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Introduction

Over the past 15 years, the field of extragalactic astronomy has pushed to high redshift and our knowledge of natal galaxies has grown dramatically. Galaxies are now routinely detected at redshifts $z \approx 6-7$ (e.g. Bouwens et al. 2010; Labbé et al. 2010; Oesch et al. 2010; Bouwens et al. 2011; McLure et al. 2011). However, there are fundamental concepts that are still poorly understood. How do galaxies get their gas? How does galactic feedback affect galaxy evolution?

1.1 Intergalactic Medium

Galaxies form out of the intergalactic medium (IGM), and there was a time, before the formation of galaxies, when all the matter in the Universe was in the IGM. Most of what we know about the IGM comes from studies of the absorption spectra of bright objects, such as QSOs. The intervening gas imprints its composition in their spectra through selective absorption of the continuum radiation. The most prominent pattern in such spectra is the Lyman-α forest of the most abundant element in the Universe, hydrogen, blueward of the QSO's Lyα emission line. It consists of a number of absorption lines, produced by neutral hydrogen clouds along the line of sight (LOS) to the QSO, where they absorb whatever continuum radiation was redshifted to the wavelength of H I Lyα (1216 Å).

The "modern" understanding of the Lyα forest dates to the early 90s, when H. Bi and collaborators realized that the linear density fluctuations in the IGM yield a realistic representation of the forest (Bi et al. 1992; Bi 1993; Bi & Davidsen 1997). This was later supported by hydrodynamical cosmological simulations (e.g. Cen et al. 1994; Zhang et al. 1995; Miralda-Escudé et al. 1996; Hernquist et al. 1996; Theuns et al. 1998). In its simplest form, the current notion is that intergalactic gas, pulled into dark matter dominated gravitational potential wells, forms sheets and filaments, and ultimately galaxies inside dark matter haloes, and these structures give rise to Lyα forest lines; sheets and filaments constitute weak absorbers, and haloes give rise to strong absorption systems. This in turn has the implication that the Lyα forest provides a map of matter distribution along the LOS to QSOs: baryons to a large extent follow the dark matter, and the hydrogen makes up for most of the baryons.

Lyα absorbers, from the weakest originating in underdense gas to the strongest arising in galaxy disks, present different stages in the odyssey of baryons, from diffuse gas to collapsed structures. Understanding their nature and their relation to galaxies is an essential step in unraveling how galaxies form and evolve.

In addition to being the reservoir of gas for galaxies, the IGM also tells a story of galactic feedback. Feedback constitutes all the processes where the current star formation and an active nucleus in a galaxy (AGN) have an impact on its evolution, e.g. through heating or removal of star-forming gas. Radiation from galaxies ionizes and heats the IGM, and supernova (SN) and AGN winds can shock heat the surrounding IGM and enrich it with elements heavier than helium (i.e. "metals" in the usual astronomical parlance), produced in stars. Such intergalactic metals also leave an imprint in the spectra of background objects, and their distribution—as revealed by absorption spectra—provides important constraints on models of galactic feedback.

1.2 Models of the Lyα forest

We choose to describe two popular models linking the underlying gas density to the absorption signature in the spectra of background objects. The fluctuating Gunn-Peterson approximation (e.g. Rauch et al. 1997), presented in §1.2.1, is appropriate for gas at and below the mean density of the Universe, while the "Jeans" approximation (Schaye 2001), presented in §1.2.2, provides a suitable description of absorption by overdense gas.

1.2.1 The fluctuating Gunn-Peterson approximation

As the radiation from background objects travels trough space, it can get scattered out of the LOS when it encounters intervening atoms of neutral hydrogen. The expected change of the background flux, F_ν, at the frequency ν, for radiation with the mean free path $\lambda_{\mathrm{mfp},\nu}$, is:

$$dF_\nu = -F_\nu \frac{dl}{\lambda_{\mathrm{mfp},\nu}}, \tag{1.1}$$

where dl is the proper path length. The mean free path can be expressed in terms of the absorption cross-section, σ_ν, and the number density of absorbing atoms, $n_{\rm HI}$, and so:

$$\frac{dF_\nu}{F_\nu} = -n_{\rm HI}\sigma_\nu dl. \tag{1.2}$$

Integration of this differential equation results in:

$$F_\nu = F_{\nu,{\rm c}} e^{-\int n_{\rm HI}\sigma_\nu dl} = F_{\nu,{\rm c}} e^{-\tau_\nu}, \tag{1.3}$$

where τ_ν is the optical depth.

The absorption cross-section for the Lyα transition ($\lambda_0 = 1215.67$ Å, $h\nu_0 = 10.2$ eV) is a function of frequency, $\sigma_\nu = \sigma_0\phi(\nu-\nu_0)$, where $\phi(\nu-\nu_0)$ is the function describing the line profile, and in the absence of line broadening it takes a form of the delta function, $\delta_{\rm D}(\nu-\nu_0)$. To estimate the optical depth as a function of observed frequency, we must integrate the expression for τ_ν along the radiation path length, i.e. from the radiation source at redshift $z_{\rm em}$ to $z = 0$:

$$\tau_{\nu,{\rm obs}} = \int_0^l n_{\rm HI}\sigma_\nu dl = \int_0^{z_{\rm em}} n_{\rm HI}(z)\sigma_\nu \left|\frac{dl}{dz}\right| dz. \tag{1.4}$$

By taking into account that $\nu = \nu_{\rm obs}(1+z)$, which implies that $dz = d\nu/\nu_{\rm obs}$, the integral takes the following form:

$$\tau(z) = \int_{\nu_{\rm obs}}^{\nu_{\rm obs}(1+z_{\rm em})} n_{\rm HI}(z)\sigma_\nu \left|\frac{dl}{dz}\right| \frac{d\nu}{\nu_{\rm obs}}. \tag{1.5}$$

In the absence of line broadening with σ_ν being a delta function, this integral becomes:

$$\tau(z) = \frac{\sigma_0\nu_0}{\nu_{\rm obs}} n_{\rm HI}(z) \left|\frac{dl}{dz}\right|. \tag{1.6}$$

Neglecting peculiar velocities, we can transform dl/dz:

$$dl = cdt = c\frac{dt}{da}\frac{da}{dz}dz = \frac{c}{\dot{a}}(-a^2)dz = -\frac{c}{H(z)}\frac{dz}{1+z}, \tag{1.7}$$

where c is the speed of light, dt is the time interval that radiation takes to travel the path length dl, $a = 1/(1+z)$ is the expansion factor of the Universe, and $H(z) = \dot{a}/a$ is the Hubble parameter. Taking this into account, and that $\nu_0 = \nu_{\rm obs}(1+z)$, the observed optical depth is:

$$\tau(z) = \sigma_0 n_{\rm HI}(z)\frac{c}{H(z)}. \tag{1.8}$$

The neutral hydrogen number density can be expressed in terms of the total hydrogen number density:

$$n_{\rm HI} = \frac{n_{\rm HI}}{n_{\rm H}}\frac{n_{\rm H}}{\bar{n}_{\rm H}}\bar{n}_{\rm H},$$

where $\bar{n}_{\rm H}$ is the mean hydrogen number density in the Universe:

$$\bar{n}_{\rm H} = \frac{\bar{\rho}_{\rm b} X}{m_{\rm H}} = \frac{X}{m_{\rm H}} \Omega_{\rm b} \rho_{0,\rm crit} (1+z)^3 \approx$$
$$\approx 7.15 \times 10^{-6}\,{\rm cm}^{-3} \left(\frac{X}{0.75}\right) \left(\frac{\Omega_{\rm b} h^2}{0.022}\right) \left(\frac{1+z}{3.4}\right)^3,$$

and $\bar{\rho}_{\rm b}$ is the mean baryonic density, X is hydrogen mass fraction, $m_{\rm H}$ is the mass of the hydrogen atom, $\Omega_{\rm b}$ is the density parameter for baryons, and $\rho_{0,\rm crit}$ is the critical density of the Universe at $z = 0$. Substituting this into equation 1.8, we get:

$$\tau(z) \approx 1.3 \times 10^5 \left(\frac{\Omega_{\rm m} h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_{\rm b} h^2}{0.022}\right) \left(\frac{X}{0.75}\right) \left(\frac{1+z}{3.4}\right)^{3/2} \frac{n_{\rm HI}}{n_{\rm H}} \frac{n_{\rm H}}{\bar{n}_{\rm H}}. \quad (1.9)$$

An interesting conclusion about the state of the IGM can be drawn from this equation. Namely, because the observed optical depth at e.g. $z = 2.4$ is $\bar{\tau}(z = 2.4) < 1$, we have $\langle n_{\rm HI}/n_{\rm H} \rangle \lesssim 7.7 \times 10^{-6}$, i.e. the IGM is highly ionized at this redshift.

Equation 1.9 can be easily related to the underlying density field if we assume that the gas is in photo-ionization equilibrium, $n_{\rm HII} n_{\rm e} \beta = n_{\rm HI} \Gamma$. In this equation β is the hydrogen recombination rate, which depends on gas temperature as $\beta \approx 4 \times 10^{-13} T_4^{-0.76}\,{\rm cm}^{-3}\,{\rm s}^{-1}$ ($T \equiv T_4 * 10^4$ K); $\Gamma \equiv \Gamma_{12} \times 10^{-12}\,{\rm s}^{-1}$ is the hydrogen photoionization rate due to the background UV radiation with mean intensity J_ν:

$$\Gamma = \int_{\nu_{\rm L}}^{\infty} \frac{4\pi J_\nu \sigma_{\rm i}(\nu)}{h\nu} d\nu, \quad (1.10)$$

where $\sigma_{\rm i}(\nu)$ is the cross-section for photoionization, and $\nu_{\rm L}$ is the frequency at the Lyman limit (i.e. 912 Å). Finally, $n_{\rm e}$ is the number density of free electrons. For highly ionized gas we can make the following approximations:

$$n_{\rm HII} \approx n_{\rm H}, \text{ and } n_{\rm e} = n_{\rm H} + 2n_{\rm He} = \frac{\rho}{m_{\rm H}} X + \frac{2\rho}{4m_{\rm H}}(1-X) = n_{\rm H} \frac{1+X}{2X},$$

after which we get:

$$\tau(z) \approx 0.45 \left(\frac{X}{0.75}\right) \left(\frac{1+X}{1.75}\right) \left(\frac{\Omega_{\rm m} h^2}{0.13}\right)^{-1/2} \times$$
$$\times \left(\frac{\Omega_{\rm b} h^2}{0.022}\right)^2 \left(\frac{1+z}{3.4}\right)^{9/2} T_4^{-0.76} \Gamma_{12}^{-1} \Delta^2, \quad (1.11)$$

where $\Delta = n_H / \bar{n}_H$ is gas overdensity.

In reality, there is some scatter in the relation between the optical depth and overdensity due to gas peculiar velocities and thermal broadening. The approximation is not appropriate in regimes where collisional ionization becomes important (e.g. in regions with $T > 10^5$ K), nor at high density because the line broadening is no longer dominated by the differential Hubble flow.

1.2.2 Jeans approximation

Schaye (2001) argued that overdense (with respect to the mean density of the Universe) Lyα absorbers are typically close to local hydrostatic equilibrium, i.e. that their characteristic size is of order of the local Jeans length. Starting from this assumption, the typical size and mass of absorbers with a given column density may be calculated. We consider these results relevant for building intuition about the physical properties of Lyα absorbers, and thus we repeat the derivation below.

The dynamical time in a cloud with characteristic density $n_{\rm H}$ is:

$$t_{\rm dyn} \equiv \frac{1}{\sqrt{G\rho}} \sim 1.0 \times 10^{15}\,{\rm s} \left(\frac{n_{\rm H}}{1\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{X}{0.75}\right)^{1/2} \left(\frac{f_{\rm g}}{0.16}\right)^{1/2}, \quad (1.12)$$

where $f_{\rm g}$ is the fraction of cloud mass in gas (i.e. the baryonic fraction). For the absorbers that Schaye considers in the paper, $f_{\rm g}$ has a value close to the universal baryon fraction ($\approx \Omega_b/\Omega_m$). The sound crossing time in such an absorber, where L is the "characteristic size" of the cloud (i.e. the scale over which the typical density is of order the characteristic density), is:

$$t_{\rm sc} \equiv \frac{L}{c_{\rm s}} \sim 2.0 \times 10^{15}\,{\rm s} \left(\frac{L}{1\,{\rm kpc}}\right) T_4^{-1/2} \left(\frac{\mu}{0.59}\right)^{1/2}. \quad (1.13)$$

In this expression $c_{\rm s}$ is the sound speed in an ideal monoatomic gas, with $\gamma = 5/3$, and μ is the mean molecular weight, and for the rest of the derivation it is set to the value suitable for a fully ionized plasma with primordial abundances, $\mu \approx 0.59$.

The pressure is $P \sim c_{\rm s}^2\rho$, which in hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{G\rho M}{r^2}, \quad (1.14)$$

where M is the cloud mass within radius r. It follows that $c_{\rm s}^2\rho/L \sim G\rho^2 L$, which in turn leads to $t_{\rm sc} \sim t_{\rm dyn}$, i.e. the sound crossing time is of order the dynamical time. Consequently, the characteristic size of such a cloud is of order the Jeans length:

$$L_{\rm J} \equiv \frac{c_{\rm s}}{\sqrt{G\rho}} \sim 0.52\,{\rm kpc}\, n_{\rm H}^{-1/2} T_4^{1/2} \left(\frac{f_{\rm g}}{0.16}\right)^{1/2} \quad (1.15)$$

The Lyα absorbers are typically discussed in terms of their column density, and for a cloud satisfying the Jeans condition, it is straightforward to relate total gas column density of a cloud to its characteristic density:

$$N_H \equiv n_{\rm H} L_{\rm J} \sim 1.6 \times 10^{21}\,{\rm cm}^{-2}\, n_{\rm H}^{1/2} T_4^{1/2} \left(\frac{f_{\rm g}}{0.16}\right)^{1/2}. \quad (1.16)$$

For clouds that are optically thin to the ionizing radiation (i.e. neutral gas column density $N_{\rm HI} \leq 10^{17.2}\,{\rm cm}^{-2}$), it is relatively easy to calculate the neutral gas column density from the total gas column density.

The neutral fraction of gas in photoionization equilibrium is:

$$\frac{n_{\rm HI}}{n_{\rm H}} = n_{\rm e}\beta_{\rm HII}\Gamma^{-1} \sim 0.46 n_{\rm H} T_4^{-0.76}\Gamma_{12}^{-1}, \tag{1.17}$$

For the rest of the calculations, the adopted value for Γ is $10^{-12}\,{\rm s}^{-1}$ (e.g. Haardt & Madau 2001), which is appropriate for $z \approx 2-4$, and the adopted value for the temperature of Lyα absorbers is $T \sim 10^4$ K (e.g. Schaye et al. 2000).

The neutral hydrogen column density can be obtained by combining equations (1.16) and (1.17):

$$N_{\rm HI} \sim 2.3\times10^{13}\,{\rm cm}^{-2}\left(\frac{n_{\rm H}}{10^{-5}\,{\rm cm}^{-3}}\right)^{3/2} T_4^{-0.26}\Gamma_{12}^{-1}\left(\frac{f_{\rm g}}{0.16}\right)^{1/2}. \tag{1.18}$$

One can also express the density in terms of the overdensity, i.e. $\Delta \equiv n_{\rm H}/\bar{n}_{\rm H}$, where:

$$\bar{n}_H \approx 7.3\times10^{-6}\,{\rm cm}^{-3}\left(\frac{1+z}{3.4}\right)^3\left(\frac{\Omega_{\rm b}h^2}{0.022}\right), \tag{1.19}$$

from which follows:

$$N_{\rm HI} \sim 1.5\times10^{13}\,{\rm cm}^{-2}\Delta^{3/2}T_4^{-0.26}\Gamma_{12}^{-1}\left(\frac{1+z}{3.4}\right)^{9/2}\left(\frac{\Omega_{\rm b}h^2}{0.022}\right)^{3/2}\left(\frac{f_{\rm g}}{0.16}\right)^{1/2} \tag{1.20}$$

We can now also relate the size of an absorber to its neutral hydrogen column density, by combining equations (1.15), (1.17), and (1.18):

$$L \sim 1.0\times10^2\,{\rm kpc}\left(\frac{N_{\rm HI}}{10^{14}\,{\rm cm}^{-2}}\right)^{-1/3} T_4^{0.41}\Gamma_{12}^{-1/3}\left(\frac{f_{\rm g}}{0.16}\right)^{2/3}, \tag{1.21}$$

and so absorbers with e.g. $N_{\rm HI} = 10^{15}$, 10^{16}, and $10^{17}\,{\rm cm}^{-2}$ are expected to have sizes $\sim$ 50, 20, and 10 physical kpc, respectively.

For spherical absorbers, the characteristic mass can be estimated as $M \sim \rho L^3$, and so the gas mass is:

$$M_{\rm g} \sim 8.8\times10^8\,{\rm M}_\odot\left(\frac{N_{\rm HI}}{10^{14}\,{\rm cm}^{-2}}\right)^{-1/3} T_4^{1.41}\Gamma_{12}^{-1/3}\left(\frac{f_{\rm g}}{0.16}\right)^{5/3} \tag{1.22}$$

Of course, absorbers are often not spherical in which case their mass cannot be estimated using this approximation.

The “Jeans” approximation breaks down for underdense absorbers because the sound-crossing time is then longer than the Hubble time, $t_{\rm sc} > t_{\rm H}$, i.e. they do not satisfy the Jeans condition.

1.3 The IGM near galaxies

The physics governing the Lyα forest is relatively simple, and thus the fluctuating Gunn-Peterson approximation is likely to describe reality reasonably well. However, the baryon physics becomes much more complicated when the matter fluctuations reach the strongly non-linear regime, where the IGM and galaxies meet. When it comes to observations, a common way of studying this interface is by identifying galaxies close to the line of sight (LOS) of background objects, and examining absorption in the spectra of background objects that coincides in redshift with foreground galaxy positions. Such observations of the galaxy surroundings are challenging.

At high redshift typical star-forming galaxies are faint, and measuring their redshifts requires significant time investment even with 8m class telescopes. Due to their faintness, most studies use galaxies only as foreground objects, while bright QSOs are used as background objects. The number of suitable bright QSOs decreases with redshift, and the number of close QSO-galaxy pairs gets even smaller. Using star-forming galaxies as background objects (e.g. Adelberger et al. 2005; Steidel et al. 2010) yields a higher number of close galaxy-galaxy pairs allowing valuable studies of the immediate galaxy surroundings, but the quality of background spectra is poorer, generally requiring stacking analyses, which in turn limits the type of studies that can be done. Progress in that respect will be possible when a new generation of 30m telescopes becomes available and the quality of galaxy spectra improves significantly (see Steidel et al. 2009, US Decadal Survey White Paper).

At low redshift observations of galaxies are easier and the number of suitable QSO candidates is higher, but studies of many astronomically interesting transitions, such as Lyα, are possible only with space-based facilities because they lie in the rest-frame UV. Significant progress is being made, however, with the UV sensitive Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope, that became available in 2009.

Needless to say, ideally we want studies of the galaxy-IGM interface performed at different redshifts because the Universal "circumstances" change dramatically from e.g. $z \approx 2$ to $z = 0$; for example, at high-z, the universe is denser, galaxies are forming stars more rapidly, active galactic nuclei are more common, and the metagalactic background radiation is more intense.

Theoretical studies of the galaxy-IGM interface are also challenging. Numerous processes that are important in this regime, such as (non-equilibrium) cooling of gas in the presence of metals, collisional ionization, gravitational shock-heating, shock-heating by galactic winds, photoionization by local sources of radiation, and self-shielding, require numerical treatment. Unfortunately, numerical simulations are not at the stage where all the relevant processes can be simulated from first principles. This is because simulating galaxy formation requires a huge dynamic range, with some processes regulated on the atomic level, and others on the scale of galaxy clusters. This is why the use of "subgrid prescriptions" for processes not captured at the current resolution level is unavoidable in simulations of galaxy formation. These subgrid prescriptions are motivated by observations, and the simulation output must be carefully scrutinized in the context of a different set of observational results. Through such a process it became clear that galactic feedback is necessary for, e.g., preventing galaxies from forming too many stars, and growing disks of realistic size (e.g. Springel & Hernquist 2003; Weil et al. 1998).

1.4 This thesis

This thesis presents research on the IGM, as revealed through Lyα absorption, in the vicinity of galaxies at $z \approx 2.4$ in the Keck Baryonic Structure Survey (KBSS, Steidel et al., 2012, in preparation), and the implications of the observed relations through comparison with the hydrodynamical cosmological simulations from the OverWhelmingly Large Simulations (OWLS) set of models (Schaye et al. 2010). This redshift is particularly suitable for simultaneous studies of the Lyα forest and galaxies, because both can be easily observed with ground-based facilities. The Lyα forest is redshifted from the rest-frame UV into the optical part of the spectrum, and the rest-frame UV spectrum of star-forming galaxies is also redshifted into the optical, allowing their efficient identification with optical filters through the Lyman Break technique (e.g. Steidel et al. 2004; Adelberger et al. 2004). The Lyα forest lines at $z \gg 2.4$ are mostly saturated, and at $z \ll 2.4$ they are quite rare, which also makes $z \sim 2.4$ exceptional. In addition, the universal star-formation rate density peaked at $z \sim 2-3$, which makes this epoch particularly informative as any interaction between galaxies and their environments should be at its peak during this time as well.

Chapter 2 presents a novel method for calibrating galaxy redshifts using absorption by the surrounding IGM. The most common way of measuring redshifts of high-z galaxies is from rest-frame UV absorption and emission lines originating in the ISM of galaxies. However, they are usually offset from the systemic redshifts due to the combination of radiative transfer effects and galactic outflows. An established way to correct for this is to calibrate the redshifts through near-IR observations of the rest-frame optical nebular emission lines, originating in the H II regions of galaxies, but such observations are currently costly, and not feasible for large samples of faint galaxies. Using KBSS galaxies and background QSOs, we have shown that it is possible to calibrate galaxy redshifts measured from rest-frame UV lines by utilizing the fact that the mean H I Lyα absorption profiles around the galaxies, as seen in spectra of background objects, must be symmetric with respect to the true galaxy redshifts if the galaxies are oriented randomly with respect to the lines of sight (LOS) to background objects.

In **Chapter 3** we present the observations of the H I optical depth near galaxies at $z \approx 2.4$ in the KBSS survey, using the pixel optical depth method to analyze the QSO spectra. We find the Lyα absorption to be enhanced out to at least 2.8 Mpc proper. We present the first two-dimensional maps of the absorption around galaxies, plotting the median Lyα pixel optical depth as a function of transverse and LOS separation from galaxies. We detect two types of redshift space anisotropies. On scales < 200 km s^{-1}, or < 1 Mpc proper, the absorption is stronger along the LOS than in the transverse direction. This "finger of God" effect may be partly due to redshift errors, but is probably dominated by gas motions within or very close to the halos. On the other hand, on scales of 1.4 - 2.0 Mpc proper the absorption is compressed along the LOS, an effect that we attribute to large-scale infall (i.e. the Kaiser effect). We measured the galaxy overdensity within a given volume as a function of pixel optical depth, and we show the covering fraction of absorbers with a given strength within 200 proper kpc from galaxies.

In **Chapter 4** we demonstrate that the observed Lyα absorption distribution near galaxies from Chapter 2 can be used to measure the masses of halos of that galaxy population. We match the observed absorption distribution to the absorption around haloes above a given mass in the cosmological simulations from the OWLS suite of models. The implied minimum halo mass is consistent with the results from the galaxy clustering analysis, and the results are robust to changes in cosmological parameters and feedback prescriptions in models. We also show that this method can be used in narrow field galaxy-QSO surveys, i.e. 30×30 arcseconds.

Inspired by recent theoretical results that imply that most of the fuel for star-formation comes into galaxies through cold accretion, i.e. without getting heated to the virial temperature of the host haloes, we examine in **Chapter 5** how much Lyα absorption near galaxies at $z = 2.25$ is produced in such cold flows. We use OWLS models and study absorption in gas selected based on its thermal history, halo membership, kinematics with respect to the galaxy, and likelihood of becoming part of the interstellar medium by $z = 0$. We also look into the physical properties of the Lyα absorbing gas, i.e. its temperature and density, as a function of distance from galaxies in OWLS models with and without SN and AGN feedback.

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