An investigation of the line of sight towards QSO PKS 0237−233*

H. Fathivavsari¹, P. Petitjean², C. Ledoux³, P. Noterdaeme², R. Srianand⁴, H. Rahmani⁴, A. Ajabshirizadeh¹,⁵

¹Department of Theoretical Physics and Astrophysics, University of Tabriz, Tabriz 51664, Iran
²Université Pierre et Marie Curie - CNRS, UMR7095, Institut d’Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France
³European Southern Observatory, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
⁴Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India
⁵Research Institute for Astronomy and Astrophysics of Maragha, Maragha 55134-441, Iran

ABSTRACT
We present a detailed analysis of absorption systems along the line of sight towards QSO PKS 0237−233 using a high resolution spectrum of signal-to-noise ratio (SNR) ~60-80 obtained with the Ultraviolet and Visual Echelle Spectrograph mounted on the Very Large Telescope. This line of sight is known to show a remarkable overdensity of C IV systems that has been interpreted as revealing the presence of a supercluster of galaxies. A detailed analysis of each of these absorption systems is presented. In particular, for the \( z_{\text{abs}} = 1.6359 \) (with two components of log \( N_{\text{HI}} \ cm^{-2} \) =18.45, 19.05) and \( z_{\text{abs}} = 1.6720 \) (log \( N_{\text{HI}} = 19.78 \)) sub-Damped Lyα systems (sub-DLAs), we measure accurate abundances (resp. \( [O/H] = -1.63\pm0.07 \) and \( [Zn/H] = -0.57\pm0.05 \) relative to solar). While the depletion of refractory elements onto dust grains in both sub-DLAs is not noteworthy, photoionization models show that ionization effects are important in a part of the absorbing gas of the sub-DLA at \( z_{\text{abs}} = 1.6359 \) (H i is 95 percent ionized) and in part of the gas of the sub-DLA at \( z_{\text{abs}} = 1.6359 \) The C IV clustering properties along the line of sight is studied in order to investigate the nature of the observed overdensity. We conclude that despite the unusually high number of C IV systems detected along the line of sight, there is no compelling evidence for the presence of a single unusual overdensity and that the situation is consistent with chance coincidence.

Key words: quasars: absorption lines – quasars: individual: PKS 0237−233

1 INTRODUCTION
Metal absorption lines seen in the spectra of high redshift quasars are thought to be produced by gas clouds associated in some way with galaxies or their progenitors. This hypothesis is supported in particular by the amplitude and scale of their clustering which are consistent with those expected from galaxies (e.g. Scannapieco et al. 2006). A few lines of sight have been known for long to contain an unusually large number of absorption systems and the reason for these puzzling observations have never been fully elucidated.

One instance of such superclustering is seen towards the two quasars Tol 1037−2703 and Tol 1038−2712 (Jakobsen et al. 1986) which have an angular separation of 17.9 arcmin in the plane of the sky, corresponding to a proper separation of 4.4 \( h^{-1} \) Mpc at \( z \sim 2 \). The spectra of the quasars each exhibit at least five C IV absorption complexes over the narrow redshift range 1.88 \( \leq z \leq 2.15 \), representing a highly significant overdensity in the number of absorbers above that expected from Poisson statistics (Dinshaw & Impey 1996). One complex lies at the same redshift along both QSO lines of sight and the rest are coincident to within \( v \leq 2000 \) km s\(^{-1}\). The fact that there are similar absorption features at the same redshift in the spectra of both these quasars signals that the two lines of sight may actually be probing the same absorbing structure. The preferred explanation for the overdensity of C IV absorption systems is that the two lines of sight are passing through material associated with an intervening supercluster (Jakobsen et al. 1986; Sargent et al. 1987; Lespine & Petitjean 1997; Srianand &...
Table 1. Solar abundances taken from Asplund et al. (2009).

| Species | O     | Si     | Mg     | S     | Fe    | Cr    | Zn    | Mn    | Ni    |
|---------|-------|--------|--------|-------|-------|-------|-------|-------|-------|
| Log Abundance | -3.31 | -4.49  | -4.40  | -4.88 | -4.50 | -6.36 | -7.44 | -6.57 | -5.78 |

Table 2. Elemental column densities in the $z_{obs} = 1.6359$ system.

| Low-ion column densities |
|--------------------------|
| $z$ | $\Delta V$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | log N(Mg i) | log N(Mg II) | log N(O I) | log N(O II) | log N(N i) | log N(Si i) | log N(Si II) |
|----|-------------------------|-----------------|-------------|-------------|-----------|-------------|------------|-------------|-------------|
| 1.63568 | -22.7                  | 10.7±0.7        | $\leq$10.21 | $\leq$12.86 | $\leq$12.22 | $\leq$12.22 | 10.95±0.07 | $\leq$10.90 |             |
| 1.63579 | -10.2                  | 2.3±0.2         | 11.94±0.00  | 9.66±0.21  | 12.77±0.04 | 11.26±0.04 | 11.95±0.13 | 11.25±0.02 | 10.80±0.06 |
| 1.63588 | 0.0                    | 4.2±0.0         | 12.86±0.00  | 10.83±0.02 | 13.23±0.01 | 12.23±0.00 | 13.01±0.01 | 12.01±0.01 | 11.74±0.01 |
| 1.63604 | +18.2                  | 5.0±0.2         | 11.76±0.00  | $\leq$9.93 | 12.73±0.05 | $\leq$10.43 | 11.67±0.26 | 11.36±0.02 | 10.96±0.05 |
| 1.63639 | +58.0                  | 4.3±1.2         | 10.79±0.05  | $\leq$9.68 | $\leq$11.98 | $\leq$10.73 | 10.52±0.03 | 10.49±0.14 |             |

| Region - R1 |
|--------------|
| $z$ | $\Delta V$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | log N(N i) | log N(Si ii) | log N(Si III) | log N(Al i) | log N(Al ii) | log N(C i) | log N(N i) |
|----|-------------------------|-----------------|------------|-------------|---------------|------------|-------------|------------|------------|
| 1.63691 | +117.1                  | 2.3±0.3         | $\leq$9.82 | 12.33±0.09  | 11.26±0.04   | 12.20±0.07 | 10.51±0.14  | $\leq$10.30 | 12.73±0.06 |
| 1.63701 | +128.5                  | 1.7±0.8         | 11.52±0.01 | 9.81±0.14   | 12.25±0.12   | 11.25±0.04 | 12.05±0.10  | 10.88±0.09  | 10.15      |
| 1.63712 | +141.0                  | 5.5±0.4         | 12.36±0.00 | 10.81±0.03  | 13.65±0.01   | 12.37±0.01 | 12.72±0.05  | 10.86±0.34  | 13.52±0.05 |
| 1.63717 | +146.7                  | 15.0±0.7        | 12.85±0.00 | 10.71±0.06  | 13.79±0.01   | 12.65±0.01 | 13.30±0.02  | 12.05±0.01  | 10.91±0.14 |
| 1.63733 | +164.9                  | 4.8±0.8         | 11.83±0.01 | 10.04±0.11  | 12.67±0.06   | 11.40±0.04 | 12.38±0.06  | 11.24±0.03  | 10.53      |
| 1.63744 | +177.4                  | 6.0±0.2         | 12.15±0.00 | 10.46±0.04  | 12.64±0.06   | 11.78±0.01 | 12.42±0.05  | 11.45±0.02  | 10.56±0.13 |
| 1.63759 | +194.4                  | 3.2±1.5         | 10.76±0.05 | $\leq$9.75  | 11.69±0.43   | 10.45±0.26 | $\leq$11.37 | 10.50±0.13  | $\leq$10.26 |
| 1.63776 | +213.7                  | 3.9±0.6         | 11.28±0.02 | $\leq$9.56  | $\leq$11.92  | 10.86±0.11 | 12.01±0.12  | 10.74±0.08  | $\leq$10.02 |
| 1.63785 | +234.0                  | 6.9±0.4         | 11.85±0.01 | $\leq$9.93  | 12.29±0.10   | 11.49±0.03 | 12.47±0.05  | 11.19±0.03  | $\leq$10.24 |

| Region - R2 |
|--------------|
| $z$ | $\Delta V$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | log N(X) |
|----|-------------------------|-----------------|---------|
| 1.63577 | -12.5                   | 22.9±1.0        | 12.87±0.02 |
| 1.63588 | 0.0                     | 5.9±0.4         | 12.17±0.05 |
| 1.63605 | +19.3                   | 4.5±0.3         | 12.15±0.03 |
| 1.63638 | +56.9                   | 4.9±0.5         | 12.22±0.06 |
| 1.63651 | +71.6                   | 11.8±4.2        | 12.01±0.13 |
| 1.63685 | +110.3                  | 16.0±2.0        | 12.86±0.02 |
| 1.63711 | +139.9                  | 7.6±1.3         | 12.91±0.26 |
| 1.63720 | +150.1                  | 10.6±2.0        | 12.65±0.47 |
| 1.63742 | +175.1                  | 12.3±1.1        | 12.19±0.04 |

$^a$ Blended with some features.

Petitjean 2001) but this concentration of objects has never been confirmed directly. It is interesting to note that C IV clustering properties are very sensitive to the choice of the column density threshold (Scannapieco et al., 2006).

Another example of an overdensity of absorption systems is observed along the line of sight to the quasar PKS 0237–233. This quasar was first discovered and studied by Arp, Bolton & Kinman (1967). Its absorption spectrum has been the subject of many studies over the years (Burbidge 1967; Greenstein et al. 1967; Burbidge et al. 1968; Bahcall et al. 1968; Boksenberg et al. 1975) with three main complexes at $z_{obs} = 1.596, 1.657, 1.674$. Foltz et al. (1993) searched the field for other QSOs to provide background sources against which the presence of absorption at the same redshifts could be investigated. They concluded that the complex can be interpreted as a real spatial overdensity of absorbing clouds with a transverse size comparable to its extent along the line of sight, that is of the order of 30 Mpc. Heisler et al. (1989) found significant clustering signal in the distribution of C IV systems out to velocities of $\Delta V \leq 10,000$ km s$^{-1}$ in a sample of 55 QSOs observed by Sargent et al. (1988). They noted that the clustering signal is dominated by a single large supercluster along the line of sight to PKS 0237–233 spanning a redshift range from $z = 1.595$ to $z = 1.6752$. More recently, Scannapieco et al. (2006) studied the line of sight correlation function of C IV systems using nineteen lines of sight observed with the Ultraviolet and Visual Echelle Spectrograph on Very Large Telescope (VLT/UVES). Their sample may not be large enough to conclude about the clustering signal beyond 500 km s$^{-1}$. Surprisingly, the redshift evolution of the C IV systems has not been studied from large samples provided by e.g. SDSS.

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contrary to what has been done for Mg ii systems. This is probably related to the difficulties in robustly detecting C iv systems at intermediate resolution because the two lines of the doublet are partially blended. Only samples based on high resolution observations are available (see D’Odorico et al. 2010).

Lines of sight with high overdensities of absorption systems are in any case rare incidences that are worth investigating in more details. In this paper, we study the line of sight towards PKS 0237–233 in great detail, using a high spectral resolution ($R = 45000$) and high signal-to-noise ratio ($S/N \sim 60 – 80$ ) spectrum taken with VLT/UVES and taken during the European Southern Observatory (ESO) Large Program "The Cosmic Evolution of the Intergalactic Medium (IGM)" (Bergeron et al. 2004).

Observations are described in Section 2. Individual systems are discussed in Section 3 and the Appendix. Results of fits are analysed in Section 4 using photoionization models. The clustering properties of C iv absorbers are presented in Section 5 and conclusions are drawn in Section 6.

2 OBSERVATIONS
The spectrum of PKS 0237–233 used for this study is of the highest SNR and spectral resolution. It was obtained using the Ultraviolet and Visible Echelle Spectrograph (UVES, Dekker et al. 2000) mounted on the ESO Kueyen 8.2-m telescope at the Paranal observatory in the course of the ESO-VLT large programme 'The Cosmic Evolution of the IGM' (Bergeron et al. 2004). PKS 0237–233 was observed through a 1.0 arcsec slit for $\sim$12 hours with dichroic #1 with central wavelengths adjusted at 3460 and 5800 Å in the blue and red arms, respectively, and for another $\sim$14 hours with dichroic #2 with central wavelengths at 4370 and 8600 Å in the blue and red arms respectively. The raw data were reduced using the UVES pipeline. Individual exposures were air-vacuum corrected and placed in an heliocentric restframe. Co-addition of the exposures was performed using a sliding window and weighting the signal by the errors in each pixel. Great care was taken in computing the error spectrum while combining the individual exposures. The final combined spectrum covers the wavelength range 3000 – 10,000 Å. A typical SNR$\sim$60 – 80 per pixel (of 0.035 Å) is achieved over the whole wavelength range of interest. The detailed quantitative description of data calibration is presented in Aracil et al. (2004) and Chand et al. (2004, 2006). We will use these superb data to make a detailed analysis of the line of sight.

In the following, we used the solar abundances (photospheric abundances), log ($X/H$)$_\odot$, from Asplund et al. (2009) listed in Table 1 and the metallicity relative to solar of species X, [$X/H$] = log X/H − log ($X/H$)$_\odot$.

3 DISCUSSION OF INDIVIDUAL SYSTEMS
This section presents the analysis of absorption profiles for several systems we chose to study in greater detail. The description of the other systems detected in the spectrum of PKS 0237–233 can be found in Appendix A.

To identify the absorption systems, we searched first for Mg ii and C iv doublets. We then identified all metal absorption associated with these systems. Finally, we checked that there is no system left unidentified by this procedure. Overall, we identify 18 absorption systems along this line of sight, three of which are sub-damped Ly$\alpha$ (sub-DLA) systems at $z_{\text{abs}}$$\sim$1.36, 1.63 and 1.67. Sub-DLAs are defined as absorption systems with N(H i) ranging from $10^{19}$ to $2 \times 10^{20}$ (Péroux et al. 2003 & Dessauges-Zavadsky et al. 2003).

We use the VPFTT package to decompose the absorption lines into multiple Voigt profile components. The VPFIT package is a least-square program which minimizes the $\chi^2$ when adjusting a multiple Voigt profile model to absorption features. The wavelengths and oscillator strengths are taken from Morton (2003). When fitting the low ion species (O i, C ii, Si ii, Mg ii, Fe ii), we assumed that they all have the same kinematic structure which means that they arise from the same components having the same Doppler parameters. For the C iv and Si iv profiles, we kept Doppler parameters independent because we noticed that even though their absorption profiles correlate very well, C iv can have broader lines especially in complex profiles (see below and also Fox et al. 2007a,b).

If an absorption is not detected at the wavelength expected from the presence of other species in the same system, a 3 $\sigma$ upper limit is determined. The redshifts of the H i components are fixed to that of metals in the case of sub-DLA systems while in the case of other systems redshifts are considered free parameters.

3.1 $z_{\text{abs}} = 1.6359$

This absorber is a sub-DLA system associated with a number of high and low ionization species spanning more than 200 km s$^{-1}$ including C ii, O i, Mg ii, Mg i, Al ii, Al iii, Fe ii, Si ii, C iv and Si iv. The velocity profiles and VPFIT solutions (where applicable) of the H i, low and high ion species are illustrated in Fig. 1. The measurements are given in Table 2.

In the following the origin of the velocities are set at $z = 1.63588$. The metal absorption features in this sub-DLA are seen in two sub-systems, one between $[-40, +80]$ km s$^{-1}$ (region R1), and another between $[+80, +250]$ km s$^{-1}$ (region R2). The low ion absorption lines clearly indicate that the bulk of the neutral gas is located at $v \approx 0$ km s$^{-1}$ and $v \approx +140$ km s$^{-1}$ ($z = 1.63717$). A damping profile fitted to the Lyman-α absorption line, with the redshift at $z = 1.63685$ (1-component fit), yields a satisfactory fit to the damping wings for $N_{\text{HI}} = 1.58 \times 10^{19}$ cm$^{-2}$ and $b = 46.0$ km s$^{-1}$. However, not only the Doppler parameter seems large for a damped system but also part of the absorption is not accounted for at $v = -80$ km s$^{-1}$ (upper panel of the representation of H 1al215 in Fig. 1). We therefore tried to conduct a 2-component fit to the Ly$\alpha$ profile, fixing the redshifts of the two components to the redshifts of the two metal sub-systems observed at $z = 1.63588$ and $z = 1.63717$. As can be seen in Fig 1 (lower panel of the
representation of H 1λ1215), the 2-component solution fits the Lyα profile much better than the single component one. The parameters of the 2-component solution are listed in Table 2 (last column). The two components have column densities of log \( N_{\text{HI}} \) = 18.45 and 19.05, respectively.

The metal lines are weak and their fit yields robust column densities. Using the Mg II and Fe II absorption profiles, we identified 14 velocity components for the low ion species. The fit to the Al II absorption profile (cyan curve in Fig. 1) was performed using the template obtained on Fe II because it is blended with Al III (blue curve) at \( z_{\text{abs}} = 1.3647 \). As can be seen from Fig. 1, the C II absorption profile as well as the velocity region where N λ1200.2 is expected, are blended with some absorption features in region R1. The N I velocity region \(-100 \leq v \leq +80 \) km s\(^{-1}\) is contaminated by the Si λ1390 absorption of a system at \( z_{\text{abs}} = 1.6574 \), and the VPFIT solution of this Si II transition is over-plotted on the observed data as a blue curve. In region R2, the C II profile also appears to be blended with the Ni λ1315 transition of a sub-DLA at \( z_{\text{abs}} = 1.6720 \), and the blue curve is the VPFIT solution of this Ni II transition over-plotted on the C II profile. We could however perform a fit of these two profiles in the R2 region.

Absorption by highly ionized gas in this absorber is seen from the C IV and Si IV doublets. N V is not detected and O VI falls outside our wavelength range. The fit to the high ion species were conducted simultaneously with 9 absorption components (Fig. 1). The Si λ1402 absorption was excluded from the fit due to severe blending with the Lyα absorption profile of a system at \( z_{\text{abs}} = 2.0422 \). Moreover, the C λ1548 profile also appears to be slightly blended in the blue with the Si λ1526 of a sub-DLA at \( z_{\text{abs}} = 1.6720 \). However, the fit was reasonably successful, yielding \( \chi^2_s = 1.25 \). All C IV and Si IV measurements are summarized in Table 2.

### 3.2 \( z_{\text{abs}} = 1.6720 \)

This absorber is also a sub-DLA in which we detect over 40 metal lines from 20 different species. A striking feature of this sub-DLA is the detection of the C I multiplet. The velocity profiles of H I and some of the neutral and singly ionized species seen in this system together with a multi-component Voigt profile fit are shown in Fig. 2. The low-ion species extend over \( \simeq 260 \) km s\(^{-1}\) in velocity space. Voigt profile fitting to the DLA absorption profile with redshift fixed to that of the strongest low-ion component gives log \( N_{\text{HI}} \) = 19.78 ± 0.05. The orange and green curves over-plotted on the data in the lower panel of Fig. 2 show the Voigt profile fits of this DLA profile. Note that, in this panel, the red curve also contains the contribution of another Lyα absorption profile evident at \( +300 \leq v \leq +420 \) km s\(^{-1}\) (cyan curve) with log \( N_{\text{HI}} \) = 15.0±0.10. The redshift of this extra Lyα component corresponds to that of a strong C IV absorption at \( z = 1.67526 \).

To facilitate the discussion of this sub-DLA, we divide the velocity profiles into 3 distinct velocity ranges marked as R1, R2, and R3. We identified 4 absorption components for the R2+R3 velocity ranges based on the fits to the Si II and Fe II profiles. In Fig. 2, the blue vertical dot-dashed lines show the boundary of the three velocity ranges whereas the black vertical dashed lines indicate the position of the four absorption components identified in the R2+R3 velocity range. In the R1 velocity range only C II, Mg II, Si II, O I,
Figure 2. The same as Fig. 1 but for $z_{\text{abs}} = 1.6720$ sub-DLA. Parameters of the fit can be found in Table 3.
Fe ii and Si iii are detected. We found that a minimum of 7 individual components were required to optimally fit the absorption features evident in R1. The red vertical dashed lines in Fig. 2 indicate the positions of the absorption components. The red wing of the Si ii λ1526 profile is blended with part of the C ivλ1548 profile of a system at z_{abs} = 1.6359 (blue shaded area in Fig. 2). Note that the Si ii λ1526 and Fe iiλ2382 transitions were only used to fit the absorption visible in the R1 velocity range. The blue shaded area in the Mg iiλ2026 (resp. Zn iiλ2026) velocity panel shows absorption from the Zn iiλ2026 (resp. Mg iiλ2026) transition of this sub-DLA. As illustrated in Fig. 2, the Al iiλ1670 is also blended with the Si ivλ1393 profile of a system at z_{abs} = 2.028, so the fit to the Al ii profile was conducted by including the contribution of this Si iv absorption. The parameters of the VPFIT solutions for the low and high ion species are listed in Table 3. The Mg ii, C ii, Al ii, and O i profiles are clearly saturated in R2 and R3, especially in R3, so only lower limits to their column densities are given in Table 3. Note that our column density upper limits are 3σ values.

Figure 3 shows the apparent column density profiles, N_a(v), for the Ni ii, Mn ii, Cr ii and Al iii transitions of this sub-DLA. There is almost no indication of saturation in these profiles except may be at v = +37 km s^{-1} in the Ni ii transitions. Here, the Ni iiλ1751 optical depth is slightly higher than those of the other two stronger transitions. This is direct evidence of hidden saturation corresponding to the situation where the Doppler parameter of the lines is smaller than the spectral resolution. In that case, the hidden saturation in Ni ii could lead to underestimate the column density by only ≈ 0.03 dex. This is of the order of the error in the column densities and is therefore not important. Despite the strength of the Al iii absorption profiles there is no sign of hidden saturation. Moreover, with a few minor exceptions, the N_a(v) curves for the two Mn ii transitions match quite well, suggesting no hidden saturation as well. However, the N_a(v) profile of the Cr iiλ2062 transition does not coincide with that of the other two transitions. This is probably due to the blending with some unidentified absorption features hidden in the profile of Cr iiλ2062. Therefore, we will adopt the Cr ii column density determined from the λ2056 and λ2066 features only.

The redshift alignment between the C i multiplet (i.e. C i and C i^{+}) and low ion species is not very good, so the fit to the C i multiplet was performed separately (see Fig. 2). The results of the fit are listed in Table 4. Since both C i and C i^{+} are clearly detected for the component at z = 1.67201, we calculate the excitation temperature, between the J = 0 and J = 1 fine structure levels of C i to be T_{ex} = 11.42 K. This is consistent with but larger than the predicted value of the Cosmic Microwave Background (CMB) temperature T_{CMB} = 7.28 K from the standard cosmology. Indeed, C i fine structure levels can be populated by other excitation processes such as collision and UV pumping (see e.g. Ge et al. 1997; Srianand et al. 2000). Moreover, Kanekar et al. (2009) report a tentative detection of H i 21 cm absorption in this system. They determined an H i 21 cm integrated optical depth of 0.076 ± 0.016 and a covering factor of 0.9 which Ellison et al. (2012) later used to derive a spin temperature of T_s = 380 ± 127 K.

Finally, absorption by highly ionized gas in this sub-DLA is seen in C iv, Si iv, N v and Si iii. Figure 4 gives the velocity profiles and VPFIT solutions of these species. The parameters are listed in Table 3. We chose not to fit the N v doublet and Si iii profiles due to severe blending and saturation. Moreover, both transitions of the Si iv doublet are partly blended with some forest absorption. In the C iv λ1548 (resp. C iv λ1550) velocity panel of Fig. 4, the blue shaded areas indicate blends with the C iv λ1550 (resp. C iv λ1548) absorption of the same system.
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Table 3. Elemental column densities for the $z_{abs} = 1.6720$ sub-DLA.

| Element | Column Density (10$^{20}$ cm$^{-2}$) |
|---------|--------------------------------------|
| C       | 3.9 ± 0.1                           |
| N       | 1.2 ± 0.1                           |
| O       | 4.5 ± 0.1                           |
| Ne      | 7.8 ± 0.1                           |
| Mg      | 1.6 ± 0.1                           |
| Mn      | 1.1 ± 0.1                           |
| Fe      | 3.2 ± 0.1                           |
| Ni      | 6.3 ± 0.1                           |
| Cr      | 1.9 ± 0.1                           |
| Zn      | 5.6 ± 0.1                           |
| Si      | 1.3 ± 0.1                           |
| S       | 2.5 ± 0.1                           |

3.3 Systems with $z > 2$

We will single out some of the systems with highest redshifts to determine whether they are intervening systems or systems associated to the quasar (see e.g. Petitjean et al. 1992).

3.3.1 $z_{abs} = 2.0422$

Figure 5 shows the velocity profiles and VPFIT solutions (wherever applicable) of the Lyo, Lyβ and high ion transitions (C IV, N V and O VI doublets) regions associated with this system. The results of the fits are listed in Table 5. As illustrated in Fig. 5, it is apparent that the H I column density of the main complex around 0 km s$^{-1}$ is very small.

$a$ Blended with other lines.

$b$ Blended with some unidentified forest absorption.

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Table 4. Column densities of the C i fine structure levels in the sub-DLA at $z_{\text{abs}} = 1.6720$.

| $z$     | $\Delta V$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | log(N(C i)) | log(N(C iv)) |
|--------|--------------------------|------------------|--------------|--------------|
| 1.67201| +1.1                     | 3.4±0.3          | 12.43±0.01   | 12.01±0.02   |
| 1.67235| +39.3                    | 7.3±1.1          | 12.20±0.06   | $\leq$11.84  |
| 1.67250| +56.1                    | 7.8±0.6          | 12.62±0.02   | $\leq$11.97  |

We derive an upper limit of log $N_{\text{HI}} < 12.90$ (blue curves in the H i velocity panels). It is interesting to note that the Si iv doublet is not detected in this system. As shown in Fig. 5, the O viλ1037 absorption is completely lost in the strong Lyα absorption of the system at $z_{\text{abs}} = 1.5965$. Moreover, the O viλ1031 profile is also severely blended with Si ivλ1190 of the system at $z_{\text{abs}} = 1.6359$. In Fig. 5, the blue curve in the O viλ1031 velocity panel is the VPFIT solution of this intervening Si ii absorption over-plotted on the observed data.

A 6-component fit was performed on the C iv doublet profiles. The 3 absorption components of the C iv doublet in the velocity range $-120 \leq v \leq -70$ km s$^{-1}$ are not seen in the N v doublet. The N viλ1242 profile around zero velocity is also partially blended with some unidentified absorption features, and we chose not to include it in the fit. We found that a successful solution is achieved for N v by fixing the Doppler parameters and redshifts of the first and third components to the values of their corresponding components in the C iv complex.

3.4 $z_{\text{abs}} = 2.1979$

We detect the C iv and Si iv doublets together with Si iiiλ1206, Lyα, Lyβ and Lyγ absorption profiles in this system. Figure 5 shows the velocity profiles and VPFIT solutions for these transitions. Note that the Lyγ profile appears to be blended with some unidentified forest lines but can still be used to constrain the H i column density. From these three H i lines we derive 15.80 < log $N_{\text{HI}} < 16.22$. Due to blending, the C ivλ1550 and Si ivλ1393 profiles were excluded from the Voigt profile fitting. Moreover, because of the lack of alignment between individual profiles, we chose not to tie the high ion species during the fitting process. The results of the fit are listed in Table 5.

3.5 $z_{\text{abs}} = 2.2028$

The velocity profiles and VPFIT solutions for this absorption system are shown in Fig. 5 and the results are presented in Table 5. We used Lyα and Lyβ absorption to derive a lower limit to the H i column density of log $N_{\text{HI}} \geq 15.47$. The Lyγ absorption profile although contaminated brings additional information to derive an upper limit of log $N_{\text{HI}} \leq 15.60$. There are two C ii transitions in the observed wavelength range, one of which (C iiλ1036) is lost in the forest. We fit the C iiλ1334 absorption feature including the contribution of the Fe iiλ1608 absorption of the system at $z_{\text{abs}} = 1.6574$ with which it is blended (see Fig. 5). The C iv and Si iv absorption profiles were fitted simultaneously without including the C ivλ1548 and Si ivλ1393 transitions. Indeed, Si ivλ1393 is blended with Al iiλ1670 at $z_{\text{abs}} = 1.6720$ and C ivλ1548 is blended with the C ivλ1550 at $z_{\text{abs}} = 2.1979$. In Fig. 5, the VPFIT solutions with (red curve) and without (blue curve) taking into account the contribution of the C ivλ1550 absorption at $z_{\text{abs}} = 2.1979$ are over-plotted on the C ivλ1548 velocity profile. The high quality of the fit further confirms the reality of the C iv doublet at $z_{\text{abs}} = 2.1979$, which was identified solely by its
unblended C ivλ1548 absorption profile. Furthermore, the Si ivλ1402 profile itself is also slightly blended with the C ivλ1548 profile at z_{abs} = 1.8994, and the fit was performed including the contribution of this interloping C iv absorption. In Fig. 5, the VPFIT solution of this interloping C iv absorption is over-plotted as a blue curve on top of the Si ivλ1402 velocity profile. Figure 5 also shows velocity profiles of 3 species we chose not to fit (i.e. C iii, Si iii and O vi). Since the C iiiλ977 profile is highly saturated, we were unable to accurately fit it even starting from the C ii profile. The Si iiiλ1206 is also suffering from blending with some unidentified forest absorption. The N v doublet is so weak that only a weak N vλ1238 absorption could be possibly present. We regard it as a possible detection. The parameters of the fit to this N v feature are also listed in Table 5. The O vi doublet is also weak and appears to be suffering from blends with forest absorption.

3.6 z_{abs} = 2.2363

This absorption system is established by the presence of the C iv and O vi doublets. The VPFIT solutions and velocity profiles are presented in Fig. 5. Table 5 lists the parameters. Although contaminated with some random forest absorption, the H i column density is very well constrained at log N_{HI} = 14.18 ± 0.05 by the steepness of the blue wing of the Lyα absorption profile as well as the presence of the unsaturated Lyδ line. Note that the absorption complex visible at the position of the Lyγ absorption of this system is due to the absorption by Si iiλ1193 of the system at z_{abs} = 1.6359 (blue curve). Furthermore, due to the blending with some forest absorption, the fit to the O vi doublet was done without including the O viλ1031 absorption profile. The VPFIT solutions for the C iv and O vi doublets required 4 and 6 components, respectively. The two O vi components at v ≈ +60 km s^{-1} and v ≈ +130 km s^{-1} are not clearly seen in the C iv profiles. The two vertical dotted lines in Fig. 5 indicate the position of the two strongest components of the O vi doublet profiles.

4 PHYSICAL CONDITIONS

In this section we present detailed analyses of the z_{abs} = 1.6359 and z_{abs} = 1.6720 sub-DLAs and we construct photoionization models using CLOUDY (Ferland et al. 1998) version C10.00 for some interesting systems.

4.1 Sub-DLA System at z_{abs} = 1.6359

The best element to derive the overall abundance in the gas is oxygen, since neutral oxygen and neutral hydrogen have very similar ionization potentials and are coupled by charge-exchange reaction. The O i to H i column density ratio yields [O/H] = −1.69 ± 0.07 (corresponding to 1/49 solar) and [O/H] = −1.65 ± 0.07 (corresponding to 1/45 solar) for the R1 and R2 velocity ranges (see Fig. 1), respectively. This indicates that the whole complex is well mixed.

A 3 σ upper limit on the N i column density implies an abundance relative to solar [N/H] ≤ −2.06 for R2 if we assume that the ionization fraction is same for nitrogen and hydrogen. The resulting nitrogen-to-oxygen ratio is
[N/O] < -0.41. The explanation of the N i/H i ratio is not as straightforward as it is for O i/H i. Although the ionization potential of hydrogen is slightly lower than that of neutral nitrogen, ionization effects can considerably affect the calculation of nitrogen abundance ([N/H]) from N i and H i in systems with total neutral hydrogen column densities \( < 10^{20} \text{ cm}^{-2} \). Thus a non negligible fraction of nitrogen may be in the form of N ii. While the redshift of this sub-DLA is too low to observe the corresponding N ii absorption lines (\( \lambda_{\text{abs}} = 2415, 2585 \text{ Å} \)) from the ground, we can investigate possible ionization effects in R1 and R2 using other low ion species, such as Al ii and Al iii. The ratio Al iii/Al ii is 0.47 and 0.08 in R1 and R2, respectively, suggesting that the ionization effect is probably negligible in the R2 region.

This absorber has an average ratio [Si ii/O i] \( \approx +0.72 \). This ratio is not consistent with nucleosynthesis considerations, since both Si and O are believed to be produced by massive stars, and indeed, are observed to have Solar abundance ratio in Galactic halo stars (Wheeler et al. 1989) and in metal poor dwarf galaxies (Thuan, Izotov, & Lipovetsky 1995). One can reconcile this inconsistency if some of the Si ii comes from partially ionized gas rather than from the neutral gas (recall that the ionization potentials of O i and Si ii are 13.61, 16.34 eV, respectively).

Since the ionization effects appear to be significant in R1 (judging from the Al iii/Al ii and [Si ii/O i] ratios) we try to model this velocity range using model calculations performed with the photoionization code CLOUDY. The R1 velocity range comprises five absorption components, and we construct a detailed model only for the dominant neutral component at \( z = 1.63588 \). In this component, the low and high ion species are very well aligned and we will assume that they arise from the same gas. The H i column density for this component is estimated to be \( N_{\text{HI}} = 18.23 \) and the calculations were stopped when this column density was reached. Relative metal abundances are considered solar and the metallicity is taken as \( Z = 0.02Z_\odot \). This metallicity is actually the O i abundance for the component of interest.

We use an ionizing spectrum that is a combination of the Haardt-Madau (H&M) extragalactic spectrum (Haardt & Madau 1996) at \( z = 1.63 \), the CMB radiation at \( z = 1.63 \) and the average Galactic interstellar medium (ISM) spectrum of Black (1987) with H i ionizing photons extinguished. Note that we used the CLOUDY built-in HM96 spectrum which includes both contributions from quasars and galaxies.

In order to determine the ionization parameter, we match the observed Si ii/Si iv and C ii/C iv ratios to the values obtained from the model. After the ionization parameter is derived, the ionization corrections are calculated. The fractional density of an element in a given ionization state is defined as \( f(X) = \frac{N(X)}{N(H)} \), and similarly for hydrogen \( f(H) = \frac{N(H)}{N(H)} \). The ionization corrections IC(X/H) are then given by:

\[
IC(X/H) = \log\left(\frac{N(X)}{N(H)}\right) - \log\left(\frac{N(X)}{N(H)}\right),
\]

or

\[
IC(X/H) = \log\left(\frac{f(X)}{f(H)}\right).
\]

These values are then subtracted from the ionic abundances to obtain the final ionization-corrected abundance of an element (see Table 6).

The lower panel of Fig. 6 (left hand side) gives the Si ii/Si iv and C ii/C iv ratios versus the ionization parameter \( \log U \). The observed ratios intercept the model curves at the ionization parameter \( \log U = -3.42 \). The upper panel of Fig. 6 (left hand side) gives the calculated column densities versus the ionization parameter for different species. In this figure, the horizontal lines indicate the observed values. The
Table 6. Elemental abundances before ([X/H]$_{raw}$) and after ([X/H]$_{corr}$) ionization correction (IC) for the sub-DLA at $z_{abs} = 1.6359$. These are the results of the CLOUDY model constructed for the single component at $z_{abs} = 1.63588$.

| (X) | [X/H]$_{raw}$ | IC([X/H]) | [X/H]$_{corr}$ | [X/O] |
|-----|--------------|-----------|----------------|-------|
| O   | $-1.69\pm0.07$ | $-0.06$   | $-1.63\pm0.07$ | $+0.00$ |
| Si  | $-0.73\pm0.06$ | $+1.03$   | $-1.76\pm0.06$ | $-0.13$ |
| Fe  | $-1.50\pm0.06$ | $+0.50$   | $-2.00\pm0.06$ | $-0.37$ |
| Mg  | $-0.97\pm0.06$ | $+0.34$   | $-1.31\pm0.06$ | $+0.32$ |

4.2 Sub-DLA System at $z_{abs} = 1.6720$

In this sub-DLA, the two velocity ranges R2 and R3 exhibit extremely different ionization properties. In region R2, the observed $N$(S ii)/$N$(O i) ratio is close to unity when the Solar metallicity of oxygen is 1.56 dex larger than that of sulphur. Note that similar ratios are observed with Si ii. This probably means that oxygen, and thus hydrogen, are highly ionized. Assuming the S/O abundance ratio is solar would imply hydrogen is ionized at 97% in this velocity range. If true, this is in contradiction with the low ionization conditions suggested by the presence of strong C i absorption. One possibility to escape this contradiction would be that C i originates in a narrow and weak component which is lost in wider and stronger O i and S ii profiles. However, it can be seen on Fig. 2 that this is not the case and the C i, O i, S ii and Si ii absorption profiles are similar. This is therefore an intriguing situation possibly calling for very special abundance ratios.

In contrast, the R3 velocity range appears to be moderately ionized. To investigate the ionization effects on the observed abundances, we constructed a series of CLOUDY photoionization models for the R3 velocity range. We adopted a neutral hydrogen column density of log $N_{HI} = 19.78$, a metallicity of $-0.54$ (from the observed Zn ii and H i column densities), and Solar relative abundances. As can be seen in the lower panel of Fig. 6 (right hand side), the observed ratio log $N$(Si ii)/$N$(Al iii) = 1.93 indicates that the ionization parameter should be close to log U = $-3.20$. Note that due to the severe saturation of the Al iii absorption profile, Si ii is used instead of Al iii. The calculated column densities are given versus ionization parameter in the upper panel of Fig. 6 (right hand side). In this figure, the horizontal dotted lines mark the observed quantities. Table 7 reports the abundances (before and after ionization correction), the ionization correction (IC), and the under/over-abundance ratios. The value of [Si/Fe] in this absorber is in good agreement with measurements of metal poor and Galactic disk stars, but is relatively low when compared with the sample of DLAs and sub-DLAs from literature (see below for references). The value of [Si/Fe] in this absorber is in good agreement with measurements of metal poor and Galactic disk stars, but is relatively low when compared with the sample of DLAs and sub-DLAs from literature (see below for references). The value of [Si/Fe] in this absorber is in good agreement with measurements of metal poor and Galactic disk stars, but is relatively low when compared with the sample of DLAs and sub-DLAs from literature (see below for references). The value of [Si/Fe] in this absorber is in good agreement with measurements of metal poor and Galactic disk stars, but is relatively low when compared with the sample of DLAs and sub-DLAs from literature (see below for references). The value of [Si/Fe] in this absorber is in good agreement with measurements of metal poor and Galactic disk stars, but is relatively low when compared with the sample of DLAs and sub-DLAs from literature (see below for references). The value of [Si/Fe] in this absorber is in good agreement with measurements of metal poor and Galactic disk stars, but is relatively low when compared with the sample of DLAs and sub-DLAs from literature (see below for references).
As discussed above, the observed O i column density is 1.56 dex lower than what is expected if [S/O] = 0. This enables us to roughly estimate the total oxygen column density to be log N(O) = 15.60. Moreover, for this velocity range, we have measurements for Si ii (log N(Si ii) = 13.33) and Si iv (log N(Si iv) = 13.31) as well as a lower limit for Si iii (log N(Si iii) ≥ 14.10). Therefore [Si/O] (≡ [Si ii + Si iii + Si iv/O]) for R2 is ≥ −0.20, which is consistent with the Solar abundance of Si/O (i.e. [Si/O] = 0).

We also tentatively identified a narrow absorption feature in the red wing of the damped Lyman-α profile of the system at z_{abs} = 1.6359 as N i absorption associated with this sub-DLA. This feature is shown in Fig. 8 along with a 3-component VPFIT solution. The VPFIT solution of the intervening damped Lyman-α profile is also incorporated into the fit. As clearly depicted in the two magnified panels of Fig. 8, the final solution could very well match the observation. The redshifts of the components are fixed to those of R3. If our identification of this N i feature is correct, then the estimated total column density of log N(N i) = 13.57 ± 0.03 would imply a mean abundance of [N/H] = −2.04 ± 0.06. For an oxygen abundance relative to solar of ∼ −0.5, this nitrogen metallicity seems small, indeed, below the secondary relation expected between the metallicities of these two elements (e.g. Petitjean et al. 2008). This may indicate that we have underestimated the N i column density because of the difficulty of the measurement or that the ionization of nitrogen is higher than that of oxygen.

We observe that Zn is slightly overabundant relative to Ni, Fe, Cr, and Mn indicating depletion of these elements onto dust. This is consistent both with the presence of a small amount of ISM-like dust as well as the abundance pattern of halo stars which have been enriched by Type II supernovae (SNe). The odd-even effect, namely the underabundance of odd-Z elements relative to even-Z elements of the same nucleosynthetic origin, is an observationally established property of Halo stars. Since Fe is more susceptible to dust depletion than Mn in the ISM, this ratio can be exploited to distinguish between dust depletion and pure Type II SNe enrichment. The [Mn/Fe] = −0.24 ± 0.07 in this sub-DLA, possibly confirms the odd-even effect, and is consistent with the sample of Halo metal-poor stars in Ryan et al. (1996). It is interesting to note that the relative abundance of Mn to Fe in this system, is in accordance with that of thick disk stars in Prochaska et al. (2000) and what has been observed in DLAs (Ledoux et al. 2002).

The degree of depletion of refractory elements onto dust grains is in any case small in this sub-DLA. Figure 9 shows the Zn/Fe abundance ratio against the Zn abundance for this sub-DLA (red square) and sub-DLAs from the literature (black dots; see below for references). Figure 9 indicates that the amount of dust depletion in this sub-DLA is consistent with that seen in other sub-DLAs with the same metallicity. In constructing the sample of sub-DLA abundances, the following sources are used: Dessauges-Zavadsky et al. (2003), Péroux et al. (2008), Meiring et al. (2007), and Meiring et al. (2009). Furthermore, the relative abundance ratio of Cr and Fe in R3 is almost solar ([Fe/Cr] = −0.07 ± 0.07). In Fig. 10 we plot the abundance of Ni, Mn, Cr, Fe and Si relative to Zn as well as Si relative to Fe. Except for the abrupt change around 55 km s$^{-1}$, the variation in the relative abundances is of the order of 0.2 dex.

### Table 7

| X   | X/H_{raw} | IC(X/H) | X/H_{corr} | X/Zn  |
|-----|-----------|---------|------------|-------|
| Zn  | −0.54±0.05 | +0.03   | −0.57±0.05 | +0.00 |
| Si  | −0.35±0.05 | +0.20   | −0.55±0.05 | +0.02 |
| Fe  | −0.09±0.05 | +0.10   | −0.79±0.05 | −0.22 |
| Cr  | −0.66±0.05 | +0.06   | −0.72±0.05 | −0.15 |
| Ni  | −0.49±0.05 | +0.19   | −0.68±0.05 | −0.11 |
| Mn  | −0.94±0.05 | +0.09   | −1.03±0.05 | −0.46 |
| S   | −0.49±0.05 | +0.15   | −0.64±0.05 | −0.07 |

#### Figure 8

N i absorption of the system at z_{abs} = 1.6720 in the wing of the Ly α profile of a system at z_{abs} = 1.6359. The orange vertical lines indicate the position of the three components identified in the system for the N i triplet (i.e. λλλ1200.7,1200.2,1199.5).

#### Figure 9

[Zn/Fe] abundance ratio versus [Zn/H] for the sub-DLA at z_{abs} = 1.6720. In this subsection we construct photoionization models using CLOUDY for the z_{abs} = 2.0422, 2.1979, 2.2028 and 2.2363 absorption systems. In the CLOUDY models of the first two systems we assumed that the extragalactic UV background of Haardt & Madau and the CMB radiation are the radiations striking the absorbing cloud. For the last two systems,
we considered the radiation field of the active galactic nuclei (AGN) deduced by Mathews & Ferland (1987). The relative abundances of the elements were assumed to be solar (see Table 1).

The reason to model these systems is to test whether these systems are under the influence of the quasar or not. We will conclude that it is the case for systems at $z_{\text{abs}} = 1.6720$ sub-DLA. The blue horizontal dot-dashed line represents zero depletion with respect to Zn (or with respect to Fe in the case of [Si/Fe]). It can be seen that the profile is fairly homogeneous.

$4.3.1 \ z_{\text{abs}} = 2.0422$

As can be seen in Fig. 5, this system comprises two absorption complexes located at $-110 \leq v \leq -70$ km s$^{-1}$ and $-25 \leq v \leq +40$ km s$^{-1}$. We chose to model the latter complex for which we have detected a number of high-ion species (i.e., C iv, N v, and O vi). The CLOUDY model was calculated for $N(\text{H} \ i) = 10^{12.90}$ cm$^{-2}$. The results of the photoionization model are illustrated in the upper left panel of Fig. 11. Using the ionic ratio $N(\text{O} \ vi)/N(\text{C} \ iv)$ in velocity space with very high metallicity and ionization parameter, this system is probably within the sphere of influence of the quasar (Petitjean et al. 1994). We note that the velocity separation between the quasar ($z_{\text{em}} = 2.233$) and the absorber is 18230 km s$^{-1}$.

$4.3.2 \ z_{\text{abs}} = 2.1979$

For this system, a series of CLOUDY models were run with a typical $\text{H} \ i$ column density $N(\text{H} \ i) = 15.98$ (the range of column density derived in this system is $15.80 < \log N(\text{H} \ i) < 16.22$). The column density ratios of log $N(\text{C} \ iv)/N(\text{Si} \ iv) = 1.01$ and log $N(\text{Si} \ iii)/N(\text{Si} \ iv) = +0.11$ yield ionization parameters of log $U = -2.12$ and $-1.99$, respectively, thus in good agreement with each other (see upper right panel in Fig. 11). A value of log $U = -2.05$ is thus adopted, which along with $Z = 0.14$ $Z_{\odot}$ could successfully reproduce the observed column densities of Si iii, Si iv and C iv.

$4.3.3 \ z_{\text{abs}} = 2.2028$

The absorption from C ii, C iii, C iv, Si iii, Si iv, and O vi are spread over about 80 km s$^{-1}$ in velocity space with very weak associated N v absorption (see Fig. 5). The grid of CLOUDY models were constructed for $N(\text{H} \ i) = 15.54$. The ionization parameter, log $U = -2.37$, was determined using the ionic ratio $N(\text{C} \ iv)/N(\text{C} \ ii)$. Adopting this ionization parameter, the model could successfully reproduce the C ii and C iv column densities with $Z = 5.4$ $Z_{\odot}$, but failed to do the same for the Si iii, Si iv, and N v. To reproduce the observations, the relative abundance of silicon (resp. nitrogen) has to be raised (resp. lowered) by 0.19 dex (resp. 0.59 dex). The upper limits to the column densities of O vi and C iii are also consistent with the model. Note that in Fig. 11 we incorporated the adjusted metallicities into the CLOUDY model of this system.

$4.3.4 \ z_{\text{abs}} = 2.2363$

This system has a redshift higher than the QSO by 306 km s$^{-1}$ and the N v absorption feature is detected albeit very weak. So it is possible that this system is under the influence of the ionizing radiation coming from the central engine.

The $\text{H} \ i$ column density is very well constrained, thanks to the presence of the less blended unsaturated Ly$\delta$ absorption profile (Fig. 5). As is depicted in Fig. 5, the O vi and C iv absorption profiles are not well aligned, indicating that these ions might not arise from exactly the same region and that the gas could be inhomogeneous.

CLOUDY models with log $N_{\text{HI}} = 14.18$ produce an ionization ratio log $N(\text{C} \ iv)/N(\text{N} \ v) = +0.5$ for an ionization parameter log $U = -1.67$ and metallicity of $Z = 0.56$ $Z_{\odot}$ (see lower right panel in Fig. 11). As illustrated in Fig. 11, this model fails to reproduce the O vi column density by 2.0 dex. Either relative metallicities are far from solar which could be explained by the proximity of the gas to the AGN, or this system is multiphase and the ionization of the O vi
Figure 11. CLOUDY photoionization models for the $z_{\text{abs}} = 2.0422$, 2.1979, 2.2028, and 2.2363 absorbers.

5 CLUSTERING PROPERTIES

In this section we study the clustering properties of metal lines (C iv, Si iv, Mg ii, and Fe ii) using the two-point correlation functions (TPCF) in redshift space, $\xi(v)$. The velocity two-point correlation function can be calculated from the pair counts of absorption lines according to:

$$\xi(v_k) + 1 = \frac{n_k}{<n_k>},$$

where $n_k$ is the number of observed pairs separated by a velocity difference $v_k$, and $<n_k>$ is the average number of such pairs that would be expected if the systems were randomly distributed in the absence of clustering. We averaged the output of 1000 Monte Carlo simulations in order to calculate $<n_k>$. We emphasize that we calculate $<n_k>$ by simply distributing the clouds we have found along this line of sight randomly. The statistical variance in these measurements is given by

$$\sigma^2 = \frac{n_k}{<n_k>^2}.$$  

The resulting correlation functions are given in Fig. 12. In this figure, the blue-dotted lines indicate $\xi(v_k) = 0$, and the 1 $\sigma$ region denoted by the two red-dotted lines on both sides of the $\xi(v_k) = 0$ line is determined by the standard deviation of $\xi(v_k)$ derived from random simulations. As depicted in Fig. 12, the overall shapes of the C iv and Si iv correlation functions are almost similar but the amplitude of the Si iv TPCF is apparently stronger than that of C iv. In the case of Mg ii and Fe ii, both the amplitude and the shape of their TPCFs are similar to that of Si iv to within their corresponding measurement errors. This is due to the fact that systems detected only by C iv are spread over large velocity ranges. In Fig. 12, the C iv TPCF without including the associated systems is overplotted on the C iv full sample TPCF as orange filled triangles. As is seen here, at all separations the TPCF remains practically unchanged.
The velocity correlation length or $\xi_0$, defined as the pair separation for which $\xi(v_0) = 1$, are $v_0 \approx 500 \, \text{km} \, \text{s}^{-1}$ for C iv and Si iv, and $v_0 \approx 250 \, \text{km} \, \text{s}^{-1}$ for the Mg ii and Fe ii TPCFs. The signal appears to drop to zero immediately after $v_0$ for all four species contrary to what is seen in Boksenberg et al. (2003, BSR03). The two-point correlation functions in Fig. 12 exhibit a steep decline at large velocities ($\geq 200 \, \text{km} \, \text{s}^{-1}$) and a smoother decline at small separations, with an elbow occurring at $\approx 150 \, \text{km} \, \text{s}^{-1}$ for the C iv and Si iv profiles and $\approx 100 \, \text{km} \, \text{s}^{-1}$ for the Mg ii and Fe ii profiles. As is seen here and was also noted in Scannapieco et al. (2006), the elbow occurs at smaller velocity separations for the Mg ii and Fe ii TPCFs in comparison with that of C iv and Si iv.

Sargent et al. (1988) and Heisler et al. (1989) found some excess in $\xi$ between 1000 and 10000 km s$^{-1}$ and some deficit between 10000 and 20000 km s$^{-1}$. In our analysis we detect some excess for the same velocity range but no deficit is seen for any velocity separation. We tried to further investigate the clustering signals on large scales by combining all C iv absorption components spreading less than 500 km s$^{-1}$ into a single system (panels e & f in Fig. 12). Here we detect several peaks in the velocity ranges 1200 – 3200 km s$^{-1}$, 4000 – 5600 km s$^{-1}$, and 7000 – 9000 km s$^{-1}$. There is also a strong peak in the velocity bin 29000 km s$^{-1}$.

We considered the possibility that these signals could be artifacts of the C iv complex decomposition. To this end, we collapsed complexes with component separations $\Delta v \leq 1000 \, \text{km} \, \text{s}^{-1}$ into single systems. The results are illustrated in Fig. 12 panels g and h. The first point to note is that the signals in the velocity range 1200 – 5600 km s$^{-1}$ which were relatively strong in panel e of Fig. 12 are now more consistent with null clustering, suggesting that the signals might have been due to the subsplitting of the extended systems. However, the two peaks at the velocities 7000 – 9000 km s$^{-1}$ are still present (see panel g of Fig. 12). Careful examination of the data indicates that the presence of these two peaks is mainly due to the clustering of the systems at $z = (1.59, 1.65)$ for the signal at $v = 7300 \, \text{km} \, \text{s}^{-1}$ and $z = (1.59, 1.67)$ for the $v = 8700 \, \text{km} \, \text{s}^{-1}$ signal. The spacing between the two systems at redshifts 1.65 and 1.67 is 1660 km s$^{-1}$, which is consistent with the separation between the two peaks. The amplitude of the correlation for the two peaks at $v = 7300$...
km s\(^{-1}\) and \(v = 8700\) km s\(^{-1}\) is estimated to be \(3.02 \pm 1.74\) and \(3.06 \pm 1.77\), respectively. Since these values were calculated for the sample where velocity separations on scales less than \(1000\) km s\(^{-1}\) have been removed it could be possible that these signals represent powers on supercluster scales. In Fig. 12, panels f and h appear to show some marginally significant signals at large velocities. The strongest signal is seen in the \(v = 29000\) km s\(^{-1}\) velocity bin. The correlation amplitude of this signal is estimated to be \(2.56 \pm 0.90\). A careful look at the data shows that this signal is getting most of its power from the coupling of the two systems at redshifts 1.36 and 1.59.

This study of the clustering properties of C\(\text{iv}\) absorbers along the line of sight towards PKS 0237−233 has revealed that C\(\text{iv}\) components tend to cluster strongly on velocity scales up to \(500\) km s\(^{-1}\). This is consistent with what has been derived from studies of the clustering properties of C\(\text{iv}\) components from large samples of intervening C\(\text{iv}\) systems (Petitjean & Bergeron 1994, Boksenberg et al. 2003, Scannapieco et al. 2006, D’Odorico et al. 2010). This strong clustering signal results from the combination of relative motions of clouds within a typical galactic halo as well as clustering between galaxies. Some signal is also seen at higher velocity separations. However, this signal is below 2\(\sigma\) which shows a steep decline at large separations (\(> 200\) km s\(^{-1}\)) and a smoother profile below \(\approx 150\) km s\(^{-1}\) (resp. \(\approx 100\) km s\(^{-1}\)). Some signals are also detected at larger velocities. These signals are getting most of their amplitude from the coupling of the systems at redshifts 1.36, 1.59 and 1.67. Despite detecting an unusually high number of absorption systems along this line of sight, no compelling evidence is found to convince us that there is a single strong overdensity of absorption systems here. However, it would be good to perform deep imaging in the field, to look for a large concentration of objects which could be responsible for the presence of the absorption features seen in the spectrum of the QSO PKS 0237−233.

6 CONCLUSION

We have presented a high SNR and high spectral resolution spectrum of QSO PKS 0237−233 and have identified most of the absorption features redward of the quasar Ly\(\alpha\) emission. Three of the 18 identified absorption systems are sub-DLAs with \(z_{\text{abs}} = 1.3647, 1.6359,\) and 1.6720. We have analyzed the latter two systems in more detail, while the one at \(z_{\text{abs}} = 1.3647,\) with metallicity \([\text{O}/\text{H}] \geq -0.33\), was studied in depth by Srianand et al. (2007).

CLOUDY models indicate that ionization is higher for the region R1 of the system at \(z_{\text{abs}} = 1.6359\), in which hydrogen is more than 95 percent ionized. In this system, we measured abundances relative to solar : \([\text{O}/\text{H}] = -1.63 \pm 0.07,\) \([\text{Si}/\text{H}] = -1.76 \pm 0.06,\) \([\text{Fe}/\text{H}] = -2.00 \pm 0.06,\) and \([\text{Mg}/\text{H}] = -1.31 \pm 0.06\) for the R1 velocity range and \([\text{O}/\text{H}] = -1.65 \pm 0.07,\) \([\text{Si}/\text{H}] = -0.99 \pm 0.06,\) \([\text{Fe}/\text{H}] = -1.63 \pm 0.06\) and \([\text{Mg}/\text{H}] = -1.54 \pm 0.06\) for the R2 velocity range. The abundance of silicon relative to oxygen (i.e. \([\text{Si}/\text{O}] = -0.13 \pm 0.09\)) in R1 indicates that dust depletion in this velocity range is not very significant, and that \([\text{Fe}/\text{O}] = -0.37 \pm 0.09\) indicates enrichment by Type II SNe.

The second sub-DLA we studied in detail is located at \(z_{\text{abs}} = 1.6720\). The velocity range of the low ions in this absorber extends over 260 km s\(^{-1}\), and is divided into three regions, R1, R2, and R3. We have presented a detailed analysis of the R3 velocity range for which we have detected most of the low ion species. Ionization models indicate that hydrogen is 50 percent ionized in R3, and we measured the following abundances of Zn, Si, and S: \([\text{Zn}/\text{H}] = -0.57 \pm 0.05,\) \([\text{Si}/\text{H}] = -0.55 \pm 0.05,\) and \([\text{S}/\text{H}] = -0.64 \pm 0.05\). We note that hidden component analyses of the Ni \(\text{ii},\) Mn \(\text{ii},\) Cr \(\text{ii},\) and Al \(\text{ii}\) transitions did not reveal any significant hidden saturation or hidden components, and we expect this to be the case for the other low ion species. Dust depletion in this system is small (\([\text{Fe}/\text{Zn}] = -0.22 \pm 0.07\)). Finally the region R2 seems to show special ionization and/or metallicity structure.

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APPENDIX A: DESCRIPTION OF THE REMAINING ABSORPTION SYSTEMS

A1 $\zabs = 1.1846$

In addition to the C iv doublet, we identify the Mg ii and Al iii doublets, Si ivλ1402, Si iiλ1526, Al iiλ1670 and Fe ii lines associated with this system. Other strong absorption lines, including Si iiλ1393 are redshifted outside of our observed wavelength range. Figure A1 shows the velocity profiles and VPFIT solutions of the absorption profiles associated with this system, and Table A1 list the parameters (redshift, Doppler parameter and column density) of the components used to fit the low and high ion species. The velocity centroids for the components are indicated by tick-marks above the profile of each transition line. We found that a minimum of 4 individual components are required to optimally fit the low ion transitions as well as the high ion species. Moreover, there is an extension of the C iv and Si iv profiles in the red up to about $+50 \text{ km s}^{-1}$.

A2 $\zabs = 1.3647$

This absorber was studied in detail by Srianand et al. (2007) using the same data. This is a sub-DLA ($\log N_{\text{HI}} = 19.30 \pm 0.30$ inferred from IUE data) with near-solar metallicity ([O/H] $\approx -0.33$). No 21-cm absorption is detected down to $\tau(3 \sigma) < 3 \times 10^{-3}$ and the observed C i excitation indicates that the gas is warm.

A3 $\zabs = 1.4681, 1.5610$

These two absorption systems are very weak and identified solely by the presence of the C iv and Lyα absorption (see Fig. A1; the Lyα absorption profile of the system at $\zabs = 1.4681$ is redshifted outside the wavelength range of the data). Note that there is an absorption feature at $v = +70 \text{ km s}^{-1}$ in the $\zabs = 1.4681$ system which seems to mimic a C iv doublet. A single component fit was conducted to the less blended C ivλ1550 absorption profile. As can be seen in Fig. A1 (blue dashed curves), the resulting fit does not coincide well with the blue wing of the C ivλ1548 profile, suggesting that the feature may not be a C iv doublet in the first place. Results of the fits are presented in Table A2.

A4 $\zabs = 1.5965$

Figure A2 shows the velocity profiles and VPFIT solutions of the neutral hydrogen and metal line transitions associated with this system. Using the Lyα absorption profile, we could determine a lower limit to the H i column density of $\log N(\text{H} \ i) > 17.85$. We identify metal absorption from C iv, Si iv, N v as well as Si iiλ1206, with no trace of low ion species. The velocity spread is $\approx 300 \text{ km s}^{-1}$. Results of the fits are presented in Table A2. We chose not to fit the N vλ1242 because its profile appears to be contaminated by some forest absorption. Moreover, the C ivλ1550 profile is
Figure A1. Velocity profiles and VPFIT solutions of the absorption seen in the $z_{\text{abs}} = 1.1846$, $z_{\text{abs}} = 1.4681$, and $z_{\text{abs}} = 1.5610$ systems. Blue shaded regions indicate blends with some unrelated features. Parameters of the fit can be found in Tables A1 & A2.

Figure A2. Velocity profiles and VPFIT solutions of the absorption profiles of the systems at $z_{\text{abs}} = 1.5965$, and 1.6109. Parameters of the fit can be found in Table A2.
Figure A3. Velocity profiles and VPFIT solutions of the low and high ion transitions in the systems at \( z_{\text{abs}} = 1.6574, 1.7221, \) and 1.7536. Blue shaded regions show blends with unrelated absorption. Parameters of the fit can be found in Tables A3 & A4.

Figure A4. Observed velocity profiles and VPFIT solutions of several transitions seen in the \( z_{\text{abs}} = 1.8994, 1.9253, \) and 2.2298 absorbers. The blue shaded region shows blends with other lines. Parameters of the fit can be found in Table A4.

blended with the Si \( \text{II} \lambda 1526 \) absorption from the sub-DLA at \( z_{\text{abs}} = 1.6359. \) The VPFIT solution for this Si \( \text{II} \) absorption derived from Si \( \text{II} \lambda 1304 \) alone is over-plotted on top of the C \( \text{IV} \lambda 1550 \) absorption profile as a blue curve in Fig. A2. As can be seen in the figure, the fit is not perfect at velocities of \( v \approx -180, \) \(-50 \leq v \leq -20 \) and \( v \approx +35 \text{ km s}^{-1}, \) but clearly within errors.

A5 \( z_{\text{abs}} = 1.6109 \)

Figure A2 shows the velocity profiles of the H \( \text{I}, \) C \( \text{IV}, \) Si \( \text{IV} \) and N \( \text{V} \) doublets associated with this system. The Ly\( \alpha \) absorption profile of this system gives a lower limit to the H \( \text{I} \) column density of \( \log N(\text{H} \text{I}) \geq 14.59. \) We identify no low ion transition for this system and based on the absence of any Si \( \text{II} \) and C \( \text{II} \) absorption we conclude that this is a high ionization system. The N \( \text{V} \) and Si \( \text{IV} \) doublets are heavily blended in the forest, therefore we only present in Fig. A2 the VPFIT solution for the C \( \text{IV} \) doublet for which we found
Table A1. Elemental column densities in the \( z_{\text{abs}} = 1.1846 \) system as well as Solar abundances.

| Low-ion column densities |
|--------------------------|
| \( z \) | \( \Delta V \text{ (km s}^{-1} \) | Ion (X) | \( b \text{ (km s}^{-1} \) | \( \log N \text{(Mg ii)} \) | \( \log N \text{(Mg i)} \) | \( \log N \text{(O i)} \) | \( \log N \text{(Fe ii)} \) | \( \log N \text{(Si i)} \) | \( \log N \text{(Al i)} \) | \( \log N \text{(Al ii)} \) | \( \log N \text{(C ii)} \) | \( \log N \text{(H i)} \) |
|--------------------------|
| 1.18433 | \(-38.4\) | \(4.9 \pm 0.4\) | \(11.27 \pm 0.02\) | \(9.48 \pm 0.36\) | \(\leq 10.28\) | \(\leq 10.50\) | \(\leq 10.65\) | \(\pm 0.07\) | \(\pm 0.03\) | \(\pm 0.03\) | \(\pm 0.03\) | \(\pm 0.03\) |
| 1.18452 | \(-12.3\) | \(2.9 \pm 0.7\) | \(11.35 \pm 0.10\) | \(9.53 \pm 0.28\) | \(\leq 10.89\) | \(\leq 10.83\) | \(\leq 10.54\) | \(\pm 0.15\) | \(\pm 0.15\) | \(\pm 0.15\) | \(\pm 0.15\) | \(\pm 0.15\) |
| 1.18461 | \(0.0\) | \(5.6 \pm 0.2\) | \(12.39 \pm 0.03\) | \(10.52 \pm 0.03\) | \(\leq 11.51\) | \(\leq 11.56\) | \(\leq 11.71\) | \(\pm 0.04\) | \(\pm 0.04\) | \(\pm 0.04\) | \(\pm 0.04\) | \(\pm 0.04\) |
| 1.18465 | \(+5.5\) | \(13.1 \pm 0.8\) | \(12.16 \pm 0.06\) | \(\leq 9.50\) | \(\leq 10.98\) | \(\leq 11.83\) | \(\leq 11.28\) | \(\leq 11.60\) | \(\pm 0.08\) | \(\pm 0.08\) | \(\pm 0.08\) | \(\pm 0.08\) | \(\pm 0.08\) |

| High-ion column densities |
|---------------------------|
| \( z \) | \( \Delta V \text{ (km s}^{-1} \) | Ion (X) | \( b \text{ (km s}^{-1} \) | \( \log N \text{(X)} \) |
|---------------------------|
| 1.18433 | \(-38.4\) | \(C \text{ iv}\) | \(5.5 \pm 1.0\) | \(12.17 \pm 0.05\) | \(1.18433\) | \(-38.4\) | \(C \text{ iv}\) | \(5.5 \pm 1.0\) | \(12.16 \pm 0.05\) | \(1.18462\) | \(0.0\) | \(C \text{ iv}\) | \(7.2 \pm 0.5\) | \(13.79 \pm 0.05\) | \(1.18466\) | \(+6.9\) | \(C \text{ iv}\) | \(7.2 \pm 0.5\) | \(13.56 \pm 0.05\) | \(1.18491\) | \(+41.2\) | \(C \text{ iv}\) | \(9.8 \pm 2.8\) | \(12.68 \pm 0.16\) | \(1.18491\) | \(+41.2\) | \(C \text{ iv}\) | \(9.8 \pm 2.8\) | \(11.99 \pm 0.21\) |

\( a \) Not at the range of the data.
\( b \) Blended with some features.

A6 \( z_{\text{abs}} = 1.6574 \)

Figure A3 presents the velocity profiles and the VPFIT solutions for the low and high ion species detected in this system. The H I Lyα feature is strongly saturated over approximately 400 km s\(^{-1}\) (see Fig. A3) with no damping wings. We therefore did not attempt to derive highly uncertain H I column densities. For the low ion species, we identified 9 distinct components based on the fits to the Mg ii column densities. The Fe ii column densities might not be so accurate. The O vi doublet for this system is outside of our observed wavelength range.

A7 \( z_{\text{abs}} = 1.7221, 1.7536 \)

These two absorption systems are very weak and identified solely by the presence of the C iv and Lyα absorption (see Fig. A3). The expected Mg ii doublet of these absorbers are either not detected or lost in the atmospheric absorption lines. The parameters of the fits are listed in Table A4.

A8 \( z_{\text{abs}} = 1.8994 \)

This is another system identified only by the presence of Lyα and the C iv doublet. No other low or high ion species is detected. The velocity profiles and VPFIT solutions for this C iv system are presented in Fig. A4 together with the wavelength ranges where Si iv doublet absorption are expected. We found 12 components were fitted individually. Due to the very large velocity spread of this system (\( \approx 650 \) km s\(^{-1}\)), part of the C iv\( \lambda 1548 \) profile is blended with the C iv\( \lambda 1550 \) profile. In Fig. A3, the blue shaded area in the C iv\( \lambda 1548 \) velocity panel (resp. C iv\( \lambda 1550 \) velocity panel) indicates absorption from the C iv\( \lambda 1550 \) (resp. C iv\( \lambda 1548 \)). The Si iv\( \lambda 1393 \) absorption is heavily blended with the absorption lines of the forest and we chose not to include it in the fit. The fits to the C iv and Si iv doublets were successful with 17 and 9 individual components, respectively. It is worth noting that due to the severe blending of the Si iv profile, our attempt to tie the C iv and Si iv absorption profiles failed, implying that the derived Si iv column densities might not be so accurate. The velocity regions where the N v doublet is expected are also depicted in Fig. A3. We could not convince ourselves that any significant N v absorption is present although some faint feature can be seen around +50 km s\(^{-1}\). Table A3 lists the redshift, value and column density along with 1 \( \sigma \) error of every velocity component from the VPFIT fit of the high ion species.
This absorption system is very weak and identified by the presence of the C IV and Lyα absorption (see Figs. A4). The expected Mg II doublets of the absorber is either not detected or lost in the atmospheric absorption lines. The parameters of the fits are listed in Table A4.
Table A3. Elemental column densities in the $z_{\text{abs}} = 1.6574$ system.

| z       | $\Delta V$ (km s$^{-1}$) | $b$ (km s$^{-1}$) | log N(Mg ii) | log N(Mg i) | log N(O i) | log N(Fe ii) | log N(Fe i) | log N(Al iii) | log N(Al ii) |
|---------|--------------------------|-------------------|--------------|--------------|------------|--------------|--------------|--------------|--------------|
| 1.65683 | −64.3                    | 5.1 ± 0.9         | 11.87 ± 0.01 | ≤ 9.67       | ≤ 11.89    | 11.32 ± 0.12 | 11.96 ± 0.14 | 11.16 ± 0.10 | 10.86 ± 0.12 | 12.82 ± 0.04 |
| 1.65691 | −55.3                    | 9.8 ± 5.7         | 11.62 ± 0.02 | ≤ 10.12      | ≤ 12.39    | 11.25 ± 0.18 | 11.58 ± 0.43 | 11.17 ± 0.12 | 12.20 ± 0.07 | 12.90 ± 0.04 |
| 1.65706 | −38.4                    | 3.5 ± 0.4         | 11.88 ± 0.01 | ≤ 9.66       | ≤ 11.89    | 11.10 ± 0.15 | 11.79 ± 0.16 | 11.13 ± 0.08 | 11.21 ± 0.04 | 12.98 ± 0.03 |
| 1.65718 | −24.8                    | 6.5 ± 0.2         | 12.38 ± 0.00 | ≤ 9.93       | ≤ 12.14    | 11.66 ± 0.05 | 12.40 ± 0.05 | 11.59 ± 0.03 | 11.56 ± 0.02 | 13.40 ± 0.01 |
| 1.65740 | 0.0                      | 9.3 ± 0.1         | 13.45 ± 0.00 | 10.96 ± 0.04 | 12.92 ± 0.09 | 12.76 ± 0.01 | 13.55 ± 0.01 | 12.57 ± 0.00 | 12.40 ± 0.01 | 14.38 ± 0.01 |
| 1.65757 | + 19.2                   | 4.8 ± 0.3         | 12.20 ± 0.01 | ≤ 9.89       | ≤ 11.67    | 11.59 ± 0.05 | 12.28 ± 0.06 | 11.36 ± 0.05 | 11.45 ± 0.03 | 13.22 ± 0.02 |
| 1.65772 | + 36.1                   | 5.0 ± 0.1         | 12.55 ± 0.00 | ≤ 10.10      | ≤ 12.28    | 11.25 ± 0.11 | 12.50 ± 0.04 | 11.75 ± 0.02 | 11.30 ± 0.04 | 13.72 ± 0.01 |
| 1.65788 | + 54.1                   | 5.7 ± 0.0         | 12.85 ± 0.00 | 10.94 ± 0.03 | 12.87 ± 0.08 | 11.94 ± 0.03 | 12.81 ± 0.02 | 11.37 ± 0.05 | 11.73 ± 0.02 | 13.96 ± 0.01 |
| 1.65815 | + 84.6                   | 4.8 ± 1.3         | 11.08 ± 0.06 | ≤ 9.70       | ≤ 12.02    | ≤ 10.28     | ≤ 11.33     | 10.67 ± 0.24 | 10.26 ± 0.38 | ≤ 13.22     |

| Low-ion column densities | High-ion column densities |
|--------------------------|---------------------------|
| $z$ | $\Delta V$ (km s$^{-1}$) | Ionic (X) | $b$ (km s$^{-1}$) | log N(X) | $z$ | $\Delta V$ (km s$^{-1}$) | Ionic (X) | $b$ (km s$^{-1}$) | log N(X) |
| 1.65604 | −153.3 | C iv | 10.6 ± 0.5 | 13.45 ± 0.02 | 1.65985 | +276.3 | C iv | 8.1 ± 3.9 | 12.26 ± 0.13 |
| 1.65621 | −134.3 | C iv | 6.9 ± 0.5 | 13.54 ± 0.03 | 1.66000 | +293.2 | C iv | 8.5 ± 0.2 | 13.36 ± 0.01 |
| 1.65639 | −114.0 | C iv | 12.1 ± 0.4 | 13.83 ± 0.01 | 1.66029 | +35.8 | C iv | 12.2 ± 0.3 | 13.11 ± 0.01 |
| 1.65662 | −88.0  | C iv | 6.4 ± 0.3 | 12.84 ± 0.02 | 1.66093 | +398.0 | C iv | 15.2 ± 0.4 | 13.06 ± 0.01 |
| 1.65688 | −58.7  | C iv | 17.0 ± 0.4 | 13.75 ± 0.01 | 1.65636 | −117.3 | Si iv | 5.4 ± 1.0 | 12.29 ± 0.04 |
| 1.65706 | −38.4  | C iv | 5.2 ± 0.4 | 12.93 ± 0.04 | 1.65662 | −88.0 | Si iv | 7.7 ± 0.9 | 12.52 ± 0.04 |
| 1.65732 | −9.0   | C iv | 21.3 ± 1.7 | 13.87 ± 0.07 | 1.65687 | −59.8 | Si iv | 12.0 ± 1.2 | 13.21 ± 0.06 |
| 1.65743 | +34.4  | C iv | 9.3 ± 1.2 | 13.35 ± 0.16 | 1.65694 | −53.0 | Si iv | 4.4 ± 0.8 | 12.84 ± 0.11 |
| 1.65773 | +37.2  | C iv | 8.1 ± 0.2 | 14.26 ± 0.02 | 1.65707 | −37.2 | Si iv | 7.2 ± 1.1 | 12.93 ± 0.06 |
| 1.65778 | +42.9  | C iv | 15.9 ± 2.2 | 13.56 ± 0.13 | 1.65724 | −18.0 | Si iv | 8.7 ± 1.4 | 13.04 ± 0.07 |
| 1.65815 | +84.6  | C iv | 9.5 ± 0.1 | 14.04 ± 0.00 | 1.65742 | +2.2 | Si iv | 11.7 ± 0.4 | 13.65 ± 0.01 |
| 1.65892 | +171.4 | C iv | 7.1 ± 0.1 | 13.29 ± 0.00 | 1.65773 | +37.2 | Si iv | 4.2 ± 0.4 | 13.45 ± 0.04 |
| 1.65937 | +222.2 | C iv | 8.6 ± 0.9 | 12.26 ± 0.03 | 1.65776 | +4.06 | Si iv | 13.8 ± 1.1 | 13.48 ± 0.02 |

a Too uncertain.
b Blended with some features.

c

from blending and we performed a 2-component Voigt profile fit to the O vi$\lambda$1037 transition, which appears to be less blended than the O vi$\lambda$1031. The fit was successful, yielding $\chi^2 = 1.12$ and $P_\chi = 0.308$. Note that, due to the poor alignment, the fit to different high-ions were performed separately. In Fig. A4, the VPFIT results are superimposed onto the observations as red lines. Table A4 gives the fit parameters.

Finally, Table A5 presents the total column densities of the C iv and Si iv species of the systems studied in this work. In this table, columns 2 & 3 indicate the velocity width of the C iv and Si iv absorption features, respectively. The last two columns also give the C iv/H i and Si iv/H i column density ratios.
Table A4. High-ion and H i column densities for the $z_{\text{abs}} = 1.7221$, 1.7536, 1.8994, 1.9253, and 2.2298 absorbers.

| $z$   | $\Delta V$ (km s$^{-1}$) | Ion (X) | $b$ (km s$^{-1}$) | $\log N(X)$ |
|-------|----------------|---------|-----------------|-------------|
| 1.72198 | $-14.3$ | H i   | 30.3           | $\geq 14.80$ |
| 1.72211 | 0.0    | C IV  | 6.0±0.2        | 12.43±0.01  |
| 1.75357 | +1.1   | H i   | 36.1           | $\geq 14.81$ |
| 1.75352 | -26.1  | C IV  | 11.3±1.4       | 12.13±0.06  |
| 1.75356 | 0.0    | C IV  | 15.5±0.6       | 12.80±0.01  |
| 1.89338 | $-110.6$ | C IV | 6.3±1.0        | 11.83±0.04  |
| 1.89901 | -45.5  | C IV  | 6.8±0.6        | 12.26±0.03  |
| 1.89921 | -24.8  | C IV  | 8.7±0.6        | 12.63±0.04  |
| 1.89945 | 0.0    | C IV  | 12.7±0.9       | 13.30±0.05  |
| 1.89957 | +12.4  | C IV  | 6.6±2.3        | 12.35±0.32  |
| 1.90005 | +62.0  | C IV  | 15.8±0.5       | 12.68±0.01  |
| 1.90039 | +97.2  | C IV  | 8.2±1.6        | 11.81±0.06  |
| 1.90062 | +120.9 | C IV  | 5.9±0.3        | 12.36±0.01  |
| 1.90140 | +201.6 | C IV  | 6.8±0.3        | 12.46±0.02  |
| 1.90161 | +223.3 | C IV  | 9.8±0.9        | 12.39±0.03  |
| 1.90182 | +244.9 | C IV  | 5.7±0.8        | 12.33±0.04  |
| 1.92533 | 0.0    | H i   | 54.6           | $\geq 15.12$ |
| 1.92527 | 0.0    | C IV  | 13.7±0.8       | 12.25±0.02  |
| 2.22979 | 0.0    | C IV  | 7.1±0.3        | 12.19±0.01  |
| 2.22978 | -1.0   | O VI  | 19.3±0.9       | 13.61±0.02  |
| 2.23016 | +34.3  | O VI  | 11.6±5.5       | 12.51±0.18  |

Table A5. Total column densities of the C IV and Si IV species of the systems studied in this work. In this table, column 1 shows the redshifts of the systems, columns 2 & 3 indicate the velocity width of the C IV and Si IV absorption features, columns 4 & 5 indicate the total column densities of C IV, Si IV, and H i, respectively, and finally, the last two columns give the C IV/H i and Si IV/H i column density ratios.

| $z$     | $\Delta V$ (C IV) [km s$^{-1}$] | $\Delta V$ (Si IV) [km s$^{-1}$] | $\log N$(C IV) | $\log N$(Si IV) | $\log N$(H i) | $\log N$(C IV)/$\log N$(H i) | $\log N$(Si IV)/$\log N$(H i) |
|---------|-------------------------------|-------------------------------|----------------|----------------|-------------|----------------|----------------|----------------|
| 1.1846  | 79.6                          | 79.6                          | 13.98±0.04     | 13.68±0.06     | $\geq 17.85$ | $\leq -2.77$  | $\leq -4.57$  |
| 1.4681  | 21.9                          |                               | 12.89±0.01     | $\geq 14.59$   | $\leq -0.53$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.5610  | 42.2                          |                               | 13.05±0.01     | $\geq 14.59$   | $\leq -0.53$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.5965  | 234.4                         | 175.5                         | 15.08±0.02     | $\geq 14.59$   | $\leq -0.53$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.6109  | 160.8                         |                               | 14.06±0.01     | $\geq 14.59$   | $\leq -0.53$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.6359  | 187.6                         | 187.6                         | 13.54±0.09     | 19.15±0.04     | $\leq -0.53$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.6574  | 551.5                         | 157.9                         | 14.84±0.02     | 14.18±0.01     | $\geq 14.3$  | $\geq 14.13$  | $\geq 14.13$  |
| 1.6720  | 582.0                         | 499.1                         | 15.08±0.01     | 19.78±0.05     | $\leq -0.53$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.7221  | single-comp.                  |                               | 12.43±0.01     | $\geq 14.80$   | $\leq -2.37$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.7536  | 26.1                          |                               | 12.89±0.02     | $\geq 14.80$   | $\leq -2.37$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.8994  | 355.5                         |                               | 13.70±0.02     | $\geq 14.80$   | $\leq -2.37$ | $\geq 14.3$   | $\geq 14.13$  |
| 1.9253  | single-comp.                  |                               | 12.25±0.02     | $\geq 15.12$   | $\leq -2.37$ | $\geq 14.3$   | $\geq 14.13$  |
| 2.0422  | 131.0                         |                               | 13.70±0.02     | $\leq 12.90$   | $\geq 14.3$   | $\geq 14.13$  | $\geq 14.13$  |
| 2.1979  | 28.1                          | 7.5                           | 13.24±0.02     | $\geq 15.98$   | $\leq -2.74$ | $\geq 14.3$   | $\geq 14.13$  |
| 2.2028  | 43.1                          | 43.1                          | 14.14±0.06     | 13.33±0.06     | $\geq 15.54$ | $\leq -2.1$  | $\geq 14.3$   | $\geq 14.13$  |
| 2.2298  | single-comp.                  |                               | 12.19±0.01     | 12.75±0.08     | $\leq -0.56$ | $\leq 14.3$   | $\geq 14.13$  |
| 2.2303  | 48.2                          |                               | 12.66±0.04     | 14.18±0.05     | $\leq -1.52$ | $\leq 14.3$   | $\geq 14.13$  |