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N. H.M. Crighton  
*Durham University*

R. Bielby  
*Durham University*

T. Shanks  
*Durham University*

L. Infante  
*Pontificia Universidad Católica de Chile*

C. G. Bornancini  
*Instituto de Astronomia Teorica y Experimental*

*See next page for additional authors*

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The VLT LBG Redshift Survey* – II. Interactions between galaxies and the IGM at $z \sim 3$

N. H. M. Crighton, 1† R. Bielby, 1,2 T. Shanks, 1 L. Infante, 3 C. G. Bornancini, 4,5 N. Bouché, 6 D. G. Lambas, 4,5 J. D. Lowenthal, 7 D. Minniti, 3,8 S. L. Morris, 1 N. Padilla, 3 C. Péroux, 9 P. Petitjean, 2 T. Theuns, 10,11 P. Tummuangpak, 1 P. M. Weilbacher, 12 L. Wisotzki 12 and G. Worseck 13

1 Department of Physics, University of Durham, South Road, Durham DH1 3LE
2 Institut d’Astrophysique de Paris, UMR7095 CNRS, Université Pierre et Marie Curie, 98 bis Bld Arago, 75014 Paris, France
3 Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile
4 Instituto de Astronomía Teórica y Experimental, IATE, Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, X5000BGR Córdoba, Argentina
5 Consejo Nacional de Investigaciones Científicas y Técnicas, Avenida Rivadavia 1917, C1033AAP Buenos Aires, Argentina
6 Department of Physics, University of California, Santa Barbara, CA 93106, USA
7 Department of Astronomy, Smith College, Northampton, MA 01063, USA
8 Vatican Observatory, V00120 Vatican City State, Italy
9 Laboratoire d’Astrophysique de Marseille, OAMP, Université Aix-Marseille & CNRS, 13388 Marseille cedex 13, France
10 Institute of Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE
11 Department of Physics, Universiteit Antwerpen, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium
12 Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
13 Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, USA

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ABSTRACT

We have measured redshifts for 243 $z \approx 3$ quasars in nine Very Large Telescope (VLT) Visible Imaging and Multi-Object Spectrograph (VIMOS) Lyman-break galaxy (LBG) redshift survey areas, each of which is centred on a known bright quasar. Using the spectra of these quasars, we measure the cross-correlation between neutral hydrogen gas causing the Ly$\alpha$ forest and 1020 LBGs at $z \approx 3$. We find an increase in neutral hydrogen absorption within $\approx 5 h^{-1}$ Mpc of a galaxy in agreement with the results of Adelberger et al. The Ly$\alpha$–LBG cross-correlation can be described by a power law on scales larger than $3 h^{-1}$ Mpc. When galaxy velocity dispersions are taken into account, our results at smaller scales ($< 2 h^{-1}$ Mpc) are also in good agreement with the results of Adelberger et al. There is little immediate indication of a region with a transmission spike above the mean intergalactic medium value which might indicate the presence of star formation feedback. To measure the galaxy velocity dispersions, which include both intrinsic LBG velocity dispersion and redshift errors, we have used the LBG–LBG redshift-space distortion measurements of Bielby et al. We find that the redshift-space transmission spike implied in the results of Adelberger et al. is too narrow to be physical in the presence of the likely LBG velocity dispersion and is likely to be a statistical fluke. Nevertheless, neither our nor previous data can rule out the presence of a narrow, real-space transmission spike, given the evidence of the increased Ly$\alpha$ absorption surrounding LBGs which can mask the spike’s presence when convolved with a realistic LBG velocity dispersion. Finally, we identify 176 C$\ IV$ systems in the quasar spectra and find an LBG–C$\ IV$ correlation strength on scales of $10 h^{-1}$ Mpc consistent with the relation measured at $\approx $Mpc scales.

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†E-mail: neil.crighton@durham.ac.uk

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1 INTRODUCTION

The interaction between galaxies and the surrounding intergalactic medium (IGM) is a crucial component of galaxy formation. The majority of baryons at $z \sim 3$ reside in the IGM (e.g. Pettitjean et al. 1993; Miralda-Escudé et al. 1996; Schaye 2001). It is from this reservoir of gas that galaxies draw fuel for star formation.

Star formation and active galactic nuclei (AGN) are in turn believed to have a significant effect on the IGM. Winds generated by supernovae in starburst events are observed to eject the interstellar medium (ISM) with velocities of hundreds of $\text{km s}^{-1}$ with respect to the host galaxy (Veilleux, Cecil & Bland-Hawthorn 2005) and are believed to be able to influence the IGM more than 100 kpc away from the galaxy (e.g. Wilman et al. 2005). Jets from AGN have been observed to extend hundreds of kpc from their host galaxy. There is considerable evidence for winds being commonplace in star-forming galaxies at $z \sim 3$. The spectra of Lyman-break galaxies (LBGs, so called because they are selected by their drop in flux at rest-frame 912 Å) show a systematic velocity offset between their Ly$\alpha$ emission features, absorption features (such as C iv, Si iv) and nebular emission features (such as H$eta$). Absorption features that are associated with the galaxy’s ISM are blueshifted by 200–300 $\text{km s}^{-1}$ with respect to the true position of the galaxy, assumed to be given by the nebular emission features (Pettini et al. 2001). This blueshift is interpreted as an outflow velocity: the metal-enriched ISM gas is being pushed out of the galaxy towards the surrounding IGM. Metal-enriched gas has also been observed up to $\sim 80$ kpc around $z \approx 2.3$ LBGs, consistent with models for accelerating outflows (Steidel et al. 2010).

This motion of matter and energy into the IGM is also an important requirement for simulations of galaxy formation, where it is needed to regulate star formation. Feedback from supernovae in starbursts is required in semi-analytic models to reproduce the faint end of the present-day galaxy luminosity function (e.g. Baugh et al. 2005). Hydrodynamical simulations have also shown that such winds can enrich the IGM with metals to levels required by observations (e.g. Theuns et al. 2002; Oppenheimer & Davé 2006).

LBGs close to background quasar sightlines allow us to measure the gas properties of the IGM close to galaxies and search for any direct evidence of feedback and winds at $z \sim 3$. Adelberger et al. (2003, 2005, hereafter A03 and A05 respectively) pioneered the first of these analyses. By measuring the cross-correlation between H$_1$ Ly$\alpha$ absorption and nearby LBGs, they showed that there is more Ly$\alpha$ absorption within $5 h^{-1} \text{Mpc}$ of LBGs compared to the mean absorption level. This was interpreted as clustering of H$_1$ gas around the galaxies, consistent with LBGs being found in overdense regions. For a significant fraction of LBGs within $1 h^{-1} \text{Mpc}$ of a quasar sightline, however, the observed absorption decreased substantially. This was interpreted as the background quasar sightline intercepting a bubble of ionized gas around some LBGs, possibly due to star formation feedback from these galaxies heating their surrounding IGM.

Winds were not expected to have such a large effect on the neutral hydrogen surrounding LBGs. Using a smoothed particle hydrodynamical (SPH) simulation, Theuns et al. (2002) found that winds had little effect on nearby H$_1$ absorption because they tended to deposit their energy into low density regions around the galaxy, leaving much of the H$_1$ gas undisturbed in filamentary structures. Subsequent theoretical SPH models (e.g. Bruscoli et al. 2003; Kollmeier et al. 2003, 2006; Kawata & Rauch 2007) were also unable to reproduce the distribution of H$_1$ absorption close to LBGs measured by A03 and A05 without invoking exotic scenarios. Semi-analytic models (e.g. Desjacques et al. 2004; Bertone & White 2006) were able to reproduce the distribution, but these assumed spherical symmetry, and so sidestepped the above geometrical considerations.

Uncertainties in the galaxy redshift or Ly$\alpha$ absorption redshift can have a large influence on their cross-correlation at small scales. Such uncertainties are caused by redshift measurement errors and any intrinsic velocity dispersion between the galaxies and nearby absorbing H$_1$ gas. If there is a narrow feature in the real-space cross-correlation, it will be suppressed by velocity dispersions when it is measured in redshift space. It is important to include these effects when attempting to reconstruct the real-space correlation function from that measured in redshift space.

We have undertaken a programme to observe LBGs with the Visible Imaging and Multi-Object Spectrograph (VIMOS) on the Very Large Telescope (VLT). This programme will assemble a spectroscopic sample of $z \sim 3$ LBGs over nine fields, each chosen to be centred on a bright ($R \sim 18$) background quasar with an emission redshift of $\geq 3$, most of which have archived echelle spectra available. The total area covered by the nine fields is $\sim 3.17$ deg$^2$, corresponding to 45 VIMOS pointings. In addition to the central bright background quasar, we have assembled a further spectroscopic sample of $R \sim 19–20, z \sim 3$ quasars in each field. With these data, we intend to measure the galaxy–galaxy and galaxy–IGM clustering properties at redshifts of $\sim 2.5–3$. We shall both extend the A03, A05 data samples to larger LBG–LBG and Ly$\alpha$–LBG transverse separations and increase the number of known small separation LBG–quasar sightline pairs at $z \sim 3$.

In this paper we present spectroscopy of the quasars inside and around our LBG fields, describe the selection of quasar candidates and list the new quasars we have identified. Our analysis focuses on the small-scale correlations between LBGs and the Ly$\alpha$ forest at separations of $<10 h^{-1} \text{Mpc}$. We compare our results to simple models and the results of A03 and A05. The paper is structured as follows. In Sections 2 and 3, we describe the galaxy and quasar samples used in our analysis. In Section 4, we describe the quasar spectra. Sections 5 and 6 present measurements of the C iv–LBG cross-correlation and Ly$\alpha$ autocorrelation, respectively. Section 7 presents the main result of our paper, the cross-correlation between Ly$\alpha$ transmissivity and LBGs. Section 8 summarizes the main findings of the paper.

We assume a cosmology with $\Omega_m = 0.3, \Omega_\Lambda = 0.7$ and $H_0 = 100 h \text{km s}^{-1} \text{Mpc}^{-1}$, where $\Omega_m$ and $\Omega_\Lambda$ are the ratios of the matter density and cosmological constant energy density to the critical density. Unless stated otherwise all distances are comoving, and magnitudes use the AB system or asinh system for Sloan Digital Sky Survey (SDSS) magnitudes.

2 GALAXY SAMPLE

We obtained galaxy spectra for this project using the VIMOS multi-object spectrograph on the VLT. A detailed description of the LBG selection and sample properties is given by Bielby et al. (2011).
The nine central bright quasars around which LBG fields were targeted. The fourth and fifth columns give the emission redshift and a rough estimate of the quasar magnitude. The last three columns give the instrument, principal investigator and unique ID number for the archived observations where they are available.

| Name            | RA (J2000) | Dec. (J2000) | z  | Mag.  | Instrument | PI   | ID      |
|-----------------|------------|-------------|----|-------|------------|------|---------|
| Q2359+0653      | 00:01:40.6 | +07:09:54   | 3.23 | V = 18.5 | HIRES     | Chaffee | K01H    |
| Q0042−2627      | 00:44:33.95 | −26:11:19.9 | 3.289 | B$_r$ = 18.47 | UVES     | Bouché | 073.A-0653 |
| J0124+0044      | 01:24:03.78 | +00:44:32.7 | 3.83 | g = 19.2  | UVES     | Prochaska | U11H  |
| Q0301−0035      | 03:03:41.05 | −00:23:21.0 | 3.23 | g = 17.6  | HIRES     | Prochaska | U11H  |
| HE0940−1050     | 09:42:53.50 | −11:04:25.9 | 3.06 | B = 17.2  | UVES     | Bergeron | 166.A-0106 |
| J1201+0116      | 12:01:44.37 | +01:16:11.7 | 3.233 | g = 17.7  | HIRES     | Prochaska | U012Hb |
| PKS 2126−158    | 21:29:12.15 | −15:38:40.9 | 3.268 | V = 17.3  | UVES     | Bergeron | 166.A-0106 |
| Q2331−0015      | 22:34:08.99 | +00:00:01.7 | 3.02 | r = 17.29 | UVES     | D’Odorico | 65.O-0296 |
| Q2348−0111      | 23:50:57.9  | −00:52:10   | 3.0235 | r = 18.68 | UVES     | Ubachs | 079.A-0404 |

In short, galaxies were selected using the Lyman break technique (e.g. Steidel et al. 1996), yielding a sample with 2.2 < z < 3.5. Deep UBR or UBVRI imaging was used to select LBG candidates, and these candidates were observed with the VIMOS multi-object spectrograph at a resolution of 180. In this paper, we use the initial set of LBG data presented by Bielby et al. It contains 1020 LBGs with spectroscopic redshifts z > 2 spread across 19 VIMOS pointings in a total area of 1.44 deg$^2$, over five of the nine fields that make up the complete survey area.

For our present analysis, we are most concerned with uncertainties on the measured LBG redshifts. There are several contributions to the redshift uncertainty; Bielby et al. quoted ~150 km s$^{-1}$ due to the wavelength calibration, ~450 km s$^{-1}$ from centroiding the Ly$_\alpha$ emission lines and ~200 km s$^{-1}$ uncertainty in transforming from the emission and absorption redshifts to the intrinsic galaxy redshift. They estimated a total error of ~500 km s$^{-1}$ in their measured intrinsic LBG redshifts, corresponding to $\Delta z = 0.007$ at $z = 3$.

3 QUASAR SAMPLE

Our quasar sample consists of R < 22 quasars with emission redshifts 2 < z < 4 in and around five LBG fields where we have reduced galaxy spectra and in four further fields that have as yet unreduced LBG observations. These consist of the following.

(1) Bright quasars at the centre of each LBG field. The LBG fields were chosen to be located around bright quasars with emission redshifts 3 < $z_{em}$ < 4 and over a wide right ascension range to enable observations to be made throughout the year. The central quasars in the five LBG fields analysed in this paper are Q0042−2627, J0124+0044, HE0940−1050, PKS 2126−158 and J1201+0116, respectively. Archived echelle spectra taken using the Ultraviolet Echelle Spectrograph (UVES) on the VLT or the High Resolution Echelle Spectrometer (HIRES) on the Keck Telescope exist for most of these quasars. The echelle spectra have a resolution of >30 000 and hence resolve the linewidths of H$\alpha$ lines in the Ly$_\alpha$ forest. There are four further fields where we will soon obtain LBG redshifts, around the central bright quasars Q0301−0035, Q2231−0015, Q2348−011 and Q2359+0653. Details for all nine central bright quasars are given in Table 1.

(2) Previously known quasars in and around each field. In addition to the central bright quasars, we searched for any other known quasars with the appropriate redshift and magnitude in either the NASA Extragalactic Database (NED)\(^1\) or the survey by Worseck, Wisotzki & Selman (2008).

We conducted a spectroscopic quasar survey targeting previously known quasars and quasar candidates using the AAOmega spectrograph on the Anglo-Australian Telescope. AAOmega is a fibre-fed, multi-object spectrograph (Saunders et al. 2004; Smith et al. 2004; Sharp et al. 2006) with a resolution of 1300 for the 385 fibres we used during most of our observations. In a single pointing, up to 400 fibres can be targeted on objects over a circular field of view with a radius of 1°.

3.1 Quasar selection for our AAOmega survey

To cross-correlate LBG positions with quasar absorption, we need background quasars with an emission redshift such that the Ly$_\alpha$ forest overlaps the redshift range of our LBG sample and a bright enough magnitude to obtain the signal-to-noise ratio (S/N) required to measure Ly$_\alpha$ forest absorption. An emission range of 2.5 < $z_{em}$ < 4 satisfies the first constraint – at lower redshift only a small portion of the forest remains above the atmospheric cut-off and at higher redshift the higher order Lyman transitions and Lyman limit absorption from redshifts of >4 make it difficult to identify Ly$_\alpha$ absorption at the LBG redshifts. We chose a magnitude limit for candidates of R = 22; this was motivated by the S/N achievable over the Ly$\alpha$ forest in several hours of exposure using AAOmega. Wolf et al. (2003) estimated a sky density for quasars with z > 2.2 and $R_{Vega}$ < 22 of ~40 deg$^{-2}$; thus, we anticipated that there would be up to ~10 such quasars inside one of our typically 0.5 x 0.5 deg$^2$ LBG fields.

To select candidates, we used the theoretical quasar tracks in ugr colour space from Fan (1999, see his fig. 13) as a guide. Our criteria for candidates were that they (1) should be point-like, (2) should be outliers in ugr colour space from the stellar locus, with the expected colours for 2.5 < z < 4.0 quasars, and (3) should have r < 22. The first two criteria are known to select quasars with redshifts of >3.0 with a relatively high completeness and efficiency for targets with i < 20.8 selected using SDSS imaging (Richards et al. 2002, but see also Worseck & Prochaska 2011). For 2.5 < z < 3.0, the expected position of quasars in ugr colour space overlaps with A, F and

\(^1\) http://nedwww.ipac.caltech.edu/
horizontal giant branch stars, making efficient selection difficult. In an attempt to find a significant number of the available quasars in this redshift range, we included objects as close to the stellar locus as was possible without introducing an unacceptably large level of contamination. However, the efficiency of our quasar selection in this range is poor.

When possible, we checked that any known quasars in our fields were recovered by our selection process. This sometimes led us to adjust our colour cuts to ensure that known quasars in the desired redshift range were included using our selection criteria. We also adjusted colour cuts to provide a sufficiently high sky density of targets (~600 over the AAOmega field of view) that allowed CONFIGURE, the software used to assign objects to the AAOmega fibres, to maximize the number of fibres used. Due to restrictions on fibre placement, not all possible candidates could be observed. In general we prioritised brighter quasar candidates with \( r < 21.5 \), those with photometric redshift estimates and those close to areas where LBG redshifts were to be measured.

Finally, for repeat observations of the same field we performed an initial identification of objects in the first set of observations. Any targets that could not be identified as quasars in the required redshift range were removed and replaced with new candidates for subsequent observations. If this exhausted our candidate list in a field, we adjusted the colour cuts closer to the stellar locus to provide more candidates.

### 3.1.1 Selection of quasars overlapping the LBG fields

To select quasars overlapping the LBG fields, we generally used the same UBR or UBV imaging that was used to select the LBG candidates (see Table 2). Selections in the central fields around Q0042−2627, Q0301−0035, J0124+0044, J1201+0116, PKS 2126−158 and Q2359+0653 were performed using the imaging data from the Mosaic cameras at Kitt Peak National Observatory (KPNO) and the Cerro-Tololo Inter-American Observatory (CTIO) described by Bielby et al. (2011). This imaging covers a 32 × 32 arcmin\(^2\) region around the central quasar. We used archived imaging taken with the Wide Field Camera on the Isaac Newton Telescope (INT) for the Q2231−0015 field. SExtractor (Bertin & Arnouts 1996) catalogues were generated from the images. For the HE 0940−1050 and Q2348−011 fields, the central field selection was performed using archived ugr imaging data from the MegaCam instrument at the Canada–France–Hawaii Telescope (CFHT) rather than the Mosaic imaging used to select LBGs. The MegaCam data reach a similar depth to the Mosaic data, but extend over a larger field of view, 1° × 1°.

The colour cuts we used to select quasar candidates varied slightly between fields, depending on the quality of the imaging, how well the photometric zero-points had been measured and the filters used. As an example, the cuts for the MegaCam images in the HE 0940−1050 field were

\[
\begin{align*}
(i) & \quad 18 < r < 22; \\
(ii) & \quad g - r < 1.1; \\
(iii) & \quad g - r < 0.54 (u - g) - 0.35 \text{ or } g - r < 0.15; \\
(iv) & \quad u - g > 0.6.
\end{align*}
\]

They are shown in the left-hand panel of Fig. 1 as dashed lines, along with similar cuts for the other field with central MegaCam imaging, Q2348−011. Candidates were required to be detected in \( g \) and \( r \), but we included candidates undetected in \( r \) if they satisfied the above criteria. The precise selections used for the Mosaic data are given by Bielby et al. (2008).

In total, we obtained spectra of 50 quasars overlapping the LBG fields in addition to the nine central bright quasars. Closed triangles in Fig. 1 show such quasars in the cases of the HE 0940−1050 and Q2348−011 fields. Across all nine fields, 30 of these 50 were previously unknown quasars uncovered using the above selection process; the remainder were previously known. The total LBG area is 3.17 deg\(^2\), over which we obtained a quasar sky density of \( \sim 18.6 \text{ deg}^{-2} \).

In the five fields we use for the cross-correlation analysis, there are 16 quasars. All of these were previously known. The Q0042−2627 field has been searched for quasars by Williger et al. (1996), and the HE 0940−1050 and PKS 2126−158 fields by Worseck et al. (2008), leaving few new quasars to be found. However, our sky densities in these fields are also low compared to other fields in the LBG area; the five fields cover 1.44 deg\(^2\), giving a density of 11.1 deg\(^{-2}\), much lower than the 18.6 deg\(^{-2}\) above. This lower density is in part due to the absence of any new candidates.

| Field     | Source | Central imaging | Surrounding imaging |
|-----------|--------|-----------------|---------------------|
|           | Source | Bands          | Area                | Depth | Source | Bands          | Depth   |
| Q2359+0653| Mosaic | UBR            | 32 × 32 arcmin\(^2\) | \( R = 25 \) | Schmidt | BR            | \( R = 21 \) |
| Q0042−2627| Mosaic | UBR            | 32 × 32 arcmin\(^2\) | \( R = 24.7 \) | Schmidt | BR            | \( R = 21 \) |
| J0124+0044| Mosaic | UBV            | 32 × 32 arcmin\(^2\) | \( I = 24.5 \) | SDSS Stripe 82 | ugriz | \( r = 24.7 \) |
| J0301−0035| Mosaic | UBV            | 32 × 32 arcmin\(^2\) | \( R = 25 \) | SDSS Stripe 82 | ugriz | \( r = 24.7 \) |
| HE 0940−1050| MegaCam | ugriz        | 1° × 1°             | \( r = 24.7 \) | Schmidt | UBR           | \( R = 21 \) |
| J1201+0116 | Mosaic | UBR            | 32 × 32 arcmin\(^2\) | \( R = 25.5 \) | SDSS | ugriz | \( r = 22.6 \) |
| PKS 2126−158| Mosaic | UBR            | 32 × 32 arcmin\(^2\) | \( R = 24.7 \) | Schmidt | UBR | \( R = 21 \) |
| Q2321−0015 | WFC   | UBR            | 32 × 32 arcmin\(^2\) | \( r = 25 \) | SDSS | ugriz | \( r = 22.6 \) |
| Q2348−011  | MegaCam | ugriz        | 1° × 1°             | \( r = 25 \) | SDSS Stripe 82 | ugriz | \( r = 24.7 \) |

For the J0124+004 field, we selected targets in the central region from an object catalogue generated from Mosaic imaging [see Bielby et al. (2011) and Bouche & Lowenthal (2004) for details].
quasars in the J0124+0044 central area beyond the central bright quasar. We are unsure of the reason for this. However, similarly large areas with very few quasars are present in the Q0301−0035 and Q2348−011 fields, which have deep Stripe 82 imaging across the entire AAOmega field. Clustering may be responsible for the clumpy quasar distribution, and it may simply have been unfortunate that a region largely empty of quasars occurs in the J0124+0044 LBG area.

3.1.2 Selection of quasars around the LBG fields

There were not enough quasar candidates overlapping each LBG area to employ all the AAOmega fibres, so we searched for candidates outside each LBG area over the full 3.1-deg² AAOmega field of view. Our motivation for finding quasars with angular separations of tens of arcminutes from LBGs was not to look for the effects of feedback – the IGM probed is much further from the LBGs than the distances across which winds are expected to have a significant effect. However, with a large number of z ~ 3 quasars over a few deg², we can measure correlations in metal or forest absorption on scales of tens of Mpc due to large-scale structure (Williger et al. 2000), constrain the 3D topology of the IGM (Pichon et al. 2001) and measure large-scale anisotropies in the 2D LBG–Lyα correlation function caused by velocity dispersion and infall. These projects are beyond the scope of our current analysis, but our quasar sample provides a valuable resource for future studies.

The deep imaging used to select LBGs does not extend across the full AAOmega field of view, so we used different imaging sources to select candidates outside the central LBG regions. For the J0124+0044, Q0301−0035, J1201+0116, Q2231−0015 and Q2348−011 fields, we used single-epoch SDSS ugr imaging catalogues. Quasar candidates were selected in three ways. First, we targeted any of the photometrically selected quasar candidates from Richards et al. (2004, 2009) with appropriate photometric redshifts. Secondly, we used the SDSS pipeline classifications (Richards et al. 2002): objects were classified in the SDSS reduction pipeline as quasar candidates based on their colours, stellar/non-stellar classification and radio detection. Only candidates with i < 20.2 were followed up for spectroscopy by the SDSS, leaving many fainter candidates without spectra. Any of these with colours consistent with our desired redshift range were added to our target list. Finally, we selected additional candidates not already selected by the above two methods using our own ugr colour cuts. Fig. 2 shows colour–colour plots for these five fields with single-epoch SDSS imaging. The points and contours show SDSS stellar objects, and the ugr selection cuts we used are shown by dashed lines. Quasars we observed, both previously known and newly discovered, inside and outside the LBG areas, are shown as triangles and circles.

Three of our equatorial fields (J0124+0044, Q0301−0035 and Q2348−011) overlap the Stripe 82 region, where repeat SDSS observations were taken for the Supernova Survey (Frieman et al. 2008). In these fields, we selected candidates using catalogues generated by combining the multi-epoch imaging. For J0124+0044 and Q2348−011, we offset the AAOmega pointing centre from the central bright quasar to maximize overlap with the Stripe 82 catalogue. The ugr cuts used to select candidates from the Stripe 82 catalogues are shown by dashed lines in Fig. 3. These cuts were modified slightly from those used on other imaging catalogues to include a box with 0.5 < u − g < 0.75 and 0.2 < g − r < 0.4, based on the colours of the photometrically selected targets from Richards et al. (2009).

Where SDSS imaging was not available (Q0042−2627, HE 0940−1050, PKS 2126−158 and Q2359+0653 fields), we used B and R catalogues generated from Schmidt photographic plates processed by the automated plate measuring machine. For the HE 0940−1050 and PKS 2126−158 fields, we also had access to Schmidt U catalogues. Candidates were selected using similar criteria to the central areas where U imaging was available or using only B − R cuts otherwise.

In total, we obtained spectra for 193 z > 2.2 quasars outside the LBG areas. 134 of these are newly discovered: 31 photo-z candidates from single-epoch SDSS imaging, 21 selected from deep LBG imaging that extended beyond the LBG areas, 40 using ugr cuts with Stripe 82 imaging, 28 selected using similar cuts to single-epoch SDSS imaging and the remaining 14 from Schmidt imaging.

3.2 Catalogue of quasars found in the AAOmega survey and completeness

Our AAOmega survey obtained spectra of 243 z > 2.2 quasars, of which 164 are newly discovered. The number of quasars found per field and their selection source are given in Table 3, and their details

Figure 1. Colour cuts used for 1° × 1° CFHT MegaCam data in the HE 0940−1050 and Q2348−011 fields. Grey points and contours show all stellar objects (XTRACTOR CLASS_STAR > 0.85) with r < 22. Objects below the borders marked by the dashed line were selected as quasar candidates. Triangles show known quasars with z ≥ 2.5 and circles show quasars with 2.2 ≤ z < 2.5. Open triangles are quasars outside the area where we have LBG observations; solid triangles are quasars overlapping the LBG fields on the sky.
Figure 2. Colour cuts for used for single-epoch SDSS data in the J0124+0044, Q0301–0035, J1201+0116, Q2231–0015 and Q2348–011 fields. Objects classified by the SDSS pipeline as stellar with $r < 22$ are shown by the grey points and contours. Objects below the borders marked by the dashed line were selected as quasar candidates. The solid line shows the region used to select candidates for the efficiency calculations in Appendix A. Triangles show known quasars with $z > 2.5$ and circles known quasars with $2.2 < z < 2.5$. Several of these quasars were classified in SDSS single-epoch imaging as non-stellar; they are shown by black circles and black triangles. They were included in our sample because of alternative selection criteria.

are given in Table C1. Their magnitude and redshift distributions are shown in Fig. 4. Some quasars with $2.1 < z < 2.5$ were also recovered by our selection criteria for $z > 2.5$ quasars. Even though little of their Ly$\alpha$ forest is observable above the atmospheric cutoff, they are still useful for other purposes such as identifying C IV absorption near LBGs or cross-correlating AGN with LBGs. There are also 10 faint $R \gtrsim 22$ quasars overlapping the LBG areas in Table C1 that we discovered in our VIMOS observations. We do not use these in the present analysis; they are described further by Bielby et al. (2011).

The right ascension and declination of quasars and LBGs in each field are shown in Figs 5–7. It is apparent from these figures that our quasar sample is not uniformly distributed on the sky. This is mostly due to the variable imaging depths used in the different fields; few quasars were found outside the LBG regions in the J1201+0116 and Q2359+0653 fields, where only Schmidt imaging was available, but we achieved a much higher density in the J0124+0044, Q0301–0035 and Q2348–011 fields where Stripe 82 imaging was available across the entire field. However, as we remarked earlier, there are large regions free from quasars even in areas where we have deep imaging. This may be due in part to large-scale structure and quasar clustering.

We can roughly estimate our sample’s completeness—the fraction of the total number of quasars in our redshift range and to the magnitude limits we have recovered—by comparing our sky densities to those for the COMBO-17 quasar survey (Wolf et al. 2003). Wolf et al. measured the number density of $R_{\text{Vega}} < 22$ quasars with $z > 2.2$ to be $\sim 40$ per deg$^2$. In Fig. 8 we show the cumulative sky densities for quasars in the central region of each of our nine fields, where deep imaging was used to select quasar candidates, compared to the incompleteness-corrected sky densities found by Wolf et al. (see their table 3). Up to $R = 21$, our densities are consistent, suggesting that our completeness is high. At $R = 22$, our sky densities drop to 50 per cent of those found by Wolf et al., suggesting that we recover only 50 per cent of these fainter quasars. This low completeness level is not surprising: for single-epoch SDSS candidates, we prioritised bright ($R < 21.5$) targets and did not observe many fainter targets; a significant fraction of candidates overlaps with the stellar locus; and for very faint targets even if a quasar was observed in poor conditions, we may have failed to identify it. For areas outside the central deep imaging, our completeness will be much poorer. Appendix A describes the efficiency of our quasar selection process and suggests ways to improve the selection efficiency for $2.5 < z < 4.0$ quasars in future surveys.
4 QUASAR SPECTRA

4.1 High-resolution quasar spectra

UVES-archived spectra are available for the bright central quasars J0124+0044, HE 0940−1050 and PKS 2126−158 and Keck/HIRES archive spectra are available for Q0042−2627 and J1201+0116. These spectra have resolution full widths at half maximum (FWHM) of 6–8 km s$^{-1}$. The UVES spectra were reduced using the UVES pipeline, and individual exposures were combined with UVES POPLER software.$^3$ The Keck spectra were reduced using the MAKEE package.$^4$ In addition, we have obtained HIRES spectra for bright quasars in the Q0042−2627 and PKS 2126−158 fields; [WHO91] 0043−265, with emission redshift $z = 3.45$, and Q212904.90−160249.0, with $z = 2.94$. Archived high-resolution spectra are also available for the central bright quasars in the four fields without LBG data; these will be presented in a future paper.

The observations of [WHO91] 0043−265 and Q212904.90−160249.0 were taken on the night of 2007 August 22 using Keck/HIRES with the red cross-disperser and C1 dekker, giving a slit width of 0.861 arcsec and a resolution of 6.7 km s$^{-1}$. Exposures were extracted and wavelength calibrated using the MAKEE package.

Fig. 9 shows the final reduced echelle spectra. In some of the spectra, there are breaks in the wavelength coverage. These are due to either separate wavelength settings that did not overlap, gaps between the CCD detectors or regions where echelle orders were too wide to be completely recorded by the detector.

4.2 Lower resolution quasar spectra

Williger et al. (1996) kindly provided us with electronic versions of the spectra that overlap the Q0042−2627 LBG field. These spectra had been extracted, wavelength calibrated and flux calibrated. They have a typical S/N of $\sim$20 per 1-Å pixel and a resolution FWHM of $\sim$2 Å. Quasars for which these spectra are available are marked by ‘Wil’ in the comment field of Table C1.

The remaining low-resolution spectra were obtained with AAOmega. Each night of the AAOmega observations, arcs and flat fields were taken for every wavelength setting used. The central coordinates, exposure times per grating for each field and observation dates are shown in Table 4. For the initial observations, we used the blue 1500V grating (resolution of 3700) and red 1000R grating (resolution of 3500) covering wavelengths of 4230–6860 Å. However, for faint quasars the S/N at wavelengths covering the Lyα forest, 4230–5700 Å, was poorer than anticipated. Therefore for the majority of our observations, we used the lower resolution blue (580V) and red (385R) gratings. Both have a resolution of 1300 and together provide a wavelength range of 3750–8900 Å. In addition to enabling a better S/N at wavelengths corresponding to the Lyα forest, the larger wavelength range for these gratings allowed us to identify more emission features and thus make more secure quasar identifications.

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$^3$ http://astronomy.swin.edu.au/~mmurphy/UVES_popler
$^4$ http://spider.ipac.caltech.edu/staff/tab/makee/
Table 3. Quasar candidates observed with AAOmega and the number of new quasars found. Columns show the field names, the candidate source, the observed candidates for that source and the number of identified quasars with $z > 2.2$. The total number of observed candidates, new quasars and the number of quasars previously known in each field is also shown.

| Field       | Type       | Candidate | New | Known |
|-------------|------------|-----------|-----|-------|
| Q0042−2627  | Central    | 32 × 32 arcmin$^2$ | 12  | 0     |
|             |            | $ugr$     | 263 | 0     |
|             |            | Total     | 275 | 0     | 16   |
| J0124+0044  | Central    | 32 × 32 arcmin$^2$ | 19  | 0     |
|             |            | Photo-$z$ | 92  | 14    |
|             |            | Stripe 82 | 145 | 20    |
|             |            | SDSS $ugr$ | 377 | 2     |
|             |            | Total     | 633 | 36    | 13   |
| Q0301−035   | Central    | 32 × 32 arcmin$^2$ | 129 | 5     |
|             |            | Photo-$z$ | 80  | 8     |
|             |            | Stripe 82 | 48  | 9     |
|             |            | SDSS $ugr$ | 351 | 8     |
|             |            | Total     | 608 | 30    | 16   |
| HE 0940−1050| Central    | 1° × 1°   | 113 | 14    |
|             | Schmidt $UBR$ |           | 382 | 8     |
|             | Total      |           | 479 | 22    | 2    |
| J1201+0116  | Central    | 32 × 32 arcmin$^2$ | 0   | 0     |
|             |            | Photo-$z$ | 2   | 1     |
|             |            | SDSS $ugr$ | 322 | 4     |
|             |            | Total     | 324 | 5     | 13   |
| PKS 2126−158| Central    | 32 × 32 arcmin$^2$ | 346 | 2     |
|             | Schmidt $UBR$ |           | 355 | 6     |
|             | Total      |           | 701 | 8     | 3    |
| Q2231−0015  | Central    | 32 × 32 arcmin$^2$ | 77  | 4     |
|             |            | Photo-$z$ | 2   | 0     |
|             |            | SDSS $ugr$ | 83  | 5     |
|             |            | Total     | 162 | 9     | 11   |
| Q2348−011   | Central    | 1° × 1°   | 219 | 16    |
|             | Photo-$z$ |           | 49  | 8     |
|             | Stripe 82 |           | 68  | 11    |
|             | SDSS $ugr$ |           | 633 | 9     |
|             | Total      |           | 969 | 44    | 13   |
| Q2359+0653  | Central    | 32 × 32 arcmin$^2$ | 251 | 10    |
|             | Schmidt $BR$ |           | 360 | 0     |
|             | Total      |           | 611 | 10    | 1    |
| All         |            |           | 4762| 164   | 88   |

4.3 Reduction of AAOmega spectra

AAOmega spectra were reduced using the 2DFDR program. Each set of AAOmega observations consists of science, arc and flat-field exposures for the blue and red gratings. 2DFDR processes each science image by subtracting a combined bias image, dividing by a combined flat-field, tracing and rectifying the spectrum of each object and generating a wavelength solution using an arc exposure. Finally it extracts each spectrum, producing a 1D spectrum for each fibre.

5 http://www.aao.gov.au/AAO/2df/aaomega/aaomega_manuals.html

Figure 4. Redshift and $R$ magnitude distribution for quasars with $R < 22$ and $z > 2.2$ in nine AAOmega fields. Each colour represents quasars from a different field. From the top of the histogram to the bottom, colours denote the Q0042−2627, J0124+0116, Q0301−035, HE 0940−1050, J1201+0116, PKS 2126−158, Q2231−0015, Q2348−011 and Q2359+0653 fields.

Figure 5. Quasar positions in the Q0042−2627 field. Grey dots show LBGs with spectroscopically confirmed redshifts. Each quasar is labelled with its number from Table C1 and the open circle is the bright central quasar. Quasars surrounded by a square box (and the central quasar) have been observed at high resolution. The area of each circle is proportional to the $R$-band quasar luminosity. The size of a quasar with $R = 19$ is shown at the bottom right for comparison. Triangles show very faint quasars ($R > 23$) that were discovered serendipitously in our VIMOS observations. North is up and east is to the left. The remaining eight fields are shown in Figs 6 and 7.
The rms for the wavelength solution for an AAOmega spectrum was typically 0.2 pixels, corresponding to $\sim 15$ km s$^{-1}$. Once the 1D spectra were extracted, we used 2DFDR to combine spectra taken on the same night using the same grating and wavelength setting into a single spectrum.

The final reduction steps removed the instrumental response from the spectra and combined the multiple wavelength settings. For our analysis we are interested in the absorption properties along each sightline, which do not require an accurate flux calibration. However, we still performed an approximate correction for the instrumental response to guide our object identification and continuum fitting. For most of the AAOmega pointings, we targeted a bright quasar with an existing flux-calibrated spectrum in the literature. We obtained an instrumental response curve for this quasar by dividing the AAOmega spectrum by the flux-calibrated spectrum and applied this curve to the rest of the AAOmega spectra in that pointing. For pointings without a flux-calibrated target, we used a response curve from a similar observation taken during the same night.

For fields where we obtained spectra using both 1500V/1000R gratings and 580V/385R gratings, we only used spectra from the lower resolution gratings. The typical S/Ns per Å in our combined spectra were $\sim 10$ at $R = 19$ and $\sim 3$ at $R = 21$.

### 4.4 Measurement of quasar redshifts

We identified quasars in the required redshift range by their Ly$\alpha$, CIV, SiIV and CIII emission features and forest absorption. The identifications were performed by eye. We measured quasar
Figure 7. Quasar positions in the PKS 2126−158, Q2231−0015, Q2348−011 and Q2359+0653 fields. The Q2348−011 pointing is offset from the central quasar to maximize overlap with Stripe 82 imaging. Symbols are the same as in Figs 5 and 6.

emission redshifts by fitting a Gaussian profile to the C\textsc{iv} emission line where it could be measured or C\textsc{iii} when C\textsc{iv} was not usable. Care was taken to account for broad absorption that can shift the apparent position of emission peaks for broad absorption line (BAL) quasars; in these cases, we fitted only the red wing of the emission line when measuring the emission-line position.

4.5 Quasar continuum fitting

In order to perform the cross-correlation analysis, we require the transmissivity in the Ly\textalpha forest for each of the quasars. This is defined as

\[ T = \frac{f}{f_c} \]

where \( f \) is the measured flux and \( f_c \) is the flux level of the continuum (the intrinsic unabsorbed quasar spectrum) in the Ly\textalpha forest. We therefore require an estimate of \( f_c \) from the forest profile. To find this, we perform a continuum fitting method based on that of Young et al. (1979) and Carswell et al. (1982).

First, the quasar spectrum is split into wavelength intervals and the mean and standard deviation are calculated within each interval. Pixels that fall below the mean by more than an arbitrary factor \( n \) times the standard deviation are rejected, and the mean and standard deviation are recalculated using the remaining pixels. This process is repeated iteratively until the remaining pixel fluxes show an approximately Gaussian distribution, with standard deviation equal to the expected 1\( \sigma \) flux errors. With the continuum level determined in these discrete intervals, a cubic spline was then used to interpolate across the whole of the spectrum. Finally, this continuum was...
adjusted by hand in regions where the fit still appeared poor, generally overdamped Lyα absorption systems and emission lines. n was determined by trial and error; a typical value was 1.2, but the best value varied with the S/N and resolution of the spectrum, and inside and outside the Lyα forest. The widths of the wavelength intervals were similarly chosen by trial and error. Narrow intervals were required over emission features and wider intervals were appropriate for the Lyα forest.

The results of this fitting process for each of the central bright quasars and two non-central bright quasars observed at high resolution are shown in Fig. 9. Typical continua fitted to the fainter AAOmega survey quasars are shown in Fig. 10.

4.6 Damped Lyα and Lyman limit systems in the sample

During our analysis of spectra in the first five LBG fields, we identified several candidate damped Lyα systems (DLAs) and sub-damped Lyα systems [also known as super Lyman limit systems (LLS)]. Regions of the Lyα forest affected by strong DLA damping wings were removed for the correlation analysis. Such systems are of interest for potential follow-up studies with higher resolution spectroscopy, and we list them in Table C2. Candidate systems were identified as strong Lyα absorption features with two or more associated metal features. We caution that the systems were identified by eye in spectra of varying quality and S/N and thus are subject to selection biases.

4.7 Quasar sub-sample used in the LBG–Lyα cross-correlation

We constructed a sub-sample of quasars with a Lyα forest suitable for cross-correlation with LBGs in the following way. We began with all quasars within 20 arcmin of a spectroscopically confirmed LBG. From these we removed any quasars that were clearly BAL quasars, showing very strong absorption in the blue wing of their C iv emission line.

In the remaining quasars, we defined the Lyα forest region used to cross-correlate with the LBGs. We used only the quasar spectral range between the quasar Lyβ and Lyα emission lines. By discarding the region below Lyβ emission, we avoided any contamination of the Lyα lines by Lyman series lines from higher redshift forest absorbers. We also excluded the range within 3000 km s$^{-1}$ of the quasar’s Lyα emission both to avoid absorbers affected by the ionizing radiation from the background quasar and to minimize the number of absorbers in our sample that may be ejected from the background quasar. Additionally, we removed any DLA systems present in the spectra from the analysis.

We excluded any regions in the low-resolution spectra where either the S/N at the continuum was very poor (<3 per pixel) or there were clearly problems with the reduction, such as poor subtraction of sky lines. For such very low S/N regions, the reliability of the continuum fit is likely to be low and systematics associated with the data reduction process is likely to be significant. For some quasars, the entire Lyα region was removed due to a poor S/N.

Any remaining quasars after applying the above criteria formed the sample we used to cross-correlate with LBG positions. This final sample was split into two further sub-samples: seven quasars with high-resolution (<10 km s$^{-1}$) spectra and nine with low-resolution spectra.
Table 4. Exposure times and central coordinates (J2000) for the AAOmega pointings. Note that the central pointings do not always coincide with the positions of the bright central quasars in Table 1. The total exposure times for each combination of grating and central wavelength are shown. The final column gives the dates when each field was observed.

| Field | RA        | Dec.      | Exposure time per grating (h) | Dates observed          |
|-------|-----------|-----------|-------------------------------|-------------------------|
|       |           |           | 580V | 385R | 1500V | 1500V | 1000R | Dates observed |
| Q2359+0053 | 00:01:45.87 | +07:11:45.3 | 3.5 | 3.5 | 0 | 0 | 0 | 2008 Jul 3, 2008 Oct 26 |
| Q0042–2627 | 00:44:34.00 | –26:11:33.0 | 0 | 0 | 2.0 | 2.5 | 4.5 | 2007 Jul 10–12 |
| J0124+0044 | 01:24:03.77 | +00:20:32.7 | 6.0 | 6.0 | 0 | 0 | 0 | 2008 Oct 24–25 |
| Q0301–0035 | 03:03:41.05 | –00:23:21.8 | 6.0 | 6.0 | 0 | 0 | 0 | 2008 Oct 24–26 |
| HE0940–1050 | 09:42:52.77 | –11:04:19.9 | 1.5 | 3.5 | 5.0 | 0 | 3.0 | 2007 Mar 18, 2008 Feb 5 |
| J1201+0116 | 12:01:43.90 | +01:16:00.1 | 1.5 | 2.5 | 1.5 | 1.5 | 3.0 | 2007 Jul 10–12, 2008 Feb 5–6 |
| PKS2126–158 | 21:29:12.40 | –15:38:46.1 | 2.5 | 2.5 | 3.0 | 2.5 | 5.5 | 2007 Jul 10–11, 2008 Jun 29 |
| Q2231–0015 | 22:34:09.16 | +00:00:05.0 | 3.5 | 3.5 | 0 | 0 | 0 | 2008 Jun 30, 2008 Jul 3 |
| Q2348–011 | 23:50:57.90 | –00:34:10.0 | 6.5 | 6.5 | 0 | 0 | 0 | 2008 Jul 2, 2008 Oct 24–26 |

(<100 km s$^{-1}$) spectra. As the systematic errors affecting the low-resolution and high-resolution samples are different, we calculate the cross-correlation for each sample separately. The quasars in each sample are given in Tables 5 and 6 and their spectra are shown in Figs 9 and 10. For five quasars in the low-resolution sample we use spectra taken in our AAOmega survey and for the remaining four we use spectra from Williger et al. (1996).

5 C IV–LBG CROSS-CORRELATION

Supernovae-driven winds are one of the processes believed to be able to enrich the IGM with metals. If they are a dominant mechanism for enriching the IGM, we might expect to see metal-rich gas surrounding LBGs, which are known to be undergoing significant star formation. The cross-correlation between C IV absorption systems and LBGs allows us to examine the clustering of metal-enriched gas around known star-forming galaxies.

By analysing the projected transverse correlation function A03 found that on scales of <5 h$^{-1}$ Mpc, the clustering strength between LBGs and C IV systems was comparable to the LBG–LBG clustering strength for log $N_{\text{CIV}}$ $\sim$ 13, smaller for smaller log $N_{\text{CIV}}$ and larger for larger log $N_{\text{CIV}}$. One explanation for this is that many of the strongest C IV systems arise in gas directly associated with LBGs seen in the same data sample, perhaps a larger scale extension of the winds inferred from C IV absorption in the LBG spectra. The weaker correlation at low log $N_{\text{CIV}}$ may be explained by C IV arising in the same large-scale structures as LBGs. By measuring absorption from foreground LBGs in the spectrum of a nearby (~10 arcsec) background LBG, A05 found that C IV gas with log $N_{\text{CIV}}$ $>$ 12.5 is found around LBGs out to a radius of 80 kpc. This analysis was recently extended to a larger sample of higher resolution LBG spectra by Steidel et al. (2010). We defer a similar analysis of our LBG spectra to a future paper. In this section, we look for C IV absorption that may be associated with LBGs that are very close to background quasar sightlines and measure the C IV–LBG cross-correlation for our sample.

5.1 Creating a C IV absorption-line catalogue

We identified absorption due to the C IV $\lambda$1548, 1550 doublet in background quasar spectra in the following way. First, we identified significant absorption features in the quasar spectrum and then we scanned each spectrum to identify possible features that were part of a C IV doublet. For the lower resolution AAOmega spectra, we also fitted Gaussian profiles to the absorption doublets. Finally, we measured the rest equivalent width of the C IV $\lambda$1548 transition for each C IV system.

Significant absorption features were identified in a similar manner to that described by Schneider et al. (1993). The equivalent width per pixel was calculated taking into account the instrumental resolution, assumed to be a Gaussian profile. We identified all features with a minimum significance level (the ratio of the equivalent width to the equivalent width error) of 4. We then scanned each spectrum by eye, searching for possible C IV systems between the quasar Ly$\alpha$ and C IV emission lines. For the HIRES and UVES spectra, once we identified C IV systems, we measured the total equivalent width of the C IV $\lambda$1548 transition. We considered any C IV absorption components that were separated by less than 500 km s$^{-1}$ to be part of a single system. The lower resolution spectra could not resolve individual C IV components, so we fitted the candidate systems identified by eye with Gaussian profiles. We checked that these fits were consistent with the relative oscillator strengths of the transitions, taking into account possible line saturation. In these lower resolution spectra, we used the deblended profile for the C IV $\lambda$1548 transition to measure a system’s equivalent width. Table C3 gives the redshifts and observed equivalent widths for C IV systems we identified towards the quasars in our sample.

5.2 C IV close to LBGs

The three LBGs in our sample closest to background sightlines have proper impact parameters of 100, 140 and 150 h$^{-1}$ kpc, respectively. The two closest of these do not show any C IV absorption within 1000 km s$^{-1}$ of the LBG nebular redshift to 3σ column density detection limits of $10^{13}$ cm$^{-2}$ (100 kpc) and $10^{12}$ cm$^{-2}$ (140 kpc). For the farthest, there is a probable LLS with both high (C IV, Si IV, O VI) and low (H I, O I, C II, Si II, Si III) ionization transitions of ~500 km s$^{-1}$ away from the LBG redshift. The two non-detections suggest that if the C IV enveloping LBGs extends beyond ~100 kpc, its covering factor must be less than unity or its column density lower than $10^{13}$ cm$^{-2}$. The LLS could be associated with the nearby LBG, but it could also be associated with a fainter, closer galaxy that does not appear in our survey. We intend to use the large number of transitions to explore the physical conditions of this system in a future analysis (see also Simcoe et al. 2006).
2.5 and at scales where linear theory

\[ z \approx \times h \]

assuming unpairs. We are in the process of assembling a larger sample of \( \mathrm{CIV} \) absorbers near LBGs using the X-shooter spectrograph on the VLT.

### 5.3 \( \mathrm{CIV} \)–LBG cross-correlation

To measure the 3D comoving separation between an LBG and a \( \mathrm{CIV} \) system, \( \Delta s \), we first find the comoving distance \( r \) to each object using

\[ r = \frac{c}{H_0} \int_{0}^{z} \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}, \]

where \( c \) is the speed of light and \( z \) is the redshift of the LBG or absorber. The separation is then given by

\[ \Delta s = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \theta}, \]

where \( r_1 \) and \( r_2 \) are the comoving distances to the LBG and absorber and \( \theta \) is their angular separation. We calculate the cross-correlation using the ratio of the number of \( \mathrm{CIV} \)–galaxy pairs in the real data to the number for a random distribution of \( \mathrm{CIV} \) absorbers for different separation bins. We generated a random \( \mathrm{CIV} \) absorber catalogue in the following way: for each sightline where we measured \( \mathrm{CIV} \) absorption, we generate \( 1000 \times N \) random absorbers with redshifts drawn at random between the maximum and minimum \( \mathrm{CIV} \) redshifts able to be detected along that sightline, where \( N \) is the number of real absorbers found along that sightline. We generated 1000 times more random absorbers to ensure that the Poisson noise introduced by the number of random pairs had a negligible contribution to the final error estimate. This method assumes that the detection limits do not change significantly along a single sightline, which is a reasonable approximation for our spectra.

Fig. 11 shows the \( \mathrm{CIV} \)–LBG correlation function as filled circles. Our \( \mathrm{CIV} \) \( \lambda1548 \) rest equivalent width distribution ranges from 0.005 to 2 Å, with a median of 0.31 Å, or \( N_{\mathrm{CIV}} = 10^{15.9} \) cm\(^{-2}\) assuming unsaturated absorption. At separations of \(<5 \) h\(^{-1}\) Mpc, A05 fitted their \( \mathrm{CIV} \)–LBG correlation function with a function of the form \( \xi(r) = (r/r_0)^{-1.6} \). They measured a clustering strength \( r_0 \approx 5 \) h\(^{-1}\) Mpc between LBGs and absorbers with \( N \approx 10^{15.9} \) cm\(^{-2}\), slightly higher than both their and our LBG–LBG \( r_0 \) values (Bielby et al. 2011). This relation is shown in Fig. 11 as a solid curve. In an attempt to increase statistical power, we measured the cross-correlation in a single bin in the range of 5–15 h\(^{-1}\) Mpc. This yielded a correlation of \( 0.20 \pm 0.16 \), where we assumed a 1σ Poisson error from the number of absorbers contributing to this bin. Thus the A05 relation is consistent with our measurement, but the strength is too low for us to detect the clustering signal with our sample size. We also split our sample into high and low equivalent width sub-samples to measure the clustering strength as a function of column density (solid and open triangles in Fig. 11). However, the results were inconclusive due to the small number of galaxy–\( \mathrm{CIV} \) pairs. We are in the process of assembling a larger sample of \( \mathrm{CIV} \) absorbers near LBGs using the X-shooter spectrograph on the VLT.

### 6 Ly\( \alpha \) AUTOCORRELATION

Before embarking on the Ly\( \alpha \)–LBG cross-correlation, we measure the Ly\( \alpha \) flux autocorrelation along quasar sightlines in our sample, with the aim of measuring the velocity dispersion of H\( \alpha \) gas giving rise to Ly\( \alpha \) absorption at the redshift of our sample. As will be shown in the next section, any velocity smoothing in the redshift direction has a large effect on our ability to detect a peak in the Ly\( \alpha \) transmissivity around LBGs. If H\( \alpha \) gas does not share the intrinsic velocity dispersion of the nearby LBGs, then its own dispersion will contribute to this velocity smoothing in the Ly\( \alpha \)–LBG signal.

Simulations show that at \( z \sim 2.5 \) and at scales where linear theory holds, the Ly\( \alpha \) forest flux autocorrelation function is given by the dark matter correlation function scaled by a constant and largely scale-independent factor (e.g. Croft et al. 2002; Slosar et al. 2009). By comparing the measured flux correlation function to the dark matter correlation, we can estimate the magnitude of the H\( \alpha \) velocity dispersion by the size of the departure from the expected correlation function on non-linear scales.

We measure the correlation function in the following way. For each pixel in the Ly\( \alpha \) forest region of each quasar, we calculate the quantity

\[ \delta = T/T - 1, \]
where \( \xi \) denotes a sum over all pixels with a comoving separation \( \Delta r \). In practice, we select some finite range of separations around \( \Delta r \) and include all pixels with separations that fall inside that range.

Fig. 12 shows the Ly\( \alpha \) forest flux autocorrelation from our high-resolution quasar sample (resolution FWHM of \( \sim 8 \) k\( \text{ms}^{-1} \)). We use this rather than the low-resolution sample because it makes the largest contribution to the LBG–Ly\( \alpha \) correlation at small scales and probes the Ly\( \alpha \) \( \xi(\Delta r) \) down to \( \sim 100\)-kpc scales. We masked any DLAs or regions with poor sky subtraction in the spectra. Error bars were estimated using a jackknife technique; we calculate \( \xi(\Delta r) \) seven times, each time removing a different quasar from the sample, and the error is then given by the standard deviation of these around the value from the full sample, times \( (7 - 1) = 6 \). We compare our results to those of Croft et al. (2002), who measured the autocorrelation using a sample of 30 high-resolution (\( \sim 8 \) k\( \text{ms}^{-1} \)), high S/N spectra. Our result is slightly higher than that of Croft et al.; this is likely due to the different redshift ranges of our samples (\( z \sim 3 \) for the Croft et al. sample and \( z \approx 3.3 \) for ours).

To explore the effect of intrinsic line broadening, instrumental resolution and incomplete wavelength coverage due to the removal of parts of spectra affected by DLAs or sky lines, we generate synthetic spectra and measure their correlation. Each synthetic spectrum has a Ly\( \alpha \) forest generated by adding absorption lines with a redshift, \( b \) parameter and column density drawn at random from the distributions over the redshift range corresponding to an observed spectrum (see Appendix C). This sample of synthetic spectra has Ly\( \alpha \) forest lines placed at random such that they reproduce the mean flux and \( b \) parameter distributions, which are well known from large samples of high-resolution spectra. However, the synthetic spectra do not show any correlation in absorption other than that caused by line broadening and instrumental effects. The autocorrelation for

\[ \int T \xi(z_{1}) \xi(z_{2}) \delta(z_{1} - z_{2}) \, dz_{1} \delta(z_{1} - z_{2}) \, dz_{2} \]

\[ = \frac{1}{\Delta z} \int T \xi(z) \delta(z - z_{0}) \, dz \]

\[ = \frac{1}{\Delta z} \int T \xi(z) \, dz \]

\[ \int T \xi(z) \, dz \]

where \( \xi \) is the mean transmissivity and \( \xi \) is the mean transmissivity at the pixel redshift. To calculate the separation in \( h^{-1} \) Mpc between two pixels, we convert the redshift of each pixel to a comoving distance using equation (2). The correlation along the sightline is then given by

\[ \xi(\Delta r) = \delta(\rho) \delta(\rho + \Delta r), \]

where \( \rho \) is the comoving distance of the galaxy.
This is measured from the mean flux along eight quasar sightlines and was used by A03. Over our redshift range, it is very similar to the more recent result by Faucher-Giguère et al. (2008). Our second approach was to measure $\mathbf{T}$ in the Lyα forest region for each individual quasar sightline. For the high- and low-resolution samples, we used the $\mathbf{T}$ estimate that gives the smallest quasar-to-quasar scatter in the Lyα–LBG cross-correlation function. For the high-resolution sample, this is the McDonald relation, and for the low-resolution sample, this is the measured mean. For the low-resolution sample, we believe that the measured mean gives less scatter by compensating for errors in the inferred continuum level over the Lyα forest. At the AAOmega spectral resolution Lyα forest lines are not resolved, and line blending means that no part of a spectrum returns to the intrinsic continuum level. Thus, our continuum fitting process will likely be offset from the true continuum level by 5–10 per cent, and using the measured mean flux minimizes the effect of such an offset.

### 7.1 Systematic effects

There are two issues that could affect the Lyα–LBG cross-correlation measurement. In addition to Lyα absorption, the forest region contains absorption from metal transitions. Thus there will be a small contribution to the measured transmissivity by metal absorption lines, decreasing the transmissivity below the expected mean value. However, we do not expect metal absorption at redshifts significantly different from a galaxy’s redshift to correlate with the galaxy position. Therefore, we do not expect metal absorption to bias any correlation signal; instead, it will tend to reduce the strength of any measured correlation.

We also cannot completely rule out a systematic offset in our LBG redshifts. As we can only measure the redshifts for the ISM absorption lines and Lyα emission lines, which are affected by winds and H\textsubscript{i} absorption, respectively, we must infer the intrinsic redshift of the galaxies using the relation from A05. This could introduce a systematic offset between our inferred LBG redshifts and the true redshifts and thus an offset between the LBG positions and Lyα absorption. A more recent relation between the Lyα, ISM and intrinsic LBG redshifts is given by Steidel et al. (2010). However, this was calibrated using an LBG sample with 2 < $z$ < 2.6, and our LBG distribution extends to $z$ ∼ 3.5. Thus for our analysis, we choose to use the A05 relation that was calibrated using a 2 < $z$ < 3.5 LBG sample. The best way to quantify any systematic redshift offsets in our sample is to obtain near-infrared emission lines for LBGs close to the quasar sightlines; we are pursuing such observations for LBGs where these lines are observable.

### 7.2 Measuring the cross-correlation

We performed the cross-correlation using the normalized quasar transmissivity profiles, $\mathbf{T}' = \mathbf{T}/\mathbf{\bar{T}}$. We calculated the Lyα–LBG cross-correlation function in 0.5 $h^{-1}$ Mpc bins by measuring the mean normalized transmissivity in all regions of the Lyα forest enclosed in a spherical shell around each LBG with inner and outer radii given by the bin edges. The separations, $s$, between each Lyα pixel and an LBG were calculated using equations (2) and (3), and the bin size was chosen to match that used by A05.

The mean transmissivity in each bin was taken to be the mean of the individual transmissivity values for each LBG contributing to that bin. The errors on each bin value were taken to be the standard error in the mean of the Lyα-to-LBG transmissivity values. We note that for points where few LBGs contribute to a bin, this will probably
underestimate the error. Finally, we scaled the mean transmissivity for the Ly\textsc{\alpha} forest of each quasar to 0.76 to enable a comparison with the results of A05.

### 7.3 Results

The VLT LBG–Ly\textsc{\alpha} cross-correlation function is shown separately for the high- and low-resolution quasar samples in Fig. 13. On scales of 3–11 h\(^{-1}\) Mpc, the two samples agree. There appears to be an offset between the low- and high-resolution samples at large separations, likely due to residual continuum-fitting errors in the low-resolution spectra.

For transmissivities in the three bins with separations of <2 h\(^{-1}\) Mpc, the low-resolution sample increases above the mean, apparently becoming inconsistent with the high-resolution sample. However, we do not believe that this inconsistency is real; rather it is a result of small-number statistics. In the three smallest separation bins, only four LBGs contribute to the measured transmissivities.

The LBG–Ly\textsc{\alpha} cross-correlation function for the combined low- and high-resolution samples is shown in Fig. 14. At scales of >2 h\(^{-1}\) Mpc, the combined VLT result is consistent with both A03 and A05 and the relationship seems reasonably well described by a power law, \(T = 0.77 - (s/0.3 \text{ h}^{-1} \text{ Mpc})^{-\gamma}\), which also describes the A05 results (see Fig. 15) and the GIMIC simulation results of Tummuangpak et al. (in preparation; see also Crain et al. 2009), even at smaller scales. The VLT data aim for good statistics at large scales, so the errors are generally larger than the A03 or A05 data at smaller scales. In the case of the first point at \(s = 0.25 \text{ h}^{-1} \text{ Mpc}\), the VLT error may be underestimated by the simple LBG–LBG error shown. In experiments where the two LBG redshifts were perturbed randomly by a velocity error drawn from a Gaussian with a width of 390 km s\(^{-1}\), a larger error was obtained for this point by a factor of \(\approx 3\). However, the transmissivity value is robust to changes in

### 7.4 Interpretation

The distance between LBGs and Ly\textsc{\alpha} pixels is measured assuming that we can convert velocity differences into distances, not taking into account any velocity dispersion or redshift errors. Intrinsic velocity dispersion of the LBGs and the H\textsc{i} gas, outflows and LBG velocity measurement errors will thus smear out any correlation between the two along the redshift direction. Bielby et al. (2011) analysed the LBG–LBG correlation function and found that it can be modelled with a real-space correlation function of \(\xi(r) = (r/r_0)^{-\gamma}\) with \(r_0 = 3.98 \text{ h}^{-1} \text{ Mpc}\) and \(\gamma = 1.9\), if convolved with a pair-wise velocity dispersion of \((w^2)^{1/2} = 720 \text{ km s}^{-1}\). In Section 6, we showed that the velocity dispersion of the H\textsc{i} gas is likely to be low; therefore, we assume that the only
contribution to the LBG–Lyα intrinsic velocity dispersion comes from the LBGs. For a single LBG the velocity dispersion measured by Bielby et al. is 720/√2 = 510 km s$^{-1}$, comprising 200 km s$^{-1}$ for the Lyα emission-line outflow error and 450 km s$^{-1}$ for the VLT VIMOS velocity measurement error, leaving 140 km s$^{-1}$ for the intrinsic velocity dispersion.

To model the effect of this dispersion, we have taken the real-space LBG–Lyα cross-correlation function that approximately fits the A05 results and GIMIC galaxy–Lyα simulations (Tummaungpak et al., in preparation), with

$$T(s) = T - (s/s_0)^{-1}, \tag{7}$$

where $s_0 = 0.3 h^{-1}$ Mpc. We convolved this in the redshift direction only using a velocity dispersion of 510 km s$^{-1}$. We did not include any contribution from infall velocities. These are not negligible (e.g. Padilla & Baugh 2002), but their contribution is likely to be small compared to the redshift uncertainties and intrinsic velocity dispersion. The result is shown in Fig. 14 by the cyan solid line. The smoothing is considerable; this is expected given that 510 km s$^{-1}$ is $\sim 5 h^{-1}$ Mpc at $z = 3$. We have also added a central transmissivity spike to the above power-law model for $T(s)$ such that $T = 1$ for $s < 1.5 h^{-1}$ Mpc, simulating the case where high transmissivity caused by putative galactic winds is found at small scales (red solid line in Fig. 14). Both convolved results in Fig. 14 match the VLT observations. A spike of width $1.5 h^{-1}$ Mpc is wider than the sub-500 kpc spike suggested by A03’s results. Thus, we also consider a narrower spike of width $0.5 h^{-1}$ Mpc (red dashed line in Fig. 14). Such a spike has very little effect on the correlation function for the uncertainties on our LBG redshifts.

The original results from A03 are also affected by velocity dispersion and velocity errors, and we now estimate the correlation function that would have been measured by A03 and A05 given the above models and the redshift uncertainties of the Keck galaxy spectra. da Ángela et al. (2008) fitted a pair-wise velocity dispersion of 400 km s$^{-1}$ to the Keck LBG–LBG z-space correlation function. This converts to a dispersion of 280 km s$^{-1}$ for a single LBG. If we assume 200 km s$^{-1}$ for outflow error and 140 km s$^{-1}$ for intrinsic velocity dispersion, then this leaves 140 km s$^{-1}$ velocity measurement error. 280 km s$^{-1}$ translates to 2.8 $h^{-1}$ Mpc, and so it is hard to see how a narrow spike width of 0.5 $h^{-1}$ Mpc seen by A03 in redshift space could be physical. In Fig. 15 we show how such a narrow spike, shown by a green solid line, is almost smoothed away by this velocity dispersion. Even the Near-Infrared Echelle Spectrograph (NIRSPEC) Hα-based LBG redshifts of A05, which have 60 km s$^{-1}$ velocity error and 140 km s$^{-1}$ intrinsic velocity dispersion, will have 150 km s$^{-1}$ or $1.5 h^{-1}$ Mpc smoothing of the real LBG–Lyα $T(s)$. In Fig. 15, we show the effect that such a velocity dispersion has on our real-space model with (red solid line) and without (blue solid line) the narrow spike. We also show a model with a broader $1.5 h^{-1}$ Mpc spike as dashed lines for each velocity dispersion.

We conclude that at $s < 2 h^{-1}$ Mpc, the VLT data could be consistent with either the existence of the $T \approx 1$ transmission spike as found by A03 or the $T \approx 0.3$ absorption found by A05. However, any $T = 1$ spike is unlikely to be as narrow as the spike originally suggested by the results of A03. The smoothing effect of even a 150 km s$^{-1}$ velocity dispersion on a spike of width $\approx 0.5 h^{-1}$ Mpc is likely to be significant.

The velocity dispersions we are using for the Keck data could be a lower limit, since Bielby et al. found that a pair-wise velocity dispersion of 700 km s$^{-1}$ best fits the LBG–LBG redshift space, $\xi(\sigma, \pi)$, correlation function from the combined Keck LRIS and VLT data. The best estimate from the Keck Low Resolution Imaging Spectrometer (LRIS) data alone is similar. This would imply a much larger intrinsic pair-wise LBG velocity dispersion of $\approx 600$ km s$^{-1}$ and an individual LBG velocity dispersion of $\approx 500$ km s$^{-1}$. This would make the models shown in Fig. 15 to be just as appropriate for the Keck LRIS data as the VLT data, given the increasing dominance of the intrinsic dispersion. This would reinforce the conclusion that the apparent spike seen by A03 is unphysically narrow. It would also suggest that the absorption feature seen by A05 has the same problem in being somewhat too narrow given the likely effect of the velocity dispersion.

Alternatively, if the absorbing H I gas has no net peculiar velocity with respect to nearby LBGs, then the contribution of the intrinsic velocity dispersion may be overestimated in the models we have presented. However, for the VLT data the measurement error is as large as any plausible intrinsic velocity dispersion, and even for the Keck data with NIRSPEC redshifts the smoothing from measurement errors alone is considerable. Thus even if LBGs and nearby H I gas share the same velocities, our modelled real-space cross-correlation will not change significantly.

Despite these warnings about the effect of inter-comparing different LBG–Lyα samples with different velocity errors, we finally compare our result to the combined A05 results, constructed by taking a weighted mean of the Lyα–LBG transmissivity results for LBGs with and without NIRSPEC redshifts in A05. We compare this to the combined VLT result in Fig. 16.

Although there is excellent agreement on scales $s > 2 h^{-1}$ Mpc, the VLT data remain slightly higher than the Keck data on scales $s < 2 h^{-1}$ Mpc. This could mean that there is still a hint of feedback in the VLT result compared to the combined Keck data. However, if the individual galaxy velocity dispersions are as low as 150 km s$^{-1}$ for the Keck (NIRSPEC) data and as high as 510 km s$^{-1}$ for the VLT data, then both data sets may be consistent with the $(s/0.3 h^{-1}$ Mpc$^{-1})$ power-law transmissivity decline (dotted line) when it is convolved with the respective velocity dispersions in the z direction (red and green solid lines). Since a $1.5 h^{-1}$ Mpc wide, velocity-convolved, transmission spike is ruled out by the Keck data alone (see Fig. 15).
transmission spike around the galaxies. The decrease can be de-
cross-correlation using simple models of forest transmissivity for the combined A05 sample, and found it to be consistent with both sets of data; this spike seems to be rejected, particularly if we use the Lyα−Lyα autocorrelation function can be qualitatively repro-
the only other models consistent with the data are the 0.5 h⁻¹ Mpc wide transmission spike models, convolved with the appropriate velocity dispersions (green and red dashed lines in Fig. 16). In both models, the transmission spike is suppressed by the velocity con-
tion. The width of the velocity distribution is ~30 km s⁻¹, much smaller than the typical velocity errors on our LBG positions, and thus it does not have a significant effect on the measured Lyα−LBG cross-correlation.

(iv) We have measured the Lyα−LBG cross-correlation for a sample of 16 background quasars with small impact parameters from foreground LBGs. The cross-correlation is consistent with the results of A05. In particular, we also see a decrease in H I transmission at Lyα−LBG separations of 2–7 h⁻¹ Mpc. This decrease can be described by a power law with index γ = 1.

(v) Uncertainties in the LBG redshifts have a significant effect on the detectability of any Lyα transmission spike around the galaxies. We have examined the effect of velocity dispersion and redshift errors on the Lyα−LBG cross-correlation using simple models of a transmission spike and found that with the measured LBG velocity dispersions a narrow transmission spike, even if present, is difficult to measure against the underlying power law. The A03 and A05 results rule out a broad (1.5 h⁻¹ Mpc) transmission spike but their data as well as our data are consistent with both a narrow (0.5 h⁻¹ Mpc) spike and no spike, once the velocity dispersion is taken into account.

In a future paper, we intend to exploit our survey’s wide field to analyse the Lyα−LBG cross-correlation function on ~20-Mpc scales, in both radial (redshift) and transverse directions, using a sample of ~2000 LBGs.

8 SUMMARY

We have presented redshifts for 252 quasars across nine fields where we are surveying LBG spectroscopic redshifts with VIMOS, 164 of which are newly discovered. Using an initial sample of 1020 LBGs in five fields and 16 of our background quasars with small impact parameters from the LBGs, we have presented a measurement of the LBG−Lyα transmissivity and LBG–C IV cross-correlation functions. Using the seven quasars in our sample with high-resolution spectra, we have also measured the Lyα−Lyα autocorrelation function. The main results of our paper are as follows.

(i) We have presented colour cuts that can be used with ugr imaging to select quasars in the redshift range 2.5 < z < 4. With imaging similar to that available for Stripe 82, they yield an efficiency of 40 per cent at a sky density of 11.2 deg⁻² for targets to r = 22. With single-epoch SDSS imaging, they yield an efficiency of 17 per cent at a sky density of 4.2 deg⁻² for r = 21.

(ii) We have identified C IV absorption systems towards quasars inside the five fields where we have measured LBG redshifts. Using these systems, we have measured the cross-correlation between C IV absorbers and LBGs for 5−15 h⁻¹ Mpc and found it to be consistent with the power-law relation measured by A03 at smaller separations.

(iii) The Lyα autocorrelation function can be qualitatively reproduced on non-linear scales by smoothing the expected dark matter correlation function with a Gaussian velocity dispersion distribution. The width of the velocity distribution is ~30 km s⁻¹, much smaller than the typical velocity errors on our LBG positions, and thus it does not have a significant effect on the measured Lyα−LBG cross-correlation.

(iv) We have measured the Lyα−LBG cross-correlation for a sample of 16 background quasars with small impact parameters from foreground LBGs. The cross-correlation is consistent with the results of A05. In particular, we also see a decrease in H I transmission at Lyα−LBG separations of 2–7 h⁻¹ Mpc. This decrease can be described by a power law with index γ = 1.

(v) Uncertainties in the LBG redshifts have a significant effect on the detectability of any Lyα transmission spike around the galaxies. We have examined the effect of velocity dispersion and redshift errors on the Lyα−LBG cross-correlation using simple models of a transmission spike and found that with the measured LBG velocity dispersions a narrow transmission spike, even if present, is difficult to measure against the underlying power law. The A03 and A05 results rule out a broad (1.5 h⁻¹ Mpc) transmission spike but their data as well as our data are consistent with both a narrow (0.5 h⁻¹ Mpc) spike and no spike, once the velocity dispersion is taken into account.

In a future paper, we intend to exploit our survey’s wide field to analyse the Lyα−LBG cross-correlation function on ~20-Mpc scales, in both radial (redshift) and transverse directions, using a sample of ~2000 LBGs.

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APPENDIX A: EFFICIENCY OF QUASAR SELECTION

How can the efficiency be improved for future surveys for $2.5 < z < 4.0$ quasars? Using our quasar sample, we can identify optimized colour cuts that attempt to recover a significant fraction of the available quasars while maintaining a relatively high efficiency. We use the three Stripe 82 fields for this purpose, where we have both single-epoch SDSS imaging and deep Stripe 82 imaging covering the entire AAOmega fields, and we have a relatively high completeness level for quasars with $21 < r < 22$. This will allow us to determine the effect of using two different imaging depths (SDSS and Stripe 82) to select quasars.

Optimized colour cuts for SDSS imaging are shown in Fig. 2 as black solid lines. These cuts were made to recover as many of the observed $2.5 < z < 4.0$ quasars in our sample, while maintaining a high efficiency. All stellar targets with $r < 22$, and $u - g, g - r$ colours satisfying the optimized cuts are selected as candidates.

For Stripe 82 imaging, we devised similar cuts shown by black solid lines in Fig. 3. The region between the two Stripe 82 selection polygons is not included as it is populated by A and F stars at brighter magnitudes ($r < 21$). At $r > 21$, we expect to probe past even the most distant A and F dwarfs [assuming $M_g \sim 2.1$ from Covey et al. (2007) and a maximum distance of 50 kpc; Jiang et al. (2006) also mentioned this point]. Thus we could in principle include this region in our selection for targets with $21 < r < 22$, but we have not done so here for simplicity.

Table A1 shows the efficiencies for the two different imaging catalogues (single-epoch SDSS and Stripe 82) using the optimized cuts...
and for the photo-\(z\) candidates selected from single-epoch SDSS imaging for comparison. For each selection method we define the efficiency as follows: given the total number of candidates in an AAOmega field, \(N_{\text{cand}}\); the number of those we observed, \(N_{\text{obs}}\); the number of candidates that were previously known to be quasars with \(2.5 < z < 4.0\), \(N_{\text{known}}\); and the number of candidates that turned out to be new quasars in the same redshift range, \(N_{\text{new}}\), then

\[
\text{efficiency} = \left( \frac{N_{\text{new}} + \frac{N_{\text{obs}}}{N_{\text{cand}}}N_{\text{known}}}{N_{\text{obs}}} \right)
\]

The second term inside the parentheses is required as we have observed only a subset of all the candidates, and this subset is biased by including known quasars.

Efficiencies to \(R = 22\) for the Stripe 82 catalogue are around 40 per cent, and for the single-epoch SDSS imaging these efficiencies are 13 per cent, or 15 per cent for photo-\(z\)-selected candidates. If we extrapolate the measured efficiencies to candidates that were not observed, we expect these selection methods to yield sky densities of 11.2 quasars per \(\text{deg}^2\) for Stripe 82, 4.0 for photo-\(z\) targets and 9.1 for single-epoch SDSS targets. This extrapolation is reasonable for the Stripe 82 and photo-\(z\) targets, but is more uncertain for the SDSS targets, as our observed candidates are highly skewed towards targets with \(r < 21\). If the efficiency at \(R > 21\) is much lower than that at \(r < 21\) (due to larger errors in the \(ug\) photometry, for example), then the true efficiencies and sky densities will be lower than those calculated here. At \(r < 21\), we have observed a large fraction of the available candidates using all the selection methods and so the extrapolation of the efficiencies is more secure. In this case, the single-epoch SDSS selection efficiency is 17 per cent, yielding a sky density of 4.2 quasars per \(\text{deg}^2\).

We conclude that it is possible to recover a sky density of \(\sim 11\ \text{deg}^{-2}\) for quasars with \(2.5 < z < 4.0\) and \(R < 22\) using simple colour cuts and star/galaxy separation on imaging of a similar depth to the combined Stripe 82 catalogues, at an efficiency of \(\sim 40\) per cent. Jiang et al. performed a similar survey for quasars using Stripe 82 imaging and they reported an efficiency of 43 per cent in the redshift range \(2 < z < 3\) for targets with \(g < 22.5\). This is consistent with our efficiency estimates, though over a lower redshift range and to a slightly different magnitude limit. We note that it is possible to recover higher densities: we achieved densities of \(\sim 14.2\ \text{deg}^{-2}\) for the Stripe 82 and photo-\(z\) targets, but is more uncertain for the SDSS targets.
in the LBG areas for this redshift range, but at a much reduced efficiency of ~5 per cent.

**APPENDIX B: GENERATING SYNTHETIC QUASAR SPECTRA**

One synthetic spectrum covering the Ly$\alpha$ forest region was created to match each observed spectrum. For each synthetic spectrum, Ly$\alpha$ forest absorption was simulated by drawing many absorption lines with redshifts, $b$ parameters and column densities drawn from the distributions observed in high-resolution spectra of the Ly$\alpha$ forest. In generating forest lines, we follow closely the procedure of Dall’Aglio, Wisotzki & Worseck (2008). The distributions we use are as follows: for line redshifts $dn/dz \propto (1 + z)^{\gamma}$, where $\gamma = 2.37$; for column densities $f(N_{\text{HI}}) \propto N_{\text{HI}}^{\beta}$, where $\beta = 1.5$; and for Doppler $b$ parameters $dn/db \propto b^{5}\exp[-b_{0}^{2}/b^{4}]$, where $b_{0} = 24$ km s$^{-1}$. Values for the parameters $\gamma$, $\beta$ and $b_{0}$ are taken from Kim, Cristiani & D’Odorico (2001), who measured them from the distribution of lines fitted to a sample of high-resolution quasar spectra.

We add forest lines to the spectrum until the mean flux in the forest region matches the measured value from McDonald et al. (2000) at the mean redshift of the forest. This flux array is then convolved with the instrumental spread function of the real spectrum. The forest absorption is multiplied by a quasar continuum generated using components derived from a principal component analysis of the continuum of low-redshift quasars (Suzuki et al. 2005). Finally we added Gaussian noise to the spectrum, varying as a function of wavelength in the same way as the real spectra.

Thus we expect the simulated spectra to reproduce the same S/N, resolution and wavelength ranges as the observed spectra, but with uncorrelated absorption (apart from the correlations introduced by intrinsic line broadening and the instrumental broadening).

We did not introduce metal lines or absorption from high column density systems (Lyman limit and DLA systems) to the simulated spectra.

**APPENDIX C: TABLES WITH QUASAR, DLA/LLS CANDIDATE AND C IV INFORMATION**

| No. | Name            | Field    | RA        | Dec.     | $z$ | Mag. | O/lap? | Comments          |
|-----|-----------------|----------|-----------|----------|-----|------|--------|-------------------|
| 1   | [WHO91] 0042–269 | Q0042–2627 | 00:44:52.24 | -26:40:09.3 | 3.33 | 18.3 | n      | Wil NED $z = 3.33$ |
| 2   | [WHO91] 0042–266 | Q0042–2627 | 00:44:35.72 | -26:23:00.2 | 2.98 | 19.5 | y      | Wil NED $z = 2.98$ |
| 3   | [WHO91] 0042–267 | Q0042–2627 | 00:45:11.33 | -26:25:50.7 | 2.81 | 19.7 | y      | NED $z = 2.81$    |
| 4   | [WHO91] 0043–259 | Q0042–2627 | 00:46:09.67 | -25:38:47.2 | 3.31 | 19.1 | n      | NED $z = 3.31$    |
| 5   | Q0042–2627      | Q0042–2627 | 00:44:33.95 | -26:11:19.9 | 3.29 | 18.5 | y      | Wil NED $z = 3.289$|
| 6   | LBQS 0041–2607  | Q0042–2627 | 00:43:58.80 | -25:51:15.7 | 2.50 | 17.1 | n      | Wil NED $z = 2.501$|
| 7   | LBQS 0041–2707  | Q0042–2627 | 00:43:51.84 | -26:51:28.6 | 2.79 | 17.9 | n      | Wil NED $z = 2.786$|
| 8   | [D87] U13682P–038 | Q0042–2627 | 00:46:41.65 | -26:12:21.7 | 2.48 | 19.2 | n      | NED $z = 2.48$    |
| 9   | LBQS 0041–2659  | Q0042–2627 | 00:44:05.85 | -26:42:04.4 | 2.46 | 18.6 | n      | Wil NED $z = 2.457$|
| 10  | [D87] U13682P–028 | Q0042–2627 | 00:45:11.33 | -26:58:32.1 | 2.34 | 19.8 | n      | Wil NED $z = 2.34$|
| 11  | [VCV96] Q0040–2606 | Q0042–2627 | 00:42:42.10 | -25:50:09.0 | 2.47 | 19.4 | n      | NED $z = 2.47$    |
| 12  | LBQS 0042–2657  | Q0042–2627 | 00:45:19.57 | -26:40:50.9 | 2.90 | 18.7 | n      | Wil NED $z = 2.898$|
| 13  | [VCV96] Q0045–2614 | Q0042–2627 | 00:47:45.07 | -25:57:40.7 | 2.35 | 19.3 | n      | NED $z = 2.35$    |
| 14  | LBQS 0041–2638  | Q0042–2627 | 00:43:42.79 | -26:22:10.2 | 3.05 | 18.3 | y      | Wil NED $z = 3.053$|
| 15  | [WHO91] 0043–265 | Q0042–2627 | 00:45:30.47 | -26:17:09.2 | 3.44 | 18.3 | y      | Wil NED $z = 3.44$|
| 16  | [WHO91] 0046–267 | Q0042–2627 | 00:48:48.65 | -26:27:04.1 | 3.52 | 19.7 | n      | NED $z = 3.52$    |
| 17  | Q004340.02–260538.1 | Q0042–2627 | 00:43:40.02 | -26:05:38.1 | 2.20 | 21.5 | y      | VIMOS serendip.    |
| 18  | Q012715.19+001828.9 | J0124+0044 | 01:27:15.19 | +00:18:28.9 | 2.27 | 21.6 | n      | Stripe 82         |

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Table C2. DLA and LLS candidates towards low-resolution quasars in our first five LBG fields. Columns show the quasar number, name, emission redshift and magnitude from Table C1, a 1σ upper limit on the candidate system’s column density (estimated using a Voigt profile with a single component of velocity width $b = 50 \text{ km s}^{-1}$), the absorber redshift and associated metals. Candidates were selected by eye and were required to have strong H I absorption with detectable absorption from two or more associated metal transitions.

| No. | Name                  | $z_{\text{qso}}$ | Mag. | Max. $N_{\text{H}1}$ | $z_{\text{abs}}$ | Metals       |
|-----|-----------------------|------------------|------|----------------------|------------------|--------------|
| 16  | [WHO91] 0043–265      | 3.44             | 18.3 | 19.8                 | 2.817            | C IV, Fe ii, Al ii |
| 25  | SDSS J012642.91+000239.0 | 3.22             | 19.7 | 20.7                 | 2.886            | C IV, Fe ii |
| 35  | Q012426.25–001708.1    | 2.67             | 21.2 | 19.3                 | 2.682            | C IV, Si iv, Si ii |
| 37  | Q012355.95–001853.4    | 3.12             | 20.5 | 19.7                 | 2.880            | C IV, C ii |
| 38  | Q012348.47–001538.8    | 2.88             | 21.1 | 19.8                 | 2.822            | C IV, Si ii, Si iii |
| 59  | Q012351.00–005958.6    | 2.59             | 21.5 | 19.9                 | 2.510            | C IV, Si iv |
| 70  | Q094224.73–120222.9    | 2.84             | 19.4 | 20.0                 | 2.498            | C IV, Si iv, Al ii |
| 72  | Q094408.14–105040.0    | 2.68             | 20.8 | 20.0                 | 2.255            | C IV, Al ii |
| 91  | Q094357.66–105435.1    | 3.00             | 20.8 | 19.9                 | 3.020            | C IV, Si iv, Si ii, Al ii |
| 92  | Q094400.94–114757.5    | 2.90             | 19.5 | 20.5                 | 2.821            | C IV, C ii |
| 108 | Q120244.72+020528.5    | 3.52             | 20.3 | 19.2                 | 3.537            | C IV, Si iv |
| 122 | Q120001.29+003432.7    | 3.36             | 20.0 | 19.2                 | 3.267            | C IV, Si iv |
| 131 | Q212904.90–160249.0    | 2.90             | 19.2 | 19.7                 | 2.162            | C IV, Si iv, Fe ii, Al ii |
| 141 | Q213007.46–153320.9    | 3.46             | 21.9 | 19.4                 | 3.267            | C IV, Si iv |
| 141 | Q213007.46–153320.9    | 3.46             | 21.9 | 19.4                 | 3.267            | C IV, Si iv |
| 142 | Q213201.80–153256.4    | 2.74             | 17.8 | 19.8                 | 2.338            | C IV, Si iv, Fe ii |

Table C3. C IV systems identified towards quasars in both our high- and low-resolution samples. The columns give the unique absorber number, the field for the absorber, the number from Table C1 of the quasar towards which the absorber was seen, the quasar’s redshift, the absorber redshift and 1σ error and the observed equivalent width (EW) in Å and 1σ error. This is a sample of the full table, which is available with the electronic version of the article – see Supporting Information.

| No. | Field      | Quasar | C IV sample | $z_{\text{qso}}$ | $z_{\text{abs}}$ | $\sigma z_{\text{abs}}$ | EW   | $\sigma$EW |
|-----|------------|--------|-------------|------------------|------------------|------------------------|------|-----------|
| 1   | HE 0940–1050 | 95     | 2.22        | 1.58144          | 0.00022          | 2.157                  | 0.065 |
| 2   | HE 0940–1050 | 95     | 2.22        | 2.19780          | 0.00026          | 0.952                  | 0.029 |
| 3   | HE 0940–1050 | 98     | 2.93        | 2.42767          | 0.00016          | 1.401                  | 0.010 |
| 4   | HE 0940–1050 | 70     | 2.84        | 2.49789          | 0.00009          | 5.073                  | 0.029 |
| 5   | HE 0940–1050 | 79     | 2.96        | 2.48853          | 0.00021          | 2.670                  | 0.060 |
| 6   | HE 0940–1050 | 79     | 2.96        | 2.89225          | 0.00009          | 2.587                  | 0.006 |
| 7   | HE 0940–1050 | 92     | 2.90        | 2.21464          | 0.00020          | 1.335                  | 0.019 |
| 8   | HE 0940–1050 | 81     | 3.48        | 2.56623          | 0.00014          | 4.665                  | 0.077 |
| 9   | HE 0940–1050 | 81     | 3.48        | 2.57830          | 0.00022          | 2.652                  | 0.079 |
| 10  | HE 0940–1050 | 81     | 3.48        | 3.13576          | 0.00026          | 2.440                  | 0.045 |
| 11  | HE 0940–1050 | 96     | 3.33        | 1.85485          | 0.00028          | 0.923                  | 0.030 |
| 12  | HE 0940–1050 | 96     | 3.33        | 2.32154          | 0.00040          | 0.510                  | 0.013 |
| 13  | HE 0940–1050 | 94     | 2.56        | 1.86486          | 0.00033          | 0.344                  | 0.005 |
| 14  | HE 0940–1050 | 94     | 2.56        | 1.88062          | 0.00032          | 0.658                  | 0.006 |
| 15  | HE 0940–1050 | 94     | 2.56        | 1.94750          | 0.00015          | 1.322                  | 0.009 |
| 16  | HE 0940–1050 | 94     | 2.56        | 2.18651          | 0.00016          | 0.932                  | 0.006 |
| 17  | HE 0940–1050 | 94     | 2.56        | 2.34047          | 0.00017          | 0.841                  | 0.007 |
| 18  | HE 0940–1050 | 72     | 2.68        | 2.25497          | 0.00037          | 2.033                  | 0.118 |
| 19  | HE 0940–1050 | 93     | 3.15        | 2.97584          | 0.00014          | 3.904                  | 0.030 |
| 20  | HE 0940–1050 | 93     | 3.15        | 3.12947          | 0.00026          | 1.035                  | 0.010 |

SUPPORTING INFORMATION

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

Table C1. Quasars with $z > 2.1$ for which we have obtained AAOGamma spectra.

Table C3. C IV systems identified towards quasars in both our high- and low-resolution samples.

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