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1 Introduction

1.1 The intergalactic medium

In the early Universe, prior to the formation of galaxies and stars, all baryons were in a gaseous phase. This gas then cooled radiatively, accreted onto virialized dark matter haloes, and eventually formed the stars and galaxies that we see today. A significant fraction of the baryons in the Universe are still predicted to reside in the gas in and around galaxy haloes, which is known as the intergalactic medium (IGM). The gas in the IGM constantly interacts with the nearby galaxies, through continuous accretion as well as outflows generated by energetic events such as explosions from supernovae (SNe). Therefore, it is crucial to study the IGM to obtain a complete picture of how galaxies form and evolve.

The IGM consists of primarily diffuse gas with a density of $n_H \approx 10^{-5} - 10^{-3}$ cm$^{-3}$, which makes it very difficult to observe in emission. Instead, we employ bright background sources known as quasars or quasi-stellar objects (QSOs), whose emission is powered by accretion onto the central supermassive black hole of a galaxy. As the light from the QSO travels towards the observer, it is continuously redshifted due to the expansion of the Universe, which allows signatures of intervening gas to be imprinted as individual absorption lines on the spectrum. Particularly at higher redshifts, the vast amount of neutral hydrogen in the Universe creates a dense series of absorption lines known as the Lyman $\alpha$ (Ly$\alpha$) forest.

In Fig. 1.1, we present the spectrum of a $z = 3.7$ QSO, where the Ly$\alpha$ forest is evident below $\lambda \sim 5700$ Å. Higher-order Lyman series transitions beginning with Ly$\beta$ are also present, and make identification of individual absorption lines in this region of the spectrum prohibitively difficult.

While it was first believed that the IGM is composed of discrete clouds, Bi et al. (1992) proposed that it takes the form of a smooth, diffuse medium, and that the Ly$\alpha$ forest can be reproduced by density fluctuations in this medium (see also Bi, 1993; Bi & Davidsen, 1997). This picture was found to be consistent with simulations (e.g., Cen et al., 1994; Miralda-Escudé et al., 1996; Theuns et al., 1998), as well as analytic models (Schaye, 2001), in which the IGM was also determined to be a good tracer of the underlying density (e.g., Tytler, 1987; Hernquist et al., 1996). This is an intuitive picture of the IGM, since baryons tend to follow the underlying dark matter, and hydrogen makes up the majority of baryons. As the gas collapses into dark matter haloes and eventually forms galaxies, the wide range of gas densities throughout this process can explain the strength of H$\text{I}$ absorbers encountered in the Ly$\alpha$ forest. The strongest absorbers are thought to trace the areas closest to galaxies, while weaker absorbers probe the sheets and filaments in intergalactic regions.
In addition to hydrogen, absorption by heavy elements such as carbon, silicon, and oxygen are also seen in QSO absorption spectra, and commonly studied transitions are marked in Fig. 1.1. These elements are necessarily synthesized in stars found in galaxies, so their presence in the diffuse IGM can put constraints on the cycle of gas through the galaxy ecosystem. As metal-line absorption can span a vast range of transition energies, the presence (or paucity) of certain ions can provide clues about the physical state of the gas. In general, ions with lower ionization energies, such as Si\textsuperscript{ii} and C\textsuperscript{ii}, reside in cooler regions of higher H\textsubscript{I} column density where they can be shielded from photoionization. On the other hand, higher ions such as C\textsuperscript{iv} and O\textsuperscript{vi} can probe hotter, more diffuse gas phases. Of course, each ion can be present in gas with some range of temperature and densities, so detailed modelling of multiple ions is required to constrain the physical conditions in detail.

The IGM is ionized by two main processes, photoionization and collisional ionization. The dominant mechanism is thought to be photoionization, as the IGM is constantly subjected to background light emitted by QSOs and galaxies known as the UV background (UVB). Because the UVB has a very low surface brightness, its normalization and shape cannot be measured directly. Rather, the properties of the UVB can be inferred from indirect observations (e.g., Bechtold et al., 1987; Adams et al., 2011), or predicted using models of QSO and galaxy radiation (e.g., Faucher-Giguère et al., 2009; Haardt & Madau, 2012). Models of the UVB are subject to large uncertainties, such as the expected luminosities of QSOs and galaxies throughout cosmic time as well as photon escape fractions. Throughout this thesis, we use the UVB model of Haardt & Madau (2001).

At temperatures $\gtrsim 10^5$ K, collisions between atoms and electrons become energetic enough to liberate electrons, and collisional ionization begins to dominate. While such temperatures are not typical of the high-redshift IGM, at lower redshifts a large amount of gas is thought to be shock-heated through gravitational infall or galactic winds. This tenuous hot phase is predicted to carry the missing baryons required to bring the baryon budget of galaxies in line with the cosmological fraction (e.g., Shull et al., 2012). The study of metal ions with high ionization energies such as O\textsuperscript{vi} and Ne\textsuperscript{vii} are of particular interest, as their ionization fractions peak at temperatures where collisional ionization dominates.

### 1.1.1 Pixel optical depth

Absorption lines from the intervening IGM can be well described by a Voigt profile, which consist of a convolution of natural or collisional broadening and thermal broadening. Fitting Voigt profiles to individual absorption lines can be a very powerful tool, as it allows the measurement of the redshift, velocity width and column density of the gas in question. However, the density of the Ly\textalpha forest makes this task very difficult at high redshift (but see e.g. Rudie et al. 2012b).

In this thesis, we use an alternative technique 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), which is described in full detail in Chapter 2. Rather than attempting to decompose the spectrum into individual absorption lines, we use the rest wavelength of the transition in question to define the region in the spectrum where we would expect to find absorption due to the ion. In Fig. 1.1, we denote the areas of the spectrum where the absorption due to H\textsubscript{i}, O\textsuperscript{vi}, C\textsuperscript{iv} and Si\textsuperscript{iv} are expected, at a redshift ranging from that of...
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Figure 1.1: A \( z = 3.7 \) QSO spectrum whose continuum has been normalized. Blueward of the QSO \( \text{Ly}\alpha \) emission (located at \( \lambda \sim 5700 \) Å), the dense collection of absorption lines forms the \( \text{Ly}\alpha \) forest. The arrows indicate the regions which have the same redshift range as the portion of the \( \text{Ly}\alpha \) forest before \( \text{Ly}\beta \) begins. \( \text{OVI} \) is coincident with the beginning the \( \text{Ly}\beta \) absorption, and due to the superposition of numerous absorption lines from \( \text{H}\i \), individual \( \text{OVI} \) absorbers are nearly impossible to discern at this redshift. In contrast, \( \text{CIV} \) and \( \text{SiIV} \) are located primarily redward of the QSO \( \text{Ly}\alpha \) emission, and suffer much less from contamination.

the QSO to where they \( \text{Ly}\beta \) forest begins in \( \text{Ly}\alpha \). The wavelength of each binned spectral pixel is then converted to a redshift, the optical depth of each pixel is given to be \(-\ln(F)\), where \( F \) is the normalized flux.

This method allows us to make corrections for saturation or contamination depending on the ion. For example, many \( \text{H}\i \) \( \text{Ly}\alpha \) pixels will be saturated, so we can look to higher-order \( \text{H}\i \) transitions to search for unsaturated counterparts. Although \( \text{CIV} \) lies redwards of the \( \text{Ly}\alpha \) forest and does not suffer from contamination by \( \text{H}\i \), we still need to make corrections due to contamination by its own doublet. Importantly, this technique allows us probe ions such as \( \text{OVI} \), which are almost completely obscured by \( \text{H}\i \). Since we know the \( \text{H}\i \) \( \text{Ly}\alpha \) optical depths, we can subtract some of the expected contribution of \( \text{H}\i \) in the \( \text{OVI} \) region.

In addition to the fact that the pixel optical depth method allows us to access particularly difficult ions at high redshift, its advantage lies in the fact that it is fast and objective, and can be applied uniformly to both observed and simulated spectra. Furthermore, it can be sensitive to weak metal-line absorption in low density gas, important for the study of the diffuse IGM. However, one shortcoming is that the interpretation is not always as straightforward as with individual absorption lines. For example, when averaging over large numbers of pixels, one is unable to differentiate between a contribution from many weak absorbers, or from few strong absorbers.

The pixel optical depth method has been used extensively to study the high redshift IGM. Schaye et al. (2003) found that the distribution of \( \text{CIV} \) in the IGM is spatially inhomogeneous, with a metallicity that depended strongly on the overdensity \( \delta \). At \( \log_{10} \delta = -0.5 \) the authors measured \( [\text{C/\text{H}}] = -3.47^{+0.07}_{-0.06} \). Other work also demonstrated that the IGM was enriched early, with a significant fraction of all silicon in place by \( z \sim 3 \) (Aguirre et al., 2004). The dominant ionization mechanism for the ions with lower ionization energies was determined to be photoionization, while \( \text{OVI} \) was found to potentially arise partly in
collisionally ionized gas (Aguirre et al., 2008).

1.1.2 Gas around galaxies

In addition to the study of gas in the IGM, the past decade has seen rapid growth of observations of the gas around galaxies, dubbed as the circumgalactic medium (CGM). Bahcall & Spitzer (1969) first proposed that the absorbers seen in the spectra of QSOs may originate from the gas in galaxy haloes. The first association between galaxies and metal-line absorbers using Mg II was made some decades later (Bergeron & Boissé, 1991; Bergeron et al., 1992). Not soon after, an abundance of observations unearthed a relationship between galaxies and metal-line absorption for ions spanning a wide range of ionization energies (e.g., Chen et al., 2001; Stocke et al., 2006; Chen & Mulchaey, 2009; Prochaska et al., 2011).

Indeed, it is not unexpected that metal-line absorption be associated with galaxies, since metals must be synthesized in stars. However, metal-rich gas can often be found at relatively large distances from the nearest known galaxy. This phenomenon is generally seen around star-forming galaxies, and is thought to be caused by the galaxies driving large-scale outflows, due to energetic processes such as SNe explosions. Such outflows are found to have velocities reaching \(100–1000\ \text{km s}^{-1}\), and have been observed across numerous epochs, from the local M82 galaxy (e.g., Bland & Tully, 1988; Lehnert et al., 1999) to nearly \(z \sim 5\) (e.g., Franz et al., 1997; Jones et al., 2012), as well as many redshifts in between (e.g., Heckman et al., 1990; Steidel et al., 1996, 1999; Pettini et al., 2000; Ajiki et al., 2002; Shapley et al., 2003; Rupke et al., 2005; Martin, 2005; Tremonti et al., 2007; Weiner et al., 2009; Quider et al., 2009; Steidel et al., 2010).

At low redshifts, most absorption lines are shifted too far into the UV to be observable from the ground (with the exception of Mg II). However, the advent of the Cosmic Origins Spectrograph on the Hubble Space Telescope has brought in an unprecedented amount of data on low redshift QSOs. Tumlinson et al. (2011) found O vI to be ubiquitous around star-forming L* galaxies. These same galaxies were also found to have significant reservoirs of cool, metal-enriched gas (Werk et al., 2014). Pushing to lower galaxy masses, metal-line absorption has also found to be common in the CGM of dwarf galaxies, with C IV being observed out to \(\approx 0.5 \ R_{\text{vir}}\) (Bordoloi et al., 2014).

At higher redshifts, while QSOs are more readily observable from the ground with UV spectrographs such as HIRES on Keck and UVES on the Very Large Telescope (VLT), galaxy spectroscopy is prohibitively expensive, making the association between absorbers and galaxies significantly more challenging. The observational data used in Chapters 2 and 3 of this thesis come from the Keck Baryonic Structure Survey (KBSS, Rudie et al., 2012b; Steidel et al., 2014), which is an ongoing galaxy survey in 15 QSO fields at \(z \sim 2.5\). This epoch is of particular interest, as it is believed to be the peak of both inflows (Faucher-Giguère et al., 2011) and star formation (e.g., Madau et al., 1996; Reddy et al., 2008), which may have a powerful impact on the CGM.

The KBSS has already provided substantial insight into the gas around galaxies at high redshifts. For H I, Rakic et al. (2011) used the pixel optical depth technique to construct the first 2-dimensional maps of absorption around galaxies. Rudie et al. (2012b) fitted Voigt profiles to thousands of individual H I absorbers, and found that the strongest H I absorbers were located within \(\lesssim 300\ \text{pkpc}\) and \(\pm 300\ \text{km s}^{-1}\) of galaxy positions. The catalogue of fitted H I absorbers was also used to study the temperature-density relation of the IGM (Rudie
et al., 2012a) and the column density distribution function (Rudie et al., 2013). Metal-line absorption was also examined by Adelberger et al. (2003) and Adelberger et al. (2005b), who found strong correlations between galaxies and C iv absorbers. Finally, Steidel et al. (2010) used down-the-barrel observations as well as galaxy pairs to characterize metal-line absorption in the inner CGM, from 0 to 125 proper kpc (pkpc), of the KBSS galaxies. In Chapters 2 and 3, we use the pixel optical depth technique to expand the study of metal-line absorption around the survey galaxies out to impact parameters of 2 proper Mpc (pMpc).

1.2 Cosmological simulations

Although dark matter and dark energy are far from being fundamentally understood, the cosmological parameters governing the large-scale structure of our Universe are constrained to high level of precision using numerous independent measurement techniques (see e.g., Planck Collaboration et al., 2013). Indeed, cosmological simulations are able to capture large-scale structure extremely well. However, the inclusion of baryonic processes in simulations is substantially more uncertain. The main issue resides in the fact that there are baryonic processes crucial to the formation of galaxies which are not resolved on the ∼kpc scales probed by cosmological simulations, for example, the formation of individual stars from molecular clouds. Thus, simulations invoke subgrid recipes to couple such processes to the resolved scales.

The specific baryonic processes that have been subject to significant debate over the last decades are collectively known as energetic feedback, which refers to any mechanism that drives gas out of the galaxy. When the first cosmological simulations were run, it was apparent that without a way to constantly remove gas from galaxies, the gas would overcool and form far more stars than observed at a fixed halo mass. While the observed galaxy stellar mass function has a shallow low mass slope and exponential decline at high masses (Schechter, 1976), the first galaxy simulations produced galaxies with masses following the power-law halo mass relation instead. At lower galaxy masses, the evacuation of gas can be explained primarily by SNe explosions. Individual explosions can form hot bubbles of gas, and the combination of multiple explosions can form a hot superbubble driving an outflow (e.g., Weaver et al., 1977; Mac Low & Ferrara, 1999). Other processes may also be important, such as stellar winds or radiation pressure. At higher galaxy masses, feedback from the accretion of matter onto the galaxy central black hole becomes important for driving out the gas.

While there is observational evidence for both star-formation driven winds (see the discussion about outflows in § 1.1.2) and AGN feedback (see Fabian 2012 for a review), simulations are unable to resolve individual supernovae or black hole accretion disks. Furthermore, it is unclear whether the energy should be injected thermally or kinetically. It is also not apparent how much energy or momentum should be coupled to the gas, and how it should be distributed amongst nearby particles. However, the implementation of these processes is actually very crucial, as the final properties of galaxies depend very sensitively on the implementation (e.g., Haas et al., 2013a). Thus, the realization of feedback in simulations remains an open problem in the field of galaxy formation theory.

Recently, the EAGLE simulations (Schaye et al., 2015; Crain et al., 2015) have approached the issue by calibrating the feedback to a handful of robust observables: the galaxy stellar
mass function, the galaxy mass-central black hole mass relation, and galaxy disk sizes, all at $z \sim 0$. So far, these simulations have shown significant promise in reproducing numerous observables which were not used to calibrate the feedback, such as the Tully-Fisher relation (Schaye et al., 2015) and the evolution of the galaxy stellar mass function (Furlong et al., 2015). In Chapters 4 and 5, we compare our observations of the high-redshift CGM and IGM to these simulations.

### 1.2.1 Gas in simulations

Because the CGM encompasses the region where infalling gas and star-formation driven outflows cross paths, its properties are predicted to be very sensitive to feedback physics in simulations. In particular, observations of metal-line absorption could be used to put constraints on the physical conditions of the gas around galaxies. Some comparisons between the observed CGM and simulations are detailed below.

At high redshifts, some simulations were unable to reproduce observations of H$\text{I}$ around massive galaxies and QSOs (Fumagalli et al., 2014; Faucher-Giguère et al., 2015). In contrast, Rakic et al. (2012) found good agreement between the H$\text{I}$ pixel optical depths around galaxies and the OWLS simulations (Schaye et al., 2010), while Rahmati et al. (2015) was also able to reconcile the observations with the EAGLE simulations. The latter work attributed this success to a combination of efficient feedback in the simulations, and also taking care to carefully mimic the characteristics of the observations. For metal-line absorption, Shen et al. (2013) performed zoom-in simulations of a massive galaxy and reproduced observations by Steidel et al. (2010) characterizing the CGM around the KBSS galaxies. However, a separate study using cosmological simulations did not find high enough C$\text{r}$ column densities, even when extreme feedback models were invoked (Suresh et al., 2015).

At low-redshift, efficient feedback is essential to match observations of metal-line absorption in the CGM, particularly at distances beyond $\sim 50$ kpc Stinson et al. (2012); Hummels et al. (2013). However, even with efficient feedback, some simulations have difficulty reproducing observations of O$\text{VI}$, possibly due to a paucity of hot gas or poor metal mixing (Hummels et al., 2013; Ford et al., 2015). Recently, the CGM has been found to be an essential, complementary discriminator between different feedback models. Liang et al. (2015) studied a zoom-in simulation of a galaxy with a stellar to halo mass ratio, star formation history, and metallicity consistent with observations. However, in spite of the apparent agreement with observations, the column densities derived from metal-line absorption in the CGM were found to be well below observed values. The authors determined that increasing the SN energy or adding feedback from cosmic rays could bring the observations of the CGM and simulations into agreement.

### 1.3 This thesis

In this thesis we study H$\text{I}$ and metal-line absorption in observations of the extended CGM of galaxies at $z \approx 2.5$ and the IGM at $z \approx 3.5$. We employ data from the KBSS, as well as archival and new observations of QSOs using the VLT/UVES spectrograph. The redshift range of 2.5–3.5 is of particular interest because it offers a glimpse into the Universe during the time when star formation was the most active. Furthermore, the UV and optical
features of galaxies are shifted into optical and IR wavelengths, respectively, making observations feasible from ground-based instruments. Using the pixel optical depth method, we are uniquely positioned to study the CGM and IGM at this crucial epoch.

In Chapter 2, we study metal absorption around $854 \approx 2.4$ star-forming from the KBSS. The KBSS galaxies lie in the fields of 15 hyper-luminous background QSOs, and have impact parameters that range from 35 pkpc to 2 pMpc. The galaxy redshifts have all been measured spectroscopically from either rest-frame UV features or nebular emission lines, which have associated measurement errors of $\approx 150$ km s$^{-1}$ and $\approx 18$ km s$^{-1}$, respectively. We employ the pixel optical depth method to create the first galaxy-centred 2-dimensional maps of the median absorption by O$_{\text{VI}}$, N$_{\text{V}}$, C$_{\text{IV}}$, C$_{\text{III}}$, and Si$_{\text{IV}}$, and update the results from Rakic et al. (2012) on H$_{\text{I}}$. We uncover a strong enhancement of the absorption relative to randomly located regions at small galactocentric distances, and find that this strong enhancement extends to at least 180 pkpc in the transverse direction, and $\pm 240$ km s$^{-1}$ along the line-of-sight (LOS, $\sim 1$ pMpc in the case of pure Hubble flow). A small but significant enhancement of absorption of C$_{\text{IV}}$ and H$_{\text{I}}$ out to our maximum impact parameter of 2 pMpc in the transverse direction is also observed. We repeat the analysis using only the 340 galaxies with redshifts measured from nebular emission lines, and find no decrease in the extent of the enhancement along the LOS. This implies that gas peculiar velocities from either infall, outflow, or virial motions, rather than redshift errors, are responsible for the redshift-space anisotropy.

In Chapter 3, we also utilize data from the KBSS to study the physical conditions of the circumgalactic gas. We find that at fixed H$_{\text{I}}$, C$_{\text{IV}}$, and Si$_{\text{IV}}$, the O$_{\text{VI}}$ absorption is strongly enhanced for impact parameters $< 180$ pkpc and LOS distances out to $\sim 350$ km s$^{-1}$. For pixels with $\tau_{\text{H}_{\text{I}}} \gtrsim 10$, we invoke ionization models to demonstrate that the relation between O$_{\text{VI}}$ and H$_{\text{I}}$ absorption is consistent with enriched, photoionized gas. However, the same models would produce unrealistically high metallicities in underdense gas for pixels with $\tau_{\text{H}_{\text{I}}} \lesssim 1$. We therefore conclude that the observations are consistent with a scenario where the gas at small galactocentric distances is collisionally ionized, with a metallicity $\gtrsim 10^{-1}$ of solar. The large velocity extent and high metallicity provide evidence that we may be probing hot, metal enriched outflows.

In Chapter 4, we compare the results of H$_{\text{I}}$, C$_{\text{IV}}$ and Si$_{\text{IV}}$ absorption from Chapter 2 to the EAGLE simulations. Sightlines are extracted from the simulations, with properties chosen to match the resolution, pixel size, and signal-to-noise ratio of the observed spectra, and the observed distributions of galaxy impact parameters and redshift errors are also considered. We find excellent agreement between the observations and simulations, for both the high optical depths close to galaxies and the enhancement observed to 2 pMpc impact parameters. Furthermore, we detect redshift-space distortions similar to those observed, and confirm that they are caused by peculiar velocities. We consider a range of different minimum halo masses, and find the best match for $M_{\text{min}}^{\text{halo}} \sim 10^{12}$ M$_{\odot}$, which agrees with independent measurements from clustering. We examine different subgrid feedback models where the strength of the stellar feedback is increased and decreased by a factor of two, and do not see a significant change in the results. This indicates that the dominant contribution to the redshift-space distortions comes from infalling or rotating gas, rather than from outflows.

In Chapter 5, we turn to examining the IGM at $z \sim 3.5$. We study pixel optical depth relations from new, high-quality absorption spectra of eight QSOs with $\langle z_{\text{QSO}} \rangle = 3.75$. 
Strong correlations are found between C\textsc{iv}, Si\textsc{iv}, O\textsc{vi} and H\textsc{i}, between C\textsc{iii} and C\textsc{iv}, and between Si\textsc{iii} and Si\textsc{iv}. We then compare these results with the EAGLE simulations, by generating mock spectra with properties similar to UVES observations. The simulations agree well with relations between O\textsc{vi} and H\textsc{i}, between C\textsc{iii} and C\textsc{iv}, and between Si\textsc{iii} and Si\textsc{iv}. However, they fall short of the median observed C\textsc{iv} and Si\textsc{iv} optical depths when binned by H\textsc{i}. At $\tau_{\text{H}i} = 1$, the discrepancy is at most $\sim 0.1$ dex, and increases to up to $\sim 1$ dex at $\tau_{\text{H}i} = 10^2$, where the H\textsc{i} optical depths may be representative of dense regions close to galaxies. We consider different ionizing background models, and we find that the model which accounts for delayed He\textsc{ii} reionization by reducing the intensity above 4 Ryd agrees well with the observations, but only for $\tau_{\text{H}i} \lesssim 10$. We explore the consequence of using a simulation with higher resolution, which would be able to resolve lower mass galaxies thought to be important for polluting the IGM, and although we do see an improvement, the tension is not fully resolved. Finally, because the relation between O\textsc{vi} and H\textsc{i} matches the observations and is insensitive to ionization model, it is likely probing collisionally ionized gas. This means that while there is sufficient enriched hot gas in the simulation, there may be a dearth of cooler gas required to reproduce observations of C\textsc{iv} and Si\textsc{iv}.