THE INTERGALACTIC MEDIUM

11.1 Introduction

The Universe evolved from the smooth conditions at $z \simeq 1100$, when the cosmic microwave background was emitted, to the complex structures we see today. The term 'Intergalactic Medium (IGM) refers to baryonic matter (gas) which is not in collapsed objects, such as stars, galaxies and black holes. Thus, at decoupling, all of the baryons were in the IGM. Even today, most of the baryons are presumably in gas outside galaxies. We come to this conclusion as follows.

In previous lectures we learnt that the cosmic density of baryons has been determined to be $\Omega_{\rm b,0}h^2 = 0.0223 \pm 0.0002$ from the analysis of the CMB fluctuations and the primordial abundance of deuterium (here as usual $h \simeq 0.7$ is the Hubble constant H_0 in units of $100\,{\rm km~~s^{-1}~~Mpc^{-1}}$).

On the other hand, large scale surveys of galaxies in the nearby Universe have allowed us to construct the galaxy luminosity function in several wavelength bands (see Figure 6.1). With assumptions about the mass-to-light ratio, the galaxy luminosity function can be translated into a galaxy *mass* function. Integrating the mass function of galaxies one obtains $\Omega_{\rm stars,0} = 0.0027 \pm 0.0005$ (e.g. Fukugita & Peebles 2004). Comparing $\Omega_{\rm stars,0}$ with $\Omega_{\rm b,0}$, it can be seen that stars (and stellar remnants) today account for only $\sim 6\%$ of the total baryon budget. Planets are irrelevant in this context, and interstellar gas (in both atomic or molecular) increases the above fraction of baryons within galaxies by less than a factor of 1.3. We conclude that most of the baryons, even today, must reside in the space *between* galaxies.

11.2 QSO Absorption Line Spectroscopy

Diffuse gas in the intergalactic medium is hard to detect directly, because the light it emits is extremely feeble (more precisely, we say it has a very

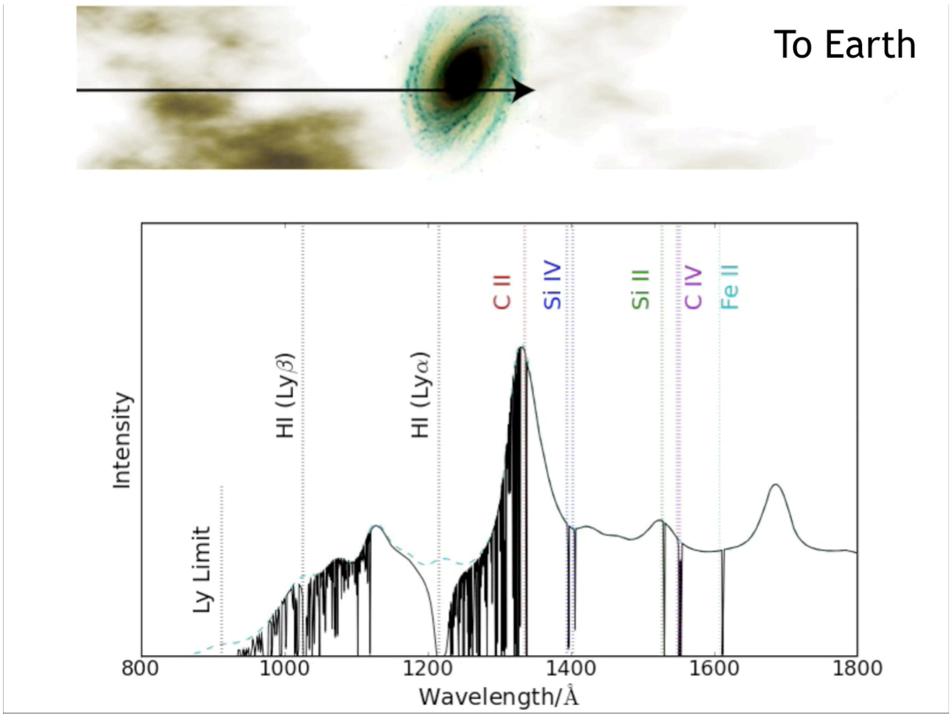

Figure 11.1: The spectra of distant QSOs bear the imprint of intervening gas—within galaxies and in the intergalactic medium—in the form of a rich variety of absorption lines (Figure courtesy of A. Pontzen).

low surface brightness).[1]

Consequently, we would remain unaware of the intergalactic medium, were it not for the absorption is produces in the spectra of bright background sources, mostly quasars (also called quasi-stellar objects, or QSOs). QSOs (the active nuclei of distant galaxies) are some of the most luminous objects in the Universe and can therefore be observed out to the largest distances (highest redshifts). Their light, on its way to our telescopes on Earth, traverses vast reaches of space. Any gas, in galaxies or between galaxies, which by chance happens to lie between the QSO and us leaves its signature on the spectrum of the QSO in the form of absorption lines (see Figure 11.1).

QSO absorption line spectroscopy has been a rich field of study, both observationally and theoretically, for nearly 50 years. Figure 11.2 shows a

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[1] One exception is *intracluster gas*, found within rich galaxy clusters. These baryons are heated to very high temperatures (several 10^7 K) by the gravitational energy released by the formation of the cluster itself. Kinetic energy gained from the gravitational field is converted to thermal energy by shocks, and radiated as X-ray *bremsstrahlung* continuous emission and X-ray emission lines from elements of the periodic table.

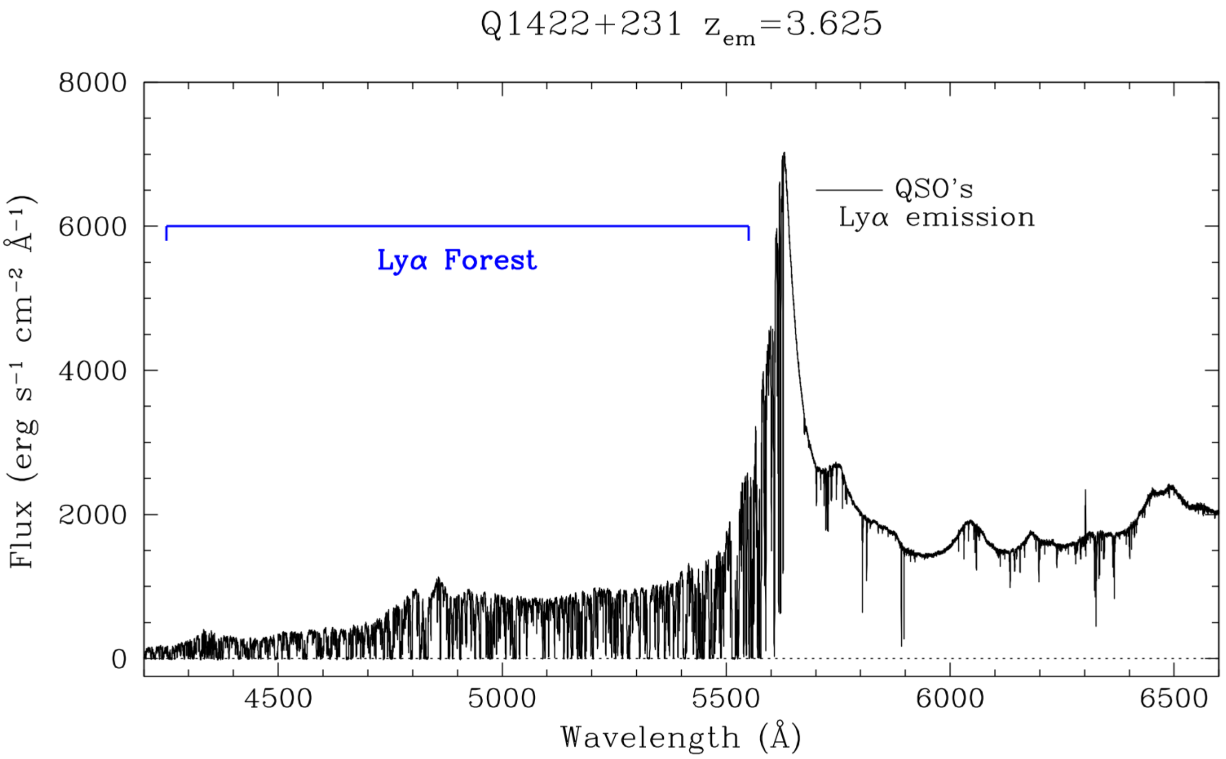

Figure 11.2: Optical spectrum of the $z_{\rm em} = 3.625$ QSO Q1422+231 recorded with the HIgh Resolution Echelle Spectrograph (HIRES) on the Keck I telescope (Reproduced from S. Ellison's Ph.D. thesis, University of Cambridge, 2000).

'typical' (i.e. one of the best!) QSO spectrum, recorded at high spectral resolution and high precision (long integration time), with the Keck I telescope (one of the world's largest optical/infrared telescopes). Note the following points:

- The spectrum is a plot of flux [energy per unit time, i.e. power, passing through a unit area per unit wavelength (or frequency) interval] vs. wavelength. In this plot the units of flux are erg $\rm s^{-1}$ $\rm cm^{-2}$ $\rm Å^{-1}$ and wavelength is in Å.
- The QSO intrinsic spectrum consists of a power-law continuum, typically $F_\lambda \propto \lambda^{-1}$, and broad (several thousand km $\rm s^{-1}$) emission lines. Both are produced close to the 'central engine', by gas close to a central super-massive black hole.
- If the spectrum includes more than one emission line, we can 'solve' for the emission redshift, $z_{\rm em}$, since $\lambda_{\rm obs} = \lambda_0 \times (1 + z_{\rm em})$ where $\lambda_{\rm obs}$ is the observed wavelength of the emission line and λ_0 is its wavelength at rest (as measured in the laboratory). In the example shown, the strongest emission line is the first line in the Lyman series of neutral

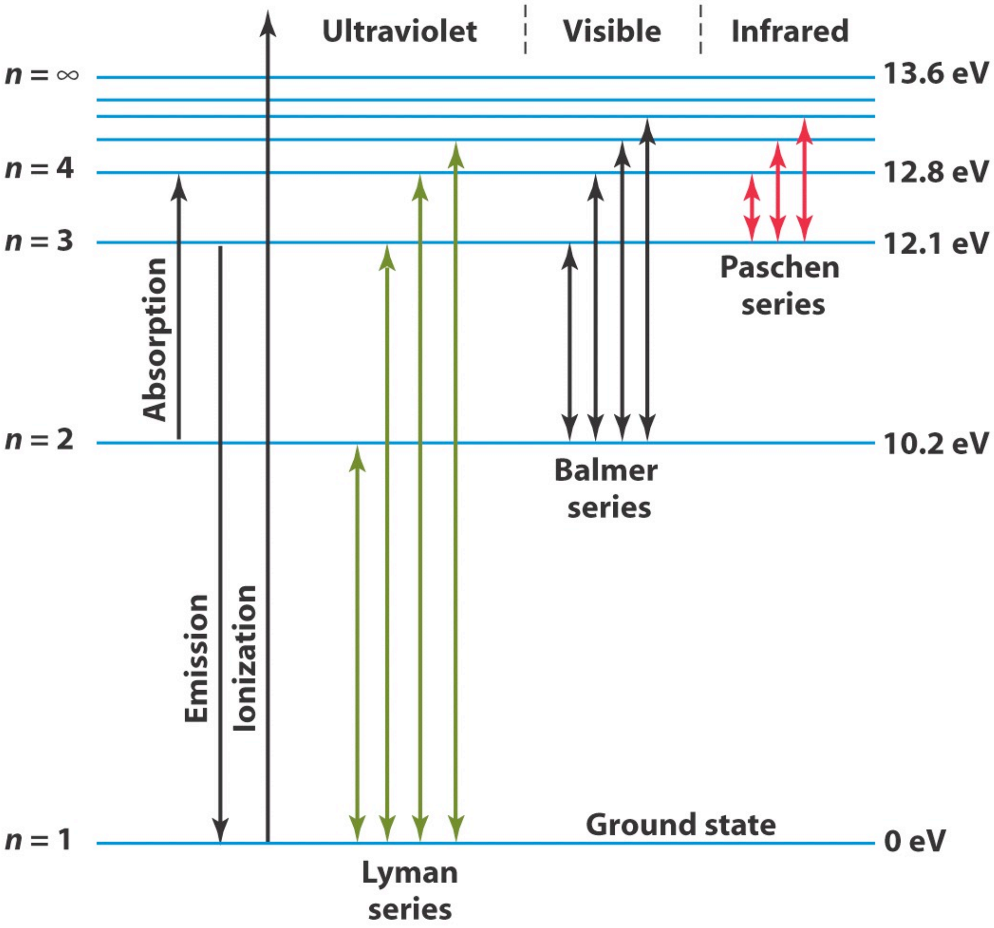

Figure 11.3: Schematic representation of the energy levels of the hydrogen atom.

hydrogen, Lyman α, corresponding to an electronic transition from the first excited level to the ground state (see Figure 11.3).

For the QSO in Figure 11.2, we have: $\lambda_{\rm obs} = 5622$ Å; $\lambda_0 = 1216$ Å; and therefore $z_{\rm em} = 3.625$. These photons were emitted 12.1 billion years ago, at a look-back time of 87% of the current age of the universe (13.81 Gyr in our cosmology with $\Omega_{\rm m,0} = 0.312$, $\Omega_{\Lambda,0} = 0.691$, and $h = 0.675$).

- Superposed on the intrinsic QSO spectrum are many narrow absorption lines. It is these lines which are the focus of QSO absorption line spectroscopy.

Absorption lines at wavelengths longer than that of the emission Lyα can usually be identified as the strongest resonance lines of the most abundant astrophysical elements (e.g. O I, C II, C IV, Mg II, Si II, Fe II) in well defined redshift systems. These are the 'metal-line' systems.

Only a minority of the lines at shorter wavelengths than the emission Lyα can be identified with metal line transitions. Most are single Lyα lines arising in clouds where the column density of gas is too low to produce metal lines—the only spectral signatures one sees are transitions from the Lyman series of H I. This is the 'Lyman alpha forest' which is thought to arise primarily in diffuse, widely distributed, gas: the InterGalactic Medium (IGM).

11.3 The Lyman alpha Forest

Lyα forest lines outnumber metal line systems by more than 50:1 (see Figure 11.4), and indeed they outnumber all other detectable tracers of cosmic structure. This provides us with a wealth of empirical data on the intergalactic medium at all redshifts, from $z = 0$ to the redshift of the most distant QSOs known, currently at $z_{\rm em} = 7.08$. The challenge is how to extract physical information about the intergalactic medium from the absorption spectrum of the Lyα forest. For example, we may be interested to know parameters such as density, temperature, degree of ionisation, chemical composition, velocity fields of the baryons in the IGM, and to explore how such properties evolve with cosmic time. All this information is encoded in data such as those shown in Figure 11.4, we just have to learn how to decipher it.

In this endeavour, we have been greatly aided by numerical simulations of the Lyα forest. In the last 20 years, the near-exponential increase in computational power (in both hardware and software) has made it possible to carry out increasingly sophisticated simulations of large volumes of the Universe to explore the growth of galaxies and large-scale structure from seed density fluctuations.

Many different groups around the world have developed sophisticated computer codes to carry out cosmological simulations. The basic idea is the same:

1. Assume a cosmological model, specified by a set of cosmological parameters, such as H_0, $\Omega_{\rm m,0}$, $\Omega_{\rm b,0}$, $\Omega_{\rm k,0}$, $\Omega_{\Lambda,0}$, σ_8 (the last parameter is a measure of clustering, which we shall encounter later in the course).

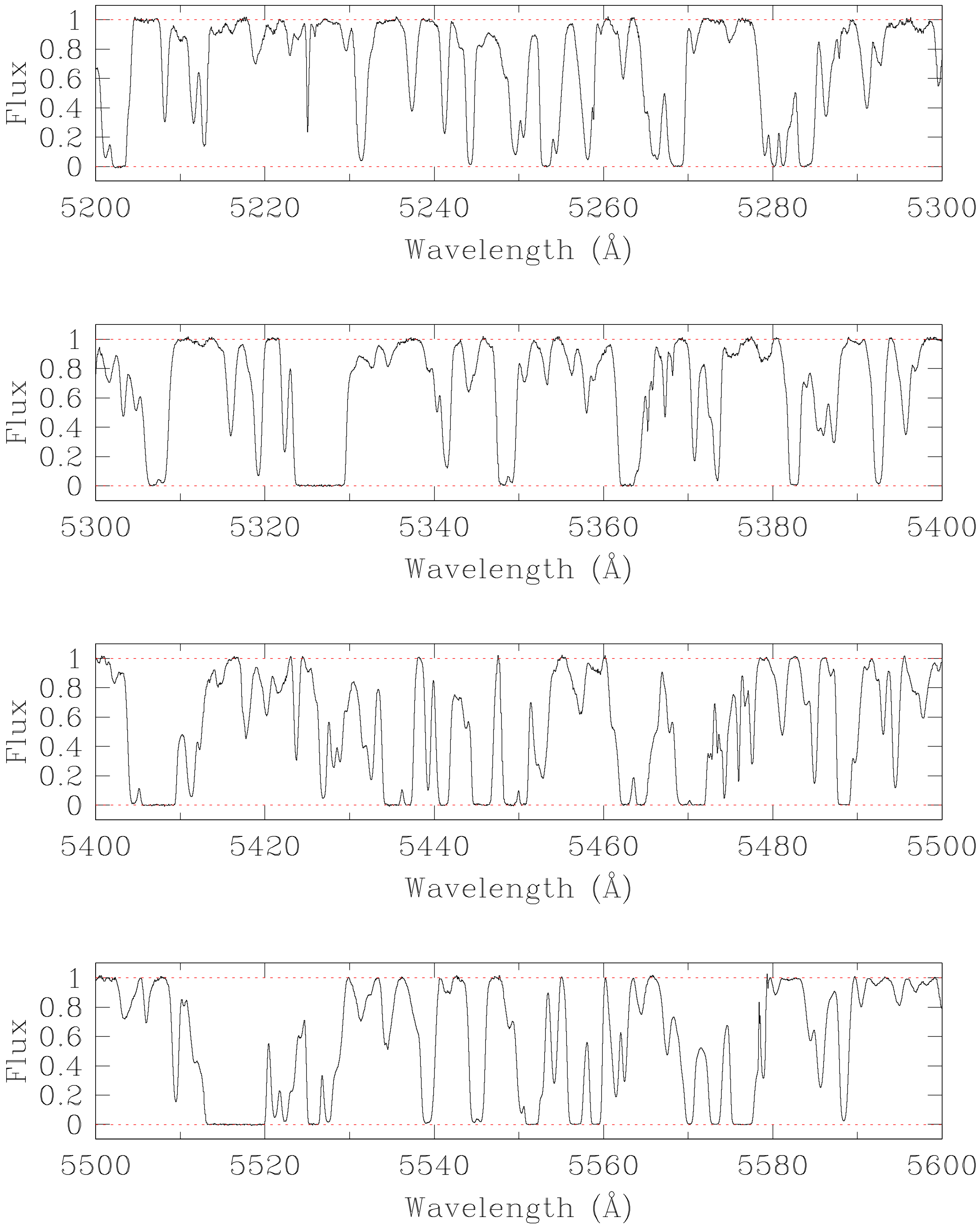

Figure 11.4: Expanded portion of the Lyα forest in the spectrum of the QSO Q1422+231 shown in Figure 11.2. The spectrum has been divided by the underlying QSO continuum; thus the quantity plotted on the y-axis is the residual intensity on a scale from 1 to 0. The resolving power of this spectrum is $R = 50,000$, or 6 km s^{-1} FWHM. At this resolution, more than 50 Lyα 'clouds' can be discerned in every 100 Å-wide panel.

2. Adopt a primordial spectrum of density fluctuations, now well determined by observations of the Cosmic Microwave Background.
3. Start at high z with a set of particles distributed uniformly (the gravitational potential is uniform) on a grid in a comoving volume.
4. Perturb the particles away from this uniform distribution according to a random realization of the primordial fluctuations.
5. The N-body code integrates the equations of motion forward:
   particle distribution $\Longrightarrow$ gravitational potential
   potential gradients $\Longrightarrow$ particle accelerations
   particle accelerations $\Longrightarrow$ particle velocities
   particle velocities $\Longrightarrow$ particle positions

   The whole process is then repeated, moving forward in time at appropriate intervals. Non-linear gravitational evolution transforms the initial fluctuations into a network of rounded voids and tunnels interleaved with sheets and filaments.
6. Introduce a background of ionizing radiation (e.g. from QSOs and star-forming galaxies) and out pops the Lyman a forest!

So, the modern view of the Lyα forest is that it is a natural consequence of hierarchical formation of galaxies and other structures in the Universe. In these cosmological simulations there is no sharp distinction between the absorption lines and the background. The Lyman alpha forest *is* the intergalactic medium which produces a 'fluctuating' Gunn-Peterson effect.[2]

It is now possible to 'study' the properties of the Lyα forest in these simulations by considering the 'spectra' produced by running sight-lines through the volumes considered. One of the advantages of these simulations is that one can 'turn a knob in the machinery', that is alter a particular parameter—for example $\Omega_{\mathrm{b},0}$, or the intensity of the ionising background—and observe directly the impact that that particular parameter has on the characteristics of the absorption spectrum. Thus, by matching simulated and real spectra, we have been able to learn a great deal about the most

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[2] In a famous paper, *"On the Density of Neutral Hydrogen in Intergalactic Space",* Astrophysical Journal, 142, 1633, 1965), Jim Gunn and Bruce Peterson were the first to point out that any neutral hydrogen uniformly distributed in the intergalactic medium would produce a smooth, continuous absorption in the spectra of distant sources, such as QSOs, at redshifts $z \leq z_{\mathrm{em}}$.

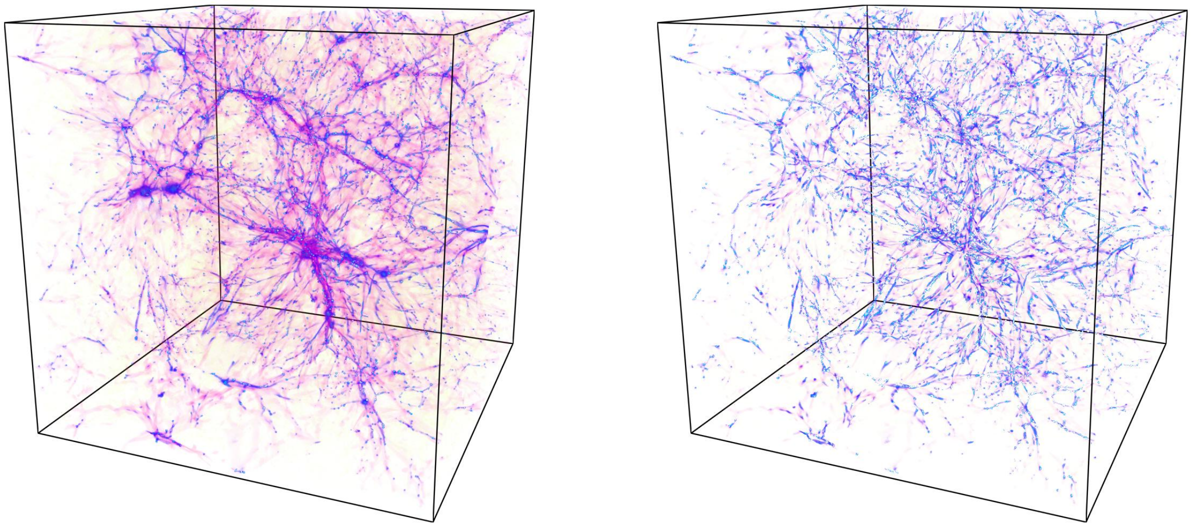

Figure 11.5: Typical output from a large-scale hydrodynamic simulation (this one is from http://www.astro.princeton.edu/∼cen/PROJECTS/p2/p2.html). The box is $25h^{-1}$ Mpc (comoving) on the side, and it contains 768^3 'particles' (a rather small number by today's standards—the simulations shown here are more than ten years old). The left panel shows the distribution of all the gas within the box at $z = 3$, while on the right we have the distribution of the *neutral* gas at the same epoch. It is possible to produce simulated Lyα forest spectra by throwing sightlines through the cube, as if we were viewing a quasar located behind the box. As we know precisely the physical properties of each particle in the simulations, it is possible to connect these properties to the profiles of the absorption lines in the fake spectra. Comparison with data then allows astronomers to interpret real Lyα forest spectra.

important properties of the IGM and their evolution through the cosmic ages. Indeed, it is fair to say that the progress made in this field over the last two decades is due as much to computational as observational advances.