The CGM and IGM at z\sim5: metal budget and physical connection

Alex Codoreanu,1,2,3⋆ Emma V. Ryan-Weber,1,2 Luz Ángela García,1,2,4
Neil H.M. Crighton,1 George Becker,5 Max Pettini,6 Piero Madau,7 and Bram Venemans8
1 Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
2 ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)
3 Centre for Transformativ Innovation
4 Universidad ECCI, Carrera 19 No. 49 - 20. Bogotá, Colombia
5 Department of Physics Astronomy, University of California, Riverside, 900 University Avenue, Riverside, CA 92521, USA
6 Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK
7 Department of Astronomy & Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, US
8 Max-Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany

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ABSTRACT

We present further results of a survey for absorption line systems in the spectra of four high redshift quasars (5.79 ≤ z_{em} ≤ 6.13) obtained with the ESO Very Large Telescope X-Shooter. We identify 36 C IV and 7 Si IV systems with a ≥ 5σ significance. The highest redshift C IV and Si IV absorbers identified in this work are at z = 5.80738 ± 0.00017 and z = 5.77495 ± 0.00038, respectively. We compute the comoving mass density of Si IV (Ω_{Si IV}) and find that it evolves from Ω_{Si IV} = 4.3^{+1.1}_{-2.1} \times 10^{-9} at <z> = 5.05 to Ω_{Si IV} = 1.4_{-0.4}^{+0.6} \times 10^{-9} at <z> = 5.66. We also measure Ω_{C IV} = 1.6_{-0.1}^{+0.4} \times 10^{-8} at <z> = 4.77 and Ω_{C IV} = 3.4_{-1.1}^{+1.6} \times 10^{-9} at <z> = 5.66. We classify our C IV absorber population by the presence of associated low and/or high ionisation systems and compute their velocity width (ΔV_{90}). We find that all C IV systems with ΔV_{90} > 200 kms^{-1} have associated low ionisation systems. We investigate two such systems separated by 550 physical kpc along a line of sight, and find it likely that they are both tracing a multi-phase medium where hot and cold gas is mixing at the interface between the CGM and IGM. We further discuss the Mg II systems presented in a previous work and we identify 5 Si II, 10 Al II, 12 Fe II, 1 C II, 7 Mg I and 1 Ca II associated transitions. We compute the respective comoving mass densities in the redshift range 2 to 6, as allowed by the wavelength coverage.

Key words: galaxies:quasars:general, galaxies:quasars:absorption lines, galaxies:statistics

1 INTRODUCTION

Absorption systems in the spectra of high redshift quasi-stellar objects (QSOs) present an opportunity to identify and study intervening metal enriched clouds during the first billion years of evolution of the Universe. Unambiguous detection of these clouds is provided by the presence of doublets with high oscillator strength such as Mg II (Kacprzak et al. 2011; Kacprzak & Churchill 2011; Kacprzak et al. 2012; Matejek & Simcoe 2012; Kacprzak et al. 2013; Bosman et al. 2017; Codoreanu et al. 2017), Si IV (Boksenberg & Sargent 2015; Songaila 2005) as well as C IV (Simcoe 2006; Ryan-Weber et al. 2006; Becker et al. 2009; Ryan-Weber et al. 2009; Simcoe et al. 2011; D’Odorico et al. 2013; Díaz et al. 2016). The rest frame ionisation wavelength and oscillator strength of each transition identified in this work are presented in Table 1.

These absorption systems are generally categorised into low and high ionisation systems. Low ionisation absorption systems (Mg II, Si II, Al II, O I and others) trace low temperature/high density regions connected to the circumgalactic medium (CGM) (eg. Steidel et al. 2010; Nielsen et al. 2013a, b; Churchill et al. 2013; Nielsen et al. 2015, 2016) while high ionisation (C IV, Si IV and others) trace high tem-
temperature/low density regions generally associated with the intergalactic medium (IGM) (eg. Schaye et al. 2003, 2007; Aguirre et al. 2004, D’Odorico et al. 2016; Finlator et al. 2016; Keating et al. 2016; García et al. 2017; Oppenheimer et al. 2017).

However, such associations and boundaries are not always applicable as C IV systems with column densities log(N/cm^2) > 13.5 have also been associated with the halos of galaxies with stellar mass (M_*) > 10^{10.5}M_0 at 0.0015 <z< 0.015 (Burchett et al. 2016). Furthermore, Steidel et al. (2010) and Turner et al. (2014) identify and measure the optical depth of C IV systems and find that they are preferentially found at a proper transverse distance of less than 200 kpc of z=2-3 galaxies. Adelberger et al. (2005) also connects C IV systems with column densities log(N/cm^2) > 14.0 to young star forming field galaxies up to z=3.3 and finds that their gas halo can extend up to 80 kpc. Thus, high ionisation systems can also be found in virialised halos where they are physically mixed with low ionisation systems.

Replicating the observed abundance and evolution of absorption systems beyond redshift 5 is a challenging task as they trace different physical environments and are sensitive to a large number of connected and correlated physical processes. For example, the galaxy contribution to the shape and amplitude of the global UV background (UVB, Oppenheimer et al. 2009) beyond redshift 5 depends on both the volume density of galaxies (Atek et al. 2015; Mason et al. 2015; Livermore et al. 2017; Bouwens et al. 2015, 2017) and the properties of both Pop II stars and the first metal-free stars (PopIII) (i.e. Heger & Woosley 2002; Yoshida et al. 2006; Hosokawa et al. 2012; Pallottini et al. 2014). The relative abundance patterns described in Becker et al. (2012) are consistent with a scenario in which metal production in Pop II stars dominates the metal budget by z=6 but, currently, there is no clear observational tracer to signal the transition from PopIII to PopII stars which is expected to occur before z=10 (Maio et al. 2010).

Furthermore, absorption systems are also sensitive to the yield and return fraction of metals (Madau & Dickinson 2014) which itself depends on both the initial mass function (Salpeter 1955; Kroupa 2001; Chabrier 2003) and the outflow models which transport those metals from the interstellar medium (ISM) to the IGM through the CGM (Ferrara et al. 2000; Madau et al. 2001; Oppenheimer & Davé 2005). Absorption systems are then an important observational discriminant as they trace diverse temperature and density regions and, provide a census of metals (Lan & Fukugita 2017) which is not limited by the brightness of the galaxies associated with the enrichment.

Recent works by Bosman et al. (2017) (B17) and Codoreanu et al. (2017) (C17) have identified a population of weak Mg II systems (W_{2796} \leq 0.3 \AA) from redshift 5 to 7. Previous works by Becker et al. (2000, 2011) have also identified low ionisation absorbers with multiple associated transitions (eg. O I, Si II, C II) beyond redshift 5. Their high incidence rates suggest that they are most likely tracing the small and numerous galaxies needed to reionise the Universe during the Epoch of Reionisation (EoR) with M_{UV} \leq -13 (Robertson et al. 2013). While these absorbers have not yet directly been connected to specific stellar populations, their presence indicates that metals, as traced by low ionisation systems, have already been well established and have a significant cross-section by redshift ~6.

While these weak Mg II systems have a significant cross-section, they do not account for a large fraction of the metal budget. C17 has shown that Mg II systems with W_{2796} \leq 1 \AA hold a small fraction (~1/50) of the comoving mass density of Mg II (\Omega_{Mg II}) in the redshift range 4.03<z< 5.45. Interestingly, C17 has also shown that \Omega_{Mg II}, as measured by all systems discovered in their work\(^2\), increases from \Omega_{Mg II} = 2.1^{+0.3}_{-0.1} \times 10^{-8} at <z> = 2.48 to \Omega_{Mg II} = 3.9^{+0.5}_{-0.4} \times 10^{-7} at <z> = 4.77. This order of magnitude increase is in contrast to the evolution of the comoving mass density of C IV (\Omega_{C IV}) which has a flat evolution across a similar redshift range (Songaila 2001; Pettini et al. 2003). For example, Boksenberg & Sargent (2015) (B15) measure a mean <\Omega_{C IV} > = 1.23 \pm 0.66 \times 10^{-8} at a mean redshift <z> = 3.20 across the redshift range 1.9 < z < 4.5 and D’Odorico et al. (2013) measure \Omega_{C IV} = 1.4 \pm 0.3 \times 10^{-8} at z = 4.818. However, from redshift 5 to 6, \Omega_{C IV} declines by a factor of 2 to 4 (Simcoe 2006; Simcoe et al. 2011; Ryan-Weber et al. 2006; Becker et al. 2009; Ryan-Weber et al. 2009; D’Odorico et al. 2013).

The evolution in \Omega_{C IV} can be driven either by a change in the ionisation state, the enrichment of the IGM (Becker et al. 2015a) or both. It is reproduced in simulations by Oppenheimer & Davé (2006), Oppenheimer et al. (2009), Cen & Chisari (2011) and García et al. (2017). However, the opposite evolution of \Omega_{Mg II} when compared to the evolution of \Omega_{C IV} does not support an increase in the metal budget as the primary driver in the evolution of \Omega_{C IV} (C17). This suggests that the evolution of \Omega_{C IV} is then mostly driven by a change in the ionisation state of the IGM resulting from changes in the UVB beyond redshift 5.

Finlator et al. (2016) investigate the impact of three different UVB prescriptions on the resulting absorber population and compare to the observational results of Becker et al. (2011) and D’Odorico et al. (2013) (D13). The three types of UVBs tested are (1) the UVB presented by Haardt & Madau (2012) (HM12), (2) a modified and directly simulated version of the HM12 UVB which accounts for inhomogeneous galaxy emissivity combined with a QSO emissivity, and (3) a QSO emissivity only. They find that while all three UVB scenarios can reproduce the column density distribution functions (CDFs) of C II, Si IV, and C IV only (2) reproduces the observed ionic ratios of Si IV/C IV and C II/C IV.

Interestingly, the QSO-only UVB model greatly overproduces photons with energies greater than 4 Ryd which is reflected in an over production of C IV (4.7 Ryd). However, at lower energies, probed by Si IV, Si II and C II, all three UVB models have similar intensities. Thus simply scaling up the intensity of the UVB would result in different ratios of Si IV/C IV and C II/C IV than a UVB which is adjusted by considering varying contributions from sources of harder photons such as QSOs or PopIII stars (Finlator et al. 2016). Recently, Doughty et al. (2018) have also shown that aligned absorber pairs (eg. multiple ions associated with the

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\(^1\) The equivalent width of the Mg II \lambda2796 transition

\(^2\) 0.117 \leq W_{2796} \leq 3.655 \AA
same enriched and ionised gas halo) can be used to improve the constraints on the UVB. They found that the observed statistics of $\text{CIV}/\text{SiIV}$ are best reproduced by a hard, spatially uniform UVB but, a single aligned $\text{SiII}/\text{SiIV}$ pair is reproduced best by the HM12 UVB prescription.

Thus, understanding the evolution of both low and high ionisation systems is then necessary as low ionisation systems (i.e. $\text{CII}$, $\text{SiII}$) are sensitive to both changes in ionisation and gas density/metallicity (Finlator et al. 2015) while $\text{CIV}$ is mostly sensitive to ionisation prescriptions (Finlator et al. 2016). Future simulations can explore if there is a preferred balance between changes to a global UVB from local sources in conjunction with different prescriptions for self-shielded halos which produce metals but do not contribute photons to the global UVB. In order to test such scenarios several questions arise:

- "How does $\Omega_{\text{SiIV}}$ evolve beyond redshift 5?"
- "What is the physical connection between low and high ionisation systems beyond redshift 5?"
- "Are low and high ionisation systems tracing distinct physical constructs or are they tracing multiphase gas at virial distances or at the interface between the CGM and IGM?"
- "What is the evolution of other species of low ionisation systems (i.e. $\text{SiII}$, $\text{CII}$, $\text{FeII}$ and others)?"

We explore these questions by searching for intervening absorption systems in four medium resolution and signal-to-noise spectra of redshift ~6 QSOs. These spectra were investigated for the presence of $\text{MgII}$ systems and the results were presented in C17. In this work, we provide the first $\Omega_{\text{SiIV}}$ values and corresponding CDDFs beyond redshift 5. We compare with $\text{CIV}$ in the range 4.92<z<6.12. We also identify $\text{SiII}$, $\text{AlII}$, $\text{FeII}$, $\text{CII}$, $\text{MgI}$ and $\text{CaII}$ associated transitions in addition to the $\text{MgII}$ discussed in C17. We discuss the details of the identification of all absorption systems in Section 2. We discuss our treatment of false positive contamination and completeness considerations in Section 3. We provide the incidence rates, comoving mass densities and CDDFs (and best fit parameters) of the $\text{SiIV}$ and $\text{CIV}$ systems identified in this work in Section 4. We present the comoving mass densities of $\text{MgI}$, $\text{CaII}$, $\text{SiII}$, $\text{AlII}$, $\text{FeII}$ and $\text{CII}$ and discuss our results in Section 5. We provide a summary and conclusions in Section 6. Throughout this paper we use a $\Lambda$CDM cosmology with $\Omega_M = 0.308$ and $H_0 = 67.8 \text{km s}^{-1} \text{Mpc}^{-1}$ (Planck Collaboration et al. 2015).

2 CANDIDATE SELECTION

The observations, exposure times, data reduction and instrument resolution are described in C17. The reduced spectra are binned with a resolution of 10 km s$^{-1}$ pixel$^{-1}$. We follow the same steps as C17 in identifying absorbers and quantifying the completeness of our survey. In short, we first create a candidate list using an automatic search algorithm whose output is then visually inspected by the lead author (AC) and a final list of candidates is created. These candidate absorbers are then fit with Voigt profiles using VPFFIT 10.0 (Carswell & Webb 2014).

2.1 Automatic Search

In order to identify $\text{CIV}$ and $\text{SiIV}$ doublets, we create a candidate list by finding all pixels of the spectra which meet the following conditions:

- a minimum 3 consecutive 5σ pixel detections;
- $\sigma_i = \frac{(1-F_i)}{W_i}$
- $W_{d1}/\sigma W_{d1} \geq 5$ or $W_{d2}/\sigma W_{d2} \geq 5$
- 0.5≤$W_{d1}/\sigma W_{d1} \leq 5$ or $W_{d2}/\sigma W_{d2} \leq 5$, searching for $\text{CIV}$
- 0.8≤$W_{d1}/\sigma W_{d1} \leq 4$ or $W_{d2}/\sigma W_{d2} \leq 4$, searching for $\text{SiIV}$

where $F_{d1}$ and $E_{d1}$ are the flux, error values associated with a pixel. $W$ and $\sigma W$ represent the equivalent width and error of the consecutive pixels associated with the $\text{CIV}$ $\lambda$1548 1550 and $\text{SiIV}$ $\lambda$1393 1402 doublet candidates where $d1$ and $d2$ denote each one of the respective candidates. The respective equivalent width ratios are chosen by the lead author in order to minimise the contamination by false positives. These ratios represent only the pixel flux and error values and do not account for possible blends with other transitions. The selection algorithm outputs 94 candidate $\text{CIV}$ systems (with 118 components) and 18 candidate $\text{SiIV}$ systems (with 40 components).

2.2 Visual check

Each candidate is visually inspected by the lead author (AC) and selected as an absorber based on the similarity of the velocity profile of the two transitions in each doublet. In C17, most of the rejected $\text{MgII}$ candidates occurred in the NII where telluric absorption and sky-line emissions heavily polluted the spectra. In the present work, the majority of the absorption path -redward of the Lyα emission peak of the QSO to within 3000 km s$^{-1}$ of the QSO redshift- for $\text{CIV}$ and $\text{SiIV}$ is in the VIS arm of X-Shooter.

The rejected candidates have mis-matched velocity profiles or are weak features dominated by RMS fluctuations. From the 94 $\text{CIV}$ candidates, 41 are accepted and from the 18 $\text{SiIV}$ candidates, 7 are accepted by the lead author as possible ‘true’ absorbers (see Figure 1 and $N$ column in Table 2). Following this selection, we search for associated ions ($\text{CII}$, $\text{SiII}$, $\text{MgI}$, $\text{AlII}$, $\text{AlIII}$, $\text{Nv}$, $\text{O}$, $\text{OVI}$, $\text{FeII}$ and $\text{CaII}$) by using the $\text{CIV}$, $\text{SiIV}$ and $\text{MgII}$ (described in detail in C17) doublets as redshift anchors for their possible location. For this task we use the PLOTSPEC package. We find 12 systems with multiple associated ions and each one is discussed in Sec. 2.4. The $\text{CIV}$ associated with system 9 in sightline ULAS J1319+0959 does not meet our 5σ discovery criteria (see section 2.1) but is included in our analysis for reasons discussed in sub-section 2.4.4. It is the only absorber ‘manually’ introduced. The rejected systems are single component systems and have no other associated transitions (i.e. $\text{FeII}$, $\text{CII}$). Thus, we are not forced to consider multiple ions when trying to ascertain the veracity of an absorption system.

3 \( (W_{d1} + \sigma W_{d1})/(W_{d2} + \sigma W_{d2}) \)

4 developed by Dr. Neil Crighton

https://github.com/nhmc/plotspec/
2.3 Voigt Profiles & Equivalent Widths

We use VPFIT 10.0 to fit Voigt profiles to the absorption lines and we do not tie associated transitions together as they could trace multi-phase gas. However, Boksenberg & Sargent (2015) allow the fixed gas temperature to vary in the range $10^4<T<10^5$K and has shown that the VPFIT retrieved column density parameters of Voigt profiles do not depend strongly on the temperature. For reference, the thermally broadened profile of a $10^5$K gas cloud results in an upper bound for the thermal broadening parameter of $b_{\text{therm}} \approx 10$ km s$^{-1}$. As recommended in Carswell & Webb (2014), we impose a minimum $b << b_{\text{expected}}$. We choose a minimum value of $b = 1$ km/s.

As the dominant source of uncertainty arises from the continuum fitting process, we adjust the continuum level by ± 5% and repeat the entire fitting procedure. This leads to the error bars associated with each set of Voigt profile parameters. The redshift ($z$) and Doppler parameter ($b$) of each absorber is fit individually and no absorbers reported in this work are highly saturated.

A system is defined as all components within $0 \leq \Delta \nu \leq 500$ km s$^{-1}$. We select this $\Delta \nu$ width range to account for the possible stellar velocity dispersion of galaxies with an intrinsic $B$ band magnitude $M_B \geq -25$ (Faber & Jackson 1976) as we have no a priori information on the associated galaxies. The velocity width of a system ($\Delta \nu_{\text{sys}}$) is then computed from the corresponding wavelength boundary ($\Delta \lambda$; Prochaska et al. 2008) enclosing 90% of the optical depth of all components. We compute the equivalent width ($W_0$) of each component over each associated $\Delta \lambda$ value. The $W_0$ of blended systems is computed from the Voigt profile fit. The total column column density of an absorption system is computed by summing the column densities of the components.

We present all identified systems, their components, equivalent width, Voigt profile parameters, associated errors and recovery levels in the system tables available in the online appendix. All visually selected systems (see sec. 2.2) from the automated output created by the detection algorithm (see sec. 2.1) are discussed in the following section.

2.4 Individual sight lines

The four QSO redshifts, apparent magnitudes and initial discoveries are described in C17. We observed each object for ~10 hours. Below, we present all C IV and SiIV absorbers along with associated transitions. Given that all Mg II absorbers have been presented in C17, we only include them in the system plots available in the online appendix (see Fig. 2 for an example). No additional Mg II absorbers are found after identifying the C IV and Si IV doublets. Blended components are marked with a § while those polluted by a sky-line or poor subtraction residual are marked with a ¶. Systems which do not meet the 5σ recovery selection criteria in their respective $(\log(N), \Delta \lambda)$ bins are identified with a *. We discuss this in detail in the follow-up Section 3.

Additionally, we present, in the online appendix, the associated transitions (Mg I, Fe II, Al II and Ca II) of Mg II discoveries from C17 with redshifts outside this paper’s search region defined by the C IV and Si IV wavelengths. For ease of understanding to those reading the following subsections in detail, we recommend to have the online appendix at hand. We only include Fig. 2 and Table 3 in the main paper as an example.

2.4.1 ULAS J0148+0600

We present 9 new systems and the highest redshift absorber in this sightline which meets our 5σ recovery selection crite-
is system 9 with \( z = 5.82630 \pm 0.00013 \). All systems and associated components are presented in detail in Section A of the online Appendix.

Systems 1, 5, 7 are single component CIV systems. System 9 is a single SiIV system with both the \( \lambda \lambda 1393 \) 1402 features blended with the CIV \( \lambda 1550 \) feature of system 7 and a Fe \( \text{ii} \) 2382 absorber at \( z \approx 3.01858 \), respectively. Furthermore, the SiIV \( \lambda 1393 \) could also be a Mg\( \text{ii} \) 2796 system at \( z = 2.4024 \). This possible Mg\( \text{ii} \) system is not chosen from the initial candidate list by the lead author due to relative velocity structure of the \( \lambda 2796 \) and \( \lambda 2803 \) features. This system is of particular interest as it falls in the redshift range 5.523 < \( z < 5.879 \) which corresponds to a large Ly\( \alpha \) trough discussed in detail by Becker et al. (2015b). This is one of two possible metal absorption systems in the corresponding redshift range. However, there are no other absorbers associated with this SiIV system and both transitions are heavily blended. Is this then a real system?

We find that this is the only SiIV system with no other associated absorbers such as CIV, Si\( \text{ii} \) or Fe\( \text{ii} \). All other SiIV systems identified in this work as well as those of B15\( ^6 \) and D13 have at least one other associated absorber. Given this extra information, we suspect that this individual SiIV absorber is a false positive. However, since we do not use such criteria for the selection of other absorbers and this system does meet our general selection criteria described in Sections 2.1 and 2.2, we include it in the absorber population statistics. These statistics are adjusted for user success/failure, false positive contamination and completeness as described in Section 3.

The second system in the redshift range 5.523 < \( z < 5.879 \) is system 8, a single component absorber anchored by SiIV with associated Si\( \text{ii} \) 1260. We note that System 8 is a marginal detection as both transitions are affected by sky-line residuals. The presence of the associated Si\( \text{ii} \) 1260 lends credibility to the detection but, itself, was identified as a possible Mg\( \text{ii} \) doublet by the automatic detection algorithm. It was not selected by the lead author as the \( \lambda 12796 \) 2803 transitions were not well matched when considering the full absorption profile composed of the Si\( \text{ii} \) 1260 component of System 8 and the SiIV \( \lambda 1393 \) component of System 6.

System 2 is anchored by CIV (CIV \( \lambda 1548 \) blended with Al\( \text{i} \) 2.45996) and Mg\( \text{ii} \) doublets. We identify associated Fe\( \text{ii} \) (Fe\( \text{ii} \) 1.2585 blended with a skyline), Mg\( \text{i} \), Si\( \text{ii} \) (blended with Fe\( \text{ii} \) at \( z \approx 2.47759 \)) and Al\( \text{i} \). System 3 is a three component CIV system. System 4 is a two component CIV system. System 6 is a two component system with CIV and SiIV absorbers. System 7 is a CIV absorber whose \( \lambda 1548 \) feature is blended with the CIV \( \lambda 1550 \) feature of System 6.

### 2.4.2 SDSS J0927+2001

We present 10 new systems and the highest redshift absorber in this sightline which meets our 5\( \sigma \) recovery selection criteria is system 10 with \( z = 5.66382 \pm 0.00020 \). All systems and associated components are presented in Section B of the online Appendix.

Systems 1, 2\( ^* \), 3, 6, 7 and 9 are single component CIV systems. Systems 4 and 10 are two component CIV systems. System 5 is a 3 component CIV system where the third component has associated Al\( \text{ii} \) 1567 which is heavily blended with a Mg\( \text{ii} \) system with \( z = 2.34879 \pm 1 \times 10^{-5} \). System 5 also has an associated Mg\( \text{ii} \) absorber. System 8 is a single component system with both CIV and SiIV absorbers.

### 2.4.3 SDSS J1306+0356

This sightline was previously investigated by D13 who confirm systems 2, 4, 8 and 9 first identified by Simcoe et al. (2011) (S11). D13 first discover systems 1, 3, 5 and 6. The highest redshift absorber in this sightline which meets our 5\( \sigma \) recovery selection criteria is system 15 with \( z = 5.80738 \pm 0.00017 \). All systems and associated components are presented in detail in Section C of the online Appendix.

We present seven new systems 7, 10, 11\( ^* \), 12, 13, 14\( ^* \) and 15 with four of them passing our 5\( \sigma \) recovery selection criteria. Systems 5, 6, 7, 10, 11\( ^* \), 12, 13, 14\( ^* \) and 15 are single component CIV systems. Systems 1 (CIV \( \lambda 1550 \) blended with the Si\( \text{ii} \) 1526 feature of system 2), 3 and 4 are two component CIV systems.

System 2 is a complex absorber anchored by CIV and Mg\( \text{ii} \) doublets with associated Al\( \text{i} \), Fe\( \text{ii} \) and Si\( \text{ii} \). We note that the Al\( \text{ii} \) 1567 component \( b \) is most likely blended with an unidentified transition which results in an artificial broadened profile. This results from the fact that we do not tie the Doppler \( b \) parameter of the ionisation systems during the Voigt profile fitting.

S11 suggest a possible CIV system at \( z = 4.702 \) and it is flagged by the automatic detection algorithm (Sec. 2.1) but the \( \lambda 1548 \) feature is contaminated by a sky-line while the possible \( \lambda 1550 \) feature is actually the \( \lambda 1548 \) feature of system 5. For these reasons, this candidate is rejected by the lead author in the visual inspection step (Sec. 2.2). During the same visual inspection step, the lead author also does not select system 2 presented by D13 (\( z = 4.58040 \pm 7 \times 10^{-5} \)) as the \( \lambda 1550 \) feature is not well matched with the \( \lambda 1548 \)’s velocity structure.

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\( ^6 \) see their Tables 2-10

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### Table 2. Median redshift values (<\( z \_\text{med} \>), redshift bins (\( \Delta z \)), number of discovered systems (\( \bar{N} \)), number of recovery selected systems (\( \bar{N} \_\text{rec} \)), adjustment scalars (\( \bar{A} \)), redshift path (\( dz \)), comoving absorption path (\( dX \)), incidence rates (\( dN/dz \)), comoving incidence rates (\( dN/dX \)) and comoving mass densities (\( \bar{\Omega} \)) for CIV and SiIV.

| ion | \( <z> \) | \( \Delta z \) | \( \bar{N} \) | \( \bar{N} \_\text{rec} \) | \( \bar{A} \) | \( dz \) | \( dN/dz \) | \( dN/dX \) | \( \bar{\Omega} \) |
|-----|----------|-------------|---------|-----------------|---------|--------|------------|-----------------|---------|
| CIV | 4.77     | 4.33-5.19   | 33      | 30              | 1.47    | 2.86   | 12.37     | 15.4 \pm 2.8    | 3.6 \pm 0.6 | 1.6 \times 10^{-8} |
|     | 5.66     | 5.19-6.13   | 8       | 6               | 2.29    | 3.13   | 14.42     | 4.4 \pm 1.2     | 0.9 \pm 0.3  | 3.4 \times 10^{-9} |
| SiIV| 5.05     | 4.92-5.19   | 2       | 2               | 2.12    | 0.43   | 1.98      | 9.8 \pm 4.7     | 2.2 \pm 1.1  | 4.3 \times 10^{-9} |
|     | 5.66     | 5.19-6.13   | 5       | 5               | 1.49    | 3.13   | 14.42     | 2.4 \pm 0.9     | 0.5 \pm 0.2  | 1.5 \times 10^{-9} |
Figure 2. System 2 identified in the ULAS J0148+0600 sightline. Each transition is identified in the bottom right of each panel. In each panel, the vertical axis is the continuum normalised flux. The horizontal axis is the velocity separation (km s$^{-1}$) from the lowest redshift component of a system. The normalised spectrum is plotted in black and the associated error is in red. The solid blue line represents the full fit to the spectra and includes other ions besides the transition identified in the bottom right of each panel. Individual components are plotted with dashed lines and are identified by a vertical label. The identified transition components are in solid blue and other transitions are in light blue.
Table 3. Absorption systems identified in ULAS J0148+0600 sightline. A system is defined as all components within 500 kms$^{-1}$ of the lowest redshift component. Each component is marked with a letter id and all associated transitions are identified in the Ion column. The table also lists $z$, $W_0$, log(N) and $b$ which are the redshift, equivalent width, column density and doppler parameter for each component Voigt profile fit. The 5σ recovery selection criteria are defined in eq. 7. No lower bound is presented for systems with $b = 1$ kms$^{-1}$ as the minimum doppler parameter we allow for a Voigt Profile is 1 kms$^{-1}$.

| Sys | ID | Ion | $z$ | $W_0$ (Å) | log(N/cm$^2$) | $b$ (kms$^{-1}$) | 5σ recovery rate |
|-----|----|-----|----|-----------|--------------|----------------|----------------|
| 1 a | CIV 1548 | 4.57120 ± 9.0 ×10$^{-5}$ | 0.042 ± 0.002 | 13.06±0.45 | 25.06±64.1 | 0.93 |
|    | CIV 1550 | 0.020 ± 0.001 | 13.24±0.38 | 31.86±67.6 | 0.96 |
| 2 a | CIV 1548| 4.89095 ± 0.00015 | 0.059 ± 0.002 | 11.98±0.27 | 47.7±52.1 | 0.96 |
|    | CIV 1550 | 0.031 ± 0.003 | 11.03±0.35 | 22.5±34.1 | 0.96 |
|    | Mg II 2852 | 4.89099 ± 6.8 ×10$^{-5}$ | 0.121 ± 0.006 | 14.43±0.08 | 17.8±34.4 | 0.96 |
|    | SII 1520 | 4.89049 ± 3.7 ×10$^{-5}$ | 0.233 ± 0.002 | 13.05±0.06 | 27.3±34.4 | 0.96 |
|    | AlII 1670 | 4.89054 ± 0.00013 | 0.268 ± 0.004 | 14.07±0.08 | 23.7±34.4 | 0.96 |
|    | FeII 2600 | 4.89056 ± 7.5 ×10$^{-5}$ | 0.522 ± 0.004 | 14.07±0.08 | 23.7±34.4 | 0.96 |
|    | FeII 2586 | 0.307 ± 0.008 | 14.07±0.08 | 23.7±34.4 | 0.96 |
|    | FeII 2382 | 0.551 ± 0.011 | 0.268 ± 0.004 | 14.07±0.08 | 23.7±34.4 | 0.96 |
|    | FeII 1608 | 0.110 ± 0.003 | 0.268 ± 0.004 | 14.07±0.08 | 23.7±34.4 | 0.96 |
| b | SII 1526 | 4.89172 ± 4.3 ×10$^{-5}$ | 0.223 ± 0.002 | 14.30±0.07 | 20.6±34.1 | 0.96 |
|    | AlII 1670 | 4.89175 ± 0.00012 | 0.243 ± 0.005 | 13.02±0.06 | 22.5±34.1 | 0.96 |
|    | FeII 2600 | 4.89176 ± 5.7 ×10$^{-5}$ | 0.208 ± 0.003 | 14.30±0.08 | 20.6±34.1 | 0.96 |
|    | FeII 2586 | 0.181 ± 0.044 | 0.208 ± 0.003 | 14.30±0.08 | 20.6±34.1 | 0.96 |
|    | FeII 2382 | 0.223 ± 0.010 | 0.208 ± 0.003 | 14.30±0.08 | 20.6±34.1 | 0.96 |
|    | FeII 1608 | 0.096 ± 0.003 | 0.208 ± 0.003 | 14.30±0.08 | 20.6±34.1 | 0.96 |
| 3 a | CIV 1548 | 4.93212 ± 0.00011 | 0.093 ± 0.002 | 13.48±0.00 | 18.7±5.74 | 0.97 |
|    | CIV 1550 | 0.052 ± 0.003 | 13.48±0.00 | 18.7±5.74 | 0.97 |
| 4 a | CIV 1548 | 4.93308 ± 0.00020 | 0.057 ± 0.002 | 13.22±0.07 | 20.8±9.50 | 0.96 |
|    | CIV 1550 | 0.029 ± 0.002 | 13.22±0.07 | 20.8±9.50 | 0.96 |
| 5 a | CIV 1548 | 4.93463 ± 0.00030 | 0.042 ± 0.003 | 13.07±0.25 | 38.3±8.97 | 0.95 |
|    | CIV 1550 | 0.022 ± 0.003 | 13.07±0.25 | 38.3±8.97 | 0.95 |
| 6 a | CIV 1548 | 4.95183 ± 0.00033 | 0.013 ± 0.002 | 12.56±0.73 | 19.2±6.5 | 0.95 |
|    | CIV 1550 | 0.006 ± 0.002 | 12.56±0.73 | 19.2±6.5 | 0.95 |
| 7 a | CIV 1548 | 4.95809 ± 0.00027 | 0.012 ± 0.002 | 12.56±0.68 | 3.58±7.76 | 0.95 |
|    | CIV 1550 | 0.006 ± 0.002 | 12.56±0.68 | 3.58±7.76 | 0.95 |
| 8 a | SiIV 1393 | 5.77495 ± 0.00008 | 0.029 ± 0.003 | 12.63±0.21 | 6.54±7.25 | 0.95 |
|    | SiIV 1393 | 0.016 ± 0.005 | 12.63±0.21 | 6.54±7.25 | 0.95 |
| 9 a | SiIV 1393 | 5.82630 ± 0.00013 | 0.035 ± 0.002 | 12.71±0.12 | 9.70±5.77 | 0.95 |
|    | SiIV 1393 | 0.019 ± 0.001 | 12.71±0.12 | 9.70±5.77 | 0.95 |

‖ denotes a component with a blended feature
‡ ‡ denotes a component polluted by a sky-line or poor subtraction residual
* denotes system which does not meet our 5σ recovery selection criteria

System 8 is a complex absorber anchored by CIV and Mg II doublets with associated AlII, Mg I, FeII and SII as first suggested by S11. System 9 is a similarly complex absorber with much weaker Mg II which we were not able to fit confidently. The systems could not be fit when the continuum was adjusted by +0.05. These two systems were discussed in C17 as they prove challenging to the system definition (all components within 500 kms$^{-1}$) and system 9 is omitted by Chen et al. (2017) from their analysis. In order to highlight these systems, we plot them together in Figure 18. We anchor the velocity scale on the bluest CIV component ($z = 4.85978 ± 3.50 ×10^{-5}$) and then plot vertical dashed lines at three 500 kms$^{-1}$ intervals. As can be seen, the reddest component of system 8 are within 500 kms$^{-1}$ of the bluest component of system 9 but each system has distinct velocity structures. We also plot vertical dashed lines at +600 and +900 kms$^{-1}$ and we discuss these systems in more detail in Section 5.3.
This sightline was previously investigated by D13 who confirm systems 6 and 9 first identified by S11 and first discover systems 1, 2, 3, 4 and 8. D13 treat our system 2 as two systems given that their distinct components are separated by $\sim 350$ kms$^{-1}$. However, in order to be consistent with our definition of a system we treat this as a single system. The highest redshift absorber in this sightline which meets our $5\sigma$ recovery selection criteria is system 9 with $z = 5.57037 \pm 0.00033$. All systems and associated components are presented in detail in Section D of the online Appendix.

We present two new systems, 5 and 7. We only use system 5 in our analysis as system 7 does not meet our $5\sigma$ recovery selection criteria. Systems 1, 2, 4, 5 and 7 are single component CIV systems. System 2 (CIV λ1550 of component $b$ is blended with the CIV λ1548 components of system 3) is a two component CIV system.

System 3 is anchored by both CIV and MgII. The CIV λ1548 features are blended with the CII component of system 9 and the CIV λ1550 of system 2. The CIV λ1550 features are blended with the SiII λ1402 features of system 6. System 6 is a two component SiIV system where component $b$ also has associated CIV. System 8 is a two component system anchored by CIV, SiIV and MgII. Component $b$ also has associated AlIII1670.

System 9 is a three component system anchored by SiIV. The CIV associated with system 9 is not detected by the automatic detection algorithm at a 5$\sigma$ cutoff but component $b$ is detected at a 3$\sigma$ selection. We introduce the absorber as it was previously discovered by S11 and D13 and has associated SiIV doublet to also anchor the redshift of the absorber. We discuss the impact of this decision on our resulting incidence line statistics (Sec. 4.1), comoving mass density calculation (Sec. 4.2) and resulting column density distribution functions (Sec. 4.3). We confirm the possible associated Cii first suggested by S11 but we do not identify any associated FeII. We do identify associated AlIII1670.

We are not able to confirm the D13 systems 2 ($z = 4.62931 \pm 8\times10^{-5}$) and 6 ($z = 4.70325 \pm 2\times10^{-5}$) as they are not flagged by our automatic detection algorithm and do not have other associated transitions to solidify the identification.

### 3 Survey Completeness and False Positive Corrections

When considering the statistics of absorption line systems we must account for the wavelength dependent signal-to-noise profile (visual vs. near-infrared) as well as the strength of the absorber (equivalent width or column density). Furthermore, one must account for the human impact if a visual inspection/user voting process selects from the output of an automatic detection algorithm. In summary, we use the prescriptions put forth in C17, which follow the steps described in Matejk & Simcoe (2012).

We first create a library of CIV and SiIV absorbers which are inserted at every $\Delta \lambda$ in the spectra of each QSO. We then search for them using the same automatic detection algorithm described in Sec. 2.1. Following this, the lead author quantifies their ability to accurately identify true absorbers (user success) as well as incorrectly identify random features or artificially spaced doublets as true absorbers (user failure). User success and user failure are computed as functions of S/N. We then turn these user success and user failure likelihoods into 2D maps with the same resolution as the recovery grids outputted by the automatic detection algorithm. We combine these and create recovery maps adjusted for user success/failure for each sightline for both CIV and SiIV doublets.

In order to account for false positive contamination, we repeat the entire analysis and completeness calculations for the artificially spaced doublets: CIV$^*$ (A11548.2049, 1553.3519) and SiIV$^*$ (A11393.76018, 1411.78580). We then combine the results of this search and analysis of artificially spaced doublets with that of the true CIV and SiIV absorbers to compute a single scalar which accounts for variable completeness across a redshift bin, the strength of the absorber, false positive contamination as well as the impact of the human interaction step (see A in Table 2). We present the details of each step below.

#### 3.1 Automatic recovery of doublets

In order to identify the true number of absorbers for a given redshift path, $dz$, we must first identify for what fraction of that path we can confidently identify the discovered absorbers. This recovery fraction is a function of both the strength of the absorber and the signal-to-noise profile of each quasar spectrum considered. As a first step, we use RDGEN (Carswell et al. 2014) to extract a library of Voigt profiles consistent with the observed components. For CIV, we extract absorbers with a column density range $12.5 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 14.5$ in 0.1 increments. For SiIV, we extract absorbers with a column density range $12.2 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 13.8$ in 0.1 increments. For each column density, we extract six profiles with a $b$ parameter value in the range $10 \leq b \leq 60$ kms$^{-1}$ with a step size of 10 kms$^{-1}$. We sample every $\Delta \lambda$ where CIV or SiIV can be observed by injecting an absorption system in 100 $\Delta \lambda$ steps. In total, we insert and search for 444288 SiIV and 1078200 CIV absorbers.

The injected systems are searched for automatically using the same simple algorithm used to create the initial candidate lists described in sec 2.1. The output of the detection algorithm is a Heaviside function, $H(\log(N), b, z)$, where $\log(N_{\text{sys}}/\text{cm}^2)$, $b$ and $z$ are the column density, Doppler parameter and redshift location of the inserted CIV and SiIV Voigt profile. The values of the output are

$$H(\log(N), b, z) = \begin{cases} 0 & \text{if the injected system is not detected,} \\ 1 & \text{if the injected system is detected,} \end{cases}$$

Next, we bin the above Heaviside function across all $b$ val-

---

7. all components within 500 kms$^{-1}$

8. described in Section 3.3
ues and redshift bins \((dz = 0.01)\) and compute the recovery fraction of an inserted doublet as
\[
L(\log(N, dz_j)) = \frac{1}{n} \sum_{i=1}^{n} H(\log(N), b, z)
\]
(2)
where \(n\) is the total number of inserted systems such that \(z \in dz_j\) with column density \(\log(N_{\text{sys}}/\text{cm}^2)\). This above expression denotes how often an inserted absorber would make it on to the initial candidate list which was then visually inspected by the lead author.

### 3.2 Adjusting for user interaction

In order to account for the ability of the lead author to accurately identify an absorber, we create a simple simulation which randomly chooses to/not to insert an absorber with/without a true rest-frame separation. This randomisation ensures that there is no a priori expectation on whether an absorber is inserted and if so, if it is a true absorber. We will describe the false absorbers in the following section (3.3). This voting process is run by eye for 12000 instances. The results (1-for discovery, 0-no discovery) are binned as a function of the boxcar S/N of the inserted feature SNR\(= W_{d1}/\sigma W_{d1}\)\(^9\).

Next, we fit the user success (using a \(\chi^2\) minimisation technique) with an exponential function of the form
\[
P_{d1}(SNR) = P_{\infty}(1 - e^{SNR/SNR})
\]
(3)
where \(P_{\infty}\) is the probability that the user will accept a true absorption system and \(S\) is an SNR exponential scale factor. Just as we found in C17 and similar to the findings of Matejek & Simcoe (2012) and Chen et al. (2017), we find that even for the best S/N regions, the user acceptance rate is not 100\%, except for the artificial doublet Si\(\text{IV}\). Following this, we next fit the user failure with a triangle function
\[
P_{\text{FP}}(SNR) = \begin{cases} 
\frac{p_{\text{FP}}^{\text{max}} (SNR/SP)}{p_{\text{FP}}^{\text{max}} (SNR/SP)} & \text{SNR} \leq SP, \\
SNR/SP & \text{SNR} > SP,
\end{cases}
\]
(4)
where \(p_{\text{FP}}^{\text{max}}\) is the maximum contamination rate which arises at \(SP\). We find that the user acceptance of injected false doublets as real approaches 0 as the SNR reaches ~13. The binned values and best fits can be seen in Figure 3. All best fit values can be seen in Table 4.

Finally, we turn the user success and user failure functional values (eqs. 3 and 4) into grids binned with the same resolution as the recovery function (eq. 2). The resulting grids are denoted as \(A(\log(N), dz_j)\) and \(A_{\text{FP}}(\log(N), dz_j)\), respectively. Following this, we combine the recovery rate (from the automatic detection) with the user success grids
\[
C(\log(N), dz_j) = L(\log(N), dz_j) \times A_{d1}(\log(N), dz_j)
\]
(5)
and an example can be seen 4. The recovery fraction corrected for user success associated with each doublet can be seen in the 5\(\sigma\) recovery rate columns of each sightline discovery table available in the online appendix (see Table 3 for an example). Thirty seven C\(\text{IV}\) systems and seven Si\(\text{IV}\) systems survive a 5\(\sigma\) cutoff. For our analysis, we only use those systems with at least one component with 5\(\sigma\) 50\% or greater recovery fraction corrected for user success, except for system 9 in ULAS J1319 + 0959 for reasons described in sub-section 2.4.4.
user success (eq. 5 and Figure 4) we must account for this

...where the recovery rate is above 50% (see eq. 5). The result-

3.3 False positives

In order to quantify the contamination by false positive
doublets, we search for the artificially spaced absorbers: CIV'\(\lambda\lambda 1548, 1553\) and SiIV'\(\lambda\lambda 1393, 1411\). We perform this
investigation in the same fashion as the search for the CIV and SiIV doublets.

We first create an initial candidate list using the same
detection algorithm described in Sec. 2.1. The automatic
detection algorithm outputs 76 CIV' and 32 SiIV' candidates.
The lead author then selects 3 CIV' and 1 SiIV' possible
absorbers. These absorbers are selected for their similar
velocity profile, with the same considerations described in
sub-section 2.2. Following this, we adjust VPFIT to fit the
above artificial doublets and measure their column density
and Doppler parameter.

Next, we extract a library of artificial ions which we
then insert and search for in the same manner and with the
same resolution as described in sec. 3.1. The results are then
binned and adjusted for user success (see eq. 5). The resulting
maps can be seen in the online appendix. As with the
physically spaced doublets, we only consider those artificial
systems with a 5σ recovery rate adjusted for user success
\(\geq 0.50\). Two CIV' and 1 SiIV' artificial systems survive this
selection.

3.4 Adjusting for varying completeness and false positives

Given the fine resolution of the recovery rate adjusted for
user success (eq. 5 and Figure 4) we must account for this
variability across a larger bin of interest in order to derive
meaningful statistics. As in C17, we first define a visibility
function \(R(dz_j)\). It is defined as 1 redward of the Lyα emission
peak to within 3000 kms\(^{-1}\) of the QSO emission redshift of the
ion in question and 0 everywhere else. We combine eq.

\[ C(\log(N), dz_j) = \begin{cases} 0 & \text{if } C(\log(N), dz_j) < 0.50, \\ 1 & \text{if } C(\log(N), dz_j) \geq 0.50 \text{ & } R(dz_j) = 1. \end{cases} \]  

(6)

This formulation identifies all redshift bins (\(dz_j\)) in which
a single component with column density \(\log(N_{sys}/cm^2)\) will
be identified in our analysis at least 50% of the time. Next,
we split the CIV redshift path in two redshift bins such that
they cover a similar recovery adjusted redshift path. That
redshift midpoint is at \(z = 5.19\).

We then bin and find the average recovery rate adjusted for user success as a function of the column density \(\log(N_{sys}/cm^2)\) of the inserted doublets CIV and SiIV (see Figure 5). For the respective redshift bins (below and above redshift 5.19), we find that for CIV, we are at least 50% complete down to \(\log(N_{sys}/cm^2)\) values of 12.75 and 13.25. For SiIV we are at least 50% complete for \(\log(N_{sys}/cm^2)\) values of 12.45 and 12.58 in the same redshift bins.

Following this, we define the average of a function in each redshift bin

\[ f(dz_j) = \frac{\int R(dz_j) \times f(\log(N), dz_j) \, dN}{\int R(dz_j) \, dN} \]  

and compute the average recovery rate adjusted for user success \(\overline{C}\), the average recovery rate \(\overline{L}\), the average user success \(\overline{A}\) and average user failure \(\overline{Af}\). Using these values, we can then compute the true number of absorbers \(N\)

\[ N = \frac{\overline{N}}{\overline{C} - \overline{L} \times \overline{Af}} \]  

(8)

In the same redshift bin, the true number of false positives

Figure 4. Example CIV 5σ completeness test results for the
ULAS J0148+0600 sightline. The x and y axis represent the wave-
length (Å) and column density \(\log(N)/cm^2\), respectively, of in-
serted systems. The top x axis represents the corresponding red-
shift of an inserted system. Their recovery rate, \(C(dN_{sys}, dz)\), is
denoted by the color bar plotted in each panel. All recovery rates
below 50% are shaded in black. Recovery rates for all sightlines
and for both real and artificial doublets are presented in Sections
F and G of the online appendix. The wavelength resolution of the
recovery function, \(C(dN_{sys}, dz)\), allows us to identify clean por-
tions of the spectra as can be seen in panel A at around −10100 Å
where the recovery rate is above 50% for even the weakest of
inserted systems.

Figure 5. Recovery rates adjusted for user success (eq. 7) for
CIV and SiIV. The vertical lines denote the \(\log(N_{sys}/cm^2)\) values
down to which we are 50% complete (12.45, 12.58, 12.75 and
13.25 respectively). The recovery of CIV past \(z = 5.19\) drops as the
redshift pushes the absorbers into the near infra-red.

\[ f(dz_j) = \frac{\int R(dz_j) \times f(\log(N), dz_j) \, dN}{\int R(dz_j) \, dN} \]  

(7)
\[ (N') \]
\[ N' = \frac{N'}{C' - L \times A^{FP}} \]
\[ F = 1 - \frac{N'}{N} \]

(9)

Thus, the false positive contamination rate is

\[ F = 1 - \frac{N'}{N} \]

We combine eqs. 8 and 10 and define a single scalar for each doublet which accounts for the variable completeness and false positive detections in a redshift bin \((A; \text{see Table 2})\)

\[ A = \frac{F}{C - L \times A^{FP}} \]

Finally, the true number of absorbers adjusted for completeness and false positive contamination is

\[ N = A \times N' \]

with associated Poisson error

\[ \sigma N = A \times \sqrt{N} \]

(13)

### 4 ABSORPTION LINE STATISTICS

When investigating the evolution of absorption systems observed in the spectra of QSOs, it is common to calculate their incidence rate \((dN/dz)\), their comoving mass density \(\Omega_{\text{ion}}\) and their column density distribution function (CDDF). The incidence rate provide a simple accounting on the number of ion\(\text{s}\) and their column density distribution function (CDDF). The integration limits on the \(\Omega\) has the added benefit of investigating the impact of integration corrected number of absorbers (eq. 12) with associated error \(\sigma N\) (eq. 13). All incidence rate values computed in this work are presented in Table 2 and can be seen Figure 6.

The true number of absorbers and associated error are computed in eqs. 12 and 13. This accounts for the contamination by false positives and variable completeness across a redshift bin. The redshift bins are selected so that the C\(\text{IV}\) path is split in almost half as described in sec. 3.4. The incidence rate in a redshift bin \(dz\) is computed as

\[ \left(\frac{dN}{dz}\right) = \frac{N \pm \sigma N}{dz} \]

(14)

where \(N\) is the completeness adjusted and false contamination corrected number of absorbers (eq. 12) with associated error \(\sigma N\) (eq. 13). All incidence rate values computed in this work are presented in Table 2 and can be seen Figure 6.

For C\(\text{IV}\), we compute \(dN/dz = 15.4 \pm 2.8\) at a median redshift \(<z> = 4.77\) and find that it drops by almost a factor of -3.5 with \(dN/dz = 4.4 \pm 1.2\) at a median redshift \(<z> = 5.66\). For Si\(\text{IV}\), we find a similar evolution with the incidence rate \(dN/dz = 9.8 \pm 4.7\) at a median redshift \(<z> = 5.05\) dropping to \(dN/dz = 2.4 \pm 0.9\) at a median redshift \(<z> = 5.66\).

In order to compare with the survey data of D13 we search their tables A1, A2, A3, A4, A5 and A6. We count a total of 79 C\(\text{IV}\) systems, 62 below redshift 5.19 \((dz = 3.86)\) and 17 above redshift 5.19 \((dz = 5.24)\). This leads to the C\(\text{IV}\) incidence rates \(dN/dz = 16.1 \pm 2.0\) at a mean redshift \(z = 4.76\) and \(dN/dz = 3.2 \pm 0.8\) at a mean redshift \(z = 5.69\). They are in good agreement with our incidence rate (including system 9 in ULAS J1319 + 0959). If system 9 is excluded, as it is the only manually introduced absorber as discussed in Sec. 2.4.4, then \(dN/dz = 3.7 \pm 1.1\). This value is still in good agreement with the D13 values.

We also count 19 Si\(\text{IV}\) systems, all above redshift 5.19 across a redshift path \(dz = 5.24\). This leads to an incidence rate \(dN/dz = 3.6 \pm 0.8\) at a mean redshift of \(z = 5.69\). Our incidence rates are well within the error bounds. This is not surprising given that 2 out of our 4 sight lines are in common with D13, whose total sample size is 6 QSOs. The incidence rates computed from the D13 tables are plotted in Figure 6.

Next, we consider if our definition of a system introduces a systematic difference between our incidence statistics and those of D13. We count system 5 in sightline ULAS J0148 + 0600, system 10 in sightline SDSS J0927 + 2001 and system 3 in sightline SDSS J1306 + 0356 as individual systems (see the online appendix). This definition could possibly underestimate the incidence rate in the respective redshift bins. However, this affects only 2 of the 37 C\(\text{IV}\) systems below redshift 5.19 and only 1 of the 8 C\(\text{IV}\) systems above redshift 5.19. The possible relative contribution to the incidence rates resulting from the system definition is then 5.4% and 12.5%, respectively. We then find that our system definition does not introduce a systematic given that the respective relative Poisson errors (see Table 2) are several times larger.

Following this, we also compare with the incidence rates from B15. We find that both the incidence rates of C\(\text{IV}\) and Si\(\text{IV}\) exhibit a flat evolution until \(z < 5\). When we consider the incidence rates of B15 only, we compute a mean incidence rate for C\(\text{IV}\) \(<dN/dz> = 14.6 \pm 3.8\). Both values are well within the error bounds of the incidence rates computed in this study below redshift 5.19. The B15 values are also plotted in Figure 6.

Next, we compute the comoving incidence rates \((dN/dX)\) by calculating the absorption path of our survey, noting that a flat behavior in \(dN/dX\) represents no comoving evolution in the cross-section of the population considered. The absorption distance is defined as

\[ X(z) = \frac{2}{3M} \left[ \Omega_{\text{M}}(1 + z)^3 + \Omega_{\Lambda} \right]^{1/2} \]

(15)

thus for a redshift bin \([z_1, z_2]\) with \(z_2 > z_1\), the absorption path between \(z_2\) and \(z_1\) is

\[ dX_{(z_2, z_1)} = X(z_2) - X(z_1) \]

(16)

For C\(\text{IV}\) we compute \(dN/dX = 3.6 \pm 0.6\) at a median
redshift \( <z> = 4.77 \) and \( dN/dX = 0.9 \pm 0.3 \) at a median redshift \( <z> = 5.66 \) while for Si IV we compute \( dN/dX = 2.2 \pm 1.1 \) at a median redshift \( <z> = 5.05 \) and \( dN/dX = 0.5 \pm 0.2 \) at a median redshift \( <z> = 5.66 \). We find that the comoving incidence rates of C IV and Si IV are not consistent with a no evolution scenario and both decrease from redshift ~5 to 6.

### 4.2 Comoving mass densities

The comoving mass density is defined as the first moment of the CDDF normalised to the critical density today:

\[
\Omega_{\text{ion}} = \frac{M_{\text{ion}}}{\rho_{\text{crit}}} = \int N f(N) dN
\]

where \( m_{\text{ion}} \) is the mass of an ion, \( \rho_{\text{crit}} = 1.89 \times 10^{-29} \text{h}^2 \text{g cm}^{-3} \) and \( f(N) \) is the CDDF. In practice, it is approximated as

\[
\Omega_{\text{ion}} = \frac{M_{\text{ion}}}{\rho_{\text{crit}}} = \frac{1}{dX} \sum_{s} \sum_{N} \sum_{k} N(\text{ion})
\]

where \( s \) represents the number of sightlines with \( \bar{N} \) discovered systems over absorption path \( dX \), each with \( k \) components with respective column density \( N(\text{ion}) \). Given that eq. 18 accounts for all \( k \) components of all \( \bar{N} \) discovered systems, it is not then susceptible to any bias resulting from the definition of a system. In order to implement the same completeness and false positive corrections described in subsection 3.4, we combine eq. 18 with eq. 11 and calculate \( \Omega_{\text{ion}} \) as

\[
\Omega_{\text{ion}} = \frac{A}{dX} \frac{M_{\text{ion}}}{\rho_{\text{crit}}} \sum_{s} \sum_{N} \sum_{k} N_{\text{sys}}(\text{ion})
\]

4.2.1 The comoving mass density of CIV

We compute the comoving mass density of C IV at the median redshifts \( <z> = 4.77 \) and \( <z> = 5.66 \) and find that, as in previous studies, it drops by approximately a factor of \(~4.7\) from \( 1.6^{+0.4}_{-0.1} \times 10^{-8} \) to \( 3.4^{+1.6}_{-1.1} \times 10^{-9} \), respectively.

We plot our values along with those from other studies in Figure 7. If we do not include system 9 in sightline ULAS J1319 + 0959 we compute \( \Omega_{\text{C IV}} = 1.3^{+0.4}_{-0.1} \times 10^{-8} \). The higher redshift Bosman et al. (2017) value is an upper limit on \( \Omega_{\text{C IV}} \) at \( <z> = 6.6 \). The dashed line represents the evolution of \( \Omega_{\text{C IV}} \) from the reference simulation of Garcia et al. (2017) (G17). In that work, a thousand lines of sight have been generated randomly inside the simulated box. The resulting spectra are first convolved with the instrumental resolution of the VLT-UVES spectrograph and then noise is added to reproduce the typical S/N of observational data. Within each sightline, CIV individual absorption features have been searched for and fitted with VPFIT.

The methodology described in G17 thus mimics the work flow of observational studies but is not impacted by observational constraints such as sky-line emission in the NIR. The synthetic absorption systems with column densities span the column density range \( 13.8 \leq \log(N/\text{cm}^2) \leq 15.0 \) are summed up to calculate \( \Omega_{\text{C IV}} \). This column density range selection for synthetic absorbers follows the findings by D13. The C IV systems discovered in this study spans \( 13.00 \leq \log(N/\text{cm}^2) \leq 14.0 \).

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10 Ch 18 512 MDW in their Table 1

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**Figure 6.** Incidence rates \( (dN/dz) \) for C IV and Si IV. The marker style and colors are described in the legend. All values measured with systems described in this work are presented in Table 2. The computation of the D13 values is described in the text. The B15 and S05 values have been adjusted to the Planck cosmology used in this work.

**Figure 7.** The evolution of the comoving mass densities of C IV as measured in this work along with other observational values from literature and the simulation of G17. The line and marker style and colors are described in the legend.

All \( A, dX \) and \( \bar{N} \) values are presented in Table 2. The associated errors are calculated by first bootstrapping 1000 times across the \( \log(N_{\text{sys}}/\text{cm}^2) \) values of each system used. A system can be selected multiple times or not at all. The resulting errors correspond to the 66% confidence interval of the resulting distribution. The B15 and D13 values have been adjusted to the Planck cosmology used in this work.
4.3 Column density distribution functions

We present, for the first time, the comoving mass density of Si	extsc{iv} ($\Omega_{\text{Si	extsc{iv}}}$) beyond redshift 5. The values of B15 and Songaila 2005 (S05) are adjusted to the Planck cosmology used in this work and can be seen, along with our values, in Figure 8. Given that we only have 2 Si	extsc{iv} systems below redshift 5.19, we simply consider the lower and upper log($N_{\text{sys}}$/cm$^2$) bounds of each component and compute the error boundary. We measure $\Omega_{\text{Si	extsc{iv}}} = 4.37 \pm 0.7 \times 10^{-9}$ at a median redshift $<z> = 5.05$ and find that it drops to $\Omega_{\text{Si	extsc{iv}}} = 1.4^{+0.6}_{-0.4} \times 10^{-9}$ by the median redshift $<z> = 5.66$.

Interestingly, the G17 simulation, which accurately reproduces the evolution of $\Omega_{\text{C	extsc{iv}}}$, also reproduces the observed relative evolution of $\Omega_{\text{Si	extsc{iv}}}$. However, it overproduces Si	extsc{iv} by an order of magnitude when considering the column density range 13.00 < log($N$/cm$^2$) < 15.00 (dash-dot line Figure 8).

If the comparison is restricted to the column density range of 12.50 < log($N$/cm$^2$) < 14.00 then they measure $\Omega_{\text{Si	extsc{iv}}} = 3.04 \times 10^{-9}$ which is within 3$\sigma$ of our measured values (see Table 2). We will discuss this in further detail in Sec. 5.1.

4.3 Column density distribution functions

We compute the respective CDFD for each ion in the following manner,

$$f(N) = \frac{n}{\Delta \log(N_{\text{sys}})} \times \frac{1}{dX}$$  \hspace{1cm} (20)

where $N_{\text{sys}}$ is the total column density of a system, $n$ is the number of corrected systems in the column density bin considered ($\Delta \log(N_{\text{sys}})$) and $dX$ is the comoving redshift path (eq. 16). The completeness functions associated with each redshift bin for C	extsc{iv} and Si	extsc{iv} can be seen in Fig. 5. We then perform a powerlaw fit to the column density distribution

$$f(N) = B \times \left( \frac{N_{\text{sys}}}{N_0} \right)^{-\alpha}$$  \hspace{1cm} (21)

where $N_0 = 10^{13.64}$. We adopt this value for $N_0$ in order to compare to the work of D13.

We follow the prescription put forth in B17 and take a maximum-likelihood expectation (MLE) approach. We simultaneously fit for $\alpha$ and $B$ and the likelihood function is defined as

$$L(\alpha, B) = P(n \mid \alpha, B) \times \Pi P(N_{\text{sys}} \mid \alpha)$$  \hspace{1cm} (22)

where $P(n \mid \alpha, B)$ is the Poisson probability of observing $n$ systems given a single instance of $\alpha$ and $B$. We normalise $P(N_{\text{sys}} \mid \alpha)$ so that the expected number of systems is $n$.

The redshift boundaries and transitions considered and best fit values with 1$\sigma$ errors are presented in Table 5. We also investigate if the choice of $N_0$ impacts our results as B17 used log($N_0$) = 13.50 and find that the new values are well within the range of values presented in Table 5. The contour plots of each fit are presented in Section II of the online appendix. An example can be seen in Figure 9. The binned values in Figures 10, 11, 12, 13, 14 and 15 are presented for a by eye comparison to the best fits obtained through the MLE method discussed above.

First, we fit the C	extsc{iv} CDFD and the best fits and binned values can be seen in Figure 10. We investigate the impact of the lowest column density considered as the C	extsc{iv} CDFD appears to flatten below log($N_{\text{sys}}$/cm$^2$) = 13.25. We exclude the lowest column density bin and do not find a significant impact on the final fit parameters. For example, when we use the full range of log($N_{\text{sys}}$/cm$^2$) in the redshift range 4.33 < $z$ < 5.19 we find the best fit values $\alpha = 1.49 \pm 0.13$ and log(B) = -13.86 ± 0.08. If we limit the range to those C	extsc{iv} systems with log($N_{\text{sys}}$/cm$^2$) ≥ 12.75, we find the best fit values $\alpha = 1.69 \pm 0.13$ and log(B) = -13.79 ± 0.08. We find that the best fit $\alpha$ parameter increases to 1.96 ± 0.36 as we move beyond redshift 5.19.

Our values are within 1$\sigma$ of the D13 values which measures $\alpha = 1.62 \pm 0.2$ (4.36 < $z$ < 5.3) and $\alpha = 1.44 \pm 0.3$ (5.3 < $z$ < 6.20). A point of difference is that our column density fitting range does not extend beyond log($N_{\text{sys}}$/cm$^2$) = 14.00 in our highest redshift bin (5.19 < $z$ ≤ 6.13) as in the D13 study.

Next, we compare the C	extsc{iv} and Si	extsc{iv} CDDFs in the same redshift range across the redshift range for which they can be both observed: 4.92 < $z$ ≤ 6.13. The results can be seen in Figure 11. For the Si	extsc{iv} CDDF we compute the best fit values $\alpha = 1.46 \pm 0.31$ and log(B) = -14.77 ± 0.25 (see Table 5). When considering the redshift boundary 5.19 < $z$ ≤ 6.13 we find that the C	extsc{iv} $\alpha$ best fit parameter does not increase, but rather decreases to $\alpha = 1.22 \pm 0.14$. This change is driven by the lack of systems with log($N_{\text{sys}}$/cm$^2$) > 14.25. We see this fluctuation as reflecting the uncertainty associated with our small sample size but we do again highlight that, in all redshift bins, our best fit parameters are within 1$\sigma$ of the D13 values.

We also present, for the first time, the Mg	extsc{ii} CDDFs and best fits in three redshift bins in the full redshift range 2.0 < $z$ ≤ 5.45. The results are based on the 5$\sigma$ recovery selected systems reported in C17 and can be seen in Table 5 and Figure 12. We find that the best fit parameter $\alpha$ is consistent with $\alpha = 1.23 \pm 0.16$ in the redshift range 2.0 < $z$ < 3.0 and $\alpha = 1.09 \pm 0.11$ in the redshift range 4.0 < $z$ ≤ 5.45. Finally, we compute the C	extsc{iv} and Mg	extsc{ii} CDDFs across the redshift range for which they can be both observed: 4.33 < $z$ ≤ 5.45. The binned values and best fits can be seen in Figure 13.
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5 DISCUSSION

We measure, for the first time, the incidence rates and comoving mass density of Si\textsc{iv} ($\Omega_{\text{Si} \textsc{iv}}$) beyond redshift 5.5 and provide additional measurements on the incidence rates and comoving mass density of C\textsc{iv} ($\Omega_{\text{C} \textsc{iv}}$) beyond redshift 4.33. All values computed in this study are presented in Table 2 and can be seen in Figures 6, 7 and 8.

The statistics associated with the C\textsc{iv} and Si\textsc{iv} doublets are adjusted for the human impact (see Section 3.2) on the output of an automated detection algorithm (see Section 2.2). We adjust for the likely contamination by false positive detections and varying completeness across redshift bins (see Section 3.4). We use the completeness adjusted values to compute (Equation 20) and fit (Equation 21) the column density distribution functions (CDDFs) of the Si\textsc{iv} and C\textsc{iv} systems identified in this work as well as the that of the Mg\textsc{ii} systems provided in Codoreanu et al. (2017). The best fit MLE parameters of the fitting functions are provided in Table 5 and can be seen in Figures 10, 11, 12 and 13.

Our study is the first to provide a comprehensive survey which compares both low and high ionisation systems beyond redshift $z = 5$. Below we compare to the the fiducial model of García et al. (2017) (G17); we also discuss the physical connection between low and high ionisation absorbers.
First, we focus on the Si\textsc{iv} systems identified in this work. As we have seen in Section 4.2.2, and as expected, the column density range of the CDDF impacts the computed $\Omega_{\text{Si}\text{iv}}$. The results from the simulation of G17 are in remarkable agreement when restricted to the column density range of Si\textsc{iv} systems discovered in this study ($12.50 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 14.00$; see Table 5) but differs by approximately an order of magnitude when we compare to the column density range considered. We observe none. Next, we consider the case that the CDDF fit of this work extends past $\log(N_{\text{sys}}) \sim 14.00$ and use the best fit values in Table 5 for the redshift range $4.92 \leq z \leq 6.13$. When considering the same column density range we calculate an expectation of $\sim 0.4$ absorbers. This suggests that future surveys which will increase $\Delta N_{\text{Si}\text{iv}}$ to beyond $\sim 40$ should observe a Si\textsc{iv} system with $14.4 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 14.8$. Future surveys with enough path length to at least detect one such system will be able to better address this issue.

While we do not detect any systems with column densities between $14.00 < \log(N_{\text{sys}}/\text{cm}^2) < 15.00$ we should have observed $\sim 12$ Si\textsc{iv} absorbers within the column density range considered. We observe none. Next, we consider the case that the CDDF fit of this work extends past $\log(N_{\text{sys}}) \sim 14.00$ and use the best fit values in Table 5 for the redshift range $4.92 \leq z \leq 6.13$. When considering the same column density range we calculate an expectation of $\sim 0.4$ absorbers. This suggests that future surveys which will increase $\Delta N_{\text{Si}\text{iv}}$ to beyond $\sim 40$ should observe a Si\textsc{iv} system with $14.4 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 14.8$. Future surveys with enough path length to at least detect one such system will be able to better address this issue.

In order to investigate this behaviour, we plot our CDDF values and best fits with the binned CDDF values from G17 (see Figure 14). As can be observed, the two distributions are in good agreement only up to $\log(N_{\text{sys}}/\text{cm}^2)\sim 14.00$. For values of $\log(N_{\text{sys}}/\text{cm}^2) > 14.00$, the Si\textsc{iv} CDDF of G17 disagrees with the extrapolation of the functional fit to the observed distribution. In order to investigate whether the Si\textsc{iv} CDDF of G17 could be representative of the true Si\textsc{iv} population, we ask how many Si\textsc{iv} systems with $\log(N_{\text{sys}}/\text{cm}^2) > 14.00$ we should have observed over the absorption path of our survey ($\Delta N_{\text{Si}\text{iv}} = 16.40$; see Table 2).

We consider the CDDF of G17 in the column density range $14.4 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 14.8$. We find that we should have detected $\sim 12$ Si\textsc{iv} absorbers within the column density range considered. We observe none. Next, we consider the case that the CDDF fit of this work extends past $\log(N_{\text{sys}}) \sim 14.00$ and use the best fit values in Table 5 for the redshift range $4.92 \leq z \leq 6.13$. When considering the same column density range we calculate an expectation of $\sim 0.4$ absorbers. This suggests that future surveys which will increase $\Delta N_{\text{Si}\text{iv}}$ to beyond $\sim 40$ should observe a Si\textsc{iv} system with $14.4 \leq \log(N_{\text{sys}}/\text{cm}^2) \leq 14.8$. Future surveys with enough path length to at least detect one such system will be able to better address this issue.
at $<z> = 4.10$. When we compare to the $\Omega_{\text{Si IV}}$ measured in this study (see Table 2), we find that $\Omega_{\text{Si IV}}$ drops by a factor of $3 \pm 2$ from $<z> = 4.10$ to $<z> = 5.05$. By $<z> = 5.66$ that factor increases to $10 \pm 7$.

For comparison we calculate the fractional evolution of $\Omega_{\text{C IV}}$ using systems identified in this work (see Table 2) and find that $\Omega_{\text{C IV}}$ decreases by a factor of $5 \pm 2$ from $<z> = 4.77$ to $<z> = 5.66$. While this seems to suggest that $\Omega_{\text{Si IV}}$ and $\Omega_{\text{C IV}}$ have similar evolutions from below to beyond redshift 5 we again highlight that our work is the only study, so far, to provide information on $\Omega_{\text{Si IV}}$ beyond redshift 5.5. Future studies will be able to provide further insight on this evolution.

Interestingly, five of the seven Si IV systems also have associated C IV. All of these Si IV systems have log($N_{\text{sys}}$/cm$^2$) $\geq 12.75$. Two of these systems, 8 and 9 in ULAS J1319 + 0959, also have associated low ionisation systems, Mg II + Al II (13670) and C II (1334) + Al II (1670) respectively. As Finlator et al. (2016) have pointed out, Si IV ($\sim 3.3$ Ry) is an intermediary transition between C II (1.8 Ry) and C IV ($\sim 4.7$ Ry). Thus, constraining both the relative evolution of Si IV, C IV and C II as well as the number density and nature/environment of Si IV and C IV systems with log($N_{\text{sys}}$/cm$^2$) $> 14$ is necessary in order to discriminate between different UVB or hydrogen self-shielding prescriptions. Given that we do not identify any Si IV systems with log($N_{\text{sys}}$/cm$^2$) $> 14$ and that all Si IV systems with log($N_{\text{sys}}$/cm$^2$) $> 12.75$ identified in this study have associated C IV we next investigate the population of C IV absorbers identified in this work.

5.2 C IV systems

As we have seen in section 4.3, and as expected, the CDDF slope is sensitive to both the sample size and the column density range of the fit. For example, the best fit parameter $\alpha$ increases from $1.22 \pm 0.14$ to $1.96 \pm 0.36$ when the column density range changes from $\Delta \log(N_{\text{sys}}$/cm$^2$) = [12.50, 14.25] to $\Delta \log(N_{\text{sys}}$/cm$^2$) = [13.00, 14.00] and sample size decreases from 13 to 6 systems (see figures 10 and 11 respectively).

As in the previous section, we compare the C IV CDDF and best fits computed in this work with the C IV G17 CDDF. The results can be seen in Figure 15. We find that both CDDFs are in excellent agreement in the column density range of the systems discovered in this work $\Delta \log(N_{\text{sys}}$/cm$^2$) = [12.50, 14.25]. Unlike the Si IV CDDF's discussed in the previous section, the C IV CDDF of G17 is in excellent agreement with an extrapolation of the functional fit to the C IV CDDF computed in this work, log($N_{\text{sys}}$/cm$^2$) $> 14.25$.

As we have discussed in the previous section, the comoving mass density is sensitive to the column density range considered. We quantify this influence by computing the fractional contribution, $f(\Omega_{\text{C IV}})$, from each column density bin, $\Delta \log(N_{\text{C IV}})$, considered in section 4.3 to the total computed $\Omega_{\text{C IV}}$:

$$f(\Omega_{\text{C IV}}) = \frac{\Omega_{\Delta \log(N_{\text{C IV}})}}{\Omega_{\text{C IV}}}$$

We find that C IV systems with log($N_{\text{sys}}$/cm$^2$) $\geq 14.00$ contribute more than 50% to the comoving mass density of C IV computed in this work, $\Omega_{\text{C IV}}$. The resulting histogram can be seen in Figure 16.

In order to further investigate C IV systems with log($N_{\text{sys}}$/cm$^2$) $\geq 14.00$, we subdivide the C IV absorber population used in this study in 4 categories based on whether or not associated absorbers are also identified at the redshift of the C IV doublet. We find:

- 25 C IV systems with no associated absorbers
- 6 C IV systems with associated low ionisation absorbers: system 3 in ULAS J0148 + 0600, system 5 in SDSS J0927 + 2001, systems 2, 8 and 9 in SDSS J1306 + 0356 and system 3 in ULAS J1319 + 0959
- 2 C IV systems with associated low & high ionisation absorbers: systems 8 and 9 in ULAS J1319 + 0959
- 3 C IV systems with associated high ionisation absorbers: system 7 in ULAS J0148 + 0600, system 8 in SDSS J0927 + 2001 and system 6 in ULAS J1319 + 0959

Following this, we compute the velocity width of each
absorber ($\Delta v_{90}$; Prochaska et al. 2008) and plot the values vs. the column density of each system in Figure 17. We find that four out of the six C\IV systems with log($N_{CIV}$/cm$^2$) $\geq$14.00 have associated low ionisation absorbers. Furthermore, we find that all C\IV systems with $\Delta v_{90}$ $\geq$ 200 kms$^{-1}$ have associated low ionisation absorbers (five of the eight absorbers). In order to highlight these boundaries, we have plotted dashed lines in Figure 17.

These findings suggest that C\IV absorbers with associated low ionisation absorbers contribute significantly to the number density and the comoving mass density of C\IV. Furthermore, these same C\IV systems are dominated by a sub-population of absorbers with broad velocity profiles ($\Delta v_{90}$ $\geq$ 200 kms$^{-1}$). Next, we focus our discussion on the two absorbers with the broadest velocity profiles, systems 8 and 9 in SDSS J1306 + 0356.

5.3 The physical connection between low and high ionisation absorbers
As we have previously discussed in section 2.4.3, we have plotted selected transitions\(^{11}\) of systems 8 and 9 together in Figure 18 in order to highlight the proximity and similar velocity structure of the associated absorbers.

Our first question is to assess if the two systems could be associated with a single galaxy. In order to investigate this possibility, we translate the velocity separation between the reddest C\IV component of system 8 and bluest Mg\II component of system 9 (component $a$ in Table A3 in C17) into a physical separation. This separation is highlighted by the black vertical dashed lines at $+$600 and $+$900 kms$^{-1}$ in Fig. 18 which correspond to redshifts 4.87051 and 4.87638, respectively. The physical distance between the two redshifts is $\sim$550 kpc\(^{12}\). Given that the systems themselves span more than 500 kms$^{-1}$ and are separated by $\sim$550 physical kpc we find that these two absorption systems are most likely tracing two separate structures rather a fortuitous double intersection of our sightline through a single system.

Understanding the environment of such C\IV and Mg\II systems is a crucial step as they have a significant impact on the associated CDDF's and comoving mass densities. Previous studies which have investigated similar Mg\II absorbers\(^{13}\) at $z < 1$ have found that such ultra strong absorbers reside in group environments. The velocity width of the absorbers can be driven by either star formation (SFR $> 5$ M$_{\odot}$yr$^{-1}$) driven outflows (Nestor et al. 2011) or intra-group interactions (Gauthier 2013). Furthermore, such strong C\IV systems (log($N_{CIV}$/cm$^2$)$>14.0$) have also been connected to dense environments populated with young and blue galaxies in the redshift range 1.8$\leq z \leq$3.3 (Adelberger et al. 2005). Are then these systems tracing similar physical environments past redshift 5?

Recently, Cai et al. (2017) also investigated the environment of these same C\IV absorbers using HST narrow band imaging to identify Ly$\alpha$ emitters (LAE). They find a single LAE candidate at an impact parameter of 205 kpc with an associated Ly$\alpha$ luminosity derived star formation rate, SFR$_{Ly\alpha}$ = 2.5 M$_{\odot}$yr$^{-1}$. This would suggest that there are no star forming galaxies with SFR $> 5$ M$_{\odot}$yr$^{-1}$ which can be associated with the absorber.

Given that the study of Cai et al. (2017) does not identify multiple star forming galaxies we favour the hypothesis that the velocity width of the absorbers is driven by tidal interactions between previous outflow material and group members with luminosities below the detection limit of the Cai et al. (2017) study. We find that these Mg\II systems likely trace a disturbed environment, a possibility recently raised by Zou et al. (2017) following their study of strong Mg\II systems in the redshift range 1.73$<z<2.43$. However, since we currently do not have any information on the associated galaxies, it is difficult to create a complete picture.

Despite this lack of information, the physical association of C\IV systems with log($N_{CIV}$/cm$^2$)$>14.0$ with low ionisation systems and their high velocity width ($\Delta v_{90} \geq 200$ kms$^{-1}$) was a possibility recently raised by Zou et al. (2017) following their study of strong Mg\II systems in the redshift range 1.73$<z<2.43$. However, since we currently do not have any information on the associated galaxies, it is difficult to create a complete picture.

\(^{11}\) C\IV ($\lambda 1548$), Mg\II ($\lambda 2796$), Si\II ($\lambda 1526$) and Fe\II ($\lambda 2600$)

\(^{12}\) 3.23 comoving Mpc

\(^{13}\) with W$_{2796} > 3$ $\AA$
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Figure 18. Selected transitions from systems 8 and 9 identified in the SDSS J1306+0356 sightline. Each transition is identified in the bottom middle of each panel. In each panel, the vertical axis is the continuum normalised flux. The horizontal axis is the velocity separation (kms$^{-1}$) from the lowest redshift component of a system. The normalised spectrum is plotted in black and the associated error is in red. The solid blue line represents the full fit to the spectra and includes other ions besides the transition identified in the bottom right of each panel (i.e. the C IV λ1550 transition). Individual components are plotted with dashed lines and are identified by a vertical label. The identified transition components are in solid blue and other transitions are in light blue. The black vertical dashed lines highlight the 0, +500, +600, +900, +1000 and +1500 kms$^{-1}$ velocity locations for reasons discussed in Sec. 5.3.

kms$^{-1}$) suggests that these systems are tracing a multi-phase medium where hot and cold gas is mixing at the interface between the CGM and IGM. Thus, in order to accurately simulate the full C IV population of absorbers this physical interaction must be accounted for.

5.4 The comoving mass densities of low ionisation systems beyond redshift ~2

We have so far provided further measurements of Ω C IV (see Section 4.2.1 and Figure 7) and presented the first measurement of Ω Si IV (see Section 4.2.2 and Figure 8) beyond redshift 5. However, as we have discussed in Section 2.2, we also search for other associated transitions at the redshift of the identified doublets. We do not identify any O I systems over the absorption path of our survey (dX = 8.93).
When considering the C\textsc{iv} and Si\textsc{iv} doublers identified in our work, we find 5 Si\textsc{ii}, 8 Al\textsc{ii}, 6 Fe\textsc{ii}, 1 C\textsc{ii} and 2 Mg\textsc{i} associated transitions with \( z \) &gt; 4.33. These transitions are associated with:
- systems 3 and 9 in sightline ULAS J0148+0600
- system 5 in sightline SDSS J0927+2001
- systems 2, 8 and 9 in sightline SDSS J1306+0356
- systems 8 and 9 in sightline ULAS J1319+0959

We find a further 2 Al\textsc{ii}, 6 Fe\textsc{ii}, 5 Mg\textsc{i} and 1 Ca\textsc{ii} associated with Mg\textsc{ii} doublers below redshift 4.33. We present these absorbers in the online appendix.

All of these transitions are associated with douplet identified absorbers which have a \textit{user success} and failure adjusted recovery rates greater than 50\% (see Section 3). As such, we consider these identifications to be robust. We do not adjust their statistics for completeness and compute their associated comoving mass densities using eq. 18. The errors are calculated using Poisson statistics. We present the comoving mass densities of Fe\textsc{ii}, Si\textsc{ii}, C\textsc{ii}, Mg\textsc{i}, Al\textsc{ii} and Ca\textsc{ii} in Table 6 and Figure 19. We compare our results with the recent work of Lan & Fukugita (2017) (LF17) which provides the comoving mass densities of these ions along with others not identified in this work up to redshift \( z \approx 2.5 \) as traced by Mg\textsc{ii} absorbers.

We find that our \( \Omega_{\text{Fe\textsc{ii}}} \) and \( \Omega_{\text{Mg\textsc{i}}} \) values are in excellent agreement with those presented in LF17 at \( z \approx 2.5 \) and exhibit a flat evolution (within 2\( \sigma \)) from redshift 2 to 5.45. This is unsurprising as the Fe\textsc{ii} and Mg\textsc{i} transitions are mostly\( ^{14} \) associated with strong Mg\textsc{ii} absorbers whose \( \Omega_{\text{Mg\textsc{ii}}} \) exhibits a similar behaviour as discussed in C17. We find a similar flat evolution when comparing the value of \( \Omega_{\text{Si\textsc{ii}}} \) computed in this work at \( <z> = 4.61 (7.5 \pm 3.8 \times 10^{-8}) \) with those of LF17 at \( z \approx 2.4 (\sim 3 \times 10^{-9}) \). Again, this is not surprising since these Si\textsc{ii} and Fe\textsc{ii} transitions are associated with the same systems.

Interestingly, we find that \( \Omega_{\text{Si\textsc{ii}}} \) drops by \( \sim 3 \) orders of magnitude from \( <z> = 4.61 (7.5 \pm 3.8 \times 10^{-8}) \) to \( <z> = 5.77 (1.8 \pm 1.8 \times 10^{-11}) \). We find only one Si\textsc{ii} system beyond redshift 5 (\( z = 5.77495 \pm 0.00038; \) see Figure 2) and it is anchored by a Si\textsc{iv} doublet. However, just as the Fe\textsc{ii} and Mg\textsc{i} systems discussed above, all other Si\textsc{ii} identified in this work are mostly\( ^{14} \) associated with strong Mg\textsc{ii} systems. We see the evolution of \( \Omega_{\text{Si\textsc{ii}}} \) from \( <z> = 4.61 \) to \( <z> = 5.77 \) as simply reflecting this association, or lack there of, and further observational studies will be able to confirm this.

Similar to the evolution of Si\textsc{ii} from redshift 2 to 5.47, we find that \( \Omega_{\text{C\textsc{ii}}} \) also drops by several orders of magnitude from \( \sim 0.5 \times 10^{-7} \) at \( z \approx 2.4 \) (LF17) to \( 6.3 \pm 6.3 \times 10^{-9} \) at \( <z> = 5.57 \) as measured in this work. However, the single C\textsc{ii} transition identified in this work is associated with a single weak Mg\textsc{ii} absorber while LF17 integrate across the full equivalent width range. When we consider the evolution of Al\textsc{ii} we find that it drops by \( \sim 2 \) orders of magnitude from redshift 4.60 to 5.47. Just as with the Si\textsc{ii} and C\textsc{ii} ions, the Al\textsc{ii} absorbers beyond redshift 5 are associated only with weak Mg\textsc{ii} absorbers while the Al\textsc{ii} absorbers below redshift 4 are mostly associated with strong Mg\textsc{ii} absorbers. These absorbers dominate the computed \( \Omega_{\text{Al\textsc{ii}}} \) at \( <z> = 4.60 \).

We find that \( \Omega_{\text{Mg\textsc{i}}} \) and \( \Omega_{\text{Fe\textsc{ii}}} \) have a flat evolution from redshift 2 to 5.45 as measured in this work. When we compare to the findings of LF17, we find a similar evolution for \( \Omega_{\text{Si\textsc{ii}}} \) and \( \Omega_{\text{Al\textsc{ii}}} \) from redshift 2 to 5. However, from redshift

\(^{14}\) except for system 2 in SDSS J1306+0356 which has \( W_{2796} = 0.734 \pm 0.062 \) \( \AA \)

\begin{table}[b]
\centering
\caption{Median redshifts (<\( z > \)), redshift paths (\( \Delta z \)), absorption distances (d\( X \)), discovered systems (N) and the comoving mass densities (\( \Omega \)) for C\textsc{ii}, Si\textsc{ii}, Al\textsc{ii} and Fe\textsc{ii} systems used in this work.}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
ion & <\( z > \) & \( \Delta z \) & d\( X \) & N & \( \Omega \) \\
\hline
Si\textsc{ii} & 4.61 & 4.41-5.00 & 7.70 & 4 & \( 7.5 \pm 3.8 \times 10^{-8} \) \\
& 5.77 & 5.00-6.13 & 17.59 & 1 & \( 1.8 \pm 1.8 \times 10^{-11} \) \\
Al\textsc{ii} & 4.60 & 4.00-5.00 & 16.78 & 8 & \( 2.2 \pm 0.8 \times 10^{-9} \) \\
& 5.47 & 5.00-6.13 & 17.59 & 2 & \( 2.4 \pm 1.7 \times 10^{-11} \) \\
Fe\textsc{ii} & 2.53 & 2.00-3.00 & 13.12 & 4 & \( 2.9 \pm 1.5 \times 10^{-8} \) \\
& 3.41 & 3.00-4.00 & 15.09 & 1 & \( 4.5 \pm 4.5 \times 10^{-9} \) \\
& 4.61 & 4.00-5.45 & 24.84 & 7 & \( 2.6 \pm 1.0 \times 10^{-8} \) \\
C\textsc{ii} & 5.57 & 5.18-6.13 & 11.32 & 1 & \( 6.3 \pm 6.3 \times 10^{-10} \) \\
& 3.41 & 3.00-4.00 & 15.09 & 2 & \( 6.7 \pm 4.7 \times 10^{-11} \) \\
Mg\textsc{i} & 2.53 & 2.00-3.00 & 13.12 & 3 & \( 5.7 \pm 3.5 \times 10^{-11} \) \\
& 3.41 & 3.00-4.00 & 15.09 & 1 & \( 1.7 \pm 1.7 \times 10^{-11} \) \\
Ca\textsc{ii} & 4.61 & 4.00-5.45 & 24.84 & 2 & \( 5.7 \pm 4.0 \times 10^{-11} \) \\
\hline
\end{tabular}
\end{table}

\textbf{Figure 19.} The evolution of the comoving mass densities of Mg\textsc{i}, Ca\textsc{ii}, Si\textsc{ii}, Al\textsc{ii}, Fe\textsc{ii} and C\textsc{ii} as measured in this study. The redshift boundaries, median redshifts and computed \( \Omega_{\text{com}} \) values along with errors can be seen in Table 6. The Mg\textsc{ii} values are taken from C17.
5 to redshift 6 $\Omega_{\text{Si} \text{II}}$, $\Omega_{\text{C} \text{IV}}$ and $\Omega_{\text{Al} \text{II}}$ drop by several orders of magnitude. This evolution results from the association of these absorbers with only weak Mg II absorbers while, from redshift 2 to 5, the Si II and Al II identified in this study are mostly associated with strong Mg II absorbers. For this reason, we caution the reader in drawing significant conclusions from their evolution as the Si II, Ca II and Al II populations identified in this work past redshift 5 are clearly limited by small number statistics. We will further investigate the full population and statistics of Mg II absorbers from redshift 2 to 7 in an upcoming paper.

6 CONCLUSION

We investigate four medium resolution and signal-to-noise spectra of z = 6 QSOs for the presence of C IV, Si IV doublets and associated transitions. These same spectra were investigated for the presence of Mg II doublets in Codoreanu et al. (2017).

We adjust the statistics of the C IV and Si IV systems for the impact of varying signal-to-noise and completeness across the redshift bins considered, the human impact on the identification methodology and false positive contamination. The details are described in Section 3. The incidence rates, absorption paths and comoving mass density values are presented in Table 2 and can be seen in Figures 6, 7 and 8.

We also compute the column density distribution functions (see Equation 20) of Si IV, C IV and Mg II and use a maximum-likelihood estimation (MLE) approach to fit the distributions (see Equation 21). The redshift boundaries and column density ranges considered are presented in Table 5 along with the best fit parameters and associated errors. The CDDFs and best fits are discussed in Section 4.3 and can be seen in Figures 10, 11, 12 and 13. Our main findings are:

1. We visually identify 41 C IV and 7 Si IV systems with 36 and 7 passing our 5σ selection criteria respectively. The highest redshift C IV and Si IV absorbers identified in our survey which meet our 5σ selection criteria are, respectively, system 15 in sightline SDSS J1306 + 0356 with $z = 5.80738 \pm 0.00038$ and 9 in sightline ULAS J0148 + 0600 with $z = 5.77495 \pm 0.00038$. The absorption systems can be seen in the online appendix. An example can be see in Figure 2.

2. We compute the incidence rates of C IV and Si IV and find that both decrease from redshift ~5 to 6. For C IV we compute $dn/dx = 3.6 \pm 0.6$ at a median redshift $<z> = 4.77$ and $dn/dx = 0.9 \pm 0.3$ at a median redshift $<z> = 5.66$. For Si IV we compute $dn/dx = 2.2 \pm 1.1$ at a median redshift $<z> = 5.05$ and $dn/dx = 0.5 \pm 0.2$ at a median redshift $<z> = 5.66$. The values computed in this work can be seen in Table 2. We combine our non comoving incidence rates with those of D’Odorico et al. (2013) and Boksenberg & Sargent (2015). The results can be seen in Figure 6 and the details are described in Section 4.1.

3. We compute, for the first time, the comoving mass density of Si IV ($\Omega_{\text{Si} \text{IV}}$) beyond redshift 5.5. We measure $\Omega_{\text{Si} \text{IV}} = 4.32^{+2.1}_{-1.3} \times 10^{-9}$ at $<z> = 5.05$ and $\Omega_{\text{Si} \text{IV}} = 1.4^{+0.6}_{-0.4} \times 10^{-9}$ at $<z> = 5.66$. We combine our findings with the values computed in the observational study of Boksenberg & Sargent (2015) and the simulations of García et al. (2017). We plot the values in Figure 8. We find that our $\Omega_{\text{Si} \text{IV}}$ values agree very well with the expectations from Garcia et al. (2017) when considering the column density range of systems identified in this work (12.50 < log($N_{\text{sys}}$/cm$^2$) < 14.00). However, when the column density range considered is increased to also include systems with $N_{\text{sys}}$<15.0, the expected $\Omega_{\text{Si} \text{IV}}$ increases by an order of magnitude. We discuss this in further detail below when comparing the Si IV CDDFs of this work vs. those of García et al. (2017). The associated absorption paths, incidence rates and number of absorbers can be seen in Table 2.

4. We also measure the comoving mass density of C IV ($\Omega_{\text{C} \text{IV}}$) beyond 4.34 and find a similar evolution as previous studies (Simcoe 2006; Simcoe et al. 2011; Ryan-Weber et al. 2006; Becker et al. 2009; Ryan-Weber et al. 2009; D’Odorico et al. 2013). We combine our results with those from literature and present them in Figure 7. We measure $\Omega_{\text{C} \text{IV}} = 1.6^{+0.4}_{-0.1} \times 10^{-8}$ at $<z> = 4.77$ and $\Omega_{\text{C} \text{IV}} = 3.4^{+1.6}_{-1.1} \times 10^{-9}$ at $<z> = 5.66$. The associated absorption paths, incidence rates and number of absorbers can be seen in Table 2.

5. We compute the CDDFs of the Si IV and C IV systems used in this work as well as the Mg II systems presented in Codoreanu et al. (2017). We then perform a MLE functional fit (see Equation 21) to the distributions and all best fit parameters can be seen in Table 5. We find that our C IV best fit parameters are within 1σ of those presented in D’Odorico et al. (2013)

6. We compare our Si IV and C IV CDDFs with those presented in and based on the simulations of García et al. (2017) as can be seen in Figures 14 and 15. We find that the C IV CDDFs are in excellent agreement even beyond the range of C IV systems identified in our study (log($N_{\text{sys}}$/cm$^2$) > 14.25). However, we find that our measured Si IV CDDF only agrees with that of García et al. (2017) in the column density range of the systems discovered in this study (12.50 < log($N_{\text{sys}}$/cm$^2$) < 14.00). We discuss this in detail in Section 5.1.

7. We find that 5 of the 7 Si IV systems have associated C IV transitions and 10 of the 36 C IV systems have associated low/high ionisation systems. We compute the velocity width of the C IV absorbers ($\Delta v_0$) and plot them vs. their log($N_{\text{sys}}$/cm$^2$) in Figure 17. We find that all C IV systems with $\Delta v_0 > 200$ kms$^{-1}$ have associated low ionisation systems.

8. We investigate the 2 absorbers with the widest velocity widths, systems 8 and 9 in SDSS J1306 + 0356. In order to highlight their complex velocity structures and proximity, we plot them on the same velocity scale zeroed on the first component of system 8 in Figure 18. These systems are also ultra strong Mg II systems (W$\lambda$7296 > 3 Å). This class of Mg II absorbers has been associated with both star formation (Nestor et al. 2011) and tidal interactions (Gauthier 2013)
in group environments below redshift 1. Recently, Cai et al. (2017) image the SDSS J1306 + 0356 field using HST and find a single LAE with SFR = 2.5 M⊙ yr⁻¹. Given this, we see it likely that these systems are tracing a multi-phase medium where hot and cold gas is mixing at the interface between the CGM and IGM. We discuss this in detail in Section 5.3.

9. We have also identified 5 Si ii, 10 Al ii, 12 Fe ii, 1 C ii, 7 Mg i and 1 Ca ii transitions associated with C IV, Si IV and Mg ii doubles. We compute the associated comoving mass density of each ion and present them in Table 6 and Figure 19. We compare our values with the work of Lan & Fukugita (2017) and find that Ω Si ii, Ω Fe ii, Ω Mg i and Ω Al i exhibit a flat evolution from redshift 2 to 5. We find that Ω Si ii, Ω C ii and Ω Al i decrease by several orders of magnitude. However, this evolution is due to the association of these systems with only weak Mg ii systems beyond redshift 5 while they are mostly associated with strong Mg ii systems below redshift 5. We discuss this in detail in Section 5.4.

We find that C IV systems with log N(sys) > 14 are preferentially physically associated with low ionisation systems and are likely to trace multi-phase gas. Further MUSE (Bacon et al. 2010) observations of these absorbers will be able to identify the physical environment and galaxies responsible for the enrichment and their local contribution to the ionisation field. Recent work by Fumagalli et al. (2017) has connected similar absorber pairs to clustered galaxy formation in filamentary structure at z = 3.22. Extending this work to z = 5 provides an exciting opportunity to explore the connection between absorption systems and the associated emission properties of the galaxies responsible for the metal pollution.

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