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5 Observations of the $z \sim 3.5$ intergalactic medium and comparison to the EAGLE simulations

We study the $z \sim 3.5$ intergalactic medium (IGM) by comparing new, high-quality absorption spectra of eight QSOs with $\langle z_{\text{QSO}} \rangle = 3.75$ to the EAGLE cosmological hydrodynamical simulations. We employ the pixel optical depth method to study how the absorption of one ion varies as a function of another, and uncover strong correlations between CIV, SiIV, OVI and H1, between CII and CIV, and between SiII and SiIV. Mock spectra were generated from the EAGLE simulations and given properties designed to mimic the observations. We find good agreement between the simulated and observed optical depth relations $\tau_{\text{OVI}}(\tau_{\text{H1}})$, $\tau_{\text{CIV}}(\tau_{\text{CIV}})$ and $\tau_{\text{SiIV}}(\tau_{\text{SiIV}})$. However, for $\tau_{\text{CIV}}(\tau_{\text{H1}})$ and $\tau_{\text{SiIV}}(\tau_{\text{H1}})$, the observed $\tau_{\text{med}}$ are higher than those measured from the simulations. The discrepancy increases from up to $\sim 0.1$ dex at $\tau_{\text{H1}} = 1$ to $\sim 1$ dex at $\tau_{\text{H1}} = 10^3$, where we are likely probing dense regions at small galactocentric distances. Invoking different models for the ionizing background radiation, including models softened above 4 Ryd to account for delayed completion of HeII reionization, can bring the observations and simulations into agreement for $\tau_{\text{H1}} \lesssim 10$. Using simulations run at a higher resolution also helps to relieve the tension, although not enough to fully explain the observed difference. The consideration of radiation from local sources could be important for ionizing H1 at small galactocentric distances, and would increase the strength of simulated metal-line absorption at fixed $\tau_{\text{H1}}$. Finally, the good agreement with the observed OVI(H1) relation, which likely probes a hot, collisionally ionized gas phase, indicates that the simulations are not in tension with the hot phase of the IGM, and suggests that the outflows responsible for the enrichment of the IGM may have insufficient cold gas.

Turner, Schaye et al.
In preparation

5.1 Introduction

It is now well established the the high redshift intergalactic medium (IGM) is enriched with heavy metals to metallicites of $10^{-5}$ to $10^{-2}$ solar (e.g., Cowie et al., 1995; Schaye et al., 2003; Simcoe et al., 2004; Aguirre et al., 2008). While metals only constitute a fraction of the total baryon budget, they play an integral role in our understanding of galaxy formation and evolution by providing a fossil record of star formation, and by impacting cooling-rates which can alter structure on many scales (e.g., Haas et al., 2013a).
Because metals are synthesized and released from stars located in very overdense environments, that they need to travel large distances to reach the diffuse IGM, and this transport is likely driven by feedback from star formation and active galactic nuclei (AGN). Although the need for inclusion of these processes in simulations is clear, the mechanisms responsible are not resolved even in state-of-the-art cosmological simulations, making their implementation uncertain. By comparing observed and theoretical metal-line absorption in the IGM, we may be able to constrain enrichment mechanisms such as outflows.

Models and simulations of the IGM have been used to make predictions about sources of metal pollution. Booth et al. (2012) determined that the observations of (Schaye et al., 2003) of C\textsc{iv} associated with weak H\textsc{i} at $z \sim 3$ can only be explained if the low-density IGM has been enriched primarily by low-mass galaxies ($M_{\text{halo}} \leq 10^{10} \, M_\odot$) that drive outflows to distances of $\sim 10^2$ proper kiloparsecs (pkpc). They calculated that $> 10\%$ of the simulated volume and $> 50\%$ of the baryonic mass in their successful model was polluted by metals. The simulations studied in Wiersma et al. (2010) predicted that at least half of the metals found in the $z = 2$ IGM were ejected from galaxies at $z \geq 3$, and that these galaxies had masses less than $M_{\text{halo}} = 10^{11} \, M_\odot$. This picture is consistent with observations by Simcoe et al. (2004), who estimate that half of all baryons are enriched to metallicities $> 10^{-3.5} \, Z_\odot$ by $z \sim 2.5$.

Studies of the IGM using the direct detection of individual metal lines can typically only probe highly overdense gas, which constitutes a very small volume fraction of the Universe. In this work, we employ an approach known as the pixel optical depth method (Cowie & Songaila, 1998; Ellison et al., 2000; Schaye et al., 2000a; Aguirre et al., 2002; Schaye et al., 2003). This technique is a valuable tool for studying the IGM, as it allows us to detect metals statistically even in low-density gas. At the redshifts studied in this work, direct detection of metal-line absorption in regions of the spectrum contaminated by H\textsc{i} is nearly impossible due to the density of the forest. Instead, by using the pixel optical depth method we can correct for contamination and derive statistical properties of absorption by metals in this region. Another advantage of this technique is that it is fast and objective, and thus can be applied uniformly to both observations and simulations.

We apply the pixel optical depth method to both observations and simulations. Our observational sample consists of new spectra of eight $3.62 \leq z \leq 3.922$ QSOs with uniform coverage and high signal-to-noise (S/N). We compare the results to the Evolution and Assembly of Galaxies and their Environments (EAGLE) cosmological hydrodynamical simulations (Schaye et al., 2015; Crain et al., 2015). The EAGLE simulations are ideal for studying metal-line absorption in the IGM, as they have been run at high resolution in a cosmologically representative volume ($\times 1504^3$ particles in a 100 cMpc box). EAGLE has been demonstrated to be in good agreement with a number of relevant observables, including the properties of H\textsc{i} absorption at $z \sim 2–3$ (Rahmati et al., 2015) and O\textsc{v} and C\textsc{iv} column density distribution functions at $z \sim 0$ (Schaye et al., 2015). Furthermore, the simulations reproduce the present-day galaxy stellar mass function, galaxy sizes and the Tully Fisher relation (Schaye et al., 2015), and have been found to match observations of galaxy colours (Trayford et al., 2015) and the evolution of galaxy stellar masses (Furlong et al., 2015).

This paper is structured as follows. In § 5.2, we describe the observations and simulations. We also summarize the pixel optical depth method, and how it is applied. The results are presented in § 5.3, and we give a discussion and conclusions in § 5.4 and 5.5, re-
spectively. Throughout this work, we denote proper and comoving distances as pMpc and cMpc, respectively. Both simulations and observations use cosmological parameters determined from the Planck mission (Planck Collaboration et al., 2013), i.e. $H_0 = 67.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.318$, and $\Omega_\Lambda = 0.683$.

5.2 Method

5.2.1 Observations

We analyze a sample of eight QSOs with $3.62 \leq z_{\text{QSO}} \leq 3.922$. They were selected based on their redshift and the existence of substantial, high S/N data taken with VLT/UVES. Initially, there were already 76.0 hours of UVES data, excluding overheads, of the QSOs. Follow-up observations to fill in the gaps and improve S/N were completed in 62.7 hours of on-source time in programmes 091.A-0833(A), 092.A-0011(A) and 093.A-0575(A) (P.I. Schaye). We note that for Q1422+23, the gaps in the UVES data were filled using archival observations with Keck/HIRES of comparable S/N and resolution (which is $\approx 8.5 \text{ km s}^{-1}$). The properties of the QSOs and the S/N of the spectra are summarized in Table 5.1.

The reduction of the UVES data was performed using the UVES-headsort and UVES-popler software by Michael T. Murphy, and binned to have a uniform velocity dispersion of $1.3 \text{ km s}^{-1}$. The HIRES data was reduced using T. Barlow’s MAKEE package, and binned on to $2.8 \text{ km s}^{-1}$ pixels. The continuum fits for the spectra were performed by hand. Any DLAs or Lyman break regions (i.e., due to strong absorbers in H$\text{i}$) were masked out, with the exception of DLAs in the Ly$\alpha$ forest, which were unmasked when recovering the H$\text{i}$ to be used for subtraction of contaminating absorption by higher-order Lyman series lines from O$\text{v}$ and C$\text{iv}$ optical depths.

To homogenize the continuum fitting errors, we implemented the automated continuum fitting procedure of Schaye et al. (2003) at wavelengths greater than that of the QSO’s Ly$\alpha$ emission, which was applied to both the observed and simulated spectra. The spectrum is divided into rest-frame bins of $\Delta \lambda = 20 \ \text{Å}$, which have central wavelength $\lambda_i$ and median flux $f_{i}$. A B-spline is then interpolated through $f_{k}$, and pixels with flux $N_f \times \sigma$ below the interpolated values are discarded, where $\sigma$ is the normalized noise array. We then recalculate $f_{k}$ without the discarded pixels, and repeat the procedure until convergence is reached. We use $N_f = 2$, which has been shown to be optimal in the C$\text{iv}$ region for spectra with a quality similar to ours, as it induces errors that are smaller than the noise by at least an order of magnitude (Schaye et al., 2003).

5.2.2 Simulations

We compare the observations to predictions from the EAGLE cosmological hydrodynamical simulations. EAGLE was run with a substantially modified version of the $N$-body TreePM smoothed particle hydrodynamics (SPH) code GADGET 3 (last described in Springel 2005). EAGLE uses the hydrodynamics algorithm “Anarchy” (Dalla Vecchia, in prep.; see Appendix A1 of Schaye et al. 2015) which invokes the pressure-entropy formulation of SPH from Hopkins (2013) and the time-step limiter from Durier & Dalla Vecchia (2012). The fiducial EAGLE model is run in a $100 \text{ cMpc}$ periodic box with $1504^3$ of both dark matter
Table 5.1: Properties of the QSOs used in this work, and the median S/N in the H I Lyα and C IV recovery regions. The columns list, from left to right, name, R.A., Dec, redshift, magnitude from Véron-Cetty & Véron (2010), and S/N in the Lyα forest region and C IV region, respectively (see § 5.2.3 for the definition of these regions).

<table>
<thead>
<tr>
<th>Name</th>
<th>R.A.</th>
<th>Dec</th>
<th>zQSO</th>
<th>Mag</th>
<th>S/N_{Lyα}</th>
<th>S/N_{CIV}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q142+23</td>
<td>14:24:38</td>
<td>+22:56:01</td>
<td>3.620</td>
<td>16.5</td>
<td>87</td>
<td>82</td>
</tr>
<tr>
<td>Q0055-269</td>
<td>00:57:58</td>
<td>-26:43:14</td>
<td>3.655</td>
<td>17.47</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>Q1621-0042</td>
<td>16:21:17</td>
<td>-23:17:10</td>
<td>3.709</td>
<td>17.23</td>
<td>78</td>
<td>92</td>
</tr>
<tr>
<td>J0124+0044</td>
<td>01:24:03</td>
<td>+00:44:32</td>
<td>3.834</td>
<td>17.90</td>
<td>48</td>
<td>59</td>
</tr>
</tbody>
</table>

and baryonic particles, and is denoted Ref-L1001504. To test convergence with resolution and box size, runs varying the number of particles and box size were also completed, and are listed in Table 5.2.

The stellar feedback in EAGLE is implemented as in Dalla Vecchia & Schaye (2012), where thermal energy is imparted stochastically. While the temperature of heated particles is always increased by $10^{7.5}$ K, the probability varies with the local metallicity and density (Schaye et al., 2015; Crain et al., 2015). The simulations include thermal AGN feedback (Booth & Schaye, 2009), also implemented stochastically (Schaye et al., 2015). Both stellar and AGN feedback have been calibrated such that the simulations match the observed $z \sim 0$ stellar mass function and galaxy–black hole mass relation, and give sensible disk-galaxy sizes. We note that of the two highest-resolution runs, Ref-L025N072 has been realized with the same subgrid parameters used in the fiducial model, while for the Recal-L025N072 the subgrid parameters were re-calibrated to better match the observed galaxy stellar mass function.

EAGLE also includes a subgrid model for photo-heating and radiative cooling via eleven elements: hydrogen, helium, carbon, nitrogen, oxygen, neon, magnesium, silicon, sulphur, calcium and iron (Wiersma et al., 2009a), assuming a Haardt & Madau (2001) UV and X-ray background. Star formation is implemented with a gas metallicity-dependent density threshold (Schaye, 2004) as described in Schaye & Dalla Vecchia (2008), followed by stellar evolution and enrichment from Wiersma et al. (2009b). Finally, details of the subgrid model for black-hole seeding and growth can be found in Springel et al. (2005); Rosas-Guevara et al. (2013) and Schaye et al. (2015).

For each of our eight observed QSOs, we synthesize 100 corresponding mock spectra using the SPECWIZARD package by Schaye, Booth, and Theuns (implemented as described in Appendix A4 of Theuns et al. 1998). To create mock spectra that resemble the observed QSOs and whose absorption features span a large redshift range, we follow Schaye et al. (2003) and stitch together the physical state of the gas taken from uncorrelated sightlines from snapshots with different redshifts. The ionization balance of each gas particle is estimated using interpolation tables generated from Cloudy (Ferland et al., 2013, version 13.03) assuming uniform illumination by a QSO+galaxy Haardt & Madau (2001) ultraviolet background (UVB). Self-shielding for H I was included by modifying the ionization fraction using the fitting functions of Rahmati et al. (2013a). The normalization of the UVB
5.2 Method

Figure 5.1: The intensity as a function of energy for the different UVB models. The different models are: HM01 QSO+galaxy (Haardt & Madau, 2001), which is our fiducial model; Q-only, which is also by Haardt & Madau (2001) but only considers an ionizing contribution from QSOs; and 4Ryd-10 (4Ryd-100), the same as the fiducial model except that the intensity is reduced by a factor of 10 (100) above 4 Ryd. The vertical light grey lines indicate the ionization energies of ions of interest. All of the UVBs have been normalized to have the same intensity as HM01 at 1 Ryd.

is set such that the median recovered Hı Lyα optical depth of the simulated QSOs agrees with that of the observations. In the EAGLE simulations, the dense particles that represent the multiphase interstellar medium are not allowed to cool below an effective equation of state. We set their temperatures to $10^4$ K when generating the mock spectra, although we note that due to the small cross section of such dense absorbers the effect of including them is negligible.

We set the simulated QSO redshifts to be identical to those of the observed sample, and we consider absorption ranging from $1.5 < z < z_{QSO}$ in every case. We include contributions from from 31 Hı Lyman series transitions beginning with Lyα, and metal-line absorption from Cııı, Cıııı, Cıııı, Feııı, Feıııı, Nıııı, Oıııı, Sıııı, Sııııı, and Sıııııı. To match the observations, the simulated spectra are convolved with a Gaussian with a FWHM=6.6 km s$^{-1}$, and resampled on to pixels of 1.3 km s$^{-1}$. For each observed QSO, we have measured the noise as a function of wavelength and normalized flux, and generated random Gaussian noise with the same variance, which is applied to the simulations.

In addition to using a QSO+galaxy Haardt & Madau (2001) UVB (which we denoted as “HM01”), we examine alternatives to the fiducial model, and have plotted their intensity as a function of energy at $z = 3.5$ in Fig. 5.1. We also consider the Haardt & Madau (2001) background using quasars only (“Q-only”), which which is much harder than the fiducial
model above ~ 4 Ryd. Furthermore, to explore the possible effects of a delayed HeII reionization, we consider UVBs that are significantly softer above 4 Ryd. To implement this, we use the QSO+galaxy model and reduce the intensity above 3 Ryd by a factor of 10 (100), which we denote as “4Ryd-10” (“4Ryd-100”).

5.2.3 Redshift range

The first step for the pixel optical depth recovery involves choosing optimal redshift limits. The fiducial redshift range is selected to lie in the Lyα forest, defined to be:

$$\frac{(1 + z_{qso}) \lambda_{Ly\beta}}{\lambda_{Ly\alpha}} - 1 \leq z \leq z_{qso} - \frac{3000 \text{ km s}^{-1}}{c}$$

(5.1)

where $\lambda_{Ly\alpha} = 1215.7$ Å and $\lambda_{Ly\beta} = 1025.7$ Å are the H\textsc{i} Lyα and Lyβ rest wavelengths, respectively. The lower limit was chosen to avoid the Lyβ forest and corresponds to the Lyβ transition at the redshift of the QSO, while the upper limit is 3000 km s$^{-1}$ bluewards of the QSO redshift to avoid any proximity effects.

For H\textsc{i}, C\textsc{iv} ($\lambda_{rest} = [1548.2, 1550.8]$ Å) and C\textsc{ii} ($\lambda_{rest} = 977.0$ Å) we use the above redshift limits. For the remaining ions, we make slight modifications, listed below, in order to homogenize the contamination. We use the notation $\lambda_{Z,k}$ which represents the rest wavelength of multiplet component $k$ of the ion $Z$.

1. O\textsc{vi} ($\lambda_{rest} = [1031.9, 1037.6]$ Å): We limit the recovery to where O\textsc{vi} overlaps with the Lyβ forest and place a cut-off at the Lyα forest region, which leads to $z_{\text{max}} = (1 + z_{qso}) \lambda_{H\text{i},Ly\beta}/\lambda_{O\text{vi},2} - 1$

2. Si\textsc{iii} ($\lambda_{rest} = 1206.6$ Å): We constrain the recovered optical depth region to not extend outside of the Lyα forest. For Si\textsc{iii}, which extends slightly bluewards into the Lyβ forest, we set $z_{\text{min}} = (1 + z_{qso}) \lambda_{Ly\beta}/\lambda_{Si\text{ii}}$.

3. Si\textsc{v} ($\lambda_{rest} = [1393.8, 1402.8]$ Å): To avoid contamination by the Lyα forest, we limit the blue end of the Si\textsc{v} recovery by setting $z_{\text{min}} = (1 + z_{qso}) \lambda_{Ly\alpha}/\lambda_{Si\text{v},1} - 1$.

5.2.4 Pixel optical depth method

We employ the pixel optical depth method, which we use to study absorption on an individual pixel basis rather than by fitting Voigt profiles to individual lines. The goal is to

### Table 5.2: Characteristics of the EAGLE simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$L$ [cMpc]</th>
<th>$N$</th>
<th>$m_b$ [M$_\odot$]</th>
<th>$m_{dm}$ [M$_\odot$]</th>
<th>$\varepsilon_{com}$</th>
<th>$\varepsilon_{prop}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref-L100N1504</td>
<td>100</td>
<td>2 x 1504$^4$</td>
<td>1.81 x 10$^6$</td>
<td>9.70 x 10$^5$</td>
<td>2.66</td>
<td>0.70</td>
</tr>
<tr>
<td>Ref-L050N0752</td>
<td>50</td>
<td>2 x 752$^4$</td>
<td>1.81 x 10$^6$</td>
<td>9.70 x 10$^5$</td>
<td>2.66</td>
<td>0.70</td>
</tr>
<tr>
<td>Ref-L025N0376</td>
<td>25</td>
<td>2 x 376$^3$</td>
<td>1.81 x 10$^6$</td>
<td>9.70 x 10$^5$</td>
<td>2.66</td>
<td>0.70</td>
</tr>
<tr>
<td>Ref-L025N0752</td>
<td>25</td>
<td>2 x 752$^3$</td>
<td>2.26 x 10$^5$</td>
<td>1.21 x 10$^6$</td>
<td>1.33</td>
<td>0.35</td>
</tr>
<tr>
<td>Recal-L025N0752</td>
<td>25</td>
<td>2 x 752$^3$</td>
<td>2.26 x 10$^5$</td>
<td>1.21 x 10$^6$</td>
<td>1.33</td>
<td>0.35</td>
</tr>
</tbody>
</table>
obtain statistics on absorption by H\textsc{i} and various metal ions in the IGM, and on how their absorption relates to one another. Our implementation is close to that of Aguirre et al. (2002), but with the improvements of Turner et al. (2014). The exact methodology is described in full detail in Appendix A of Turner et al. (2014), and we summarize it here.

After restricting the redshift range, the first step is to convert the flux of every pixel of ion Z and multiplet component k to an optical depth $\tau_{Z,k}(z) = -\ln(F)$, where $F(\lambda)$ is the normalised flux at $\lambda = \lambda_k(1 + z)$. Then, depending on the ion, corrections are made for saturation or contamination, as described below.

1. For H\textsc{i} Ly$\alpha$, while there is very little contamination in the Ly$\alpha$ forest, the absorption in many of the pixels will be saturated, and we use the higher order Lyman series transitions to correct for this. Specifically, if we consider a Ly$\alpha$ pixel to be saturated, we look to $N = 16$ higher-order Lyman lines (beginning with H\textsc{i} Ly$\beta$), and take the minimum optical depth, scaled to that of Ly$\alpha$, of all unsaturated pixels at the same redshift (if any). If we are unable to correct the pixel due to saturation of the higher-order transitions, we set it to a flag value of 10$^4$. Finally, we search for and discard any contaminated pixels, by checking that higher-order transitions do not have optical depth values significantly below what would be expected from the scaled H\textsc{i} Ly$\alpha$ optical depth.

2. For O\textsc{vi} and C\textsc{iii}, we can use the corrected H\textsc{i} Ly$\alpha$ optical depths to estimate and subtract contamination by H\textsc{i}. We do so beginning with H\textsc{i} Ly$\beta$ ($N = 2$) and use higher-order Lyman series orders up to $N = 5$. For saturated O\textsc{vi} and C\textsc{iii} pixels, the optical depth is not well defined and therefore the above subtraction is not performed. Instead, we leave the pixel uncorrected, unless the saturation can be attributed to H\textsc{i}, in which case the pixel is discarded.

3. Si\textsc{iv} and O\textsc{vi} are both closely-spaced doublets, and we can use this fact to correct for contamination. To do so, we scale the optical depth of the weak component to match that of the strong component, and take the minimum of the two components modulo noise. We only take the scaled optical depth of the weaker component if it is significantly lower (when taking into account the noise array) than the stronger component.

4. For C\textsc{iv}, which is a strong transition redward of the Ly$\alpha$ forest, the largest source of contamination is by its own doublet. To correct for this, we perform an iterative self-contamination correction. We first discard any pixels determined to be contaminated by other ions, by checking whether the optical depth of a pixel is too high to be explained by half of the associated stronger component combined with twice the associated weaker component. We then subtract the estimated contribution of the weaker component from each pixel, iterating until convergence is reached.

5.2.5 Analysis

For the analysis, we would like to see how the absorption from one ion varies with that from another. The procedures used here are also described in § 3.4 and 4.2 of Aguirre et al.
(2004). As an illustrative example, we will consider the ions C\textsc{iv} and H\textsc{i}. For a single observed QSO, we use the recovered pixel optical depths to construct a set of pixel pairs where each pair shares the same redshift. We then divide the ions into bins of log $\tau_{\text{H}\text{i}}$, and take the median $\tau_{\text{H}\text{i}}$ and $\tau_{\text{C}\text{iv}}$ in each bin, to obtain $\tau_{\text{C}\text{iv}}(\tau_{\text{H}\text{i}})$, which from this point forward we will denote as $\tau_{\text{C}\text{iv}}(\text{H}\text{i})$. The result of this procedure applied to one of our QSOs is shown in Fig. 5.2, and we briefly describe the characteristics here.

We make note of two different regimes within the C\textsc{iv}(H\textsc{i}) relation. The first is on the right-hand side of Fig. 5.2, where $\tau_{\text{H}\text{i}} \gtrsim 1$. Here, the median C\textsc{iv} optical depth increases with H\textsc{i}, which indicates that the pixels are probing gas enriched by C\textsc{iv}. The value of $\tau_{\text{C}\text{iv}}(\tau_{\text{H}\text{i}})$ constrains the number density ratio of C\textsc{iv} to H\textsc{i}. Next, we turn to the region with $\tau_{\text{H}\text{i}} \lesssim 1$, where $\tau_{\text{C}\text{iv}}$ is approximately constant. This behaviour arises because the median C\textsc{iv} optical depths reach values below the flat level $\tau_{\text{min}}$, which is essentially a detection limit set by noise, contamination, and/or continuum fitting errors. An important caveat to keep in mind throughout this work is that the median recovered metal-line optical depth is not necessarily representative of typical intrinsic pixel optical depths for a given H\textsc{i} bin. In particular, as the metal-line optical depths approach the flat level, it is likely that many individual pixels in a given H\textsc{i} bin have intrinsic metal optical depths at or below the flat level itself. In this case, the median recovered metal optical depth will be determined by the fraction of pixels that have optical depths above the flat level.

To construct the C\textsc{iv}(H\textsc{i}) relation for the observed spectra, H\textsc{i} bins containing fewer than 25 pixels total, are discarded. Furthermore, we divide each spectrum into chunks of 5 Å, and discard any bins containing fewer than 5 unique chunks. To measure errors on $\tau_{\text{C}\text{iv}}$, we create new spectra by bootstrap resampling the chunks 1000 times with replace-
We then measure $\text{C} \nu \left( \text{H}_\beta \right)$ for each bootstrap realization of the spectrum and take the error in each $\tau_{\text{H}_\beta}$ bin to be the $1\sigma$ confidence interval of all realizations.

For the simulated spectra, we measure $\text{C} \nu \left( \text{H}_\beta \right)$ for each mock spectrum, and require that each $\tau_{\text{H}_\beta}$ bin have at least 5 pixels in total. Next, we combine the results for all 100 mock spectra associated with a single observed QSO by measuring the median $\text{C} \nu$ optical depth in each $\tau_{\text{H}_\beta}$ bin for all spectra, and we discard any bin containing contributions from fewer than 5 spectra. Errors are calculated by bootstrap resampling the spectra 1000 times.

Next, we compute the flat levels $\tau_{\text{min}}$, by taking the median of all pixels that have $\tau < \tau_c$, and take $\tau_c = 0.1$ when binning in $\text{H}_\beta$ and 0.01 when binning in $\text{C} \nu$ and Si$\nu$. To estimate the error on $\tau_{\text{min}}$, for the observations we again divide the spectrum into 5 Å chunks, measure $\tau_{\text{min}}$ for 1000 bootstrap realizations, and take the $1\sigma$ confidence interval. For the simulations, we calculate $\tau_{\text{min}}$ for each spectrum, and take the final value to be the median value from all 100 spectra.

Finally, we would like to combine the results from the different QSOs. Because our sample is uniform in terms of S/N, we simply combine the binned data points directly without subtracting $\tau_{\text{min}}$. However, because the implementation of the noise, continuum fitting errors and contamination in simulations is not completely accurate, the flat levels differ from the observations. To account for this offset, we linearly add the difference between flat levels ($\tau_{\text{min}}^{\text{obs}} - \tau_{\text{min}}^{\text{sims}}$) to the median optical depths in the simulations. We have verified that performing this step before the QSOs are combined does not modify the results. Next, to measure the combined median values, we perform $\chi^2$ fitting of a single value of $\tau_{\text{C} \nu}^{\text{med}}$ to all points in the bin, which is plotted against the central value of each $\text{H}_\beta$ bin (in contrast to the results from individual QSOs, which are plotted against the median of all $\text{H}_\beta$ pixel optical depths in each bin). We discard any data points that have contributions from fewer than four QSOs, and the $1\sigma$ errors are estimated by bootstrap resampling the QSOs. The combined results for $\text{C} \nu \left( \text{H}_\beta \right)$ can be seen in the left panel of Fig. 5.3.

### 5.3 Results

We begin by examining relations involving metal-line optical depths against $\text{H}_\beta$ in Fig. 5.3, where we have plotted $\text{C} \nu \left( \text{H}_\beta \right)$, Si$\nu \left( \text{H}_\beta \right)$ and O$\nu \left( \text{H}_\beta \right)$ from left to right. The grey points with error bars represent the observations, while the curves show results from simulations, with different colours indicating variations in the UVB model. The data from the observations is presented in Table 5.3.

These relations can potentially probe gas metallicity as a function of density, as explained below using $\text{C} \nu$ as an illustrative example. The equation for metallicity can be written as follows:

$$\left[ \frac{\text{C}}{\text{H}} \right] = \log_{10} \left( \frac{\tau_{\text{C} \nu}}{\tau_{\text{H}_\beta}} \right) \left( \frac{f(\lambda)_{\text{H}_\beta}}{f(\lambda)_{\text{C} \nu}} \right) \frac{n_\text{C}}{n_\text{H}} \frac{n_{\text{H}_\beta}}{n_\text{H}} - \left[ \frac{\text{C}}{\text{H}} \right]_{\odot}, \quad (5.2)$$

where $f$ and $\lambda$ are the oscillator strength and rest wavelength. While $\tau_{\text{C} \nu}/\tau_{\text{H}_\beta}$ can be measured from the data, $n_\text{C}/n_{\text{C} \nu}$ and $n_{\text{H}_\beta}/n_\text{H}$ need to be estimated. If the gas being probed is photoionized, which has been found to be a reasonable assumption for $\text{C} \nu$ and Si$\nu$ (Schaye et al., 2003; Aguirre et al., 2004), then $\text{H}_\beta$ is considered a good tracer of the density (Schaye, 2001), even on an individual pixel basis (Aguirre et al., 2002). Thus, fixing the gas
Figure 5.3: Median recovered pixel optical depths binned by H\textsc{i} for C\textsc{iv} (right), Si\textsc{iv} (centre) and O\textsc{vi} (right). The data from eight QSOs have been combined, and the 1σ error bars are measured by bootstrap resampling the QSOs. The black circles show the data, while the curves denote the results from simulations, where different colours represent variations in the UVB and we show the 1σ error region around the fiducial HM01 model. The median $\tau_{\text{min}}$, which is the same for the observations and simulations by construction, is indicated by the dashed horizontal line. The data from the observations is provided in Table 5.3. We find that the simulation run with the fiducial UVB systematically underpredicts the median C\textsc{iv} and Si\textsc{iv} optical depths. The discrepancy is lessened by invoking a softer UVB (4Ryd-10 and 4Ryd-100), although the metal optical depths associated with the strongest H\textsc{i} absorption is still underestimated by ~ 0.5 dex. In contrast, the predicted O\textsc{vi}(H\textsc{i}) relation (right panel) is insensitive to the UVB models, and in good agreement with the observations.
temperature at $2 \times 10^4$ K (typical for a moderately overdense IGM region, e.g. Schaye et al. 2000b; Lidz et al. 2010; Becker et al. 2011), we can estimate the gas density from $\tau_{\text{HI}}$ using equation 5 of Turner et al. (2015).

With the density and temperature fixed, the ionization fractions of H$\text{I}$ and C$\text{IV}$ can be predicted from CLOUDY ionization modelling. Therefore, equation 5.2 illustrates that at fixed $\tau_{\text{HI}}$, the metallicity will only depend on $\log_{10} \tau_{\text{CIV}}$ under these assumptions. Thus, in the left panel of Fig. 5.3 where we examine the C$\text{IV}$($\text{HI}$) relation, if our assumption of photoionization equilibrium holds then a higher C$\text{IV}$ at fixed H$\text{I}$ will correspond to a higher metallicity at fixed density.

In the following analysis, we will consider the results in two different regimes, separated by $T_{\text{HI}} \sim 10$. The reasons for this are: (1) if the gas being probed is mainly in photoionization equilibrium, then higher H$\text{I}$ optical depths will be probing dense regions closer to galaxies, rather than the diffuse IGM, and (2) in this regime the H$\text{I}$ pixel optical depths will be highly saturated, and even though this is corrected for in our recovery procedure, the final values still suffer from large uncertainties compared to their unsaturated counterparts.

With the above in mind, we can interpret the results of Fig. 5.3. First focusing on the left panel, we find that at fixed H$\text{I}$, the observed median C$\text{IV}$ optical depths are significantly higher than in the fiducial UVB simulations. The discrepancy increases from $\sim 0.1$ dex at $\tau_{\text{HI}} = 1$ to $\sim 0.5$ dex at $\tau_{\text{HI}} = 10$ and $\sim 1$ dex at $\tau_{\text{HI}} = 10^2$. This suggests that at a given gas overdensity, the carbon abundance in the simulations could be lower than that of the observations by up to $\sim 0.5$ dex ($\sim 1.0$ dex for $\tau_{\text{HI}} \lesssim 10$ ($\tau_{\text{HI}} \gtrsim 10$). Next, we examine different UVB models. While the harder Q-only background provides a worse match to the observations, 4Ryd-10 and 4Ryd-100 fare much better. Although these models still fall short of the observed $\tau^\text{med}_{\text{CIV}}$ by about $0.5$ dex in the highest $\tau_{\text{HI}}$ bin, the softest background

<table>
<thead>
<tr>
<th>$\log_{10} \tau_{\text{bin}}$</th>
<th>C$\text{IV}$($\text{HI}$)</th>
<th>S$\text{II}$($\text{H}$I)</th>
<th>O$\text{VI}$($\text{H}$I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-9.00$</td>
<td>$-2.90$</td>
<td>$-2.85$</td>
<td>$-1.10$</td>
</tr>
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</tr>
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<td>$-2.84_{-0.09}^{+0.08}$</td>
<td>$-1.12_{-0.04}^{+0.04}$</td>
</tr>
<tr>
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<td>$-2.89_{-0.04}^{+0.04}$</td>
<td>$-2.83_{-0.06}^{+0.06}$</td>
<td>$-1.09_{-0.03}^{+0.04}$</td>
</tr>
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<td>$-3.04_{-0.10}^{+0.17}$</td>
<td>$-2.87_{-0.07}^{+0.08}$</td>
<td>$-1.14_{-0.04}^{+0.06}$</td>
</tr>
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<tr>
<td>$0.10$</td>
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</tr>
<tr>
<td>$0.70$</td>
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<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
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<td>$-2.55_{-0.07}^{+0.07}$</td>
<td>$-0.98_{-0.02}^{+0.02}$</td>
</tr>
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<td>$1.30$</td>
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<td>$-2.89_{-0.21}^{+0.07}$</td>
<td>$-1.05_{-0.06}^{+0.06}$</td>
</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>$1.90$</td>
<td>$-1.46_{-0.05}^{+0.05}$</td>
<td>$-1.87_{-0.12}^{+0.12}$</td>
<td>$-0.83_{-0.08}^{+0.10}$</td>
</tr>
</tbody>
</table>
is nearly fully consistent with the observations for $\tau_{\text{HI}} \lesssim 10$.

In the centre panel of Fig. 5.3, we show Si\textsc{v}\,(\text{H}1), and find results that are qualitatively similar to those for C\textsc{iv}\,(\text{H}1), but with overall better agreement between the simulations and observations. While for $\tau_{\text{HI}} \gtrsim 10$ the Si\textsc{v} optical depths are underestimated by the fiducial UVB simulations by a factor ranging from $\sim 0.2$ dex at $\tau_{\text{HI}} = 10$ up to $\sim 0.8$ dex at $\tau_{\text{HI}} = 10^{2}$, below this threshold the discrepancy only reaches $\sim 0.1$ dex. Invoking the softest UVB model leads to near agreement for all but the highest H\textsc{i} optical depth.

Next, we consider the O\textsc{v}\,(\text{H}1) relation in the right panel of Fig. 5.3. While C\textsc{iv} and Si\textsc{v} are expected to mainly probe cool photoionized gas, O\textsc{v} reaches its peak ionization fraction of $\sim 0.2$ at $T = 3 \times 10^{7}$ K, which is close to temperatures expected of shocks associated with accretion events or winds. Simulations predict that O\textsc{v} around massive galaxies resides primarily in collisionally ionized gas (e.g. Stinson et al., 2012; Ford et al., 2013; Shen et al., 2013). Applying ionization modelling to observations also provides evidence that O\textsc{v} near strong H\textsc{i} can probe this hot gas phase (e.g, Aguirre et al., 2008; Danforth & Shull, 2008; Savage et al., 2014; Turner et al., 2015).

Indeed, the results from the right panel of Fig. 5.3 differ considerably from the previous two relations. Firstly, the simulation realized with the fiducial UVB is almost fully consistent with the observations, with any discrepant points offset by a maximum of 0.2 dex (note the smaller dynamic range of the $y$-axis compared to the previous panels). Furthermore, while the alternate UVBs have slightly lower $\tau_{\text{Ov}}$ than the fiducial model, overall we do not find significant differences between the models. This suggests that in EAGLE the O\textsc{v}\,(\text{H}1) relation may be probing a primarily collisionally ionized gas phase, where variations in the ionization background do not have a significant impact on the results. We note that if the pixel optical depths do not originate predominantly from photoionized gas, then $\tau_{\text{HI}}$ can no longer be used as a measure of the density.

While metal ions as a function of $\tau_{\text{HI}}$ can probe the metallicity-density relation, examining different ionization states of a single element can the physical properties of the gas, because the ionization fractions that set the relative optical depths will only depend on the temperature, the density, and the UV radiation field (but not on the metallicity). These optical depth ratios have previously been used to determine that the gas probed by C\textsc{iv} and Si\textsc{v} is consistent with being in photoionization equilibrium (Schaye et al., 2003; Aguirre et al., 2004).

Fig. 5.4 examines C\textsc{iii}(C\textsc{iv}) and Si\textsc{iii}(Si\textsc{v}), and the observational data is provided in Table 5.4. Looking first at C\textsc{iii}(C\textsc{iv}), we find that HM01 is consistent with all of the C\textsc{iv} bins, while the remaining models fall short of the highest point. We also see that for this relation, the harder Q-only background is favoured compared to the softer variations. The 4Ryd-100 model does particularly poorly, and differs from the observations by up to 0.4 dex. Next, we find the Si\textsc{iii}(Si\textsc{v}) relation to be somewhat less constraining. While the HM01 model presents the largest discrepancy with the data, the difference is not more than $\sim 0.1$ dex when the errors are considered, and is only seen in the highest Si\textsc{v} bins. Indeed, Si\textsc{iii} overlaps mainly with the Ly\alpha forest and we do not perform any contamination correction, so we consider it more uncertain than C\textsc{iii}. Thus, we find good agreement between the data and the fiducial UVB model for both relations, which suggests that the temperature and density of the gas probed by C\textsc{iv} and Si\textsc{v} pixels is consistent between the observations and simulations.

In Fig. 5.5 we examine relations between different metal ions, which trace relative abun-
Figure 5.4: The same as Fig. 5.3, but showing CIII(CIV) and SiIII(SiIV), and with the data from observations presented in Table 5.4. Unlike for relations binned by H1, different ionization states of the same element are not sensitive to the metallicity of the gas. We find that for CIII(CIV), the simulations and data are in good agreement for the fiducial ionizing background, and the observations particularly disfavor the softest UVBs. The SiIII(SiIV) relation is somewhat less constraining, and while the median SiIII optical depths from HM01 model are slightly above the observed values, the discrepancy is no more than 0.1 dex and only seen in the highest SiIV bins. This indicates that the temperature and density of the gas probed by pixels with detected CIV and and SiIV is well captured by the simulations, without needing to invoke modifications to the ionizing background.

Table 5.4: Observational data from Figs. 5.4 and 5.5. The format is the same as Table 5.3, but here we present relations binned by either CIV or SiIV optical depths. The left column indicates the central value of the CIV or SiIV bin, and the subsequent columns list the median recovered optical depths for the relation denoted in the top row. The row where log10 τbin = −9 provides the median log10 τmin of the eight QSOs.

<table>
<thead>
<tr>
<th>log10 τbin</th>
<th>CIII(CIV)</th>
<th>SiIII(SiIV)</th>
<th>SiIV(CIV)</th>
<th>OVI(CIV)</th>
<th>OVI(SiIV)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>−0.50</td>
<td>−2.78</td>
<td>−1.06</td>
<td>−1.10</td>
</tr>
<tr>
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<td>−0.54±0.03</td>
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<td>−1.17±0.08</td>
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</tr>
<tr>
<td>−1.70</td>
<td>−0.71±0.03</td>
<td>−0.54±0.04</td>
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<td>−1.07±0.03</td>
<td>−1.10±0.03</td>
</tr>
<tr>
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<td>−1.04±0.02</td>
<td>−1.08±0.04</td>
</tr>
<tr>
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<td>−0.72±0.07</td>
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</tr>
<tr>
<td>−1.10</td>
<td>−0.64±0.09</td>
<td>−0.44±0.06</td>
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</tr>
<tr>
<td>−0.90</td>
<td>−0.37±0.06</td>
<td>−0.41±0.32</td>
<td>−1.98±0.07</td>
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<td>−0.86±0.04</td>
</tr>
<tr>
<td>−0.70</td>
<td>0.01±0.16</td>
<td>−0.18±0.10</td>
<td>−1.57±0.18</td>
<td>−0.60±0.08</td>
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</tr>
<tr>
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<td>...</td>
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</tr>
<tr>
<td>−0.30</td>
<td>...</td>
<td>...</td>
<td>−0.87±0.17</td>
<td>−0.89±0.31</td>
<td>...</td>
</tr>
<tr>
<td>−0.10</td>
<td>...</td>
<td>...</td>
<td>−0.82±0.01</td>
<td>−0.40±0.00</td>
<td>...</td>
</tr>
</tbody>
</table>
Figure 5.5: The same as Fig. 5.3, except showing \text{Si\textsc{iv}(C\textsc{iv})}, \text{O\textsc{vi}(C\textsc{iv})} and \text{O\textsc{vi}(Si\textsc{iv})} from left to right, which probe relative abundances. The data from the observations is given in Table 5.4. In the left panel, we find that \( \tau_{\text{med}} \) is underestimated by the simulations, and is insensitive to the choice of UVB. Next, for \text{O\textsc{vi}(C\textsc{iv})} and \text{O\textsc{vi}(Si\textsc{iv})} we observe a stronger sensitivity to different ionizing background models compared to \text{O\textsc{vi}(H\textsc{i})}. For these relations, we observe a better match between the fiducial and hardest UVB models (HM01 and Q-only), in tension with the results from \text{C\textsc{iv}(H\textsc{i})} and \text{Si\textsc{iv}(H\textsc{i})} relations, where we find a strong preference for the softer ionization backgrounds (see Fig. 5.3).
dances and physical conditions. The data for this figure is provided in Table 5.4. For example, Si/C, which can be estimated using the Si\textsuperscript{II}/C\textsuperscript{IV} relation, has been found to be greater than solar by a factor of a few (e.g., Songaila, 2001; Boksenberg et al., 2003; Aguirre et al., 2004). In the left panel of Fig. 5.5, we plot the median Si\textsuperscript{II} optical depth against C\textsuperscript{IV}. While the results are not very sensitive to the choice of ionizing background, all UVB models present a paucity of Si\textsuperscript{II} with respect to the observations. Since [Si/C] is not fixed in the simulations, this may indicate that at z ∼ 3.5 they have lower [Si/C] than observed.

We briefly draw attention to the bin centred at log_{10} τ_{\text{C\textsuperscript{IV}}} = −0.3, where the median Si\textsuperscript{II} optical depth deviates starkly from the rest of the points. The same behaviour is also seen in the central panel of Fig. 5.5, in which we examine O\textsuperscript{VI}(C\textsuperscript{IV}). To find the origin of this inconsistency, we turn to the relations of individual QSOs, in Figs. 5.13 and 5.14. In the case of Q13I7–507 (the upper right panel of both figures), the median Si\textsuperscript{II} and O\textsuperscript{VI} optical depths are unusually low in this C\textsuperscript{IV} bin, while having relatively small error bars (the median optical depths of different QSOs are combined in linear space). We conclude that these points from Q13I7–507, likely the result of small number statistics, are responsible for the anomaly in the Si\textsuperscript{II}(H\textsc{i}) and C\textsuperscript{IV}(H\textsc{i}) relations.

The centre panel of Fig. 5.5 shows τ_{\text{med}}^{\text{OVI}} binned by τ_{\text{C\textsuperscript{IV}}}. In contrast to the O\textsuperscript{VI}(H\textsc{i}) relation (Fig. 5.3, right panel), it is apparent that the median O\textsuperscript{VI}(C\textsuperscript{IV}) optical depth depends strongly on the choice of UVB. This is consistent with the picture that C\textsuperscript{IV} primarily traces photoionized gas, which will be sensitive to the ionizing background. We find that the fiducial HM01 model is most consistent with the data for this relation, even when including the bin centred at log_{10} τ_{\text{C\textsuperscript{IV}}} = −0.3. Finally, in the right panel of Fig. 5.5 we show O\textsuperscript{VI}(Si\textsuperscript{IV}). Except for log_{10} τ_{\text{Si\textsuperscript{IV}}} ≥ −0.5, we observe a much weaker sensitivity to UVB compared to O\textsuperscript{VI}(C\textsuperscript{IV}), but we still find that the fiducial model provides the best match to the data.

5.4 Discussion

In the previous section, we compared observations of pixel optical depth relations to the EAGLE simulations. We considered a fiducial QSO+galaxy HM01 UVB (Haardt & Madau, 2001), as well a harder QSO-only model, and two softer UVBs with reduced intensity above 4-Ryd by factors of 10 and 100, respectively. For O\textsuperscript{VI}(H\textsc{i}), we found an insensitivity to the ionizing background model, and saw good agreement between the simulations and the data. However, the observed median optical depths from the C\textsuperscript{IV}(H\textsc{i}) and Si\textsuperscript{IV}(H\textsc{i}) relations were measured to be systematically higher than those derived from the simulations using the fiducial UVB. The discrepancy is found to be up to ~ 0.5 dex below τ_{\text{H\textsc{i}}} = 10 and up to 1 dex for H\textsc{i} bins above this threshold. For Si\textsuperscript{IV}(H\textsc{i}), invoking the softest UVB (4Ryd-100) fully alleviates the tension, while for C\textsuperscript{IV}(H\textsc{i}) we still find this model fall short of the data, but only for τ_{\text{H\textsc{i}}} ≥ 10. In this section, we would like to discuss possible reasons for this observed mismatch.

Can the discrepancies between the observations and simulations be attributed to differences in the UVB? We have indeed found better agreement with the observed C\textsuperscript{IV}(H\textsc{i}) and Si\textsuperscript{IV}(H\textsc{i}) relations using our softest UVBs, 4Ryd-10 and 4Ryd-100. The reduced intensity above 4 Ryd disfavors ionization to higher states, increasing the abundances of Si\textsuperscript{IV} and C\textsuperscript{IV}. The Haardt & Madau (2001) models take He\textsc{II} reionization into account, and predicts that the He\textsc{II} fraction already reaches 50% at z ∼ 6. However, recent studies
suggest that the reionization process is patchy, with HeII optical depths still high above 
$z \gtrsim 3$ (e.g., Shull et al., 2010; Worseck et al., 2011). Thus, the work presented here probes the 
epoch where the observed gas may be subject to a heavily fluctuating UVB above 4 Ryd. The much better match of the 4Ryd-10 and 4Ryd-100 UVBs suggest that HeII reionization could be complete too early in the simulations. Turning to other optical depth relations, we find that CIII(1) and SiII(1) do not strongly rule out the 4Ryd-10 and 4Ryd-100 models. While these soft UVBs are inconsistent with OVI(1), it is only for bins where $\log_{10} \tau_{CIV} \gtrsim -0.7$, which are higher than relevant for Fig. 5.3.

An alternative effect could be the presence of ionization due to stellar light from nearby galaxies, which is thought to be important for absorbers are rare as Lyman limit systems (Schaye, 2006; Rahmati et al., 2013b). The strength of the ionizing radiation emitted by galaxies drops sharply above 4 Ryd, but could strongly ionize H$_1$, lowering the typical optical depths. If H$_1$ optical depths are lower, than at a fixed H$_1$ the metal line optical depths will be higher. This could explain the larger discrepancy seen at $\tau_{H_1} \gtrsim 10$, where the pixel optical depths are probing denser gas at small galactocentric distances compared to lower H$_1$ optical depths. However, since it is difficult to estimate the shape and normalization of this ionizing radiation (and it likely should not be applied uniformly), we leave testing of this explanation to a future work.

Another possibility is that the metallicity in the simulations is too low, and/or that the metals are not getting out far enough in the IGM. A too low metallicity or volume filling fraction of enriched gas could occur if the simulations are not resolving the low-mass galaxies (containing at least 100 star particles) with $M_\star = 2.3 \times 10^7 \, M_\odot$, almost an order of magnitude below that of our fiducial model, where a 100 star particle galaxy would have stellar mass of $1.8 \times 10^8 \, M_\odot$. Indeed, we find that relations involving CIV are not fully converged at our fiducial resolution, and invoking the highest-resolution model for CIV(H$_1$) results in an increase in $\tau_{CIV}^{med}$ of up to $\sim 0.3$ dex in the highest H$_1$ bins. This result suggests that our fiducial simulation may be missing metals ejected from galaxies with stellar masses below $\sim 1.8 \times 10^8 \, M_\odot$. However, while a higher resolution should certainly bring the observations and simulations closer to agreement, the effect does not appear to be strong enough to fully explain the differences seen in the CIV(H$_1$) relation, and furthermore the SiIV(H$_1$) relation shows almost no change when the resolution is increased. Therefore, we believe that other effects may be at play.

An important piece of information to consider is the good agreement between the observed and simulated OVI(H$_1$) relations. The insensitivity of the different UVB models to $\tau_{OVI}^{med}$ (when binned by H$_1$) suggests that the gas is primarily collisionally ionized, and hence that OVI(H$_1$) is probing a hotter gas phase than CIV(H$_1$) and SiIV(H$_1$). From this, we can conclude that the simulations correctly capture the hot gas in the IGM at $z \sim 3.5$.

Aguirre et al. (2005) found an even more severe underestimation of simulated median CIV optical depths, with the tension also being alleviated by invoking a softer UVB. In con-
In this work we used pixel optical depth relations to study the $z \sim 3.5$ IGM, taking data from a sample of eight $\langle z_{\text{QSO}} \rangle = 3.7$ QSOs, and compared our results with the EAGLE simulations. The QSOs were observed with VLT/UVES, and their spectra are uniform in their S/N and coverage. We employed the pixel optical depth technique to obtain H I and metal-line absorption partially corrected for the effects of noise, contamination, and saturation. The resulting pixel optical depth relations were compared to those derived from mock spectra generated from the EAGLE simulations. The mock spectra were synthesized to have a resolution, pixel size, S/N and wavelength coverage closely matched to the observations. We have considered a fiducial QSO+galaxy UVB (Haardt & Madau, 2001), as well
as a harder QSO-only model and models with reduced intensity above 4 Ryd by factors of 10 and 100, respectively. The fiducial EAGLE model has been run in a cosmologically representative box size (100 cMpc) at a relatively high resolution (2 × 15043 particles), and the supernova and AGN feedback has been calibrated to reproduce the z ∼ 0 galaxy stellar mass function, galaxy-black hole mass relation, and galaxy disk sizes. Our conclusions are listed below.

- We have detected strong correlations for the observed C\textsc{iv}(H\textsc{i}), Si\textsc{ii}(H\textsc{i}), O\textsc{v}(H\textsc{i}) relations, as well as for C\textsc{iii}(C\textsc{iv}) and Si\textsc{iii}(Si\textsc{iv}) (Figs. 5.3 and 5.4).

- We find that for the C\textsc{iv}(H\textsc{i}) and Si\textsc{ii}(H\textsc{i}) relations, the observed metal-line optical depths are higher than the simulations run with the fiducial HM01 UVB. For C\textsc{iv}(H\textsc{i}), we find a discrepancy of up to ∼ 0.1 dex at τ_{H\textsc{i}} = 1, ∼ 0.5 dex at τ_{H\textsc{i}} = 10, and ∼ 1 dex at τ_{H\textsc{i}} = 10², where we believe we are probing gas at high densities and small galactocentric distances. For Si\textsc{ii}(H\textsc{i}) the agreement is slightly better, and we find that the observed data points are higher by up to ∼ 0.2 dex at τ_{H\textsc{i}} = 10 up to ∼ 0.8 dex at τ_{H\textsc{i}} = 10². In contrast, O\textsc{v}(H\textsc{i}), which likely probes a hotter gas phase, provides good agreement with the data (Fig. 5.3).

- We consider UVBs that differ from the fiducial HM01 model, including a harder quasar-only background (Q-only) and softer backgrounds with 10 and 100 times reduced intensity above 3 Ryd (3Ryd-10 and -100). The softer models, which may be more realistic than our fiducial background if He\textsc{ii} is still partially ionized at z ∼ 3.5, are a better match to the C\textsc{iv}(H\textsc{i}) and Si\textsc{ii}(H\textsc{i}) relations, and can nearly reproduce the observations for τ_{H\textsc{i}} ≲ 10. The results of the O\textsc{v}(H\textsc{i}) relation are insensitive to the change in UVB, which suggests that O\textsc{v} is tracing predominantly collisionally ionized gas (Fig. 5.3).

- Examining relations that investigate different ionization states of the same element, C\textsc{iii}(C\textsc{iv}) and Si\textsc{iii}(Si\textsc{iv}), we find good agreement between the observations and simulations for both the fiducial UVB and softer models (Fig. 5.4).

- Unlike O\textsc{v}(H\textsc{i}), the O\textsc{v}(C\textsc{iv}) and O\textsc{v}(Si\textsc{iv}) relations demonstrate sensitivity to the UVB for τ_{C\textsc{iv}} ∼ 10⁻¹ and τ_{Si\textsc{iv}} ∼ 1, and we find O\textsc{v}(C\textsc{iv}) is best described by the hardest models (the fiducial HM01 and Q-only). The dependence on the ionizing background suggests that O\textsc{v} pixels with associated strong C\textsc{iv} and Si\textsc{iv} reside in a cooler, photoionized gas phase compared to the gas probed by O\textsc{v}(H\textsc{i}) (Fig. 5.5).

- We discuss possible reasons why C\textsc{iv} and Si\textsc{iv} optical depths with associated H\textsc{i} are underestimated by the fiducial simulations, and we consider a combination of four explanations to be the most likely.

1. Ionization by local sources may be important to include in the simulations. Since the strength of the radiation emitted by stars typically falls sharply above 4 Ryd, this would ionize H\textsc{i} while having a much smaller effect on the metals, which would increase the median metal-line absorption for a fixed H\textsc{i}. This explanation is particularly viable for τ_{H\textsc{i}} ≳ 10, where we may be probing small galactocentric distances.
2. The completion of HeI reionization in the HM01 simulations may arrive too early, or it may be too uniform, since the observations indicate that it could be quite patchy around $z \sim 3.5$ (e.g., Shull et al., 2010; Worseck et al., 2011). This explanation is supported by the better agreement with the 4Ryd-10 and 4Ryd-100 models to the CIV(HI) and SiIV(HI) observations. However, even the 4Ryd-100 model cannot fully explain the CIV(HI) observations for $\tau_{HI} \gtrsim 10$.

3. The simulations may not be resolving the low-mass galaxies required to pollute the diffuse IGM. We find that invoking the highest-resolution simulations, Ref- and Recal-L025N0752, improves the agreement with the observed CIV(HI) relation by $\sim 0.3$ dex at $\tau_{HI} \sim 10^2$. While resolution likely plays a role, the magnitude of the effect is not large enough to fully explain the discrepancy, particularly for the SiIV(HI) relation, which we find to be almost insensitive to the resolution increase.

4. The stellar feedback in the simulations may be driving outflows that contain insufficient cold gas. The agreement between the observed and simulated OVI(HI) relation, which probably traces collisionally ionized gas, indicates that the simulations correctly capture this hotter gas phase, and that it contains enough metals. However, if the gas is overall too hot with respect to the observations, then more CIV and SiIV will be ionized to higher energy levels, leading to a paucity of pixels with detected $\tau_{CIV}$ and $\tau_{SiIV}$.

Thus, the combination of a too hard UVB, and energetic stellar feedback creating outflows without enough cool gas, are likely the cause of the disparity we find between the observed and simulated CIV(HI) and SiIV(HI) relations.

For future work, we would like to use the simulations to pinpoint which galaxies are responsible for the IGM pollution. We can generate spectra using subsets of the gas particles in the simulations. By only including (or excluding) gas particles around galaxies of specific halo masses, we can determine the most important contributors to IGM enrichment. Furthermore, we plan to measure the scatter in the simulations, in order to compare with the results of Aguirre et al. (2005), who found that the metal distribution in their simulations was less homogeneous than observed. On the observational side, we are currently obtaining data using the VLT/MUSE integral field unit (Bacon et al., 2010), to perform a blind galaxy survey (through Lyα emission) in the QSO fields. We will be able to combine the galaxy redshifts and impact parameters with QSO absorption information to study the HI and metal-line absorption of the circumgalactic medium of faint Lyα emitters. By comparing these results to observations, we may be able to better identify the source of the remaining discrepancy between EAGLE and the $z \sim 3.5$ IGM.

5.A Resolution tests

In this appendix, we test the numerical convergence of the EAGLE simulations. We first examine the effects of varying the simulation box size. In Fig. 5.6, where we show optical depth relations derived from the fiducial Ref-L100N1504 simulation, as well as from the reference runs in 50 and 25 cMpc volumes with the same resolution. To create these optical
depth relations (which in this case are not designed to mimic observations of any particular QSO), we have generated 100 spectra with $z_{\text{QSO}} = 3.94$, chosen such that the redshift of the Ly$\alpha$ forest is centred around the $z = 3.53$ EAGLE snapshot. The S/N was set to be 75 throughout each spectrum, and the UVB was the default Haardt & Madau (2001) model. We find that the optical depth relations in Fig. 5.6 are converged for the two largest box sizes (50 and 100 cMpc).

Next, in Fig. 5.7 we explore the effects of the numerical resolution, to both test for convergence and to investigate whether pushing to lower galaxy masses may impact the enrichment of the IGM. For this, we use the 25 cMpc box, for which simulations have been run with resolutions higher than the fiducial one used in this work. There are two versions of the highest-resolution simulation L025N0752: one that has been run using the subgrid physics of the reference model (Ref-) and one that has been recalibrated to better match the $z \approx 0$ galaxy stellar mass function (Recal-). We present the optical depth relations for the above high-resolution runs, as well as for our fiducial resolution ($2 \times 376^3$ particles in the 25 cMpc box) and finally a lower-resolution of $188^3$ particles.

In the upper left panel of Fig. 5.7, we examine C$\text{IV}$($\text{H}i$) and find sensitivity to resolution in the highest $\text{H}i$ bins ($\tau_{\text{H}i} \gtrsim 10^2$). For the lowest-resolution run, the median C$\text{IV}$ optical depth is $\approx 0.5$ dex lower than for the fiducial model, while points from the highest-resolution simulations are up to $\approx 0.3$ dex above those of the fiducial run. For the remaining optical depths relations, the differences are very small ($\lesssim 0.1$ dex).

These results primarily indicate that our fiducial resolution is nearly converged. However, we do find some sensitivity to resolution in relations involving C$\text{IV}$. The suggests that a higher resolution results in more carbon and/or temperature conditions that favour triply-ionized carbon. However, we note that the effect is not large enough to completely resolve the discrepancy with observations found in Fig. 5.3. Furthermore, Si$\text{IV}$($\text{H}i$) shows very little sensitivity to resolution.

### 5.B Results from single QSOs

In this appendix, we present the pixel optical depth relations derived from individual QSOs, which were combined to obtain the relations shown in Figs. 5.3, 5.4, and 5.5. Here we display the optical depth relations in the same order as they appear in the paper: C$\text{IV}$($\text{H}i$) (Fig. 5.8), Si$\text{IV}$($\text{H}i$) (Fig. 5.9), O$\text{VI}$($\text{H}i$) (Fig. 5.10), C$\text{III}$($\text{C}IV$) (Fig. 5.11), Si$\text{III}$ (Si$\text{IV}$) (Fig. 5.12), Si$\text{IV}$ (C$\text{IV}$) (Fig. 5.13), O$\text{VI}$ (C$\text{IV}$) (Fig. 5.14), and O$\text{V}$ (Si$\text{IV}$) (Fig. 5.15).
5.B Results from single QSOs

Figure 5.6: Convergence with respect to simulation box size, where we plot the same optical depth relations as were presented in Figs. 5.3, 5.4, and 5.5, but without combining different QSOs. For clarity, we only show the error region around the fiducial model (L100N1504), which was determined by bootstrap resampling the mock spectra. We find that our fiducial simulation is converged.
Figure 5.7: The same as Fig. 5.6, but showing convergence with respect to the numerical resolution and using a 25 cMpc box. Our fiducial resolution is given by the L025N0376 run, and indicated by the solid line and shaded error region. While the lowest-resolution run, Ref-L025N088, deviates significantly from the others (especially for the C IV (H I) relation), we find mostly good agreement between the fiducial intermediate- and high-resolution runs, which demonstrates that the fiducial resolution is nearly converged. However, the higher-resolution runs predict about 0.3 dex higher $\tau_\text{med}^\text{C IV}$ at $\tau_{\text{H I}} \sim 10^5$, indicating the the C IV associated with these rare, strong absorbers has not yet converged.
Figure 5.8: Median CIV optical depth in bins of $\tau_{HI}$ for all eight QSOs. The black points represent the observed data, while the curves show results from simulated spectra created using different UVB models. The 1σ error bars on the observations were estimated by bootstrap resampling chunks of the spectrum, while the error regions shown for the fiducial simulation were calculated by bootstrap resampling the 100 mock spectra used to generate the data. The value of $\tau_{min}$ is indicated by the dashed line for the observations, and the dotted lines for the simulations.
Figure 5.9: Same as Fig. 5.8, but for $\text{Siv(H)}$. 
5.B Results from single QSOs

Figure 5.10: Same as Fig. 5.8, but for O\textsubscript{VI}(H\textsc{I}).
Figure 5.11: Same as Fig. 5.8, but for CIII(CIV).
Figure 5.12: Same as Fig. 5.8, but for SiII(SiIV).
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Figure 5.13: Same as Fig. 5.8, but for Si IV (C IV).
Results from single QSOs

Q1422+23, z = 3.62

Q0055−269, z = 3.655

Q1317−507, z = 3.7

Q1621−0042, z = 3.709

QB2000−330, z = 3.773

PKS1937−101, z = 3.787

J0124+0044, z = 3.834

BRI1108−07, z = 3.922

Figure 5.14: Same as Fig. 5.8, but for OVI(CIV).
Figure 5.15: Same as Fig. 5.8, but for O\textsc{v}I(S\textsc{ii}v).