0.10	0.31
3b	6.9 E	5.0 S	8.5	25.75±0.09	25.64±0.20	0.11
4b	8.2 E	6.4 S	10.4	25.55±0.07	22.25±0.02	0.13
5b	3.3 W	8.2 S	8.9	25.53±0.08	24.79±0.10	0.13
6b	5.6 W	7.7 S	9.5	26.03±0.12	26.41±0.40	0.08
7b	8.8 W	1.7 S	8.9	26.73±0.21	24.88±0.10	0.04
8b	0.7 E	0.3 S	0.8	26.92±0.10	~	0.04

Table 2. Vega magnitudes of objects identified within $\sim 10''$ from the QSO lines of sight, with the observed offsets in RA and DEC (in arcsec), and projected impact parameter (in arcsec). Objects near Q1108 are in the upper 5 rows, and near Q1408 in the bottom 8 rows. The magnitudes are corrected for Galactic extinction. The last column gives the luminosity fraction relative to a U^* galaxy at $z = 2$, which has an apparent magnitude $U_A = 24$. The uncertainties are 0.01 for this fraction.

In the Q1408 field, a faint object ($U_{AB} \sim 27.6 \pm 0.1$ mag within a radial aperture of $1''.5$) is detected at an offset of $0''.8$ to the south-east of the QSO as displayed in Fig. 2, and labeled as object no. 8b. At $z = 2$ the projected distance is 7 kpc. The object appears elongated with a size of about $2''.5 \times 2''$ in the frame with a Gaussian convolution width of $1''.5$. To estimate whether a faint object is present also in the R band, the QSO is subtracted using the brighter field stars as PSF reference. No additional point sources were visible after the subtraction. To estimate the detection limit of a resolved object against the glare of the brighter QSO, we add artificial objects nearby the bright QSO, and then subtract the PSF to recover the artificial object. These experiments show that we can recover an object with a $FWHM$ of $1''.5$ and $R = 25$ mag at a distance of $0''.8$ by PSF subtraction. This places a rough upper limit on the colour: $U - R < 2.8$ for the object no. 8b.

3.3. High redshift DLA host galaxies?

In the previous sections we investigated whether some of the spatially nearby galaxies are the hosts of the $z = 2$ Mg II absorption systems, but a related question is whether some of the galaxies could be the hosts of the $z > 3$ DLA systems.

For both fields, the two high redshift DLAs absorb all emission immediately bluewards of the Lyman break. This suggests that the objects detected in the U band images are not likely to be the host galaxies of the $z > 3$ DLA systems because no UV emission bluewards of the Lyman limit break should be able to escape the cloud, at least along the QSOs line of sight. Only object no. 1b in Q1408 is detected in the R band but not in the U band, and this could potentially be the host of one of the DLAs. However, the impact parameter is quite large (44 kpc at $z \approx 3.8$) compared to a typical value of ~ 10 kpc found for the few confirmed DLA galaxies at $z > 2$ (Møller et al. 2002; Weatherley et al. 2005). Numerical models also predict small impact parameters of the order or less than 10 kpc for DLA systems (Nagamine et al. 2007; Pontzen et al. 2008). However, little is currently known about the extension and morphology of gaseous disks around high redshift galaxies from observations.

Even though no UV photons bluewards of the Lyman limit can escape the DLA clouds along the line-of-sight, they can

escape along other directions with a smaller optical depth. In such a special gas geometry, the emission from the DLA host galaxies can be detected in both the U and the R bands. If the escape fraction of the galaxies is substantial, the Lyman continuum emission could be still observed, and in the images the galaxy would be visible at some distance from the QSO lines of sight. Assuming an escape fraction $f_{1500}/f_{900} = 2.9\text{--}4.5$ as observed for two Lyman break galaxies (Shapley et al. 2006), we can calculate the rest frame flux ratio which corresponds to a colour $(U - R)_{AB} \sim 2.2$. Objects no. 4b and 7b in the Q1408 field have colours consistent with being at a redshift of $z > 3$, but the colours are also consistent with lower redshift evolved galaxies. With $R = 22.25$ mag for object no. 4b, it would have a luminosity of $7L^*$ if it were at $z = 3.8$ relative to an $R^* = -23.0$ galaxy (Gabasch et al. 2006) while 7b would have a luminosity of $0.7L^*$. Considering that such bright objects are rare, it is more likely that object no. 4b has a lower redshift, and possibly is a member of a group as discussed above. In addition, object no. 7b would have an impact parameter of 65 kpc at $z = 3.8$. Since the objects are faint for follow up spectroscopy, near-IR images of the field can be used instead to investigate the spectral energy distribution and to determine the photometric redshift. Before such observations are made we cannot claim the detection of the hosts of the DLAs.

4. SFR limits

4.1. SFRs from the UV continuum

The limiting magnitude of $U_{AB} = 28.0$ corresponds to a SFR of $0.6 M_\odot \text{ yr}^{-1}$ for a galaxy at $z = 2$. At the redshift of the Mg II absorbers, the U band measures the emission at 1200–1400 Å in the rest frame of the absorbers. To estimate the SFR in the UV region, we extrapolate calibrations from other studies.

The conventional conversion from a UV flux to the SFR (Kennicutt 1998) is valid from 1500–2800 Å, where spectra of star forming galaxies are flat. Bluewards of 1500 Å the flux decreases, so we analyse template spectra to estimate the SFR given the U band flux. We use the template spectra from Bruzual & Charlot (2003) of instantaneous star burst populations with ages < 100 Myr and a Salpeter initial mass function.

age	0.02Z _⊙	0.2Z _⊙	0.4Z _⊙	1Z _⊙
10 Myr	1.1	1.3	1.4	1.5
50 Myr	1.7	1.9	2.3	2.9
100 Myr	2.3	2.9	3.7	5.5
200 Myr	3.5	5.1	7.3	14.9

Table 3. Conversion factor A for Eq. (1) calculated for different galaxy template ages and metallicities relative to the solar value, $Z_{\odot} = 0.02$.

Galaxy template spectra are created with the observed U band magnitude at the redshift of the absorber. The template flux bluewards of 1215 Å is reduced to reflect that 15% of the flux is absorbed in the Ly α forest at $z = 2$ (Dall'Aglio et al. 2009). No Ly α emission is present in the template spectrum. From this template the flux at the rest frame 1500–2800 Å is used to calculate the SFR using the standard conversion (Kennicutt 1998), which has an intrinsic scatter of $\sim 30\%$.

The SFR conversion depends also on the age and metallicity of the template for which we have to select appropriate values. Since strong Mg II absorbers have about 50% chance of being DLAs (Rao et al. 2006; Ellison et al. 2009), we use typical low metallicities measured for the DLA population (Wolfe et al. 2005). Models of chemical evolutions of the DLAs at high redshifts show that they are typically a few 100 Myr old (Dessauges-Zavadsky et al. 2004). A notable exception is the DLA towards Q B2230+02, which has a relatively high metallicity and an age of 3 Gyr (Dessauges-Zavadsky et al. 2007). The conversion from luminosity to SFR is given by

$$\text{SFR} (\text{M}_{\odot} \text{ yr}^{-1}) = A \times 10^{-28} L_{\nu} (\text{erg s}^{-1} \text{ Hz}^{-1}), \quad (1)$$

where L_{ν} is the luminosity measured around 1200 Å in the rest frame of the galaxy. For a 100 Myr, 0.2 solar metallicity template, we calculate $A = 2.9$ in Eq. (1). Since the factor A depends on the metallicities and ages of the galaxies, we derive the conversion factor for the SFR using a series of templates of varying ages and metallicities (see Table 3) corresponding to the available template metallicities in Bruzual & Charlot (2003).

If the Ly α emission line is very strong we over estimate the SFR with this procedure, since a pure Ly α line indicates a smaller SFR as described in Sect. 4.2. Hence the SFRs that we give are considered to be conservative.

It is possible that the galaxies responsible for the strong absorption systems are extended low surface brightness objects. We compute the apparent magnitude and UV flux for an object detected at the 3σ significance level as a function of radius. To calculate the limiting magnitude for a signal-to-noise ratio of $S/N=3$ we use $m_{\text{lim}} = z_p - 2.5 \log(S/N \sqrt{n_{\text{pix}}} \sigma / t)$, where z_p is the FORS zero point measured in magnitudes, $n_{\text{pix}} = \pi(r/0.25)^2$ is the number of pixels within an aperture radius r (in arcsec), and 0.25 is the plate scale of the CCD (″/pixel). σ is the standard deviation of the pixel values measured in the reduced CCD frame, and t is the integration time measured in seconds. Given these values, a point source has with a FWHM=1″ has a radial $n_{\text{pix}} = 2$, which at $z = 2$ corresponds to ~ 4 kpc in the adopted cosmology. The limiting flux increases with increasing aperture, so for more extended galaxies the SFR limit is less strong.

With the observations, we can place a strong constraint on the SFR for an object located directly in the lines of sight of the QSOs. Figure 4 shows the limiting SFR for the lines of sight to the two QSOs as a function of the radial aperture. At large

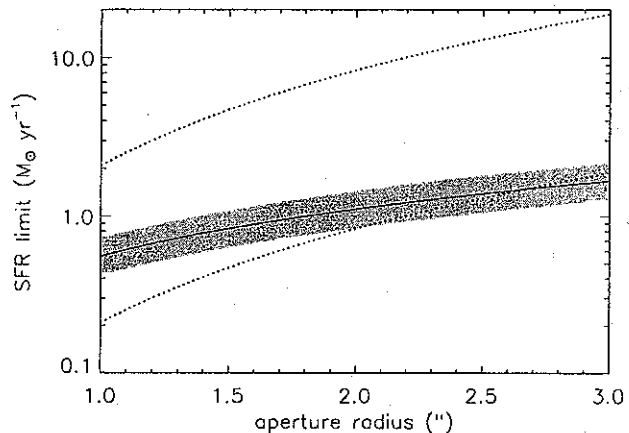


Fig. 4. The limiting SFRs in the two QSO lines of sight (solid line with the uncertainty represented as the shaded area) converted from the limiting magnitude calculated as a function of radial apertures. The limits have been calculated from the original unsmoothed U band images. At $z = 2$ one arcsec corresponds to 8.1 kpc in projection. The upper dotted line shows the average SFR per unit area in DLA galaxies of $10^{-2} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ while the lower dotted line represents a value of $10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ corresponding to the lower limit in Wolfe et al. (2004).

apertures of 3″, the SFR limit is within $2 \text{ M}_{\odot} \text{ yr}^{-1}$ including uncertainties. Compared to typical LBGs which have an average SFR measured from the unobscured UV emission of $8 \text{ M}_{\odot} \text{ yr}^{-1}$ (Erb et al. 2006a), our observations probe high redshift galaxies which are significantly fainter. Similarly, extended continuum emission from DLA galaxies is not detected in the Hubble ultra-deep field (Wolfe & Chen 2006), possibly due to a smaller star formation efficiency in DLAs relative to LBGs.

Wolfe et al. (2004, 2008) estimate the SFR surface density of DLA galaxies to lie in the range $10^{-2} - 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ depending on the state of the neutral gas. These values are represented by the dotted lines in Fig. 4. If the absorbing galaxies we are looking for in emission are similar to the DLA absorption systems investigated by Wolfe et al. (2004) we should be able to detect them if the star formation extends uniformly over the galaxy discs. Only the weakest star-forming DLA galaxies would remain undetected. The non detections indicate that galaxies with extended star formation, specifically at the high rate of $10^{-2} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, are unlikely to be present in the two QSO lines of sight. Alternatively, a high SFR density in a small dwarf galaxy system with a radius $\lesssim 4$ kpc has a SFR below the detection limit.

The most nearby point source objects (no. 2a, 2b in the two fields) have $\text{SFR} = 0.5 \text{ M}_{\odot} \text{ yr}^{-1}$ for Q1108 and $4.9 \text{ M}_{\odot} \text{ yr}^{-1}$ for Q1408, respectively, if they are the absorbing galaxies. The extended object no. 8b near Q1408 has $\text{SFR} = 0.6 \text{ M}_{\odot} \text{ yr}^{-1}$.

4.2. SFRs from Ly α emission

In the hypothetical case that the U band flux comes entirely from a Ly α emission line from the galaxies at $z = 2$, the line flux for the object no. 2a in Q1108 is $2.5 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$. For Q1408 the line flux is $10.0 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $1.3 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ for objects no. 2b and 8b, respectively. This in turns corresponds to a SFR of $0.5 \text{ M}_{\odot} \text{ yr}^{-1}$ for object no.

2a in the Q1108 field and $2.3 M_{\odot} \text{ yr}^{-1}$ and $0.3 M_{\odot} \text{ yr}^{-1}$ for objects no. 2b and 8b near Q1408. To calculate these flux densities, we use the case B recombination scenario (Osterbrock 1989), a flux ratio of $\text{Ly}\alpha/\text{H}\alpha = 10$, and the conversion between $\text{H}\alpha$ luminosity and SFR from Kennicutt (1998). This last assumption of a pure $\text{Ly}\alpha$ emission line object is not justified in the case of Q1408, because the continuum emission is detected in the R band, but it serves the purpose of calculating the SFR for comparison to that estimated from the UV continuum.

The $\text{Ly}\alpha$ photons are effectively quenched in the presence of dust, so the above SFR are strict lower limits. Since the SFR estimated from the UV is higher than estimated from the $\text{Ly}\alpha$ flux by a factor of 3, the unobscured SFR may be somewhere between these values.

We note that the estimated $\text{Ly}\alpha$ flux densities and luminosities are in the same range as those measured for the few detections of $\text{Ly}\alpha$ emission from DLA galaxies (Møller et al. 2004; Weatherley et al. 2005, and references therein). This is probably not a coincidence, but likely reflects that the searches for emission from DLA galaxies are carried out to the detection limit of currently available instruments.

5. Strong Mg II systems

5.1. Velocity spreads

The UVES data of Q1108 shows a wealth of absorption lines and a detailed analysis will be presented elsewhere. The systemic redshift is found to be $z = 1.8692$ from narrow metal absorption lines of Mg I $\lambda 2852$ and the Fe II lines. The Mg II $\lambda\lambda 2796, 2803$ line profiles are complex with several components spread over a velocity of $\Delta v = 308 \text{ km s}^{-1}$, as typically seen for strong Mg II absorbers (Nestor et al. 2007). The same spread is seen in the C IV $\lambda 1549$ doublet. The bulk of the Mg II absorption is spread over a smaller velocity range of $\approx 150 \text{ km s}^{-1}$ surrounded by weaker satellites at larger velocities. This places the absorber among the strong, but not extremely strong Mg II absorbers. A smaller velocity spread of the dominant absorption components is seen from other non saturated lines such as the Fe II $\lambda 2374$ line, as demonstrated in Fig. 5. The velocity spread of the Mg II line is twice that suggested by the correlation with the equivalent width $\Delta v \text{ (km s}^{-1}\text{)} \approx 70 \text{ (km s}^{-1} \text{ \AA}^{-1}\text{)} \times W_r^{\lambda 2796} \text{ (\AA)}$ (Murphy et al. 2007). Using the Mg II absorption line velocity spread to calculate the D -index (Ellison 2006) gives $D = W_r/\Delta v \times 1000 = 8.0$. For values of $D > 7$ the probability that the absorber is a DLA is 50–55% (Ellison et al. 2009).

To compare with previous studies (Ledoux et al. 2006), we measure the velocity spread of the Fe II $\lambda 2374$ line which satisfies the criterion that the maximum residual emission lies between 0.1 and 0.6 times the continuum level. From the central wavelength defined by the redshift of the system, we measure the velocity range over which 90% of the apparent optical depth (Savage & Sembach 1991) is seen. We find $\Delta V_{90} = 79 \text{ km s}^{-1}$ as demonstrated in Fig. 5. Unsaturated lines typically have smaller velocity spreads relative to the Mg II lines, which may be composed of more components that contribute to the total line width due to their stronger transition.

5.2. Metallicities

Since the $\text{Ly}\alpha$ absorption lines corresponding to the Mg II systems lie in the absorbed parts of the QSO spectra, we cannot determine the metallicities as usually done for strong absorption systems. In the absence of an exact metallicity measurement for

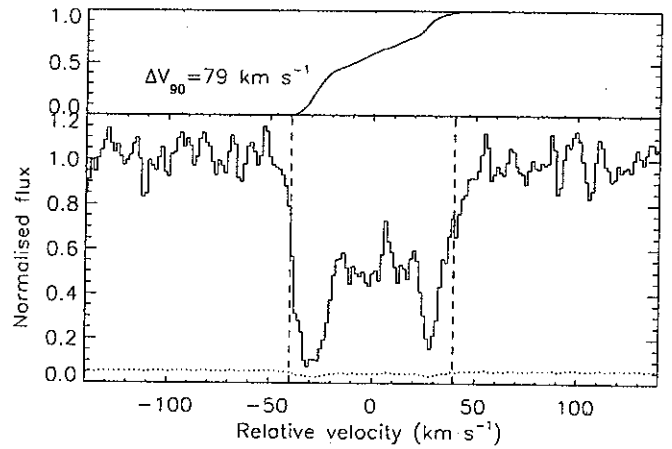


Fig. 5. The bottom panel shows the velocity profile of Fe II $\lambda 2374$ from the UVES data, and the dotted line shows the error spectrum. The upper panel demonstrates the integrated, normalised, apparent optical depth, and the vertical dashed lines in the spectrum indicate the wavelengths within which 90% of the absorption is seen.

the Mg II absorbers, we assume that the absorbing clouds are actually DLAs. Consequently, some derivations in this section are only valid if the objects are DLAs, for which the probability is 50%. In case the Mg II absorbers are sub-DLAs we point out the conclusions for this category. We use calibrations and scaling relations found for DLAs and sub-DLAs in the literature to derive the metallicities, and use the conventional notation of the metallicity $[M/H] \equiv \log[N(M)/N(H)] - \log[N(M)/N(H)]_{\odot}$.

A relation between the metallicity and velocity spread as measured by the ΔV_{90} parameter has been found for DLAs around $z = 2$ (Ledoux et al. 2006). Using this relation and the spread measured from the UVES data of Q1108, the metallicity of the galaxy is expected to be $[M/H] = -1.4 \pm 0.4$. A similar correlation exists for sub-DLAs, for which Dessauges-Zavadsky et al. (2009) suggest a $[\text{Fe}/H]$ metallicity which is larger by 0.4–0.6 dex for a given velocity spread. Using $[\text{Zn}/H]$ as a tracer of the sub-DLA metallicities, Meiring et al. (2009) find no correlation with velocity, but find systematically larger values for sub-DLAs relative to DLAs.

Another calibration uses the measured values of $W_r^{\text{Si II } \lambda 1526}$ which correlates with the metallicity in high redshift DLAs (Prochaska et al. 2008). To use this relation for the Mg II absorber towards Q1108 we need $W_r^{\text{Si II } \lambda 1526}$, but that line is strongly contaminated by other absorption lines in the $\text{Ly}\alpha$ forest of the QSO. Instead we use the observed relation which suggests that the widths of the lines roughly scale inversely with their wavelengths: $W_r^{\text{Mg II } \lambda 2796}/W_r^{\text{Si II } \lambda 1526} = 3$ (Prochaska et al. 2008). These relations suggest a metallicity $[M/H] = -1.0 \pm 0.1$ for the Mg II absorber in agreement with the previous metallicity estimate.

These low metallicities are typical for high redshift DLAs (Pettini et al. 1994; Prochaska et al. 2003). Observations have indicated that sub-DLAs have higher metallicities on the average (Péroux et al. 2003; Péroux et al. 2008; Meiring et al. 2009), while an investigation of the redshift dependence demonstrated that this is only true at lower redshifts ($z < 1.7$) (Dessauges-Zavadsky et al. 2009).

5.3. Expected galaxy magnitudes

We can estimate the magnitude for low metallicity galaxies if a luminosity metallicity relation exists for DLA galaxies (Ledoux et al. 2006), again assuming that the clouds are DLAs. A DLA galaxy with 10% solar metallicity is expected to be faint: $R \sim 26.1$ mag or $0.06L^*$ at $z = 2$ according to the metallicity–luminosity relation in Ledoux et al. (2006). Such a relation is valid provided the absorption lines velocity spread is used as a proxy for the dark matter halo circular velocity, and there is a direct relation between the halo mass and a galaxy luminosity (Haehnelt et al. 2000). In the case of a lower metallicity ($[M/H] = -1.8$) the galaxy would be even fainter: $R \sim 30$ mag. Extrapolating this relation to derive magnitudes for sub-DLAs with metallicities as large as $[M/H] = -0.4$ gives $R = 23.1$. As described in Sect. 3.1, the $U - R$ colour of galaxies at $z = 2$ depends on the age of the most recent dominant starburst, but generally blue colours are expected for young galaxies. Thus, the expected magnitude is $U \sim 26.6$ in the 10% solar metallicity case. Our survey is deeper than this limit, so we would be able to detect the continuum emission from the Mg II galaxies. The non detection of emission within $2''$ of line of sight is consistent with the very low metallicity case. If the cloud is a sub-DLA instead, a brighter host galaxy is possible, but since no bright galaxies are found close to the QSO lines of sight, it would have to have a large impact parameter.

Using instead the observed luminosity-metallicity relation either at low (Tremonti et al. 2004) or at higher redshift (Erb et al. 2006a), we rely on extrapolation of the observed relations and metallicities derived from emission line diagnostics. We assume that metallicities determined from emission and absorption lines are the same, and that there are no metallicity gradients. The luminosity metallicity relation in Tremonti et al. (2004) shifts by 0.35 dex in metallicity relative to the relation for galaxies at $z \sim 2$ (Erb et al. 2006a). This relation suggests that a 10% solar metallicity DLA galaxy has $U \sim 31$ mag, i.e. well below the detection limit of our data, while a 0.4 solar metallicity sub-DLA has $U \sim 28$ mag.

For the strong Mg II absorber towards Q1408, we can only estimate the metallicity from the $W_r^{\text{Mg II} \lambda 2796}$ calibration in Turnshek et al. (2005) and Murphy et al. (2007). This calibration gives $-0.9 < [M/H] < -0.7$, provided that the cloud is a DLA system. While higher resolution spectra are needed to investigate the velocity spread, the SDSS spectra indicate that the Mg II line of Q1408 has a width that is 20–30% lower than in Q1108. Hence the metallicity could be lower, and the absorbing galaxy should be fainter than that towards Q1108.

6. Discussion and summary

Using the absorption of background QSO light by intervening DLAs at $z > 3$, we look for the galaxies responsible for intervening strong Mg II systems at $z \approx 2$ along two lines of sight. The velocity spreads and equivalent widths of the absorption lines indicate that the strong Mg II systems are possible DLAs. Very deep images obtained for these two QSOs reveal no galaxies directly in the line of sight to a limiting magnitude of $U_{AB} = 28.0$. The most nearby objects are located at impact parameters of $\sim 5''$, corresponding to about 40 kpc at $z \approx 2$. While no point sources are found close to the lines of sight, we find evidence for the presence of a more extended structure in a smoothed U band image of the field of Q1408. This structure has a much smaller impact parameter of 0.8 or 7 kpc at $z \approx 2$. Such extended low

surface brightness objects would be impossible to detect after PSF subtraction of the bright background QSOs.

We consider two possible reasons for the non detections of nearby point sources. Either the galaxies are too faint, or the impact parameters are large. The first possibility, that the galaxies are very faint and below the detection limit, is in agreement with low metallicity absorbers. However, this hypothesis must be justified based on several assumptions and extrapolations.

Firstly, since the metallicities cannot be measured exactly because the Ly α absorption lines lie in the absorbed part of the QSO spectra, we have to rely on the correlation between DLA/sub-DLA metal-line velocity width and metallicity to estimate $[M/H]$. Secondly, we must assume that the objects are DLAs, and not LLS which generally have larger metallicities for a given absorption line width. Finally, we must extrapolate the metallicity luminosity relation observed for DLAs. These assumptions lead to an expected magnitude of the galaxy below the detection limit.

The closest galaxies to the line of sight of the QSOs are located at 40 kpc. They have luminosities of $0.03L^*$ and $0.3L^*$ corresponding to SFR of 0.5 and $4.9 M_\odot \text{ yr}^{-1}$, respectively for the Q1108 and Q1408 fields assuming that the redshifts are indeed $z \approx 2$. The luminosities are in agreement with Rao et al. (2003), who found that Mg II absorbers at $z < 1$ arise in $0.1 L^*$ galaxies, but in contrast to the results in O’Meara et al. (2006), who found brighter galaxies ($0.3 - 1.2L^*$ within 25 kpc) for two different fields at $z \approx 2$. In comparison, the strong Mg II galaxies which intervene the sight lines to GRBs are of similar luminosities than in the objects in the two FORS fields, but are typically found at smaller impact parameters (Pollack et al. 2009). The galaxies studied by O’Meara et al. (2006) could, however, be at lower redshift than the absorption systems. Spectroscopic confirmation in these four fields including ours would be of great interest. The SFRs we derive for the two fields are similar to those determined from spectroscopic observations of the galaxies responsible for strong Mg II systems at lower redshifts ($0.8 < z < 1$) (Bouché et al. 2007), but these galaxies are generally found at smaller impact parameters (20 ± 12 kpc).

While the impact parameters for the two closest objects are larger than the size of neutral gas discs in high redshift gas rich (proto-)galaxies as estimated in simulations (Nagamine et al. 2007), observational results in this area is still very limited. The kinematics of high redshift DLAs are inconsistent with a large rotating disc scenario (Zwaan et al. 2008). In order to explain the larger velocities of high redshift DLAs relative to local H I discs, there may be a population of DLAs that arise in starburst winds or from tidal interactions of galaxies, just as hypothesised for strong Mg II systems (Bond et al. 2001; Bouché et al. 2007). Clouds with DLA column densities can be located several tens of kpc from the galaxy centre as seen from observations (Ellison et al. 2007) which is also supported by simulations of the halos of massive galaxies at redshifts $z = 3$ (Pontzen et al. 2008).

In order to investigate whether the Mg II absorption systems are associated with the low luminosity galaxies at a considerable impact parameter, spectroscopic data of the galaxies are necessary, which is challenging due to their faintness. Nevertheless, the Ly α fluxes for pure emission line objects are within the reach of current spectrographs. Specifically, IFU observations are useful in the search for Ly α emission lines very near to the QSO lines of sight, and especially when the objects are extended. Such observations can simultaneously be used to determine the redshifts of the other galaxies within $10''$ of the line of sight to the QSOs.

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List of Objects

- 'Q0458-020' on page 2
- 'SDSS J110855+120953' on page 3
- 'SDSS J140850+020522' on page 3
- 'Q B2230+02' on page 7

Cume #345

4 (8) Questions; 90 Points Possible; 70 Points, 77%, Guaranteed Pass)
Given September 12, 2009

Uncovering strong Mg II absorbing galaxies: imaging below the Lyman limit

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(arXiv:0908.3893v1; M12015 MNRAS)

Please start each question (by number) on a new sheet of paper, write on only one side of the paper, and staple them together in order of question number when finished. It is strongly suggested that you read the abstract very carefully. I will also say that the § 1, Introduction, is very helpful.

1. [25 pts] The Lyman break and Lyman Break Technique [Hint: thinking about Figures 1 and 2 may be helpful].

(a) [10 pts] Consider a redshift $z = 0$ star-bursting galaxy, AGN, or quasar. Explain in your own words what a Lyman break feature in the spectrum of said galaxy, AGN, or quasar is. Include:

- What element is involved?
- What ionization stage of the element is involved?
- Exactly what physical process is occurring that gives rise to the break feature?
- At what wavelength does the break occur?
- What overall wavelength range does the feature extend over?

The Lyman break feature is due to the ionization from the ground state of neutral hydrogen. All photons with energies greater than the ionization potential of ground-state neutral hydrogen are capable of ionizing hydrogen. The energies are $E \geq hc/\lambda$, where $\lambda = 912 \text{ \AA}$. Thus, virtually all photons with wavelengths less than $912 \text{ \AA}$ are removed from the line of sight. The break refers to the rapid drop in or vanishing of transmitted (detected) flux below $912 \text{ \AA}$. For the break to occur, the column density of neutral hydrogen has to be very high, well above $10^{17.3} \text{ atoms cm}^{-2}$.

(b) [5 pts] Draw a picture of a spectrum, observed counts versus wavelength, and include a Lyman break. Be sure that your wavelengths are labeled properly. Label the break and/or the region over which the break extends.

See Figure 1, attached

(c) [10 pts] The Lyman break technique is an imaging method used to find high redshift galaxies, AGN, or quasars. In your own words, describe how the Lyman break technique is applied in practice. That is, for example, let's say you were searching for $z = 3$ galaxies, AGN, or quasars. How would you design and carry out your experiment and what would you look for as the signature of a $z = 3$ object? Be very specific about the wavelength(s) you are targeting for your observations.

At redshift $z = 3$, the Lyman break would be shifted to the observed wavelength $\lambda = 912(1+z) = 3648 \text{ \AA}$. That is, a $z = 3$ galaxy/AGN/QSO surrounded by optically thick neutral hydrogen will have an observed spectrum such that the flux below $3648 \text{ \AA}$ is virtually all absorbed due to the ionization of the hydrogen. The Lyman break technique involves imaging in a filter above the observed break wavelength and then again in a filter below this wavelength, usually the U band. One looks for "U-band drop outs", i.e., sources that appear in the redder filter(s) but are below detection levels in the U band filters. The drop out sources are candidate $z = 3$ galaxies!

2. [12 pts] The authors apply a variation of the Lyman break technique; they are looking for dim high redshift galaxies that lie in projection very near to a much brighter background quasar. In §2, Observations, the authors describe their selection method.

(a) [6 pts] Explain, briefly, the method that the authors employ, including how this exploits the presence of the Lyman break feature, and why it is powerfully effective for searching for these dim galaxies. Include in your answer:

- What critical role the $z \simeq 3$ damped Ly- α absorbers (DLAs) play?
- To maximize their search, why did they require DLAs? Why not some other type of absorption system (what physical quantity is important)?

The authors want to find galaxies that may lie in projection very very near to or directly in front of the quasar. The best way to do this is to try and block out the quasar light at observed wavelengths where the galaxies are expected to be bright. One way to block out the quasar light is to pick quasars having optically thick neutral hydrogen intervening to them at $z \simeq 3$. Damped Ly- α absorbers (DLAs) are perfectly suited, in that they create a Lyman limit with observed wavelength $\sim 3648 \text{ \AA}$. Then, galaxies where the Ly- α emission is strong for observed wavelengths below this observed break can be seen unobstructed by the vanished quasar light. Since Ly- α is at $1215 \text{ \AA}$, then galaxies at redshift $1215(1+z) < 3648$, or $z < 2.0$ will have strong emission where the observed quasar light is vanished. DLAs are required because the authors needed to be certain that the neutral hydrogen was very optically thick to ensure complete and total absorption of the quasar light below the observed break wavelength. The important physical quantity is the neutral hydrogen column density, or optical depth.

(b) [6 pts] Following the selection of the quasars, the authors have data that provides for them the redshifts of the galaxies they are trying to image.

- What are these data?
- How many galaxies are they trying to find?
- What are the redshifts of these galaxies?

It is well established that Mg II absorption in quasar spectra selects gas along the quasar line of sight that is associated with a galaxy. Thus, given the redshift of a Mg II absorber, one should expect to find a galaxy at that same redshift in the projected proximity to the quasar. There are two $z \simeq 2$ Mg II absorbers in the selected sample (by design of the experiment). See Table 1 of the paper. In Q1108, there is a Mg II absorber at $z = 1.869$, and in Q1408, there is a Mg II absorber at $z = 1.9816$. The authors are hoping to find the galaxies associated with these two Mg II absorbers.

3. [24 pts] Redshifted Absorption and Velocities

(a) [4 pts] Say you know there is a Mg II absorber at $z = 1.5$. If the rest-frame wavelength of Mg II is $2796 \text{ \AA}$, at what wavelength would you expect to observe the Mg II $\lambda 2796$ absorption profile?

The observed wavelength is $\lambda_{\text{obs}} = \lambda_{\text{rest}} \cdot (1+z) = 2796(1+1.5) = 6990 \text{ \AA}$.

(b) [10 pts] Lets say that the above profile has a full rest-frame velocity spread of 100 km/s . What is the observed wavelength range over which you expect to see the absorption. [HINT: careful, remember this system is at $z = 1.5$.]

The Doppler formula is $\Delta v/c = \Delta \lambda/\lambda$. This, of course, applies in the rest-frame. Thus, $\Delta \lambda_{\text{rest}} = (100/c) \cdot 2796 = 0.932 \text{ \AA}$. To obtain the observer's frame wavelength spread, we multiply by $1+z$. Thus, $\Delta \lambda_{\text{obs}} = 2.5 \cdot 0.932 = 2.33 \text{ \AA}$. This is the expected wavelength range. If we assume that the velocity spread is symmetric, the observed wavelength range is $6990 \pm 0.5 \Delta \lambda_{\text{obs}}$, giving $6988.83\text{--}6991.16 \text{ \AA}$.

(c) [10 pts] Now reverse the question. You see an absorption line centered at wavelength $5000 \text{ \AA}$ and you identify the line as Mg II $\lambda 2796$. The observed wavelength spread across the profile is $5 \text{ \AA}$. What is the rest-frame velocity spread of the Mg II absorbing gas.

The observed wavelength is obtained from $\lambda_{\text{obs}}/\lambda_{\text{rest}} = (1+z)$, which yields $z = 0.78$. The rest-frame wavelength spread is $\Delta \lambda_{\text{rest}} = \Delta \lambda_{\text{obs}}/(1+z) = 5/1.78 = 2.8 \text{ \AA}$. Thus, the rest-frame velocity is $\Delta v = c \cdot (2.8/2796) = 300 \text{ km/s}$.

4. [29 pts] The ΔV_{90} parameter.

(a) [4 pts] In words, what is the ΔV_{90} parameter.

Per the words of the authors, ΔV_{90} is "the velocity range over which 90% of the apparent optical depth is seen." We define the apparent optical depth below for part (c).

(b) [5 pts] Let's say that you measured ΔV_{90} for a redshifted Mg II $\lambda 2796$ profile in some data you obtained. From the information given in *this* paper alone, could you estimate $[M/H]$ for the absorbing gas? If not, which reference(s) mentioned in the paper would you need to examine in order to find the information required to make the estimate?

NO. In this paper, the authors do not supply the conversion formula. Assuming that the Mg II absorbers are DLAs, you would need to examine the paper by Ledoux et al. (2006). Assuming that the Mg II absorbers are sub-DLAs, you would need to consult the paper by Dessauges-Zavadsky et al. (2009).

(c) [20 pts] Ok, backing up one step. Let's say that you have a Mg II $\lambda 2796$ profile in some data you obtained and you want to measure ΔV_{90} . To your chagrin, this paper, nor any of the papers in the literature anywhere provide an equation or describe the method on how to compute ΔV_{90} . Thus, you need to determine how to make the calculation on your own (this scenario is common in research). Derive an expression for ΔV_{90} in terms of the cut off velocities v_+ and v_- so that you can therefore make the calculation.

[HINTS: Lets say that the word "absorption" translates to the quantity known as the flux decrement, $1 - f(v)/f_c(v)$, where $f(v)$ is the observed flux at velocity v , and $f_c(v)$ is the continuum (unabsorbed) flux at velocity v . You do not need to know the form of $f(v)$; you are not being asked to evaluate your relationship. Also, examine Figure 5, where the vertical dashed lines illustrate the locations of $v_+ = +40$ and $v_- = -40$ km/s. There is more than one way to write this expression. Partial credit will be given for correct mathematical ideas and written explanations.]

You must determine the velocities v_- and v_+ such that when you add up the absorption strength between these velocities, you obtain 90% of the total absorption strength. What's more, the definition is clearly designed so that 5% of the absorption is cut off outside v_- and 5% outside of v_+ . Assuming "absorption" translates to $1 - f(v)/f_c(v)$, one possible definition is:

$$\frac{\int_{-\infty}^{v_-} [1 - f(v)/f_c(v)] dv}{\int_{-\infty}^{\infty} [1 - f(v)/f_c(v)] dv} = 0.05 \quad \frac{\int_{v_+}^{\infty} [1 - f(v)/f_c(v)] dv}{\int_{-\infty}^{\infty} [1 - f(v)/f_c(v)] dv} = 0.05 \quad (1)$$

Using expressions of this type, you would then need to "hunt and peck" to find the v_- and v_+ that solve these equations. Note that there is one unknown per equation. It is not uncommon to have the unknown variable be a limit of integration. In practice, one would root solve these equations. Given these integrals, it is probably not too difficult to imagine slightly different definitions that yield the values of v_- and v_+ . Once these velocities are determined, we have $\Delta v_{90} = v_+ - v_-$. In reality, the definition is based upon the "apparent optical depth", which is determined from inverting $f(v)/f_c(v) = \exp(-\tau_v)$. The apparent optical depth is then $\tau_v = \ln[f_c(v)/f(v)]$. For the proper calculation, the quantity $1 - f(v)/f_c(v)$ is replaced with $\ln[f_c(v)/f(v)]$ in the above integrals. Can you see the problem if the profile becomes saturated, so that $f(v) = 0$. How would *you* handle this in practice?

Fig 1.

