Probing the IGM–galaxy connection at $z < 0.5$ – II. New insights into the galaxy environments of $\text{O\ VI}$ absorbers in PKS 0405–123

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ABSTRACT
We present new absorption-line analysis and new galaxy survey data obtained for the field around PKS 0405–123 at $z_{\text{QSO}} = 0.57$. Combining previously known $\text{O\ VI}$ absorbers with new identifications in the higher S/N ultraviolet (UV) spectra obtained with the Cosmic Origins Spectrograph, we have established a sample of 7 $\text{O\ VI}$ absorbers and 12 individual components at $z = 0.0918–0.495$ along the sightline towards PKS 0405–123. We complement the available UV absorption spectra with galaxy survey data that reach 100 per cent completeness at projected distances $\rho < 200$ kpc of the quasar sightline for galaxies as faint as $0.1 L_\alpha$ ($0.2 L_\alpha$) out to redshifts of $z \approx 0.35$ ($z \approx 0.5$). The high level of completeness achieved at faint magnitudes by our survey reveals that $\text{O\ VI}$ absorbers are closely associated with gas-rich environments containing at least one low-mass, emission-line galaxy. An intriguing exception is a strong $\text{O\ VI}$ system at $z \approx 0.183$ that does not have a galaxy found at $\rho < 4$ Mpc, and our survey rules out the presence of any galaxies of $L > 0.04 L_\alpha$ at $\rho < 250$ kpc and any galaxies of $L > 0.3 L_\alpha$ at $\rho < 1$ Mpc. We further examine the galactic environments of $\text{O\ VI}$ absorbers and those ‘Ly$\alpha$-only’ absorbers with neutral hydrogen column density $N(\text{H I}) > 13.6$ and no detectable $\text{O\ VI}$ absorption features. The Ly$\alpha$-only absorbers serve as a control sample in seeking the discriminating galactic features that result in the observed $\text{O\ VI}$ absorbing gas at large galactic radii. We find a clear distinction in the radial profiles of mean galaxy surface brightness around different absorbers. Specifically, $\text{O\ VI}$ absorbers are found to reside in regions of higher mean surface brightness at $\rho \lesssim 500$ kpc ($\Delta \mu_R \approx +5 \text{ mag Mpc}^{-2}$ relative to the background at $\rho > 500$ kpc), while only a mild increase in galaxy surface brightness is seen at small $\rho$ around Ly$\alpha$-only absorbers ($\Delta \mu_R \approx +2 \text{ mag Mpc}^{-2}$). The additional insights gained from our deep galaxy survey demonstrate the need to probe the galaxy populations to low luminosities in order to better understand the nature of the absorbing systems.

Key words: surveys – galaxies: haloes – quasars: absorption lines – galaxies: star formation.

1 INTRODUCTION

Ultraviolet (UV) absorption lines in the spectra of background sources represent the most sensitive available means of observing the diffuse gas that permeates the universe. The $\text{O\ VI} \lambda\lambda 1031, 1037$ doublet in particular has received attention as a tracer of the warm–hot phase of the intergalactic medium (IGM; e.g. Cen & Ostriker 1999), the galaxy outflows thought to be responsible for the chemical enrichment of the IGM (e.g. Oppenheimer & Davé 2006) and the intragroup medium (Mulchaey et al. 1996). While independent surveys of $\text{O\ VI}$ absorbers in the spectra of distant quasars (QSOs) have uncovered a large number of these systems supporting the notion of $\text{O\ VI}$ doublets being a sensitive tracer of warm–hot gas, the reported number density of $\text{O\ VI}$ absorbers from different surveys shows a scatter much beyond the individual measurement errors (e.g. Burles & Tyler 1996; Tripp & Savage 2000; Tripp, Savage & Jenkins 2000; Prochaska et al. 2004; Richter et al. 2004; Danforth & Shall 2008; Thom & Chen 2008; Tripp & Savage 2008; Tilton et al. 2012). At the same time, cosmological simulations incorporating momentum-driven winds have been able to reproduce the observed $\text{O\ VI}$ absorption column density function, but ambiguity remains in attributing the majority of low-redshift $\text{O\ VI}$ absorbers to either cool, photoionized gas (e.g. Kang et al. 2005; Oppenheimer & Davé 2009; Oppenheimer et al. 2012) or the warm–hot phase of the IGM (cf. Smith et al. 2011; Tepper-García et al. 2011; Cen 2012; Stinson et al. 2012).

Key insights into the physical origin of $\text{O\ VI}$ absorbers can be gained from a detailed examination of their galactic environments.
Observations designed to constrain the properties of gaseous haloes of known galaxies have shown that emission-line galaxies exhibit near-unity $\text{OVI}$ covering fractions ($\kappa_{\text{VI}}$) at projected distances $\rho \lesssim 150\,\text{kpc}$ and $\kappa_{\text{VI}} \approx 64$ per cent at $\rho < 350\,\text{kpc}$, while absorption-line galaxies exhibit $\kappa_{\text{VI}} \lesssim 30$ per cent on similar scales (Chen & Mulchaey 2009; Tumlinson et al. 2011). The large incidence of OVI absorbers around star-forming galaxies may be explained by a causal connection between star formation and the production of OVI absorbing gas, but the non-negligible covering fraction of such gas around an evolved galaxy population becomes difficult to explain under the same scenario.

While surveys of galaxies associated with known OVI absorbers have revealed a correlation between the presence of star-forming galaxies and OVI absorbers at modest projected separations $\rho \lesssim 350\,\text{kpc}$ (Prochaska et al. 2006; Stocke et al. 2006, 2013; Chen & Mulchaey 2009; Mulchaey & Chen 2009; Wakker & Savage 2009), the galaxy survey data are not sufficiently deep and complete for a detailed examination of the galactic environment immediate to the absorbers. Dedicated surveys around UV bright QSO sightlines are typically limited to bright galaxies with $R$-band magnitudes brighter than $AB(R) \approx 19.5$ limiting sensitivity to $L \approx 1.1 L_\odot$ at $\alpha < 0.1$ (e.g. Prochaska et al. 2011). Although the study of Wakker & Savage (2009) includes galaxies fainter than $L = 0.1 L_\odot$ at $\alpha < 0.02$, the incompleteness of their galaxy catalogue is unknown. Survey incompleteness complicates the interpretation of the galaxy–absorber studies (Stocke et al. 2006, 2013). To date, a high completeness level ($\approx 95$ per cent) for galaxies of $R \lesssim 23$ and $\Delta \theta < 2$ arcmin from the QSO sightline has been reached in only one QSO field (HE 0226−4110 in Chen & Mulchaey 2009). To improve the statistics, our group is continuing the effort to collect high-completeness galaxy survey data in multiple QSO fields.

In this paper, we present new galaxy survey data obtained for the field around PKS 0405−123 at $z_{\text{QSO}} = 0.57$. Our galaxy survey in this field has reached 100 per cent completeness within $\rho = 200\,\text{kpc}$ of the QSO sightline for galaxies as faint as $0.1 L_\odot$ ($0.2 L_\odot$) out to redshifts of $\alpha \approx 0.35$ ($\alpha \approx 0.5$). PKS 0405−123 is among the brightest QSOs on the sky, for which high-quality UV echelle data have been obtained using the Space Telescope Imaging Spectrograph (STIS; Woodgate et al. 1998), and extremely high quality UV spectra have been obtained using the new Cosmic Origins Spectrograph (COS; Green et al. 2012) on board the Hubble Space Telescope (HST). The intermediate redshift of the QSO provides a long redshift path length for probing intervening absorption systems. Previous systematic searches in the STIS and Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000) spectra have uncovered six OVI absorption systems at $z_{\text{OVI}} \lesssim 0.09−0.5$ (Prochaska et al. 2004; Howk et al. 2009) and 11 additional strong Lyα absorbers of neutral hydrogen column density log $N(\text{H I}) \geq 13.6$ at $z_{\text{HI}} = 0.03−0.5$ (e.g. Williger et al. 2006; Lehner et al. 2007). Recent targeted searches in the new COS spectra have further uncovered an Ne viii absorber associated with the strong OVI absorber at $z = 0.495$ (Narayanan et al. 2011) and a new component associated with the previously known OVI absorber at $z \approx 0.167$ (Savage et al. 2010).

To complement the available highly complete galaxy survey data, we have carried out a new systematic search of absorption features in the new COS spectra. Here we discuss new insights into the origin of OVI absorbing gas that we have learned from combining the improved absorption-line measurements and highly complete galaxy survey data. The paper proceeds as follows. In Section 2, we present the full archival COS spectrum of PKS 0405−123 and new galaxy redshifts in our survey. In Section 3, we review measurements of the absorbers enabled by the COS spectrum including (1) a tentative detection of an OVI absorber at $z = 0.2977$, (2) a new OVI absorber at $z = 0.3615$ and (3) $\text{NIV}$ associated with a known OVI absorber at $z = 0.3633$. In Section 4, we discuss the galaxy environments of all seven OVI absorbers along this sightline and compare them to the galaxy environments of strong Lyα absorbers with no detected OVI. Finally, in Section 5, we briefly discuss the implications of our findings.

Throughout the paper, we adopt a $\Lambda$ cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. We also adopt a non-evolving, rest-frame absolute $R$-band magnitude ($\text{AB}$ of $M_R \approx -21.17$ for $L_\odot$ galaxies based on Blanton et al. (2003). Unless otherwise stated, we perform $k$-corrections using the Sbc galaxy template from Coleman, Wu & Weedman (1980).

## 2 DATA

PKS 0405−123 is a well-studied sightline with available imaging and UV spectroscopic data in the FUSE and HST archives (Chen & Prochaska 2000; Prochaska et al. 2004; Williger et al. 2006; Lehner et al. 2007). Different galaxy surveys have been carried out in this field identifying galaxies associated with absorption-line systems uncovered in the UV spectra (Spinrad et al. 1993; Ellington & Yee 1994; Chen et al. 2005; Prochaska et al. 2006; Chen & Mulchaey 2009). Recently, PKS 0405−123 was targeted for HST/COS UV spectroscopy at significantly higher S/N than the archival STIS spectra. This new data set led to the discovery of an interesting OVI absorber with no detectable Hα at $\Delta v \approx -300\,\text{km}\,\text{s}^{-1}$ from a previously detected OVI absorber in a partial Lyman-limit system at $z = 0.1671$ (Savage et al. 2010). We have analysed the full COS spectrum of PKS 0405−123 (Fig. 1) together with new and existing galaxy survey data for a comprehensive study of the galactic environments of absorbing clouds uncovered along this QSO sightline.

### 2.1 COS spectroscopy

PKS 0405−123 was targeted for COS observations by two separate HST programmes (PI: Keith Noll, PID = 11508 and PI: James Green, PID = 11541). The two programmes together acquired 17 exposures, totalling 22.2 ks with the G130M grating (covering the spectral range 1150−1450 Å and full width at half-maximum spectral resolution of FWHM = 16 km s$^{-1}$), and 4 exposures, totalling 11.1 ks with the G160M grating (1400−1800 Å, FWHM = 16 km s$^{-1}$). The exposures were acquired at different central wavelengths in order to provide contiguous wavelength coverage despite the gap between COS detectors. We retrieved the 1D individual calibrated spectra from the HST archive and combined them using a custom suite of software (see Yoon et al. 2012 for details). Specifically, individual spectra from the two detector segments were aligned and co-added using a common Milky Way absorption line as a reference (e.g. Si iii 1206) and then combined into a single one-dimensional spectrum. These co-addition routines work with photon counts rather than flux-calibrated data to allow for an accurate error estimate in the low-count regime (e.g. Gehrels 1986). A well-known issue with far-ultraviolet (FUV) spectra obtained using COS is the presence of fixed-pattern noise due to the grid wire in the COS FUV detectors. Such pattern noise can be reduced by the use of multiple FP-POS settings (see the COS Instrument Handbook). As described above, PKS 0405−123 was observed by two different programmes and in many exposures of different FP-POS settings. The effect of such fixed-pattern noise is therefore minimal in the final stack. To ensure consistency with previous results, we set a
Probing the IGM–galaxy connection

common zero-point by aligning the co-added COS spectrum with the archival FUSE and STIS spectra prior to the combination of the G130M and G160M data. This alignment led to minor (≪FWHM) higher order corrections to the COS wavelength calibration. By comparing the COS spectrum with the archival STIS spectrum, we estimate that errors in the wavelength calibration limit the accuracy of line centroids to ≈4 km s⁻¹.

The resulting high-resolution spectrum (see Fig. 1) enabled the new detections of O VI systems in addition to a number of other lines and significantly stronger upper limits on key ions. The new detections are discussed in detail in Section 3.

2.2 Galaxy survey

Previous spectroscopic surveys of galaxies in the PKS 0405–123 field reached ≈80 per cent completeness within a 3 arcmin radius of the QSO sightline for galaxies brighter than $R = 21$ and ≈50 per cent for galaxies between $R = 21$ and 22 (e.g. Chen & Mulchaey 2009). These surveys identified galaxies associated with half of the known O VI absorbers along this QSO sightline; however, a detailed study of the galaxy environments that includes sub-$L_*$ galaxies requires a higher survey completeness at fainter magnitudes. To improve the survey depth, we acquired new galaxy spectra with the Magellan telescopes using the Inamori-Magellan Areal Camera & Spectrograph (IMACS; Dressler et al. 2011) and the Low Dispersion Survey Spectrograph 3 (LDSS3) (see Table 1 for a summary of the observations). In addition, we confirmed a number of photometric stars using the Dual Imaging spectrograph (DIS) on the Apache Point Observatory (APO) 3.5 m. The IMACS and LDSS3 data were reduced using the Carnegie Observatories System for MultiObject Spectroscopy (COSMOS¹) as described in Chen & Mulchaey (2009). The APO DIS spectra were reduced using a slightly modified version of the Low-REDUX pipeline written by J. Hennawi, S. Burles and J. X. Prochaska.² Galaxy redshifts were determined both by cross-correlation with the Sloan Digital Sky Survey (York et al. 2000) templates and by fitting of galaxy eigenspectra as in Chen & Mulchaey (2009). In nearly all cases, the two independently determined redshifts were in good agreement ($|\Delta z| \leq 0.0003$), but in the small number of cases for which they were not, SDJ and HWC determined the best redshift by refitting and visual inspection. All assigned redshifts were visually inspected to determine

Table 1. Journal of spectroscopic observations.

| Telescope       | Instrument/setup                     | FWHM (Å) | No. of targets | Exposure time (ks) | Date     |
|-----------------|-------------------------------------|----------|----------------|--------------------|----------|
| Magellan Baade  | IMACS/f2/200l, 1 arcsec slitlets     | 9        | 17             | 3.6                | Nov. 2012|
|                 |                                     | 12       | 3.0            |                    | Feb. 2011|
|                 |                                     | 150      | 5.4            |                    | Nov. 2012|
|                 |                                     | 140      | 5.4            |                    | Feb. 2011|
| Magellan Clay   | LDSS3/VPH all 1 arcsec slitlets      | 10       | 24             | 7.2                | Feb. 2011|
| APO 3.5 m       | DIS/B400 and R300, 1.5 arcsec long slit | 5        | 23             | Varies            | Oct.–Dec. 2012|

¹ http://code.obs.carnegiescience.edu/cosmos
² http://www.ucolick.org/~xavier/LowRedux/
their reliability, and galaxy spectra were further classified as either absorption-line dominated or emission-line dominated. The final object catalogue is presented in Table 2.

The new IMACS/LDSS3 observations include 225 new galaxies without previously known redshifts, providing an unprecedented level of completeness in the field when combined with previous surveys. Specifically, the survey is 100 per cent (≈90 per cent) complete for galaxies brighter than \( R = 22 \) (\( R = 23 \)) within 1 arcmin of the QSO sightline. The relevant figure of merit, however, is the completeness as a function of galaxy luminosity, physical impact parameter and redshift which is shown in Fig. 2 along with a galaxy-redshift histogram.\(^3\) The survey is 100 per cent complete for \( L > 0.1L_\odot \), galaxies at an impact parameter less than \( \rho = 100 \) kpc and \( >90 \) per cent complete at \( \rho < 200 \) kpc at all redshifts \( z < z_{\text{QSO}} \). The completeness level decreases somewhat at larger impact parameters due to our targeting priority, but even at \( \rho > 500 \) kpc, the survey is \( \geq 75 \) per cent complete for \( L > 0.1L_\odot \), galaxies at \( z < z_{\text{QSO}} \). The high level of completeness is visually captured by the \( HST \) image of the field labelled with galaxy redshifts (Fig. 3).

We note that in addition to the many foreground galaxies spectroscopically identified near the QSO line of sight, there exists a clear overdensity of galaxies at the redshift of the QSO. The galaxy catalogue is therefore also valuable for studying AGN fuelling (e.g. Ellingson & Yee 1994).

### 3 NEW MEASUREMENTS OF ABSORPTION-LINE SYSTEMS

The higher S/N of the new COS data ensured both improved measurements of previously known transitions and new detections along the sightline. We conducted a systematic search of new absorption

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### Table 2. The photometric and spectroscopic catalogue of galaxies around PKS 0405−123°. The full table is available on the journal webpage.

| ID | RA (J2000) | Dec. (J2000) | \( \delta \theta \) (arcsec) | \( \rho^h \) (kpc) | \( R \) (mag) | \( z_{\text{spec}} \) | Quality | Object type | Galaxy class | \( L/L_\odot^b,f \) |
|----|-------------|-------------|-----------------------------|-------------------|------------|----------------|---------|-------------|-------------|----------------|
| 80001\(^a\) | 04:07:48.9 | −12:11:33 | 7.8 | 35 | 21.65 ± 0.00 | 0.5715 | A | G | E | 0.95 |
| 90001 | 04:07:49.1 | −12:11:38 | 9.9 | 45 | 22.10 ± 9.99 | 0.5697 | A | G | E | 0.62 |
| 80003\(^a\) | 04:07:49.1 | −12:11:43 | 11.7 | 53 | 21.10 ± 0.00 | 0.5709 | A | G | A | 1.57 |
| 80004\(^a\) | 04:07:49.2 | −12:11:49 | 12.8 | 58 | 19.97 ± 0.00 | 0.5678 | A | G | A | 4.36 |
| 80005\(^a\) | 04:07:48.6 | −12:11:52 | 15.5 | 70 | 21.54 ± 0.00 | 0.5656 | A | G | A | 1.01 |
| 1883 | 04:07:48.3 | −12:11:21 | 15.8 | 78 | 21.69 ± 0.12 | 0.6883 | A | G | E | 1.69 |
| 90002 | 04:07:49.5 | −12:11:41 | 16.3 | 74 | 22.10 ± 9.99 | 0.5715 | A | G | E | 0.63 |
| 1920\(^a\) | 04:07:47.4 | −12:11:26 | 18.5 | 96 | 22.77 ± 0.19 | 0.7797 | A | G | A | 0.97 |
| 1862 | 04:07:49.1 | −12:11:21 | 18.5 | 78 | 22.63 ± 0.17 | 0.4942 | A | G | E | 0.25 |
| 1866 | 04:07:48.8 | −12:11:58 | 22.0 | 100 | 21.40 ± 0.10 | 0.5713 | A | G | E | 1.19 |
| 80010\(^a\) | 04:07:49.8 | −12:11:48 | 23.1 | −1 | 21.70 ± 0.00 | 1.4657 | B | G | E | −1.00 |
| 1820\(^a\) | 04:07:49.9 | −12:11:49 | 24.8 | 113 | 21.75 ± 0.13 | 0.5686 | A | G | A | 0.85 |
| 1854 | 04:07:49.2 | −12:12:04 | 29.6 | 136 | 21.23 ± 0.09 | 0.5779 | A | G | E | 1.44 |

Notes. \(^a\)ID, coordinates and \( R \)-band photometry from Prochaska et al. (2006) except for objects with IDs 800## or 900## which were added from Ellingson & Yee (1994) or based on visual inspection of the DU Pont/WFCCD or \( HST \) images.

\(^b\)Given a value of \( −1 \) when not available due to lack of a secure redshift or when not applicable.

\(^c\)Redshift and classification quality: A→ secure (\( \geq 2 \) features), B→ 1 feature, C→ observed but no features and N→ not observed.

\(^d\)Object classification: Q→ QSO, G→ galaxy, S→ star and U→ unknown.

\(^e\)Galaxy classification: E→ emission-line dominated, A→ absorption-line dominated and N→ n/a.

\(^f\)Measured from \( R \)-band photometry as discussed in the text.

\(^g\)Redshift and classification from new data presented in this paper.

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Figure 2. Summary of our galaxy survey results. The curves at the top show the estimated survey completeness for \( L > 0.1L_\odot \) galaxies as a function of redshift at projected distances of \( \rho < 100, 200, 300, 400 \) and \( 500 \) kpc of the QSO sightline. The bottom histograms show the redshift distributions of all galaxies (black) and absorption-line-dominated galaxies (red, solid) in the final combined spectroscopic catalogue. For comparison, we show the expected redshift distribution based on a non-evolving \( R \)-band luminosity function adapted from Blanton et al. (2003), taking into account our survey incompleteness as a function of galaxy luminosity and redshift (solid black line). Spikes in the histogram that deviate significantly from expectations are due to large-scale galaxy overdensities in the QSO field. The redshifts of \( \text{O} \)\( \text{VI} \) absorbers (vertical ticks) and the QSO (Q) are shown along the top of the figure.

\(^3\) We estimated the completeness function using the observed completeness as a function of magnitude and angular separation from the QSO sightline and smoothed with a \( \Delta z = 0.1 \) boxcar function to remove fluctuations due to small number statistics.
Probing the IGM–galaxy connection

Figure 3. HST/Wide Field Planetary Camera 2 image of PKS 0405–123 augmented with an image from the DuPont telescope (Prochaska et al. 2006) where HST imagery is unavailable. The orientation of the field is indicated by the N–E arrows that appear in the upper-left corner. Redshifts are shown to the right of the corresponding galaxy except in crowded areas where an arrow is used to indicate association. Galaxies foreground to the QSO are shown in red, while background galaxies (\(z \gtrsim z_{\text{QSO}}\)) are shown in black. Galaxies associated with O\(\text{VI}\) absorbers (with velocity offsets \(|\Delta v| < 300 \text{ km s}^{-1}\)) are marked by solid red boxes, while galaxies associated with Ly\(\alpha\) absorbers and no detectable O\(\text{VI}\) are marked by dotted red boxes. Stars are labelled with blue circles and galaxies without secure redshifts are marked in purple either by redshift (based on a single emission line) or \(R\)-band magnitude if no redshift is available. A dotted circle centred on the QSO with 1 arcmin radius is shown to provide scale. In addition to the many foreground galaxies spectroscopically identified near the QSO line of sight, there exists a clear overdensity of galaxies at the redshift of the QSO.

features in the COS spectra of PKS 0405–123 and identified four features that were previously unknown. These include (1) a tentative detection of a new O\(\text{VI}\) absorber at \(z = 0.2977\), (2) a new O\(\text{VI}\) component at \(\Delta v = +170 \text{ km s}^{-1}\) from a previously known metal-line absorber at \(z = 0.3608\) and (3) N\(\text{V}\) absorption associated with a known O\(\text{VI}\) system at \(z = 0.3633\). Combining previous results with the new findings yielded a sample of 7 O\(\text{VI}\) absorbers and 12 individual components found at \(z = 0.0918–0.495\) along the sightline towards PKS 0405–123.

We measured the line profiles of both new and known O\(\text{VI}\) absorbers, as well as their associated H\(\text{I}\) and other metal transitions based on a Voigt profile analysis using the \textsc{vpfit} package\(^4\) (Carswell et al. 1987) and the empirical COS line spread function (LSF).\(^5\) The COS LSF exhibits broad wings which contain up to 40 per cent

\(^4\) http://www.ast.cam.ac.uk/~rfc/vpfit.html
\(^5\) http://www.stsci.edu/hst/cos/performance/spectral_resolution/
of the flux (Ghavamian et al. 2009). The use of the empirical LSF in the Voigt profile fitting is therefore necessary in order to properly account for the absorption that falls in the wings of the LSF. In the cases of line blending, we employed a simultaneous fit of a minimum number of separate components that are necessary to produce a reasonable $\chi^2$ value. For non-detections, we calculated the $3\sigma$ rest-frame equivalent width limit over a 300 km $s^{-1}$ spectral window (significantly broader than the wings of the COS LSF) and converted this to the corresponding $3\sigma$ limit in column density assuming that the gas is optically thin. The results are summarized in Table 3, where we list for each species the velocity offset $\Delta v$ relative to the systemic redshift of each absorber $z_{sys}$ as defined by the dominant $H\alpha$ component, the Doppler parameter $b$ and the best-fitting column density. We also include in Table 3 measurements from the literature for completeness. Here we briefly describe the properties of newly detected absorption features.

At $z = 0.1826$ and 0.1829, two $O\ vi$ components were found in previous searches (Prochaska et al. 2004; Thom & Chen 2008). We confirm both detections and reevaluate the absorber properties with a simultaneous fit of both components in the COS data. The lower redshift $O\ vi$ component is characterized by an $O\ vi$ column density log $N(O\ vi) = 13.75 \pm 0.02$ and Doppler width $b = 32 \pm 3$ km $s^{-1}$, and is merely $\approx 9$ km $s^{-1}$ offset from a previously identified $H\alpha$ absorption component with log $N(H\alpha) = 14.69 \pm 0.01$ and $b = 33 \pm 1$ km $s^{-1}$. The higher redshift $O\ vi$ component is characterized by log $N(O\ vi) = 13.88 \pm 0.02$ and $b = 21 \pm 1$ km $s^{-1}$. No other ions have been detected with a $3\sigma$ upper limit of log $N < 12.8$ for both $N\alpha$ and $Si\ iv$ absorption. Prochaska et al. (2004) reported an upper limit of log $N < 12.4$ for $C\ iii$ absorption. The best-fitting Voigt profiles of the $O\ vi$ doublet along with those of Ly$\alpha$ and Ly$\beta$ absorption are presented in the left column of Fig. 4.

At $z = 0.2977$, we report a tentative detection of an $O\ vi$ absorber at $\Delta v \approx 8$ km $s^{-1}$ from a previously identified Ly$\alpha$ absorber. The $O\ vi$ absorption profile is relatively broad with log $N(O\ vi) = 13.61 \pm 0.02$ and $b \approx 60$ km $s^{-1}$. The $\lambda 1037$ member is detected at an $\approx 3\sigma$ level of significance, but the model slightly overpredicts the absorption strength of this weaker member which appears to be contaminated by other absorption features. No other metal absorption is detected in the COS spectrum. Our Voigt profile analysis shows that the Ly$\alpha$ transition is best described by two components separated by $\Delta v = 65$ km $s^{-1}$, with one component containing log $N(H\alpha) = 13.89 \pm 0.05$ at $z = 0.2976$ and the other containing log $N(H\alpha) = 13.34 \pm 0.2$ at $z = 0.2979$. The best-fitting Voigt profiles of the $O\ vi$ doublet along with those of Ly$\alpha$ and Ly$\beta$ absorption are presented in the middle-left column of Fig. 4.

At $z = 0.3615$, we also report the detection of a new $O\ vi$ component with log $N(O\ vi) = 13.80 \pm 0.01$ and $b = 30 \pm 1$ km $s^{-1}$ at $\Delta v = +170$ km $s^{-1}$ from a previously known absorption complex at $z = 0.3608$ (e.g. Prochaska et al. 2004). Similar to the $O\ vi$ absorber at $z = 0.1829$, we do not detect additional metal-line systems associated with this new $O\ vi$ component. There is possible $O\ iv$ absorption at $z \approx 0.3608$ with log $N(O\ iv) = 13.38 \pm 0.05$ detected in the COS spectrum, but it cannot be confirmed due to contaminating features at the location of the second doublet member. The best-fitting Voigt profiles of the $O\ vi$ doublet along with those of Ly$\alpha$ and Ly$\beta$ absorption are presented in the middle-right column of Fig. 4.

Finally, the $O\ vi$ absorption system previously identified at $z = 0.3633$ with log $N(O\ vi) = 13.36 \pm 0.05$ and $b = 10 \pm 1$ km $s^{-1}$ displays the possible presence of an associated $N\alpha$ doublet in the new COS spectrum. Prochaska et al. (2004) identified $H\alpha$, $O\ iv$, $N\alpha$ and $C\ iii$ absorption associated with this $O\ vi$ absorber, $\ldots$

Table 3. Summary of line properties of known $O\ vi$ absorbers.

| Element | $\Delta v$ (km $s^{-1}$) | $b$ (km $s^{-1}$) | log $N$(cm$^{-2}$) | References$^a$ |
|---------|-----------------|-----------------|-----------------|-----------------|
| $H\alpha$ | 0 | 38 $\pm$ 2 | 14.52 $\pm$ 0.05 | 1 |
| $C\ iv$ | 0 | $<12.90$ | 2 |
| $N\alpha$ | 0 | $<12.67$ | 2 |
| $O\ vi$ | $+20$ | 13.83 $\pm$ 0.04 | 1 |
| $Si\ iv$ | 0 | $<12.66$ | 2 |
| $z_{sys} = 0.0918$ |
| $H\alpha$ | 0 | 40 $\pm$ 2 | 14.65 $\pm$ 0.05 | 1 |
| $C\ iv$ | 0 | $<12.90$ | 2 |
| $N\alpha$ | 0 | $<12.97$ | 2 |
| $O\ vi$ | 0 | 13.70 $\pm$ 0.20 | 1 |
| $Si\ iv$ | 0 | $<12.64$ | 2 |
| $z_{sys} = 0.09658$ |

$^a$: Prochaska et al. (2004); 2: this work; 3: Savage et al. (2010); 4: Narayanan et al. (2011).

$^b$: Tentative detection due to contamination of the $\lambda 1037$ member.

$^c$: Measurements obtained with a simultaneous fit to the transitions assuming that these absorbers originate in the same gas.

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Probing the IGM–galaxy connection

Figure 4. Absorption profiles of two O\text{VI} absorbers and a tentative detection (left three columns) and the N\text{V} doublet detected in a known metal-line absorber (right column) in the high-quality COS spectrum, along with the associated H\text{I} Ly\alpha and/or Ly\beta transition. The continuum normalized spectrum is shown in black solid line and the associated 1\sigma errors are plotted in black dotted line. The best-fitting model profiles from a Voigt profile analysis (Section 3) are shown in red. Spectral regions contaminated by other absorption systems are plotted in grey. We do not plot data at velocities greater than $\Delta v > +120$ km s$^{-1}$ for the Ly\beta line of the $z = 0.1826$ absorber because in this range, the QSO flux is nearly completely attenuated by Milky Way Ly\alpha absorption. We consider the O\text{VI} absorber at $z = 0.2977$ a tentative detection, because the observed depth of the $\lambda 1037$ member appears shallower than the expectation of the doublet based on the fit of the $\lambda 1031$ member. Note that the bottom two rows are shown with a partial y-range from 0.5 to 1.2 to improve the visibility of weak features. This partial y-range prevents the errors from being displayed in the bottom two rows.

although the H\text{I} absorbing component is $\Delta v = +20$ km s$^{-1}$ away from the O\text{VI} absorber. We confirm the presence of C\text{III} absorption with $\log N$(C\text{III}) = 12.48 $\pm$ 0.07 and detect N\text{V} with $N$(N\text{V}) = 13.01 $\pm$ 0.08 at the redshift of the O\text{VI} absorber. The measurements were obtained based on a simultaneous fit of Voigt profiles to all three transitions, assuming that these ions originate in the same gas. Allowing independent fits to the line centroids of N\text{V} and C\text{III} does not improve the model fit. The best-fitting Voigt profiles of Ly\alpha, C\text{III} $\lambda 977$, O\text{VI} $\lambda 1031$ and N\text{V} $\lambda 1238$ are presented in the right column of Fig. 4. Both O\text{V} and N\text{V} are highly ionized species, whereas C\text{II} is at a much lower ionization state. The presence of these ions together strongly supports a photoionization scenario for the absorbing gas (see Prochaska et al. 2004). Based on the observed relative abundance of C\text{II} and O\text{V}, Prochaska et al. (2004) derived an ionization parameter of $\log U = -1.4 \pm 0.2$ and a minimum metallicity of solar for the absorbing gas assuming that all of the observed $N$(H\text{I}) is associated with the O\text{VI} absorbing gas.

Including the tentative detection of an O\text{VI} absorber at $z = 0.2977$, we have a total of seven O\text{VI} absorbers along the sightline towards PKS 0405$-$123. In addition, this sightline contains additional 11 strong Ly\alpha absorption systems of $\log N$(H\text{I}) $>$ 13.6 (Williger et al. 2006; Lehner et al. 2007) with no detectable absorption from heavy ions. The high S/N of the COS spectrum enables stronger limits (cf. Prochaska et al. 2004) on the associated O\text{VI} column densities. We define a subsample of ‘Ly\alpha-only’ absorbers of these strong Ly\alpha absorbers with no associated O\text{VI} absorption to a sensitive upper limit. The properties of these Ly\alpha-only systems are summarized in Table 4.

4 THE GALAXY ENVIRONMENTS OF O\text{VI} AND LY\alpha-ONLY ABSORBER

The highly complete survey data of faint galaxies in the field around PKS 0405$-$123 offer a new opportunity to re-examine the galaxy environments of O\text{VI} absorbers. In particular, we compare our findings with previous results from a shallower survey which concluded

$^6$We associate the H\text{I} components identified by Lehner et al. (2007) with one another provided $|\Delta v| < 300$ km s$^{-1}$. Lehner et al. (2007) restricted their study to absorbers with $z < 0.5$ so we include systems identified by Williger et al. (2006) at $z > 0.5$ as well. For each system, we adopt the total H\text{I} column density and the redshift of the strongest H\text{I} component.
that O VI absorbers trace a diverse set of environments including the haloes of individual galaxies, galaxy groups, filamentary-like structures and galaxy voids (e.g. Prochaska et al. 2006). In addition, we compare the galaxy environments of the O VI absorbers with those of Lyα-only absorbers which constitute a control sample in seeking the discriminating galactic features that result in the observed O VI absorbing gas at large galactic radii. Throughout, we associate galaxies with absorbers provided the projected line-of-sight velocity between the absorber and the galaxy is |Δv| < 300 km s⁻¹. All galaxies spectroscopically identified at an impact parameter ρ < 1 Mpc and a velocity offset |Δv| < 300 km s⁻¹ of the O VI and Lyα-only systems are presented in Tables 5 and 6, respectively.

The galactic environments of O VI absorbers uncovered in our survey are presented in Fig. 5. We find that O VI primarily traces overdense galaxy environments with at least one emission-line galaxy found within ρ ≈ 300 kpc. Specifically, the O VI absorber at z = 0.0918 was originally attributed to a filamentary structure connecting three galaxy groups at ρ = 1–3 Mpc (Prochaska et al. 2006). However, we have uncovered four dwarf, emission-line galaxies at ρ ≤ 300 kpc, the closest of which is at ρ = 70 kpc and Δv = +140 km s⁻¹. Similarly, the absorbers at z ≈ 0.3608 had been attributed to the intragroup medium of a group of passive galaxies found at ρ = 1–3 Mpc. Our survey has revealed a dwarf emission-line galaxy (L = 0.08 L*) at ρ = 320 kpc and Δv ≈ 0 km s⁻¹ in addition to the known massive absorption-line galaxy previously found at ρ = 230 kpc. The only intriguing exception is the O VI absorption system at z ≈ 0.183, which exhibits two strong components separated by 70 km s⁻¹. This O VI absorber does not have an associated galaxy at ρ < 300 kpc. Our galaxy survey rules out the presence of any galaxies of L > 0.04 L* at ρ < 250 kpc and the presence of any galaxies of L > 0.3 L* at ρ < 1 Mpc. The lack of galaxies found in the vicinity suggests that this metal-enriched absorber resides in an apparent void. Finally, the O VI absorber at z = 0.495 with the associated Ne VIII doublet (Narayanan et al. 2011) is found to be associated with an emission-line galaxy at ρ = 110 kpc (Chen & Mulchaey 2009). Our new survey has not uncovered any additional galaxies in the vicinity of the absorber. We are able to rule out the presence of any galaxies with L > 0.1 L* at ρ < 200 kpc.

We also present in Fig. 5 the galaxy environments of O VI and Lyα-only absorbers. Considering the increasing survey incompleteness of faint (<0.1 L*) galaxies with increasing redshift, we separate the galaxy–absorber sample into four redshift bins. For each redshift bin, we show the spatial and velocity distributions of galaxies around O VI absorbers in the left column and Lyα-only absorbers in the right column. Each panel is centred at the QSO, while galaxy

### Table 4. Summary of line properties of strong Lyα absorbers with no detectable O VI absorption.

| Element | Δv (km s⁻¹) | b (km s⁻¹) | log N(cm⁻²) | References |
|---------|-------------|------------|-------------|------------|
| H I     | 0           | 54 ± 4     | 13.79 ± 0.02| 1          |
| OVI     | 0           | <13.62     | 3           |
| H I     | +193        | 32 ± 6     | 13.29 ± 0.06| 1          |
| C IV    | 0           | <12.94     | 3           |
| N V     | 0           | <12.71     | 3           |
| OVI     | 0           | <12.95     | 3           |
| Si IV   | 0           | <12.83     | 3           |
| H I     | −208        | 22 ± 2     | 13.54 ± 0.04| 1          |
| H I     | +75         | 18 ± 4     | 13.27 ± 0.09| 1          |
| N V     | 0           | <13.11     | 3           |
| OVI     | 0           | <12.85     | 3           |
| Si IV   | 0           | <12.42     | 3           |
| H I     | 0           | 55 ± 7     | 13.61 ± 0.04| 1          |
| C III   | 0           | <12.37     | 3           |
| N V     | 0           | <13.13     | 3           |
| OVI     | 0           | <13.16     | 3           |
| H I     | −99         | 54 ± 24    | 13.23 ± 0.11| 1          |
| H I     | 0           | 23 ± 2     | 13.69 ± 0.03| 1          |
| OVI     | 0           | <12.89     | 3           |
| Si IV   | 0           | <12.53     | 3           |
| H I     | 0           | 30 ± 2     | 13.82 ± 0.03| 1          |
| N V     | 0           | <13.04     | 3           |
| OVI     | 0           | <13.12     | 3           |
| H I     | 0           | 38 ± 2     | 14.25 ± 0.03| 1          |
| H I     | +115        | 25 ± 5     | 13.53 ± 0.05| 1          |
| H I     | +251        | 31 ± 5     | 13.57 ± 0.05| 1          |
| C III   | 0           | <12.14     | 3           |
| N V     | 0           | <13.05     | 3           |
| OVI     | 0           | <13.00     | 3           |
| H I     | 0           | 33 ± 2     | 14.98 ± 0.02| 1          |
| C III   | 0           | <12.00     | 3           |
| N V     | 0           | <13.10     | 3           |
| OVI     | 0           | <13.28     | 3           |
| H I     | 0           | 40 ± 2     | 14.38 ± 0.03| 1          |
| H I     | +149        | 26 ± 6     | 13.58 ± 0.07| 1          |

### Table 4 – continued

| Element | Δv (km s⁻¹) | b (km s⁻¹) | log N(cm⁻²) | References |
|---------|-------------|------------|-------------|------------|
| N V     | 0           | <13.12     | 3           |
| OVI     | 0           | <13.28     | 3           |

References:
1 Lehner et al. (2007); 2 from FUSE data published in Prochaska et al. (2004); 3 this work; 4 Williger et al. (2006).
positions are marked with circles for emission-line galaxies and triangles for absorption-line galaxies. The symbols are colour-coded to indicate the line-of-sight velocity between each galaxy and the absorber. The symbol size specifies galaxy luminosity as shown in the figure legend. To help visualize the surface density of surrounding galaxies, we also introduce a grey-scale showing luminosity-weighted galaxy surface density where each galaxy is represented by a Gaussian with FWHM = 300 kpc.

A qualitative finding based on Fig. 5 is that a larger fraction of Lyα-only absorbers appear in underdense or relatively isolated galaxy environments in comparison to those of O VI absorbers. Considering all the absorbers together, six of the seven O VI absorption systems at $z < 0.5$ along the sightline are associated with at least one galaxy with $\rho \lesssim 300$ kpc. Four of the six O VI absorption systems at $z < 0.4$ are found in a group of multiple galaxies with $\rho \lesssim 300$ kpc. In contrast, of the 11 additional Lyα-only absorbers, only 3 have associated galaxies found at $\rho < 300$ kpc.

To quantify the potential difference in the observed galactic environments between O VI and Lyα-only absorbers, we perform two separate tests in the following discussion. First, we examine the mean radial profiles of galaxy properties averaged over all systems in each subsample. Secondly, we examine the distribution of galaxy properties within each subsample. In both tests, the comparisons are based on both the surface density of the galaxies and the surface brightness of star light.

### Table 5. Summary of spectroscopically identified galaxies at $\rho < 1$ Mpc and $|\Delta v| < 300$ km s$^{-1}$ of O VI absorbers.

| ID     | RA (J2000) | Dec. (J2000) | $\Delta \alpha$ (arcsec) | $\Delta \delta$ (arcsec) | $\Delta \theta$ (arcsec) | $\rho$ (kpc) | $R$ (mag) | $z_{\text{spec}}$ | Galaxy classification | $L/L_*$ |
|--------|------------|-------------|--------------------------|--------------------------|--------------------------|--------------|-----------|-----------------|----------------------|----------|
| 1835   | 04:07:49.4 | −12:12:16   | 14.2                     | −39.3                    | 41.8                     | 71           | 21.31     | ±0.10          | E                     | 0.02     |
| 2055   | 04:07:44.4 | −12:11:24   | −59.1                    | 12.7                     | 60.4                     | 102          | 21.30     | ±0.09          | E                     | 0.02     |
| 2080   | 04:07:43.2 | −12:11:48   | −76.7                    | −11.3                    | 77.5                     | 132          | 21.27     | ±0.09          | E                     | 0.02     |
| 2212   | 04:07:40.2 | −12:13:44   | −120.7                   | −127.3                   | 175.4                    | 299          | 21.94     | ±0.13          | E                     | 0.01     |
| 1698   | 04:07:52.6 | −12:15:49   | 61.1                     | −252.3                   | 259.6                    | 439          | 19.74     | 0.07           | E                     | 0.07     |
| 1457   | 04:07:58.1 | −12:12:24   | 141.8                    | −47.3                    | 149.5                    | 267          | 19.03     | ±0.07          | E                     | 0.15     |
| 1602   | 04:07:54.2 | −12:14:45   | 84.6                     | −188.3                   | 206.5                    | 370          | 19.01     | ±0.07          | E                     | 0.15     |
| 1601   | 04:07:54.2 | −12:14:50   | 84.6                     | −193.3                   | 211.0                    | 379          | 16.74     | ±0.06          | E                     | 1.24     |
| 2254   | 04:07:39.7 | −12:05:42   | −128.0                   | 354.7                    | 377.1                    | 679          | 18.74     | ±0.07          | E                     | 0.20     |
| 1659   | 04:07:54.4 | −12:03:07   | 87.5                     | 509.7                    | 517.1                    | 931          | 17.99     | ±0.06          | E                     | 0.39     |
| 80006  | 04:07:48.3 | −12:11:03   | −1.9                     | 33.7                     | 33.7                     | 96           | 21.04     | ±0.00          | E                     | 0.08     |
| 1753   | 04:07:51.2 | −12:11:38   | 40.6                     | −1.3                     | 40.6                     | 116          | 17.43     | ±0.06          | E                     | 2.13     |
| 1786   | 04:07:50.6 | −12:12:25   | 31.8                     | −48.3                    | 57.9                     | 256          | 19.34     | ±0.07          | E                     | 1.38     |
| 1967   | 04:07:45.9 | −12:11:09   | −37.1                    | 27.7                     | 46.3                     | 233          | 18.58     | ±0.07          | E                     | 0.08     |
| 1716   | 04:07:52.5 | −12:11:56   | 59.7                     | −19.3                    | 62.7                     | 316          | 23.01     | ±0.21          | E                     | 0.08     |
| 1862   | 04:07:49.1 | −12:11:21   | 9.8                      | 15.7                     | 18.5                     | 112          | 22.63     | ±0.17          | E                     | 0.25     |

$^a$Galaxy classification: E→ emission-line dominated and A→ absorption-line dominated.

#### 4.1 Do O VI and Lyα-only absorbers share similar azimuthally averaged galaxy distributions out to 1 Mpc?

To determine whether or not O VI and Lyα-only absorbers occur in similar galaxy environments, we measure the mean radial profile of the galaxy distribution around these absorbers by first stacking the observed 2D distribution of galaxies around individual absorbers shown in Fig. 5 and then computing an azimuthal average in annuli with increasing radius. The left-hand panel of Fig. 6 displays the mean galaxy surface density profiles around O VI absorbers (dashed line) and Lyα-only absorbers (solid line). Error bars show our estimate of uncertainties due to counting statistics (e.g. Gehrels 1986). It is clear that there exists an overdensity of galaxies within a $\rho \approx 500$ kpc radius of O VI absorbers, which is not seen around Lyα-only absorbers.

Such distinction between O VI and Lyα-only absorbers is also seen in the observed mean surface brightness profiles around these absorbers (the right-hand panel of Fig. 6). In this case, error bars are computed using a jackknife resampling technique to estimate uncertainties due to sample variance. While the mean galaxy surface brightness profile around O VI absorbers exhibits a steep rise of $\Delta \mu_B \approx +5$ mag Mpc$^{-2}$ towards the inner regions at $\rho \lesssim 500$ kpc, only a mild increase of $\Delta \mu_B \approx +2$ mag Mpc$^{-2}$ is seen in the galaxy surface brightness profile around Lyα-only absorbers.
4.2 Do O\textsc{vi} and Lyα-only absorbers share similar galaxy distribution functions in the inner 500 kpc?

The exercise presented in Section 4.1 shows that the ensemble average of the radial profiles of galaxy surface density and surface brightness exhibits different characteristics at \( \rho \lesssim 500 \text{ kpc} \) between O\textsc{vi} and Lyα-only absorbers. Here we focus on the inner regions of \( \rho = 500 \text{ kpc} \) radius around individual absorbers and examine whether there is a difference in the variation of galaxy properties within each subsample. This exercise provides further insights into the immediate galactic environments of individual absorbers.

The left-hand panel of Fig. 7 shows the cumulative fraction of absorbers originating in environments of no more than \( N_{\text{gal}} \) Galaxies. It shows that while 16 per cent of O\textsc{vi} absorbers occur in environments where no galaxies are found within a radius of \( \rho = 500 \text{ kpc} \), more than 50 per cent of Lyα-only absorbers occur in such ‘voids’. However, the samples are small and a Kolmogorov–Smirnov (KS) test shows that the probability that both types of absorbers are drawn from a similar underlying environment distribution is 20 per cent.

Next, we examine the mean surface density of star light averaged over the area within a 500 kpc radius in units of rest-frame R-band magnitude per square Mpc. This quantity allows us to account for missing galaxies that are too faint to be detected in our survey by including the survey limit in our analysis. Including non-detections, the right-hand panel of Fig. 7 shows the maximum possible cumulative fraction of absorbers arising in environments with mean galaxy surface brightness fainter than the designated value \( \mu_B \). Similar to the surface density plot in the left-hand panel, we find that as much as 60 per cent of Lyα-only absorbers originate in environments with galaxy surface brightness fainter than \( \mu_B \approx -19 \text{ mag Mpc}^{-2} \), while no more than 35 per cent of O\textsc{vi} absorbers are found in such
Probing the IGM–galaxy connection

Figure 5. The galaxy environments of O\textsc{vi} absorbers and strong Ly\alpha absorbers of log $N$(H\textsc{i}) > 13.6 with no detectable O\textsc{vi} (designated as ‘Ly\alpha-only’ systems). Considering the increasing survey incompleteness of faint ($<0.1 L_\ast$) galaxies with increasing redshift, we separate the galaxy–absorber sample into four redshift bins. For each redshift bin, we show the spatial and velocity distributions of galaxies around O\textsc{vi} absorbers in the left column and Ly\alpha-only absorbers in the right column. Each panel is centred at the QSO, while positions of galaxies with projected line-of-sight velocity $|\Delta v| < 300$ km s$^{-1}$ of the absorber are marked with circles for emission-line galaxies and triangles for absorption-line galaxies. The symbols are colour-coded to indicate the line-of-sight velocity between each galaxy and the absorber. The symbol size specifies galaxy luminosity as shown in the figure legend. To help visualize the surface density of surrounding galaxies, we also introduce a grey-scale showing a luminosity-weighted galaxy surface density where each galaxy is represented by a Gaussian with FWHM = 300 kpc. The luminosity weighting assigns $L \geq L_\ast$ galaxies a peak of 1, $0.1 \leq L < L_\ast$ galaxies a peak of 0.7 and $L < 0.1 L_\ast$ galaxies a peak of 0.4.

5 DISCUSSION AND CONCLUSIONS

The high level of completeness achieved at faint magnitudes by our survey has allowed us to probe the galaxy populations to low luminosities and obtain better understanding of the nature of the absorbing systems. We have shown that O\textsc{vi} absorbers previously attributed to a gaseous medium connecting massive galaxy groups are, in fact, more closely associated with less massive groups containing at least one dwarf, emission-line galaxy. In total, four of seven known O\textsc{vi} absorbers along the PKS 0405−123 sightline reside in galaxy ‘groups’ that contain at least one star-forming member.

Two of the seven are found nearby an emission-line galaxy and only one O\textsc{vi} absorber is found in a galaxy void. Therefore, we conclude that O\textsc{vi} absorbers primarily trace gas-rich environments as indicated by the presence of at least one low-mass, emission-line galaxy seen in our survey. However, the presence of O$^+$ ions could either be the result of starburst-driven outflows or due to stripped material from galaxy interactions that also trigger star formation.

This is in stark contrast to lower ionization transitions such as Mg\textsc{ii} that are found to reside primarily in the haloes of isolated galaxies both with and without star formation (Steidel et al. 1997). One exception is those ultra-strong Mg\textsc{ii} absorbers with rest-frame absorption equivalent width $W_r(2796) > 3$ Å. Three of these ultra-strong Mg\textsc{ii} systems have been targeted for follow-up galaxy surveys and all three are found in groups containing multiple super-$L_\ast$ galaxies (e.g. Whiting, Webster & Francis 2006;
Figure 5 – continued

Figure 6. Mean radial profiles of the galaxy distribution around O\textsc{vi} and Ly\textalpha-only absorbers. The left-hand panel shows the mean surface density of galaxies versus projected distance around O\textsc{vi} (dashed line) and Ly\textalpha-only (solid line) absorbers, and the right-hand panel shows the mean surface brightness profiles. Galaxy density error bars are computed from Poisson confidence intervals while surface brightness uncertainties are computed using a jackknife resampling technique to indicate uncertainties due to sample variance. It is clear that there exists an overdensity of galaxies within a $\rho \approx 500$ kpc radius of O\textsc{vi} absorbers, which is not seen around Ly\textalpha-only absorbers. Similarly, the mean galaxy surface brightness profile around O\textsc{vi} absorbers exhibits a steep rise by $\Delta \mu_R \approx +5$ mag Mpc$^{-2}$ towards the inner regions at $\rho \lesssim 500$ kpc, while the galaxy surface brightness profile around Ly\textalpha-only absorbers remains comparatively flat with $\Delta \mu_R \approx +2$ mag Mpc$^{-2}$.

Nestor et al. 2011; Gauthier 2013), with an inferred group halo mass of $M_h \sim 10^{13} M_\odot$. The galaxy ‘groups’ found around O\textsc{vi} absorbers in our survey contain primarily low-luminosity (and presumably low-mass) galaxies (see also Mulchaey & Chen 2009), and are therefore not as massive as those found near ultra-strong Mg\textsc{ii} absorbers. A detailed comparison of the dynamics between galaxies and absorbing gas may lead to further insights into the physical origin of these O\textsc{vi} absorbers.

In addition, our analysis reveals a clear distinction in the radial profiles of mean galaxy surface density and surface brightness.
around different absorbers. Specifically, O VI absorbers are found to reside in galaxy overdensities with significantly higher mean galaxy surface density and surface brightness at \( \rho \leq 500 \) kpc, while only a mild increase in galaxy surface brightness is seen at small \( \rho \) around strong Ly\( \alpha \)-only absorbers.

On the other hand, Chen & Mulchaey (2009) showed that both strong Ly\( \alpha \) absorbers of \( \log N(\text{HI}) \geq 14 \) and O VI absorbers exhibit a comparable clustering amplitude as emission-line-dominated galaxies. The apparent discrepancy between the finding of this paper and those of Chen & Mulchaey (2009) may be explained by the intrinsic difference in the sample definition. Our current study is based on galaxies and absorbers found in a single field, and therefore limited by the small sample size. In particular, we have defined a controlled Ly\( \alpha \)-only sample that includes Ly\( \alpha \) absorbers that are as weak as \( \log N(\text{HI}) \approx 13.6 \) in order to have a sufficiently large sample for a statistical analysis. In contrast, the O VI absorbers in the comparison sample all have associated Ly\( \alpha \) with \( \log N(\text{HI}) > 14 \). It is therefore unclear whether the observed distinction between the galactic environments of O VI and Ly\( \alpha \)-only absorbers represents a fundamental difference between metal and H\( \alpha \) absorbers, or between high and low H\( \alpha \) column density clouds. We expect that such uncertainty in the interpretation of the observations will be resolved with a larger sample of galaxy and absorber data from different fields complemented by multiband imaging data. Together, these data will help constrain galaxy star-formation rates and reveal the presence of any faint tidal features (e.g. Chen & Mulchaey 2009).

Lastly, an intriguing outcome of our deep galaxy survey is the discovery of an O VI absorber that is likely to reside in a ‘void’. This O VI absorption system at \( z \approx 0.183 \), which exhibits two strong components separated by 70 km s\(^{-1}\), does not have other ionic transitions detected to sensitive limits (Table 3; see also Prochaska et al. 2004). Our galaxy survey data rule out the presence of any galaxies of \( L > 0.04 L_\odot \) at \( \rho < 250 \) kpc or the presence of any galaxies of \( L > 0.3 L_\odot \) at \( \rho < 1 \) Mpc. The lack of additional ionic transitions associated with this absorber suggests that the gas may be hot and collisionally ionized. Also the lack of galaxies found in the vicinity suggests that this absorber resides in an apparent void, similar to an O VI absorber at \( z = 0.06807 \) for which Tripp et al. (2006) ruled out the presence of galaxies of \( L > 0.04 L_\odot \) at \( \rho < 200 \) kpc. While a likely explanation for the origin of the gas is the warm–hot IGM, it is unclear whether the relatively narrow line width is consistent with a diffuse intergalactic origin.

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*Figure 7.* Cumulative fraction of absorbers originating in environments with no more than \( N_{\text{gal}} \) galaxies within a radius of \( \rho = 500 \) kpc (left-hand panel) and with mean surface brightness (averaged over the area of 500 kpc radius) fainter than rest-frame \( R \)-band magnitude \( \mu_R \) per square Mpc (right-hand panel). While a larger fraction of Ly\( \alpha \)-only absorbers (>50 per cent versus 16 per cent for O VI absorbers) arise in environments where no luminous galaxies are found within a radius of \( \rho = 500 \) kpc, no statistically significant distinction can be made between the cumulative fraction of galaxy surface density around O VI and Ly\( \alpha \)-only absorbers based on these small samples. Specifically, a Kolmogorov–Smirnov (KS) test on their cumulative distribution functions shows that the probability that O VI and Ly\( \alpha \)-only absorbers are drawn from a similar parent galaxy environment distributions is at most 20 per cent (galaxy density) and 8 per cent (surface brightness).
3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

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SUPPORTING INFORMATION

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

Table 2. The photometric and spectroscopic catalogue of galaxies around PKS 0405−123 (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1137/-/DC1).

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