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Andrew J. Fox, \(^1,2\)† Jacqueline Bergeron\(^2\) and Patrick Petitjean\(^2,3\)

\(^{1}\)European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura, Santiago 19, Chile

\(^{2}\)Institut d’Astrophysique de Paris, UMR 7095 CNRS, Université Pierre et Marie Curie, 98bis Boulevard Arago, 75014 Paris, France

\(^{3}\)LERMA, Observatoire de Paris, 61 Avenue de l’Observatoire, 75014 Paris, France

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ABSTRACT

With the goal of investigating the nature of O VI absorbers at high redshifts, we study the effects of proximity to the background quasar. In a sample of 16 quasars at \( z_{\text{QSO}} \) between 2.14 and 2.87 observed at high signal-to-noise ratio and 6.6 km s\(^{-1}\) resolution with the Very Large Telescope/Ultraviolet and Visual Echelle Spectrograph (VLT/UVES), we detect 35 O VI absorption-line systems (comprising over 100 individual O VI components) lying within 8000 km s\(^{-1}\) of \( z_{\text{QSO}} \). We present component fits to the O VI absorption and the accompanying H\(\alpha\), C IV and N V. The systems can be categorized into nine strong and 26 weak O VI absorbers. The strong (intrinsic) absorbers are defined by the presence of either broad, fully saturated O VI absorption or partial coverage of the continuum source, and in practice all have \( \log N(\text{O VI}) \gtrsim 15.0 \); these systems are interpreted as representing either quasar-driven outflows or gas close to the central engine of the active galactic nuclei. The weak (also known as narrow) systems show no partial coverage or saturation, and are characterized by \( \log N(\text{O VI}) < 14.5 \) and a median total velocity width of only 42 km s\(^{-1}\). The incidence \( dN/dz \) of weak O VI systems within 2000 km s\(^{-1}\) of the quasar down to a limiting equivalent width of 8 mÅ is 42 ± 12. Between 2000 and 8000 km s\(^{-1}\), \( dN/dz \) falls to 14 ± 4, equal to the incidence of intervening O VI absorbers measured in the same spectra. Whereas the accompanying H\(\alpha\) and C IV column densities are significantly lower (by a mean of \( \sim 1 \) dex) in the weak O VI absorbers within 2000 km s\(^{-1}\) of \( z_{\text{QSO}} \) than in those at larger velocities, the O VI column densities display no dependence on proximity. Furthermore, significant offsets between the H\(\alpha\) and O VI centroids in \( \sim 50 \) per cent of the weak absorbers imply that (at least in these cases) the H\(\alpha\) and O VI lines are not formed in the same phase of gas, preventing us from making reliable metallicity determinations and ruling out single-phase photoionization model solutions. In summary, we find no firm evidence that quasar radiation influences the weak O VI absorbers, suggesting they are collisionally ionized rather than photoionized, possibly in the multiphase haloes of foreground galaxies. Non-equilibrium collisional ionization models are needed to explain the low temperatures in the absorbing gas, which are implied by narrow-line widths (\( b < 14 \) km s\(^{-1}\)) in over half of the observed O VI components.

Key words: intergalactic medium – quasars: absorption lines – cosmology: observations.

1 INTRODUCTION

Quasars are ideal backlighters for absorption-line spectroscopy, thanks to their high luminosities and flat continua. Yet in addition to allowing us to detect foreground absorbers, quasars also create and influence them, through the effects of outflows and ionizing radiation. The enhanced level of ionizing radiation in the vicinity of quasars gives rise to the line-of-sight proximity effect, the observed decrease in the number density of Ly\(\alpha\) forest lines (equivalent to a decrease in the mean optical depth, and an increase in the level of hydrogen ionization) at velocities approaching the quasar (Carswell et al. 1982; Murdoch et al. 1986; Tytler 1987; Bajtlik, Duncan & Ostriker 1988; Lu, Wolfe & Turnshek 1991; Bechtold 1994; Rauch 1998; Scott et al. 2000; Guimaraes et al. 2007; Faucher-Giguère et al. 2008).

To obtain an unbiased view of absorbing structures in the high-
\( z \) Universe, one needs to remove the effects of proximity from samples of metal-line systems. The broad absorption-line (BAL)
systems, easy to identify in quasi-stellar object (QSO) spectra because of their optically thick absorption extending over thousands of km s\(^{-1}\), are clearly connected to the quasar. BALs trace high-velocity QSO outflows at the speed of up to 0.1c (e.g. Turnshek 1984, 1988), and are seen in 10–15 per cent of quasar spectra at \( z > 1.5 \) (Weymann et al. 1991;Trump et al. 2006). A separate category of mini-BAL systems, with fully saturated absorption profiles and total velocity width <2000 km s\(^{-1}\), has also been identified (Turnshek 1988; Churchill et al. 1999; Yuan et al. 2002; Misawa et al. 2007b). As with BALs, mini-BALs are interpreted as tracing outflows ejected by QSOs. A more difficult task is to decide whether narrow absorbers in quasar spectra are either created or ionized by the QSO. The traditional way to do this employs the displacement velocity from the quasar, \( \delta v \equiv v_{\text{QSO}} - v_{\text{abs}} \). So-called ‘associated’ or ‘proximate’ absorbers, typically defined as narrow absorbers at \( \delta v < 5000 \) km s\(^{-1}\) (Weymann et al. 1979; Foltz et al. 1986;Anderson et al. 1987; Hamann & Ferland 1999) are often removed from intervening samples because of the possibility they may be intrinsic.\(^1\) Arguments in favour of an intrinsic nature for many proximate absorbers include time-variability of absorption, partial coverage of the continuum source, detection of excited ionic states implying high gas densities, profiles that are smoother than intervening absorbers and supersolar metallicities (Wampler, Bergeron & Petitjean 1993; Møller, Jakobsen & Perryman 1994; Petitjean, Rauch & Carswell 1994; Savaglio, D’Odorico & Møller 1994; Tripp, Lu & Savage 1996; Barlow & Sargent 1997; Hamann 1997; Hamann et al. 1997a,c;Ganguly et al. 1999; Petitjean & Srianand 1999; Srianand & Petitjean 2000; Hamann, Netzer & Shields 2000; Ganguly et al. 2001;Hamann et al. 2001; Narayan et al. 2004; Ganguly et al. 2006).

Using a velocity cut-off to differentiate intervening and intrinsic absorbers has two main problems: quasar-ejected intrinsic systems can appear at higher \( \delta v \) (Hamann, Barlow & Junkkarinen 1997b;Richards et al. 1999; Richards 2001; Misawa et al. 2007a; Nestor, Hamann & Rodríguez 2008) and intervening systems can appear at lower \( \delta v \) (Møller, Warren & Fynbo 1998; Sembach et al. 2004).

So are many genuine intervening systems lost when they are excluded from absorber samples just because of their proximity to the quasar? In this paper, we investigate the transition between proximate and intervening absorbers. We focus on O\( \text{I}\) absorbers, which trace either warm-hot (\( T \gtrsim 10^5 \) K) collisionally ionized plasma, or photoionized gas subject to a hard ionizing spectrum extending to energies above 113.9 eV (the ionization potential to create O\( \text{I}\)). O\( \text{I}\) absorbers are of interest for many reasons, including the significant role they play in the baryon and metal budgets, the window they provide on intergalactic metal enrichment and their ability to trace energetic galaxy/Intergalactic Medium (IGM) interactions such as accretion and galactic winds. After the first detection of O\( \text{I}\) absorbers at \( z = 2-3 \) by Lu & Savage (1993), much work has been done in the era of 10-m class telescopes to characterize their properties (Schaye et al. 2000; Bergeron et al. 2002; Carswell, Schaye & Kim 2002; Simcoe, Sargent & Rauch 2002, 2004; Bergeron & Herbert-Fort 2005, hereafter BH05; Simcoe et al. 2006; Lopez et al. 2007; Aguirre et al. 2008; Gonçalves, Steidel & Pettini 2008).

Here, we ask a simple question: is there a proximity effect in O\( \text{I}\)? In other words, can we see the signature of quasar photoionization, in terms of correlations between the ionization properties of absorbers and their proximity to the quasar? To address this issue, we form a sample of proximate O\( \text{I}\) absorption systems at \( z = 2-3 \) using a homogeneous set of high-resolution Very Large Telescope/ Ultraviolet and Visual Echelle Spectrograph (VLT/UVES) quasar spectra, and we then compare their properties to a sample of intervening (i.e. non-proximate) O\( \text{I}\) absorbers observed in the same set of spectra; the intervening sample has been published by BH05, but it has since been enlarged from 10 to 12 sight lines. We also briefly compare our results on O\( \text{I}\) absorbers at \( z = 2-3 \) to those obtained in the low-redshift Universe with space-based ultraviolet spectrographs. This paper is thus a study of both the proximity effect and the nature of O\( \text{I}\) absorbers in general, and is structured as follows. In Section 2, we describe the data acquisition and reduction, and our absorber identification and measurement processes. In Section 3, we discuss the observational properties of proximate O\( \text{I}\) absorbers. In Section 4, we discuss the implications of our results, and we then present a summary in Section 5. Throughout this paper, we adopt a Wilkinson Microwave Anisotropy Probe (WMAP) 3-yr cosmology with \( \Omega_M = 0.27, \Omega_\Lambda = 0.73 \) and \( h_{70} = 1 \) (Spergel et al. 2007).

## 2 DATA ACQUISITION AND HANDLING

### 2.1 Observations

The ESO–VLT Large Programme _The Cosmic Evolution of the IGM_ has built a homogeneous sample of high resolution, high signal-to-noise ratio quasar spectra for use in studying the high-redshift IGM. Twenty bright quasars (most with \( V < 17 \)) in the redshift range 2.1–3.8 (median \( z_{\text{QSO}} = 2.44 \)) were selected for observation, deliberately avoiding sight lines that contain high column density damped Ly\( \alpha \) absorbers. The observations were carried out with the UVES spectrograph (Dekker et al. 2000) on VLT UT2 at Paranal, Chile, using a total of 30 nights of service-mode telescope time between 2001 June and 2002 September. The observations were taken in good seeing conditions (\(<0.8 \) arcsec) and at airmass \(<1.4\), with both blue and red dichroics (Dic1 346 + 580, Dic1 390 + 564 and Dic2 437 + 860 settings), giving complete spectra from 3000 to 9000 Å. The data reduction was conducted using the _MIDAS_ pipeline described in Ballester et al. (2000), and then continued were fitted using a third-degree spline function interpolated between regions free from absorption. The full details of the reduction process are given in Chand et al. (2004) and Aracil et al. (2004). The 2 × 2 binning mode was used, giving a rebinned pixel size of 2.0–2.4 km s\(^{-1}\). The spectral resolution of the data, \( R \approx 45,000 \), corresponds to a velocity resolution of \( \approx 6.6 \) km s\(^{-1}\) [full width at half-maximum (FWHM)]. Typical signal-to-noise ratios per pixel in the spectra are \( \approx 35 \) at 3500 Å and \( \approx 60 \) at 6000 Å. Among the 20 quasars, 16 are at \( z < 3 \). These form the basic sample for this paper. The four cases at \( z > 3 \) were excluded because the density of the Ly\( \alpha \) forest at these redshifts renders futile searches for O\( \text{I}\).

The emission-line redshifts of 10 of the 16 quasars in our sample have been carefully determined by Rollinde et al. (2005, and references therein), and we adopt their values. For the remaining six quasars, we take \( z_{\text{QSO}} \) from Scannapieco et al. (2006). Each of these quasar redshifts is based on a combination of the observed H\( \alpha \), Mg\( \text{II} \), C\( \text{IV} \) and Si\( \text{IV} \) emission-line redshifts, allowing for systematic shifts in the displacement velocities of the various lines (e.g. Tytler & Fan 1992). The uncertainty on each \( z_{\text{QSO}} \) is of the order of 500 km s\(^{-1}\) (Rollinde et al. 2005).

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\(^1\) We favour the use of the term ‘proximate’ since it involves no assumption about the absorber origin.
2.2 Identification of O VI systems

We searched systematically through the 16 quasar spectra in our sample for O VI absorbers within 8000 km s$^{-1}$ of the quasar redshift. This velocity range corresponds to redshifts between $z_{\text{min}} = z_{\text{QSO}} - (1 + z_{\text{QSO}}) 8000$ km s$^{-1}$/c and $z_{\text{QSO}}$. Our choice of velocities up to 8000 km s$^{-1}$ from the quasar was made in order to investigate whether a transition occurs at 5000 km s$^{-1}$, the conventional cut-off between proximate and intervening systems. In practice, we also searched for (and found) O VI absorbers at up to 2500 km s$^{-1}$ beyond the quasar redshift, indicating the presence of high velocity inflows towards the quasar.

32 O VI absorbers were identified by their presence in both lines of the O VI $\lambda\lambda$1031.926, 1037.617 doublet in the correct ratio through the line profile, i.e. $\tau_\lambda(v, \lambda 1031)/\tau_\lambda(v, \lambda 1037) = 2$, where the apparent optical depth $\tau_\lambda(v) = \ln[F_\lambda(v)/F(v)]$, and where $F(v)$ and $F_\lambda(v)$ are the observed flux level and estimated continuum flux level, respectively, as a function of velocity. In addition, three O VI absorbers were identified in one line of the O VI doublet only, with partial blending in the other O VI line, but with corresponding absorption seen in C IV and H I at exactly the same redshift. Together the sample consists of the 35 O VI systems listed in Table 1. We define the system redshift $z_{\text{abs}}$ by the position of the strongest O VI component in the system, i.e. the wavelength of maximum optical depth. In each system, we looked for accompanying absorption in H I (Ly$\alpha$, Ly$\beta$, and Ly$\gamma$), C IV $\lambda\lambda$1548, 1550 and N V $\lambda\lambda$1238, 1242 at the same redshift $z_{\text{abs}}$.

We denote the velocity displacement of each absorber from the quasar as $\delta v \equiv c(z_{\text{QSO}} - z_{\text{abs}})/(1 + z_{\text{abs}})$. A negative value corresponds to an absorber moving towards the quasar. The O VI

<table>
<thead>
<tr>
<th>QSO</th>
<th>$z_{\text{QSO}}$</th>
<th>$z_{\text{abs}}$</th>
<th>$\delta v$</th>
<th>$\delta \log \tau_{\text{O VI}}$</th>
<th>log $N$(O VI)$^c$</th>
<th>log $N$(N V)</th>
<th>log $N$(C IV)</th>
<th>log $N$(H I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HE 0015-4326</td>
<td>2.789</td>
<td>2.6998</td>
<td>7230</td>
<td>14.97 ± 0.04$^\dagger$</td>
<td>13.14 ± 0.01$^\dagger$</td>
<td>13.33 ± 0.10$^\dagger$</td>
<td>14.29 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>HE 0151-4326</td>
<td>2.789</td>
<td>2.7134</td>
<td>6100</td>
<td>14.81 ± 0.01$^\dagger$</td>
<td>13.95 ± 0.05$^\dagger$</td>
<td>13.39 ± 0.01</td>
<td>14.58 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>HE 1158-1843</td>
<td>2.449</td>
<td>2.4426</td>
<td>560</td>
<td>16.14</td>
<td>14.76 ± 0.50$^\dagger$</td>
<td>14.44 ± 0.01$^\dagger$</td>
<td>13.33 ± 0.20</td>
<td></td>
</tr>
<tr>
<td>HE 1341-1020</td>
<td>2.135</td>
<td>2.1169</td>
<td>1740</td>
<td>16.09</td>
<td>14.78 ± 0.16$^\dagger$</td>
<td>14.26 ± 0.03$^\dagger$</td>
<td>14.68 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>HE 1341-1020</td>
<td>2.135</td>
<td>2.1473</td>
<td>1170</td>
<td>15.48</td>
<td>&gt;14.80</td>
<td>&gt;14.81</td>
<td>16.47 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>HE 2347-4342</td>
<td>2.871</td>
<td>2.8916</td>
<td>1590</td>
<td>15.44</td>
<td>14.20 ± 0.01$^\dagger$</td>
<td>13.94 ± 0.01</td>
<td>13.91 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>HE 2347-4342</td>
<td>2.871</td>
<td>2.8972</td>
<td>2020</td>
<td>15.31</td>
<td>&gt;14.66</td>
<td>&gt;14.72</td>
<td>14.45 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>HE 2347-4342</td>
<td>2.871</td>
<td>2.9041</td>
<td>2540</td>
<td>15.86</td>
<td>13.72 ± 0.01</td>
<td>&gt;14.69</td>
<td>16.29 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>PKS 0329-255</td>
<td>2.736</td>
<td>2.7089</td>
<td>2190</td>
<td>&gt;15.08</td>
<td>13.28 ± 0.01</td>
<td>13.60 ± 0.01</td>
<td>14.89 ± 0.14</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Velocity separation between absorber and quasar, in km s$^{-1}$. A negative value indicates the absorber is at higher redshift than the quasar. Errors are $\sim 500$ km s$^{-1}$, reflecting the uncertainties in $z_{\text{QSO}}$.

$^b$O VI line width containing the central 90 per cent of the integrated optical depth, in km s$^{-1}$. Only given for the weak absorbers, since it cannot be measured for a saturated line.

The column densities in this table (with $N$ in cm$^{-2}$) were determined by summing the column densities of the individual components in our Voigt profile fits, with the component errors added in quadrature. For saturated absorbers, we present lower limits on the column density. The symbol $^\dagger$ denotes absorbers with evidence for partial coverage of the continuum source; these column densities should be considered lower limits. For non-detections of C IV or N V, we present a 3$\sigma$ upper limit to log $N$, based on the null measurement of the equivalent width. Absorbers marked $^\ddagger$ are not formally detected at 3$\sigma$ significance, but a fit was executed none the less because of weak features in the line profiles at exactly the same redshift as O VI (see Fig. 1).
systems almost always contain multiple components clustered together. We thus define $\delta v$ both for each absorber and for each individual O VI component. The uncertainties on all velocity displacements are dominated by the $\approx 500 \text{ km s}^{-1}$ uncertainty of the quasar emission redshifts.

2.3 Classification of O VI systems

After identifying 35 proximate O VI systems, we found that they could be classified into the following.

(i) Seven strong O VI systems, which are defined by showing both fully saturated O VI lines extending over tens to hundreds of km s$^{-1}$, and strong (often saturated) N v and C iv absorption. In practice, we find that these seven systems all show $\log N(\text{O VI}) > 15.0$ and are at $\delta v < 3000 \text{ km s}^{-1}$, with four of the seven at $\delta v < 0$ ($z_{\text{abs}} > z_{\text{QSO}}$), i.e. the strong systems are strongly clustered around $z_{\text{QSO}}$. The strong systems are interpreted as being intrinsic to the quasar. Three of the strong systems are classified as mini-BALs, but no full (classical) BAL systems are present in our sample. Partial coverage of the continuum source is present in many of the strong systems, as evidenced by the failure to find a successful Voigt profile fit to the O VI profiles, even though the velocity structure is common among the two members of the doublet. This confirms an intrinsic origin because partial coverage of the continuum source only occurs when the absorbing gas is physically close to the active galactic nuclei (AGN). The strong systems contain multiple components, with a mean of 5.9 components per system.

(ii) 26 weak O VI systems, also known as narrow systems, which are unsaturated and show no evidence for partial coverage, i.e. we were able to conduct successful Voigt profile fits to the two lines of the O VI doublet. The weak systems all have $12.80 < \log N(\text{O VI}) < 14.50$, clearly separated from the strong systems, but coincident with the range of O VI column densities observed in intervening systems (BH05). Their total line widths are narrow, with a median and standard deviation of $\delta v_{\text{QSO}} = 42 \pm 33 \text{ km s}^{-1}$, where $\delta v_{\text{QSO}}$ is the line width encompassing the central 90 per cent of the integrated optical depth. The weak O VI systems are accompanied by C iv absorption in 24/26 cases and in 9/26 cases by N v. An mean of 1.9 components per system is required to fit these weak absorbers.

There were two intermediate cases that presented difficulties in their classification: the systems at $z = 2.6998$ and 2.7134 towards HE 0151−4326. Neither of these systems shows a saturated O VI profile, and their O VI column densities lie in-between the values shown by the strong ($>15.0$) and weak ($<14.5$) populations. However, differences between the profiles of the two doublet lines of O vi, and between the two lines of N v, in similar velocity ranges are strongly suggestive of partial coverage. This implies they should be classified as intrinsic. For this reason, we place these systems in the strong category, and our final sample consists of nine strong systems and 26 weak systems.

In addition to the different O VI (and N v and C iv) column densities, there are several lines of evidence that support the notion that the strong and weak samples trace physically different populations. The strong population have velocities (relative to $z_{\text{QSO}}$) that distribute differently, with $4/9$ at $z_{\text{abs}} > z_{\text{QSO}}$, whereas 22/26 weak absorbers are at $z_{\text{abs}} < z_{\text{QSO}}$. The strong population shows markedly different H/O VI ratios than the weak population (see Section 3.5). Finally absorbers in the strong population frequently show evidence for partial coverage of the continuum source. Whereas the strong absorbers are clearly associated with the quasar (e.g. Turnshek 1984; Weymann et al. 1991; Hamann & Ferland 1999), either tracing QSO outflows or inflows near the central engine of the AGN, the origin of the weak O VI absorbers is less clear. They are often called ‘associated’ because of their proximity in velocity to the quasar, but there is not necessarily any physical connection. In the rest of this paper, we investigate the properties of this weak, proximate sample.

2.4 Component fitting

We used the vpfit software package$^3$ to determine the column densities, line widths and central velocities of the O VI components in each system. The number of components to be fit was usually self-evident from inspection of the line profiles, but in case of doubt we used the minimum number of components necessary. Our sample of 35 O VI systems comprises 101 components. We also fit, when possible, the H i, N v, C iii and C iv absorption, independently of the O VI fits, i.e. we did not fix any component velocity centroids or line widths when fitting the various ions. In the case of the H i lines, we simultaneously fit Ly$\alpha$ with whichever of Ly$\beta$, Ly$\gamma$ and Ly$\delta$ were unblended. The total column densities in each ion in each system were obtained by summing the component column densities, with the individual column density errors added in quadrature to produce the overall error estimate. All the Voigt profile fits are included in Fig. 1 (please see the end of the paper for Fig. 1), which shows the absorption-line spectra for each system in our sample. The total column density of each high ion and H i in each system is given in Table 1. The detailed results of the component fits to O VI, N v, C iv and H i in the weak sample are given in Table 2. All velocities in Table 2 are given on a scale relative to the system redshift $z_{\text{abs}}$.

In addition to the component fits, we measured the total column densities in each system using the apparent optical depth (AOD) method of Savage & Sembach (1991). This method has the advantage of requiring no assumptions about the component structure: it simply requires a choice of minimum and maximum velocities for the integration. It will return accurate column densities so long as saturated structure is not present. Whereas saturation is obvious if resolved, because the flux goes to zero, unresolved saturation can be difficult to detect. In the case of a non-detection of C iv or N v, we measured the (null) equivalent width in this ion over the velocity range in which O VI is detected, and found the 3$\sigma$ error on this measurement. We then converted this maximum allowed equivalent width into a column density limit using a linear curve-of-growth. For example, if the equivalent width measurement was 0 $\pm$ 10 mÅ, we derived a 3$\sigma$ column density limit $N_{\text{lim}} \text{H}_\alpha$ using $E_{\text{lim}} = 30$ mÅ and the relation $N_{\text{lim}} = 1.13 \times 10^{17} E_{\text{lim}}/\lambda^2$ (with $N_{\text{lim}}$ in cm$^{-2}$ and $\lambda$ in Å). The atomic data were taken from Morton (2003).

In many of the strong absorbers, partial coverage of the continuum source is present. Indeed, we use this as a criterion to classify an absorber as intrinsic. Partial coverage is indicated by a similar velocity structure in the two members of a doublet, but with inconsistent optical depths in each ion. In the case of partial coverage, the equation $F(v) = F_0 e^{-\tau(v)}$ is no longer valid

$^3$ Available at http://www.ast.cam.ac.uk/~rfc/vpfit.html.
Table 2. Component fit results to weak O vi absorbers.

<table>
<thead>
<tr>
<th>QSO</th>
<th>$z_{abs}$</th>
<th>Ion</th>
<th>$v_0$ (km s$^{-1}$)</th>
<th>$b$ (km s$^{-1}$)</th>
<th>log ($N$ in cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE 0001−2340</td>
<td>2.2571</td>
<td>O vi</td>
<td>−81.0 ± 1.1</td>
<td>16.7 ± 1.2</td>
<td>13.45 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>HE 1158−1843</td>
<td>2.4279</td>
<td>O vi</td>
<td>−52.6 ± 23.9</td>
<td>33.7 ± 14</td>
<td>12.47 ± 0.40</td>
</tr>
<tr>
<td></td>
<td>...</td>
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<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>PKS 0327−23</td>
<td>2.2028</td>
<td>O vi</td>
<td>4.3 ± 1.1</td>
<td>26.5 ± 1.4</td>
<td>13.80 ± 0.02</td>
</tr>
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</table>

Note: The table continues with additional entries for various QSOs, ions, and their respective parameters.
### 3 RESULTS

In this section, we present a discussion of the overall properties of the population of proximate O\textsc{vi} absorbers at $z = 2$–3. Although we discuss ionization processes, a detailed discussion of the physical conditions in the individual systems that make up our sample is beyond the scope of this paper. Some of the systems in our sample are discussed in more detail elsewhere. These include the proximate absorbers towards HE 2347–4342 (Fechner et al. 2004), and towards HE 1158–1843, PKS 0329–255 and Q 0453–423 (D’Odorico et al. 2004).

#### 3.1 Location of absorbers in velocity space

The number of proximate O\textsc{vi} absorption-line systems seen in each quasar spectrum varies between zero and five. There are two quasar spectra in our sample without O\textsc{vi} absorption detected within 8000 km s$^{-1}$ of QSO: HE 2217–2818 ($z_{\text{QSO}} = 2.41$) and Q0002–422 ($z_{\text{QSO}} = 2.77$). There are two quasars with five proximate O\textsc{vi} absorbers in their spectra: PKS 0237–23 ($z_{\text{QSO}} = 2.233$) and HE 1341–1020 ($z_{\text{QSO}} = 2.135$). To illustrate the location in velocity space of the absorbers, we show in Fig. 2 the velocity displacement of all absorbers, strong and weak, for each quasar. Weak absorbers in this study, relative to their background quasar. Weak absorbers are shown in red, and strong absorbers in blue. The location of $\delta v = 0$, i.e. $z_{\text{abs}} = z_{\text{QSO}}$, is shown with a solid black line. Negative values for $v_{\text{abs}}$ imply that the absorber is approaching the quasar. The dashed green lines show the velocity at which $F_{\text{QSO}} = F_{\text{EGB}}$ assuming Hubble flow (see the text).

#### 3.2 Presence of other ions

The presence and strength of absorption in other ionic species in the proximate O\textsc{vi} absorbers provides important information on the ionization conditions. H\textsc{i} absorption is detected in each of the 35 O\textsc{vi} systems, always in Ly$\alpha$ and occasionally up to Ly$\delta$. Higher...
order Lyman lines may also be present, but they lie deep in the Lyα forest where blending and low signal-to-noise ratio aggravate the search for detections. All but two of the O VI systems show C IV detections (the exceptions are the absorbers at \( z_{\text{abs}} = 2.2378 \) towards PKS 0237 – 23 and \( z_{\text{abs}} = 2.6610 \) towards PKS 0329 – 255, both of which are weak O VI systems with low O VI column densities). 9/9 strong O VI systems contain N v, whereas 9/26 weak O VI systems contain N v. Therefore, while the presence of N v is a feature of all strong systems, it does not imply that an O VI system is strong. Finally, C III absorption is seen in 13/26 weak systems, and 7/9 strong systems. However, because C III λ977 lies in the Lyα forest, it is often blended and hence not detectable even if present, so these fractions should be treated as lower limits.

### 3.3 O VI system column densities

A plot of the total O VI column densities in each absorber versus proximity (Fig. 3, top panel) shows the distinction between the strong and weak populations. The strong population all show \( \log N \gtrsim 15.0 \) and are (with two exceptions) clustered around \( z_{\text{abs}} = z_{\text{QSO}} \), whereas the weak population lies between the detection limit of \( \log N \approx 12.80 \) (corresponding to a limiting equivalent width of 8 mÅ) and 14.5. Once the strong systems have been removed, the underlying weak population shows no dependence of \( N(\text{O VI}) \) with proximity to the quasar. To investigate this further, we split the sample into O VI absorbers at \( \delta v < 2000 \text{ km s}^{-1} \) and those at \( 2000 < \delta v < 8000 \text{ km s}^{-1} \). This division is motivated by an observed enhancement in \( \delta v / \delta z \) below 2000 km s\(^{-1}\) (Section 3.7), as well as this representing the expected size of the proximity zone (Section 3.1). A two-sided Kolmogorov–Smirnov (KS) test shows that the probability that the distribution of \( \log N(\text{O VI}) \) for absorbers at \( < 2000 \text{ km s}^{-1} \) is different from those at \( > 2000 \text{ km s}^{-1} \) is only 17% per cent. There is also no clear correlation between the quasar redshift and the total O VI column, as shown in the lower panel of Fig. 3. We do note that the ratio of weak systems to strong systems changes from 6.3 (19/3) at \( z < 2.5 \) to 1.2 (7/6) at \( z > 2.5 \), but the statistics are too small for us to investigate this further.

### 3.4 O VI component column densities and b values

Proximity effects may occur at the component level, as well as the system level. To investigate this, we compare in Fig. 4 the component properties returned by VPFIT (column densities and line widths) of the weak O VI absorbers with \( b \). We include for comparison the O VI components from the intervening sample of BH05. As with the system column densities, there is no trend for the component O VI column densities to correlate with proximity to the quasar.

The distributions of \( \log N \) and \( b \) for the O VI components in our sample are shown in Fig. 5. We include the following component distributions as separate curves: the components at \( \delta v < 2000 \text{ km s}^{-1} \), those at \( 2000 < \delta v < 8000 \text{ km s}^{-1} \), and the intervening absorbers from BH05. A two-sided KS test finds the probability that the \( \log N \) distributions for the samples at \( < 2000 \text{ km s}^{-1} \) and \( 2000–8000 \text{ km s}^{-1} \) are different (i.e. drawn from distinct parent populations) is only 23% per cent. Comparing the \( \delta v < 2000 \text{ km s}^{-1} \) components to the intervening sample, we do not find any difference valid at more than the 1.0σ level, with the intervening sample showing a median log \( N(\text{O VI}) \) of 13.54, and the \( \delta v < 2000 \text{ km s}^{-1} \) sample showing a median of 13.45. This is an important result considering the intervening sample was measured independently in BH05, not in this analysis.

Turning to the component line widths, we find that among the proximate weak sample, 29 out of 48 components (60 per cent) are narrow (\( b \leq 14 \text{ km s}^{-1} \)). Characterizing the \( b \)-value distributions, we

---

**Table 3. Size of quasar spheres-of-influence at 912 Å.**

<table>
<thead>
<tr>
<th>QSO</th>
<th>( \log L_{\text{912}} ) (erg s(^{-1}) Hz(^{-1}))</th>
<th>( D^b ) (Mpc)</th>
<th>( \delta v^c ) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE 0001–2340</td>
<td>31.65</td>
<td>7.7</td>
<td>1700</td>
</tr>
<tr>
<td>HE 2217–2818</td>
<td>31.99</td>
<td>11.4</td>
<td>2600</td>
</tr>
<tr>
<td>PKS 0237–23</td>
<td>31.67</td>
<td>7.8</td>
<td>1700</td>
</tr>
<tr>
<td>PKS 0329–255</td>
<td>31.58</td>
<td>7.1</td>
<td>1800</td>
</tr>
<tr>
<td>PKS 1448–232</td>
<td>31.53</td>
<td>6.7</td>
<td>1400</td>
</tr>
<tr>
<td>Q 0002–422</td>
<td>31.72</td>
<td>8.3</td>
<td>2200</td>
</tr>
<tr>
<td>Q 0109–3518</td>
<td>31.82</td>
<td>9.3</td>
<td>2200</td>
</tr>
<tr>
<td>Q 0122–380</td>
<td>31.63</td>
<td>7.5</td>
<td>1600</td>
</tr>
<tr>
<td>Q 0329–385</td>
<td>31.28</td>
<td>5.0</td>
<td>1100</td>
</tr>
<tr>
<td>Q 0453–423</td>
<td>31.71</td>
<td>8.2</td>
<td>2100</td>
</tr>
</tbody>
</table>

\(^a\)Monochromatic luminosity at Lyman limit, derived from the \( B \) magnitude and \( F_B \sim \lambda^{-0.5} \) (Rollinde et al. 2005).

\(^b\)Distance at which \( F_{\text{QSO}} = F_{\text{EGB}} = 6 \times 10^{-21} \) erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) at \( z = 2.5 \) (Haardt & Madau 1996).

\(^c\)Velocity separation from QSO at \( D \) assuming Hubble flow, with \( H(z) \) calculated at \( z_{\text{QSO}} \), \( H(z = 2.5) = 246 \text{ km s}^{-1} \text{ Mpc}^{-1} \).
find that the probability that the population at \( \delta v < 2000 \text{ km s}^{-1} \) is different from the intervening distribution is less than 50 per cent. The median \( b \)-value in the intervening sample is 12.7 km s\(^{-1}\); in the sample at \( \delta v < 2000 \text{ km s}^{-1} \), it is 12.3 km s\(^{-1}\). However, an excess of systems with \( b = 20–30 \text{ km s}^{-1} \) is observed for components in the 2000–8000 km s\(^{-1}\) range, as can be seen in the lower panel of Fig. 4.

Finally, we compare the line width distribution of the O\( \text{VI} \) components in the weak proximate sample with the C\( \text{IV} \) and N\( \text{V} \) line width distributions (in the same sample). The line widths of C\( \text{IV} \) and N\( \text{V} \) distribute differently than those of O\( \text{VI} \), without the strong tail extending between 10 and 25 km s\(^{-1}\) seen in the O\( \text{VI} \) distribution. 77 per cent of C\( \text{IV} \) components and 90 per cent of N\( \text{V} \) components show \( b < 14 \text{ km s}^{-1} \). These differences indicate that it cannot be assumed that the C\( \text{IV} \), N\( \text{V} \) and O\( \text{VI} \) arise in the same volumes of gas.

In summary, among the weak O\( \text{VI} \) absorbers at \( z = 2–3 \), there is no compelling evidence for any difference in the column density and line width distributions between the intervening and proximate O\( \text{VI} \) populations, but within the proximate sample, the O\( \text{VI} \) line widths distribute differently than those of N\( \text{V} \) and C\( \text{IV} \).

3.5 H\( \text{I} \) column density

The median and standard deviation of the logarithmic H\( \text{I} \) column density in the weak proximate O\( \text{VI} \) sample is \( \log N(\text{H} \text{I}) = 14.66 \pm 0.95 \), with a total range covered in \( \log N(\text{H} \text{I}) \) of over four decades. The H\( \text{I}/\text{O} \text{VI} \) ratio (integrated over all components in each system) varies enormously, taking values between 0.02 and 1500. In Fig. 6 (top panel), we plot the H\( \text{I}/\text{O} \text{VI} \) column density ratio against the H\( \text{I} \) column density. Within both the strong and weak samples, a trend is evident in which H\( \text{I}/\text{O} \text{VI} \) rises with increasing \( N(\text{H} \text{I}) \). However, the two populations are clearly distinct, in that the weak systems show much higher H\( \text{I}/\text{O} \text{VI} \) ratios at a given \( N(\text{H} \text{I}) \). The clear segregation of the weak and strong systems on this plot supports our contention that they represent two separate populations.

In the lower panels of Fig. 6, we explore whether the H\( \text{I} \) column density in the weak proximate sample depends on \( \delta v \). We find that \( N(\text{H} \text{I}) \) distributes very differently at \( \delta v < 2000 \text{ km s}^{-1} \) than at \( \delta v > 2000 \text{ km s}^{-1} \). The \( N(\text{H} \text{I}) \) distribution for the \( \delta v > 2000 \text{ km s}^{-1} \) subsample is strongly clustered around \( \log N(\text{H} \text{I}) \approx 15 \), whereas the distribution for the \( \delta v < 2000 \text{ km s}^{-1} \) subsample is centred near \( \log N(\text{H} \text{I}) \approx 14 \) (see the bottom panel). A KS test shows the two distributions differ at the 99.97 per cent level. Consequently, there
is also a difference in the mean H/\text{O} VI ratio above and below 2000 km s^{-1}, but this is due to the proximity effect in N(H I), not in N(O \text{ VI}), which shows no correlation with proximity to the quasar. The finding that N(H I) correlates with \( \delta v \) has an important implication: it implies that \( \delta v \) does correlate with physical distance to the quasar. If \( \delta v \) was dominated by peculiar motions rather than Hubble flow, and so was uncorrelated to physical proximity to the quasar, then the two N(H I) distributions shown in the bottom panel of Fig. 6 would not be distinct. The fact that they are so different allows us to make the general assumption that proximity in velocity does imply proximity in distance.

### 3.6 C IV and N V column densities

The logarithmic C IV column densities in the proximate O VI sample cover over 2 dex, with a median value and standard deviation of log(N(C IV)) = 12.64 ± 0.60. N V is detected in nine weak absorbers, with log(N(N V)) between 11.54 and 13.60. Comparisons between the C IV column density and \( \delta v \), and between N V column density and \( \delta v \), as well as the dependence of the high-ion column density ratios with \( \delta v \), are presented in Fig. 7. In a similar fashion to H I, N(C IV) in the weak O VI absorbers depends strongly on \( \delta v \), with the absorbers at \( \delta v < 2000 \text{ km s}^{-1} \) showing column densities clustered around log(N(C IV)) ≈ 12.4, and those at \( \delta v > 2000 \text{ km s}^{-1} \) showing values centred at log(N(C IV)) ≈ 13.3. A two-sided KS test shows that the N(C IV) distributions in the two velocity intervals differ at a significance level of 93 per cent. This leads to a difference in the mean C IV/O VI ratio between the two velocity bins, with lower ratios at lower velocity. There is no indication that either N(N V) or N V/O VI depends on \( \delta v \), though the smaller sample size of N V (because of the non-detections) prevents us from making statistically meaningful conclusions.

In order to study the high-ion velocity structure more closely, we present in Figs 8(a) and (b) apparent column density profiles as a function of velocity, for each weak proximate O VI absorber.

**Figure 6.** Analysis of N(H I) and the H/\text{O} VI ratio in the proximate O VI sample. The column densities are integrated over all components in each absorber. In the top panel, a dashed line delineates the locations of the strong (blue) and weak (red) samples in a plot of H/\text{O} VI versus H I. In the central two panels, we show that both N(H I) and H/\text{O} VI show a dependence on proximity. The bottom panel shows the histogram of N(H I) for the weak O VI absorbers, split into two subsamples: those at \( \delta v < 2000 \) and \( \delta v > 2000 \text{ km s}^{-1} \). A significant difference exists between these two histograms, with the absorbers closer in velocity to the quasar showing lower N(H I).
Figure 7. Dependence of $N$(O\textsc{vi}), $N$(C\textsc{iv}), $N$(C\textsc{iv})/$N$(O\textsc{vi}), $N$(N\textsc{v}) and $N$(N\textsc{v})/$N$(O\textsc{vi}) on $\delta v$, for the weak proximate O\textsc{vi} sample. Downward-pointing arrows denote non-detections. The right-hand side column shows the histograms of each quantity plotted on the left-hand side, split into subsamples at $\delta v < 2000$ and $>2000$ km s$^{-1}$ from the quasar. In the lower two panels, the nine N\textsc{v} detections are shown with open circles to distinguish them from the non-detections. Only detections are included in forming the histograms. Whereas there is no discernable effect for $N$(O\textsc{vi}) to depend on $\delta v$, $N$(C\textsc{iv}) distributes very differently at $<2000$ than at $>2000$ km s$^{-1}$. The N\textsc{v} sample is too small to draw conclusions about whether $N$(N\textsc{v}) depends on $\delta v$.

single-phase have been pointed out before (Giroux, Sutherland & Shull 1994; Reimers et al. 2001).

3.7 Calculation of dN/d$z$ for proximate O\textsc{vi}

In this section, we derive the incidence of proximate O\textsc{vi} absorption, in terms of the traditional dN/d$z$, and also in terms of the number of absorbers detected per 2000 km s$^{-1}$ interval in $\delta v$. Note that because we are working at $z \gg 0$, relativistic effects cause the relationship between velocity and redshift intervals to be $dv \approx c dz/(1 + z)$. Before calculating the incidence of proximate O\textsc{vi} absorption, we correct the redshift path for blending with the Ly\alpha forest, since O\textsc{vi} is only identifiable in unblended regions of the spectrum. To estimate the number of O\textsc{vi} absorbers that were missed due to Ly\alpha forest contamination, we looked for C\textsc{iv} absorbers within 8000 km s$^{-1}$ of $z_{\text{QSO}}$ in which the accompanying O\textsc{vi} is blended, and found five. These are listed in Table 4. This method should provide a good estimate for the O\textsc{vi} incompleteness, since first O\textsc{vi} is detected in all proximate C\textsc{iv} absorbers in which the O\textsc{vi} data are unblended, and secondly C\textsc{iv} is unblended by the Ly\alpha forest, so no C\textsc{iv} systems should be missed down to a limiting equivalent width of $\approx 2$ mÅ. The limiting equivalent width for the C\textsc{iv} search is smaller than the limiting equivalent width for the O\textsc{vi} search because C\textsc{iv} lies in a higher S/N region of the spectrum.

The total redshift path within 8000 km s$^{-1}$ of 16 quasars (at $\langle z_{\text{QSO}} \rangle = 2.44$) is 1.48. Because there are five 'missing' O\textsc{vi} systems, we estimate our O\textsc{vi} completeness to be 35/(35 + 5) = 84 per cent, implying that a path equal to 0.25 is blended near O\textsc{vi}, so that the corrected redshift interval for the proximate O\textsc{vi} search is 1.24. In this path, 26 weak systems (comprising 48 components) are...
High ion and H\textsc{i} apparent column density profiles for each weak proximate O\textsc{vi} absorber. The C\textsc{iv} (blue), H\textsc{i} (black) and N\textsc{v} (green, where present) profiles have been scaled to allow their shape to be compared with O\textsc{vi}. For the high ions, the AOD profiles are formed from the data themselves. For H\textsc{i}, we show the AOD profile of the best-fitting model to the Lyman series absorption lines. The green vertical lines show the velocity range over which the AOD measurement is made. Annotated on the top right-hand side of each panel is the proximity to the quasar. In cases where the O\textsc{vi} and C\textsc{iv} profiles show similar line centres and line widths, we add a tick to the C\textsc{iv} label. In cases where the O\textsc{vi} and H\textsc{i} profiles show similar velocity centroids (but not necessarily the same width), we add a tick mark to the H\textsc{i} label. Cross marks next to the C\textsc{iv} and H\textsc{i} labels indicate significant differences between the profiles of these ions and O\textsc{vi}, e.g. centroid offsets of $>10$ km s$^{-1}$, indicating that the lines do not form in the same phase of gas as the O\textsc{vi}. detected. So $dN/dz$ of the weak O\textsc{vi} systems at $\delta v < 8000$ km s$^{-1}$ is $21 \pm 5$, where the errors on the counts are assumed to be Poissonian. However, this is an average value, and when we break down the absorbers into those at $\delta v < 2000$ and $2000–8000$ km s$^{-1}$, we find a marked change in the incidence: $dN/dz$ triples within 2000 km s$^{-1}$, from $14 \pm 4$ to $42 \pm 12$.\footnote{We have included the four weak O\textsc{vi} absorbers at $\delta v < 0 (z_{\text{abs}} > z_{\text{QSO}})$ in the 0–2000 km s$^{-1}$ bin, since regardless of their peculiar velocity they must lie in front of the quasar. Even without these, $dN/dz$ in the 0–2000 km s$^{-1}$ bin is $28 \pm 8$, twice the incidence in the 2000–8000 km s$^{-1}$ bin.} When counting components rather than systems, a similar increase in the incidence is observed within 2000 km s$^{-1}$ of $z_{\text{QSO}}$. These results are shown in Fig. 9, and are also summarized in Table 5. Note how the intervening incidence of BH05 is recovered in the range 2000–8000 km s$^{-1}$.  

3.8 Comparison of $z \approx 2.5$ and 0 absorbers

A considerable amount of work has been invested in studying O\textsc{vi} in the low-redshift IGM using the Far-Ultraviolet Spectrographic Explorer and the Hubble Space Telescope (HST) orbiting observatories (Bergeron et al. 1994; Burles & Tytler 1996; Tripp, Lu & Savage 1996; Tripp, Savage & Jenkins 2000; Savage et al. 2002;
Table 4. Proximate C IV with blended O VI.

<table>
<thead>
<tr>
<th>QSO</th>
<th>zQSO</th>
<th>zabs</th>
<th>δv (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE 0001−2340</td>
<td>2.2670</td>
<td>2.1870</td>
<td>7530</td>
</tr>
<tr>
<td>HE 0151−4326</td>
<td>2.7890</td>
<td>2.6956</td>
<td>7580</td>
</tr>
<tr>
<td>HE 1341−1020</td>
<td>2.1350</td>
<td>2.1065</td>
<td>2750</td>
</tr>
<tr>
<td>HE 2347−4342</td>
<td>2.8710</td>
<td>2.8781</td>
<td>−550</td>
</tr>
<tr>
<td>Q 0122−380</td>
<td>2.2030</td>
<td>2.1472</td>
<td>5320</td>
</tr>
</tbody>
</table>


By comparing our results obtained from proximate O VI absorbers at z = 2–3 with the z ≈ 0 results, we can search for evolution of the highly ionized gas content of the Universe. Since the intensity of the extragalactic ultraviolet (UV) background rises with redshift (Haardt & Madau 1996), one might expect to see higher photoionized O VI column densities at higher redshift. Simultaneously, the fraction of baryons in warm-hot gas is predicted to decrease with increasing redshift (Davé et al. 2001), since at early cosmic epochs there has not been adequate time for gas to accrete and virialize into dark matter-dominated potential wells.

Based on an analysis of low-redshift (0.15 < z < 0.5) O VI absorption-line systems and with a sensitivity limit of \( W_r > 30 \) mÅ, Tripp et al. (2008) report that dN/dz is enhanced by a factor of ≈3 at velocities < 2 500 km s\(^{-1}\) from the quasar compared to higher velocities.

Figure 9. Number of weak O VI absorbers as a function of proximity to the quasar. Plotted are the number of O VI systems per 2000 km s\(^{-1}\) bin of δv over our sample of 16 quasars. The corresponding values of dN/dz are shown on the right-hand side, corrected for the blended redshift path. The errors on the counts are assumed to be Poissonian; plotted are the 1σ errors. We use a smaller bin for the range −1000 to 0 km s\(^{-1}\); these absorbers lie in front of the quasar and so are included in the 0–2000 km s\(^{-1}\) bin in our final dN/dz calculations. The incidence of intervening O VI systems is shown as the green data point; there is no significant difference in dN/dz between the absorbers at 2000–8000 km s\(^{-1}\) and the intervening sample.
to the intervening sample, with \( dN(\text{O} vi)/dz = 16 \pm 1 \) for the intervening systems and \( dN(\text{O} vi)/dz = 5 \pm 1 \) for those at \( \delta v < 2.5 \text{ km s}^{-1} \). Our result for weak \text{O} vi systems at \( z = 2–3 \) with \( W_R > 30 \text{ mÅ} \) and \( \delta v < 2000 \text{ km s}^{-1} \) is 32 ± 10, lower than the low-redshift result by a factor of 8–6. However, comparing the high- and low-redshift results for \( dN/dz \) can be misleading, because redshift has a highly non-linear relationship with spatial dimensions, that depends on cosmology. With our adopted cosmology, then in the interval \( z = 0.15 \) to 0.5, \( dN(\text{Gpc}) = 3.63 \text{ d} \), whereas for the interval \( z = 2 \) to 3, \( dN(\text{Gpc}) = 1.22 \text{ d} \), where \( dN \) is the comoving radial distance, and where we have used the online cosmology calculator of Wright (2006). Correcting for these factors to calculate the number density of weak \text{O} vi absorbers per unit comoving distance, a better indicator of the space density of \text{O} vi, we derive the results listed in Table 6. Here, we see evidence that the space density of \text{O} vi absorbers increases with redshift, by a factor of 2 between \( z = 0.15–0.5 \) and 2–3. This increase is observed independently for both the proximate and intervening absorbers.

### 4 DISCUSSION

The BAL, mini-BAL and intrinsic systems, which together we classify as strong systems based on their fully saturated \text{O} vi absorption, strong accompanying \text{C} iv absorption, and frequent evidence for partial coverage, are well understood as being formed in either QSO-driven outflows or inflows in the immediate vicinity of the AGN central engine (see review by Hamann & Ferland 1999). Here, we focus on the weak (narrow) proximate systems, which represent a separate population. Is there any evidence that these weak systems are directly photoionized by the quasar? We report two results that address this question, though their interpretation is not straightforward. First, in our sample of proximate \text{O} vi absorbers at \( z = 2–3 \), there is an enhancement by a factor of 3 in the incidence \( dN/dz \) of weak \text{O} vi absorbers within 2000 km s\(^{-1}\) of the quasar versus those in the interval 2000 to 8000 km s\(^{-1}\). A similar enhancement is seen near low-redshift quasars (Tripp et al. 2008). While at face value this could be interpreted as a proximity effect, in which quasars preferentially ionize nearby clouds more often than they photoionize more distant clouds, this is not the only explanation. The enhancement in \( dN/dz \) could also be explained by an overdensity of galaxies near quasars, and where the \text{O} vi absorbers are located in the gaseous haloes of these galaxies (Young, Sargent & Boksenberg 1982). It is well known that quasars are preferentially formed in cluster environments, particularly at high redshift (Croom et al. 2005; Shen et al. 2007). This idea is supported by the observation that the internal properties of the weak \text{O} vi absorbers are not dependent on redshift or proximity to the quasar.

Secondly, there are statistically significant differences between the \( \text{H}/\text{O} vi \) and \( \text{C} iv/\text{O} vi \) ratios measured in the weak \text{O} vi populations above and below 2000 km s\(^{-1}\), with the weak absorbers at \( \delta v < 2000 \text{ km s}^{-1} \) showing a median \( \text{H}/\text{O} vi \) ratio lower by a factor of 8–6, and a median \( \text{C} iv/\text{O} vi \) ratio lower by a factor of 2–3 than those at 200 < \( \delta v < 8000 \text{ km s}^{-1} \). Again, at face value, these results could be interpreted as proximity effects, in which gas closer to the quasar shows a higher ionization level than intervening gas. However, closer inspection finds that while \( N(\text{H} i) \) and \( N(\text{C} iv) \) show a tendency to decrease as \( \delta v \) decreases, \( N(\text{O} vi) \) is uncorrelated with \( \delta v \), i.e. it is the behaviour of \( N(\text{H} i) \) and \( N(\text{C} iv) \) alone that is driving the trends seen in the column density ratios, not the behaviour of \( N(\text{O} vi) \). Importantly, the \( \text{H} i \) and \( \text{C} iv \) proximity effects imply that proximity in velocity does correlate with proximity in distance, which supports the idea that the velocities of the weak absorbers are dominated by the Hubble flow.

Because \text{O} vi-H\text{C} iv velocity centroid offsets are observed directly in \( \approx 50 \) per cent of the weak systems, single-phase photoionization models for the \text{O} vi, \text{C} iv and \text{H} i are inadequate for at least half the absorbers in our sample. Indeed, the non-dependence of \( N(\text{O} vi) \) on proximity casts doubt on whether photoionization by the background QSO creates the \text{O} vi at all. Photoionization by nearby stellar sources of radiation is also unlikely, since such sources do not emit sufficient fluxes of photons above 54 eV (the He ii ionization edge) to produce the observed quantities of \text{O} vi. We cannot rule out photoionization by the quasar in every individual case, for example the absorber at \( z = 2.4183 \) towards HE 1122–1649, which shows strong \text{O} vi but barely detectable \text{C} iv, as do several proximate \text{O} vi absorbers reported by Gonçalves et al. (2008). None the less, \( N(\text{O} vi) \) does not depend on proximity in the way that \( N(\text{H} i) \) and \( N(\text{C} iv) \) do. Thus, we infer that the sizes of spheres-of-influence around quasars, which are implied the shapes of Gunn–Peterson troughs (Zheng & Davidsen 1995; Smette et al. 2002), and from studies of proximate absorption in lower ionization species, such as \text{Mg} ii (Vanden Berk et al. 2008; Wild et al. 2008) and \text{C} iv (Foltz et al. 1986; Vestergaard 2003; Nestor et al. 2008), are dependent on photon energy, and the presence of a sphere of photons at energies above 113.9 eV (capable of ionizing \text{O} iv to \text{O} v) has yet to be demonstrated.

Thus, we turn to collisional ionization models. Since the line widths of a significant fraction (\( \approx 60 \) per cent) of the components in the weak \text{O} vi absorbers are low enough (\( b < 14 \text{ km s}^{-1} \)) to imply gas temperatures below 188 000 K, collisional ionization \textit{equilibrium} can be ruled out because essentially no \text{O} vi is produced in gas in CIE at these temperatures (Sutherland & Dopita 1993; Gnat & Sternberg 2007). Indeed, the narrow-line widths of many intergalactic \text{O} vi absorbers at \( z \approx 2 \) have led various authors to conclude that photoionization is the origin mechanism (Bergeron et al. 2002;

### Table 5. Weak \text{O} vi absorbers at \( z = 2–3 \): summary of \( dN/dz \) statistics (8 mÅ sensitivity).

| Category | \( |\delta v| < 2000^a \) | 2000 < \( \delta v < 8000^a \) | Intervening$^b$ |
|----------|-----------------|-----------------|------------|
| Systems  | 42 ± 12         | 14 ± 4          | 14 ± 2     |
| Components | 87 ± 17         | 23 ± 5          | 35 ± 6     |

$^a$Range in velocity relative to \( z_{\text{QSO}} \) (in km s\(^{-1}\)).

$^b$Based on BH05; in the updated intervening sample 58 systems are seen over a total \( \delta z \) of 4.09, complete down to \( \log N(\text{O} vi) = 13.11 \).

### Table 6. \( dN(\text{O} vi)/dz \) statistics (30 mÅ sensitivity).

<table>
<thead>
<tr>
<th>Category$^a$</th>
<th>Sample</th>
<th>( z = 0–0.5^b )</th>
<th>( z = 2–3^b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems</td>
<td>Proximate (( \delta v &lt; 2000 ))</td>
<td>14 ± 1</td>
<td>26 ± 8</td>
</tr>
<tr>
<td></td>
<td>Intervening (( \delta v &gt; 5000 ))</td>
<td>4 ± 1</td>
<td>8 ± 2</td>
</tr>
<tr>
<td>Components</td>
<td>Proximate (( \delta v &lt; 2000 ))</td>
<td>30^5 ± 8</td>
<td>71 ± 14</td>
</tr>
<tr>
<td></td>
<td>Intervening (( \delta v &gt; 5000 ))</td>
<td>6 ± 1</td>
<td>21 ± 3</td>
</tr>
</tbody>
</table>

$^a$The entries in this table list the incidence of weak \text{O} vi absorbers per unit comoving distance, in units of Gpc\(^{-1}\); the entries were derived by correcting \( dN/dz \) for cosmology, and are presented for both proximate and intervening absorbers, at low and high redshift, and for systems and components.

$^b$Derived using results from Tripp et al. (2008).

$^c$Derived from BH05 result.
Carswell et al. 2002; Levshakov et al. 2003; BH05; Reimers et al. 2006; Lopez et al. 2007). However, non-equilibrium collisional ionization models cannot be ruled out so easily. Indeed one expects that collisionally ionized gas at ‘coronal’ temperatures of a few $\times 10^5$ K, where O\textsc{vi} is formed through collisions, will be in a non-equilibrium state. This is because the peak of the interstellar cooling curve exists at these temperatures, and so the cooling time-scales are short. When the cooling times are shorter than the recombination time-scales, ‘frozen-in’ ionization can result at temperatures well below those at which the ions exist in equilibrium (Kafatos 1973; Shapiro & Moore 1976; Edgar & Chevalier 1986), provided that there is a source of $\sim 10^5$ K gas in the first place.

There are at least two physical reasons why collisionally ionized, million-degree regions of interstellar and intergalactic gas could arise in the high-z Universe. The first is the (hot-mode) accretion and shock heating of gas falling into potential wells (Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006), a process which is incorporated into cosmological hydrodynamical simulations (Cen & Ostriker 1999; Davé et al. 2001; Fang & Bryan 2003; Kang et al. 2005; Cen & Fang 2006), and creates what is referred to as the warm–hot IGM (WHIM). However, these models generically predict that the fraction of all baryons that exist in the WHIM rises from essentially zero at $z = 3$ to 30–50 per cent at $z = 0$, so little WHIM is expected at the redshifts under study here. The second reason is the presence of galactic-scale outflows, which due to the energy input from supernovae are likely to contain (or even be dominated by) hot, highly ionized gas (see recent models by Oppenheimer & Davé 2006; Fangano, Ferrara & Richter 2007; Kawata & Rauch 2007; Samui, Subramanian & Srianand 2008). There is strong observational evidence for outflows at redshifts of $\sim 2$–3 (Heckman 2002), including blueshifted absorption in the spectra of Lyman break galaxies (Pettini et al. 2000, 2002; Shapley et al. 2003), the presence of metals in the low density, photoionized IGM (the Lyα forest; e.g. Aracil et al. 2004; Aguirre et al. 2005, 2008), though see Schaye, Carswell & Kim (2007), and the presence of super-escape velocity C\textsc{iv} components in the spectra of damped Ly\alpha (DLA) galaxies (Fox et al. 2007b). In addition, collisionally ionized gas in galactic haloes at high redshift has been seen directly through detections of O\textsc{vi} and N\textsc{v} components in DLAs (Fox et al. 2007a), albeit with much broader system velocity widths than in the proximate absorbers discussed here. O\textsc{vi} absorbers with lower H\textsc{i} column density may probe the outer reaches of such haloes or ‘feedback zones’ (Simcoe et al. 2002; BH05).

We explore the ability of non-equilibrium collisional ionization models to reproduce the data in our proximate O\textsc{vi} sample in Fig. 10, which shows the C\textsc{iv}/O\textsc{vi} versus N \textsc{v}/O\textsc{vi} ratio–ratio plane. We take the isobaric non-equilibrium model at log $T = 5.00$ (consistent with the observed O\textsc{vi} component line widths) from Gnat & Sternberg (2007), computed using solar abundances, and then find the values of [N/O] and [C/H] which are required to reproduce the observations. The models for 0.1 and 0.01 solar absolute abundances, and for the isochoric case, predict similar values. The non-equilibrium models are not capable of reproducing the observed ratios when solar relative elemental abundances are used. However, if [N/O] takes values between $-1.8$ and 0.4, and [C/O] between $-1.9$ and 0.6, it is possible to explain the observed column densities in each weak proximate system with a non-equilibrium collisional ionization model. Note that we have not corrected these model predictions for the effect of photoionization by the extragalactic background; the model represents the pure collisional ionization case. Hybrid collisional + photoionization models would help in making progress in this area (see discussion in Tripp et al. 2008).

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Comparison of predictions of non-equilibrium collisional ionization models with the observed column density ratios in our weak proximate sample. Non-detections of N \textsc{v} (C\textsc{iv}) lead to upper limits on the x- (y-) axis. We take the predictions from the isobaric non-equilibrium collision ionization model of Gnat & Sternberg (2007) for an absorber at $T = 10^5$ K (higher temperatures are ruled out by the component line widths). The model is fairly insensitive to changes in the overall abundance level, but is sensitive to non-solar relative abundances. The dashed green lines show the range of values of [N/O] and [C/O] that are required to fit the proximate data with this collisional ionization model.

### 5 SUMMARY

We have presented a study of proximate ($\delta v < 8000$ km s$^{-1}$) O\textsc{vi} absorbers in the spectra of 16 quasars observed at high signal-to-noise ratio and 6.6 km s$^{-1}$ resolution with VLT/UVES. The quasars are at redshifts between 2.14 and 2.87. We found 35 proximate O\textsc{vi} absorbers comprising 101 components. We used component fitting software to determine the properties of the absorption, studied the statistical properties of the sample and addressed the ionization conditions in the gas. Our study has produced the following results.

(i) None of the 35 O\textsc{vi} systems are strong, with log N(O\textsc{vi}) $\gtrsim 15.0$. These absorbers all show detections of C\textsc{iv} and N\textsc{v}, and show either broad, fully saturated, mini-BAL-type O\textsc{vi} absorption troughs extending over tens to hundreds of km s$^{-1}$, or evidence for partial coverage in the high-ion profiles. A mean of 6.0 O\textsc{vi} components are seen in the strong absorbers. The strong absorbers are formed either in QSO-driven outflows or in the immediate vicinity of the quasar.

(ii) 26 of the 35 O\textsc{vi} systems are weak, and show log N(O\textsc{vi}) $< 14.5$. These systems are narrow, with a median velocity width $\delta v_{90}$ of 42 km s$^{-1}$. The weak systems all contain detectable H\textsc{i}, all but two show C\textsc{iv} and 9/26 show N\textsc{v}. We find a mean of 1.9 O\textsc{vi} components per weak system. Approximately 60 per cent of these O\textsc{vi} components have Doppler b-values $<14$ km s$^{-1}$. The gas in these narrow components is constrained by the line widths to be at $T < 188,000$ K.

(iii) Among the weak sample there is no correlation between the O\textsc{vi} column density and the proximity to the quasar. This is true when using either the component- or the system-level column densities. Two-sided KS tests confirm that the column density distributions of the intervening and weak proximate O\textsc{vi} samples are
statistically indistinguishable. The O\textsc{vi} column density also does not correlate with redshift.

(iv) Among the weak sample, there are differences between the line width distribution of the O\textsc{vi} components and the distributions of the C\textsc{iv} and N\textsc{v} components. The C\textsc{iv} and N\textsc{v} distributions are strongly peaked below $b = 10 \text{ km s}^{-1}$ and do not show the tail of absorbers with $b$-values between 10 and 25 km s$^{-1}$ seen in the O\textsc{vi} distribution.

(v) There is a significantly lower N(H\textsc{i}) in the weak O\textsc{vi} absorbers with $\delta v < 2000 \text{ km s}^{-1}$ than in those with $\delta v > 2000 \text{ km s}^{-1}$. The difference in the median N(H\textsc{i}) between these two samples is $\sim 1.0 \text{ dex}$. We interpret this as a manifestation of the H\textsc{i} proximity effect, and it leads to a trend in which the H\textsc{i}/O\textsc{vi} ratio is lower for absorbers within 2000 km s$^{-1}$ of the QSO than for those at higher $\delta v$. An identical trend is observed for C\textsc{iv}, with the median N(C\textsc{iv}) lower by $\approx 0.8 \text{ dex} < 2000 \text{ km s}^{-1}$ than at $\delta v > 2000 \text{ km s}^{-1}$.

Thus, C\textsc{iv} and H\textsc{i} behave differently than O\textsc{vi}.

(vi) Apparent column density profile comparisons show that O\textsc{vi} and C\textsc{iv} show significantly different velocity structure in 13 of the 24 weak O\textsc{vi} absorbers where C\textsc{iv} is detected. Offsets between the centroid of the H\textsc{i} model and the O\textsc{vi} components are seen in 14/26 weak proximate cases. Therefore, at least half of the weak O\textsc{vi} systems are multiphase.

(vii) Down to a limiting rest equivalent width of 8 mÅ, the number density of weak O\textsc{vi} systems within 2000 km s$^{-1}$ of the background quasar is $dv/dz = 42 \pm 12$ (87 $\pm$ 17 for components). Between 2000 and 8000 km s$^{-1}$ in $\delta v$, $dv/dz$ falls to $14 \pm 4$ (23 $\pm$ 5 for components), equal to the incidence of intervening O\textsc{vi} measured by BH05. Thus, an enhancement in $dv/dz$ by a factor of 3 is seen at $\delta v < 2000 \text{ km s}^{-1}$.

(viii) We compare the incidence $dv/dz$ of O\textsc{vi} absorbers at high ($z = 2$–3) and low ($z = 0$–0.5) redshift. After correcting for cosmology, the incidence of O\textsc{vi} systems with $W_\lambda > 30 \text{ mÅ per unit comoving distance}$ at $z = 2$–3 is twice the value at $z = 0$–0.5. This increase is seen for both proximate and intervening absorbers.

(ix) Because O\textsc{vi}–C\textsc{iv}–H\textsc{i} velocity offsets are observed in half the sample, single-phase photoionization models are (at least for these cases) unable to explain the data. Indeed, the non-dependence of N(O\textsc{vi}) on proximity casts doubt on whether photoionization creates the O\textsc{vi} at all. Instead, we propose that the weak O\textsc{vi} absorbers trace collisionally ionized regions that exist as part of multiphase galactic or protogalactic structures. In order to reconcile the collisional ionization hypothesis with the narrow-line widths measured in approximately 60 per cent of the O\textsc{vi} components, the gas must be out of CIE. This can be explained by a scenario in which initially hot gas is cooling down through the coronal regime at $T \sim 10^5 \text{ K}$. The observed high-ion column density ratios and line widths in the proximate O\textsc{vi} absorbers can be explained by models of non-equilibrium collisionally ionized gas at $T \approx 10^5 \text{ K}$, but only if the relative elemental abundances are non-solar: we require [N/O] to be in the range $-1.8$ to 0.4 and [C/O] between $-1.9$ and 0.6, to explain the data with these models.

(x) Future O\textsc{vi} surveys do not need to remove absorbers (and thus compromise the sample size) that happen to lie at 2000–8000 km s$^{-1}$ relative to the quasar. A better approach would be to remove those showing either N(O\textsc{vi}) $\gtrsim 15.0$ or evidence for partial coverage.

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(Continued on next page)
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Figure 1. Absorption-line spectra of all proximate O\textsc{vi} systems in the UVES large programme. Strong absorbers are shown first, followed by the weak absorbers. Our Voigt profile fits are shown in red. In many of the C\textsc{iv} and N\textsc{v} panels, the data are shown over a limited range in the y-axis, for clarity. The green vertical lines indicate the velocity range of the AOD integration. The label 'PC' indicates regions where partial coverage of the continuum source affects the line profiles. At the top of each column, we annotate our classification and the proximity of the absorber to the quasar.
Figure 1 – continued
Figure 1 – continued
Figure 1 – continued

WEAK, $\delta v = 3720$ km s$^{-1}$
HE 1122+1649 $z = 2.3062$

WEAK, $\delta v = -727$ km s$^{-1}$
HE 1122+1649 $z = 2.4103$

WEAK, $\delta v = 1845$ km s$^{-1}$
HE 1158+1643 $z = 2.6279$

WEAK, $\delta v = -451$ km s$^{-1}$
HE 1158+1643 $z = 2.4542$

Flux (Arbitrary Units)

$\mbox{H I} 972$ ($\Lya$)
$\mbox{H I} 1025$ ($\Lya$)
$\mbox{c IV} 1548$
$\mbox{c IV} 1550$
$\mbox{O VI} 1030$
$\mbox{N V} 1238$
$\mbox{c IV} 1550$
$\mbox{O VI} 1030$

$\mbox{c III} 977$
$\mbox{H I} 972$ ($\Lya$)
$\mbox{H I} 1025$ ($\Lya$)
$\mbox{c IV} 1548$
$\mbox{c IV} 1550$

$\mbox{H I} 1215$ ($\Lya$)
$\mbox{H I} 1215$ ($\Lya$)
$\mbox{H I} 1215$ ($\Lya$)
$\mbox{H I} 1215$ ($\Lya$)
$\mbox{H I} 1215$ ($\Lya$)

$-200$ to $100$ km s$^{-1}$
Figure 1 – continued
Figure 1 – continued
Figure 1 – continued
Figure 1 – continued
Figure 1 – continued