Lyman Alpha Forest

The Lyman alpha forest is an absorption phenomenon seen in the spectra of high redshift QSOs and galaxies (figure 1). It is the only direct observational evidence we have of the existence and properties of the general INTERGALACTIC MEDIUM, and, as we have reason to believe, of most of the baryonic matter contents of the universe.

On its way to us the light of a bright, distant QSO passes through intervening intergalactic gas and through gas clouds associated with foreground galaxies. Absorption by the gas modifies the spectra of the background objects and imprints a record of the gas clouds' physical and chemical states on the observed background QSO and galaxy spectra. The whole arrangement is reminiscent of a giant cosmic slide projector, where a QSO plays the role of the light bulb, and the intervening gas clouds are the slides, changing the colors of the light source by absorbing parts of the (white) spectrum.

The name 'Lyman α forest' refers to the appearance of the optical QSO spectra, which show a forest of hundreds of sharp absorption lines, mostly from the neutral hydrogen (H I) Lyman α line, superimposed on the more smoothly varying QSO continuum (figure 2). Almost all the lines in the Lyman α forest correspond to the same atomic transition (which at 1215.67 Å is in the ultraviolet wavelength region). The phenomenon was first observed in the optical waveband ($\sim$ 4000–9000 Å) implying that the gas clouds causing the absorption are highly redshifted by the Hubble expansion. The absorption systems appear spread out into a 'forest' of lines because each line is redshifted by a different amount in proportion to the absorbing cloud's distance from us. The stronger ones among the absorption systems do show further spectral signatures in addition to their Lyα line: higher-order Lyman series lines begin to be detectable for absorption systems with Lyα close to saturation. Clouds with H I column densities larger than $N \sim 10^{17}$ cm^{-2} start showing a discontinuity due to continuous absorption at a rest frame wavelength 912 Å, beyond the limit of the Lyman series. These 'Lyman limit systems' occupy a column density regime where a gas cloud starts shielding itself against ionizing radiation from the outside. Clouds with even higher column densities ($N > 10^{19}$ cm^{-2}) exhibit the damping wings caused by the internal finite lifetime of the Lyα transition. The gas in these 'damped Lyα' systems (see LYMAN ALPHA ABSORPTION: THE DAMPED SYSTEMS) is almost completely self-shielded and mostly neutral. Most absorption systems with $N > 10^{14.5}$ cm^{-2} also show metal absorption lines (triply ionized carbon and silicon, and some other common elements and ionization stages). For that reason the higher column density systems are usually referred to as 'metal' or 'heavy element' systems. Here we are concerned only with the low column density gas, i.e., those absorption systems where the Lyα line is not saturated, which we will refer to as the Lyα forest proper. There definitely is an overlap between metal systems and Lyα forest systems in this restricted definition, but we have theoretical reasons to believe that there is a genuine dichotomy between intergalactic gas (represented by the Lyα forest), even if partly polluted by metals, and the invariably metal-enriched higher column density systems, thought to be related to galaxies.

Lyα forest absorption systems have now been observed from REDSHIFT zero (with UV satellites) up to the highest redshifts at which background light sources (QSOs and galaxies) can still be found (currently $z \sim 5$–6).

The Gunn–Peterson effect: where does the absorption come from?

Lyα forest absorption in a QSO spectrum was predicted and first detected by Gunn and Peterson (1965). The basic idea is as follows: going back in time an increasing fraction of the total baryonic mass of the universe must be in the form of gas. The absorption cross-section of the Lyα line of neutral hydrogen is large enough that even if only a small fraction of the total mass of the universe were in the form of H I the redshifted Lyα lines should completely absorb a part of the spectrum of any background light source. The absorption should essentially assume the shape of an absorption trough in a QSO spectrum, extending blueward from the Lyα emission of the QSO. This particular absorption pattern is referred to in the literature as the 'Gunn–Peterson effect'. Gunn and Peterson did detect such a trough but the light of the QSO was not completely absorbed and there was some residual light left in the spectral region in question. The relative weakness of the absorption could mean two things: (a) there is little hydrogen left in intergalactic space and by the time the Lyα forest is observed most of the matter has already condensed into galaxies. Or (b) most of the hydrogen is not in neutral form, where it can produce Lyα absorption, but is fully ionized.

QSO surveys (see QUASISTELLAR OBJECTS: SURVEYS) later showed that the second possibility is more important: the combined ionizing radiation output from all known QSOs at high redshift amounts to a UV radiation field probably strong enough to keep most of the baryonic matter in the universe highly ionized—i.e., if the baryons are predominantly in the form of a more or less homogeneously distributed gas.

This conclusion is based on the assumption that the gas is in approximate photoionization equilibrium with the cosmic UV background field, i.e., the rate of recombinations of electrons with protons to form neutral hydrogen balances the rate of ionizations from the ground state of H I,

$$n_e n_p \alpha(T) = n_{HI}\Gamma. \quad (1)$$

Here Γ is the rate of photoionizations per neutral hydrogen atom, caused by the hydrogen-ionizing portion of the UV background field. The quantities n_e, n_{HI} and n_p refer to the number densities of electrons, neutral hydrogen atoms, and protons (= ionized hydrogen), respectively.

Later observations of QSOs with higher spectral resolution (< a few hundred km s^{-1}) showed that

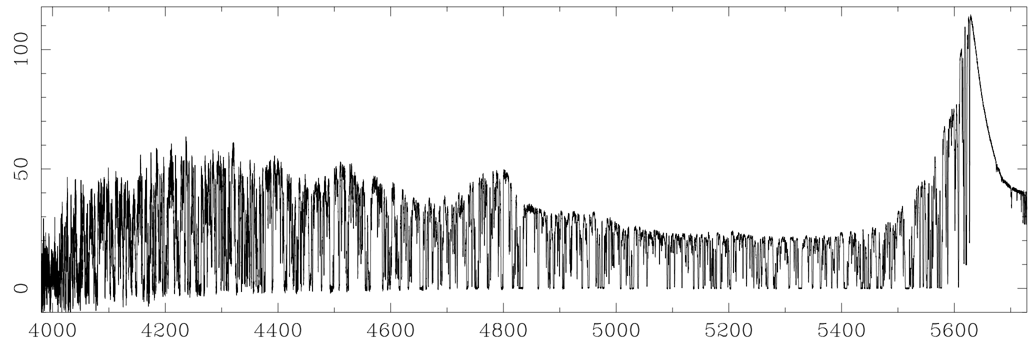

Figure 1. High resolution spectrum of the Lyα forest part of a redshift 3.63 QSO, taken with the HIRES spectrograph on the Keck 10 m telescope in Hawaii. The plot shows the flux of the QSO in arbitrary units versus the observed wavelength in units of Angstroms. The noise level can be judged from the longer wavelength wing of the broad, intrinsic Lyα emission line of the QSO (near 5650 Å). All of the ragged features are high redshift absorption lines. Most of the lines between the QSO's Lyα and Lyβ emission lines (the humps at 5650 and 4750 Å) are due to Lyα absorption by intervening gas. The actual rate of incidence of absorbers decreases towards shorter wavelengths (lower redshifts). Nevertheless, the line density increases to the blue because higher order absorption lines from the Lyman series appear and overlap randomly with Lyα lines of systems at lower redshift.

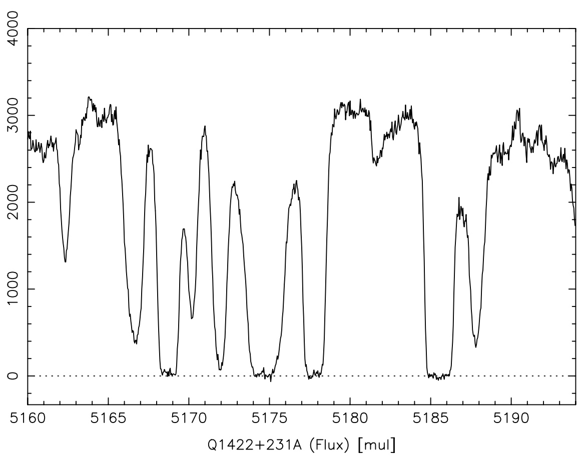

Figure 2. Detailed section of the previous spectrum. The image shows a number of absorption lines all corresponding to the neutral hydrogen (H I) Lyα 1215.67 Å transition. Lines close to saturation (= zero flux in the line center) have neutral hydrogen column density typically around $N \sim 10^{14.2}$ cm^{-2}, corresponding to a gas density enhanced by roughly an order of magnitude with respect to the mean density of the universe. The mean redshift of the stretch shown is $z = 3.248$. The spectral region extends over 3480 km s^{-1}. For a flat $\Omega = 1$ universe this corresponds to a spatial extent of approximately 9.6 h^{-1} Mpc along the line-of-sight.

what appeared as a smooth absorption 'trough' to earlier observers is in fact a ragged 'forest' of hundreds of individual absorption lines. In other words, the distribution of neutral hydrogen in the universe is inhomogeneous on scales down to the width of a typical Lyα line (see below). The degree of clumpiness appears magnified by the absorption pattern in the QSO spectra, because the residual (= unabsorbed) portion of the QSO's flux $I \propto e^{-\tau}$ depends exponentially on the Lyα optical depth τ, which itself depends almost quadratically on the gas density (or the electron density n_e; for a highly ionized gas at constant temperature). Thus small density fluctuations produce enhanced fluctuations in the optical depth. The Lyα forest absorption is observed in velocity space, and a convergent velocity field (e.g., a collapsing gas cloud) could also produce absorption 'lines'. Caustics in velocity space may form if several gas volume elements are moving at the same velocity relative to the observer. Indeed, if Lyα clouds are produced by gravitational collapse, both overdense regions and infall should contribute to an absorption line.

Spectroscopy of the Lyα line is an incredibly sensitive method to detect baryonic matter at any redshift. The photoionization cross section of neutral hydrogen is so large that an extremely tenuous gas at or below the mean density of the universe can be detected easily in absorption. The method of choice for studying the Lyα forest is optical high resolution spectroscopy, with a spectral resolution $\Delta\lambda/\lambda > 30\,000$ sufficient to resolve Lyα lines thermally broadened by the photoionization heating from the UV background. With 8 m class telescopes, a spectrum of a QSO suitable for further analysis of the Lyα forest absorption can be obtained within a few hours of observing time.

Basic observational properties of Lyα absorbers

Early models of Lyα absorption systems envisaged the absorption lines as arising from discrete 'clouds' of gas in intergalactic space. The clouds would be analoguous to galaxies, but the gas densities appeared too tenuous and too highly ionized to give rise to star formation. Moreover, the average clustering of the lines in velocity space was too weak for the clouds to be related directly to galaxies. Thus the gas giving rise to Lyα absorption systems came to be referred to as 'Lyα clouds' or 'intergalactic clouds', to distinguish it from gas associated with galaxies. It it is worth keeping in mind that even the term 'cloud' does already imply a prejudice as to the spatial distribution of the gas.

Before the advent of cosmogonies dominated by DARK MATTER (which could have supplied the gravitational attraction necessary to hold together the gas), it was thought more likely that the intergalactic clouds would be confined by the pressure of an even hotter and more tenuous intercloud medium. In this model, a cloud would be homogeneous, static or slowly expanding and, at least for some of its lifetime, in thermal photoionization equilibrium with the UV background.

Such an object has a simple observational signature in absorption. With only the intrinsic atomic line width of the Lyα transition and purely thermal motions contributing to the absorption line broadening, an individual line profile consists of a convolution of a Lorentzian resonance curve and a Maxwell–Boltzmann velocity distribution. The result is a so-called Voigt profile. Each such profile is fully specified by only 3 parameters: its position in velocity space (redshift), its column density (i.e. the number of neutral hydrogen atoms per unit area), and its line width (traditionally expressed in terms of the Doppler parameter $b = \sqrt{2}\sigma$, where σ is the standard deviation of the Maxwellian velocity distribution). The Lyα forest as a whole can then be characterized in terms of the distribution functions of these three quantities.

Column densities

Let us define $\mathrm{d}\mathcal{N}/\mathrm{d}N$ as the number of absorption lines, $\mathrm{d}\mathcal{N}$, per unit redshift with an H I column density between N and $N + \mathrm{d}N$. This function tells us how likely it is for our line-of-sight to a background QSO to intersect a cloud with a given H I column density N. Observationally, for H I column densities N spanning the amazing range from 10^{12} to 10^{22} cm^{-2} the distribution was found to be well-parametrized by a single power law in column density,

$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}N} \propto N^{-1.5}. \qquad (2)$$

To give an idea of the normalization, there are hundreds of unsaturated lines ($N < 10^{14.5}$ cm^{-2}) per unit redshift but, typically, less than one damped Lyα system ($N > 10^{21}$ cm^{-2}). For comparison, a QSO spectrum at redshift 3 covers $\Delta z \sim 0.6$ of the Lyα forest (between the QSO redshift and the redshift corresponding to the onset of the Lyβ series).

The distribution of absorption systems in velocity space

We may consider two limiting cases. (a) The distribution of absorbers over very large (Gigaparsec) scales; this is is equivalent to a distribution in time or redshift, as the universe changes considerably during the time it takes a light ray to traverse a Gigaparsec. (b) The distribution on small (Megaparsec) scales; here we expect local astrophysics (gravity, galactic outflows, nearby sources of ionizing radiation) to affect the clustering of the lines in velocity space.

(a) The evolution of the number of absorption lines $\mathcal{N}$ with time or redshift z (and with a column density above a certain threshold) traditionally has been approximated by a power-law in $(1 + z)$,

$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}z} \propto (1 + z)^{\gamma}. \qquad (3)$$

For a universe where Lyα clouds are non-evolving, $0 < \gamma < 1/2$, depending on the cosmological model. With the observational baseline now extending from the local universe out to redshift five it has become clear that γ is not constant with time. In the local universe ($z \sim 0$) up to redshift ~ 1.5, γ is consistent with the above no-evolution values. However, beyond redshift $z \sim 1.5$ there is a sharp increase in the number of absorption lines, with γ rising up to a value $\gamma \sim 5$ by redshift $z \sim 4$.

There is a general trend for the number of absorption lines to increase with redshift, but in any individual QSO spectrum there is a relative lack of absorption systems close to the redshift of the QSO. This so-called 'proximity effect' has been ascribed to the ionizing radiation produced by the QSO itself, which reduces the neutral hydrogen fraction for gas close to the QSO. The effect can be used to measure the strength of the ionizing background radiation: consider a point at a distance from the QSO, where the number of Lyα systems has declined by half as compared to the average line density in the Lyα forest. At this point the intensity of ionizing radiation from the QSO must equal the intensity of the general UV background. Knowing the luminosity of the QSO we can compute the flux at that point, and thus, the intensity of the ionizing background. This method, though fraught with many uncertainties, has yielded the first measurement of the ionizing UV background.

(b) The small-scale distribution of absorption lines in velocity space along the line-of-sight, often referred to as 'clustering', has yielded only limited information about the nature of the Lyα forest systems. If the clustering is measured with the same methods used for galaxy surveys, namely by applying the two-point-correlation function to discrete absorption lines, there is a significant signal only for the highest column density ($N > 10^{15}$ cm^{-2}) systems. These stronger absorption lines are invariably accompanied by absorption from heavier elements (carbon, silicon, oxygen, iron in various stages of ionization), so the high column density clouds must in some way be more closely associated with galaxies as the production sites of the metals. The observed stronger clustering of this gas may arise when gas clouds move in a galactic gravitational potential well, or they may just reflect stellar ejecta in the interstellar medium of those galaxies. However, most of the Lyα forest consists of weaker lines, which do not cluster along the line-of-sight appreciably. Gas densities inferred for the weaker lines are likely to be much lower than for galaxies. If gravity is the main structure forming agent it is not very surprising that lower density regions are clustered more weakly.

Searches for voids in the Lyα forest similar to those seen in the spatial distribution of galaxies have been equally unsuccessful, implying again that most Lyα absorption systems are more homogeneously distributed in space than galaxies.

Absorption line widths

The width of an absorption line is a measure of the total velocity distribution in the gas. Both microscopic (thermal motion) and macroscopic processes (turbulence, bulk flows, broadening of an extended object by the Hubble expansion) may contribute to the line profile. Without an *a priori* theory about line formation the total width b of the line profile can only be used as an upper limit to the width due to any individual process. As an example, the Doppler parameter of a thermally broadened absorption line with an additional Gaussian contribution describing turbulence in the gas is given exactly by

$$b = \sqrt{\frac{2kT}{m} + b_{\mathrm{turb}}^2} \qquad (4)$$

where T is the temperature of the gas, k is Boltzmann's constant, m is the mass of the hydrogen atom, and b_{turb} is the turbulent contribution to the Doppler parameter.

At redshift $\sim$ 3 observations show the Doppler parameters b to be distributed according to a Gaussian with a mean $\overline{b}$ between 25 and 30 km s^{-1}, and a cutoff b_{cut} below about 19 km s^{-1}, i.e.,

$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}b} \propto \exp\left(\frac{(\overline{b}-b)^2}{2\sigma_{\mathrm{b}}^2}\right) \quad \text{for } b \geq b_{\mathrm{cut}} \qquad (5)$$

$$= 0 \qquad \text{for } b < b_{\mathrm{cut}}, \qquad (6)$$

This analytic relation gives a good description of the actual distribution. Doppler parameters below the cutoff are very rare, but there appears to be a weak non-Gaussian tail towards larger Doppler parameters. The parameters of the distribution quoted vary somewhat among different researchers, but there is agreement in that the line widths at higher redshifts (3.5–4.5) are lower by perhaps 25% .

If the broadening were purely thermal then typical b values as discussed above would correspond to upper limits on the gas temperature $T \leq$ 3–5 $\times 10^4$ K.

Size, density, and ionization state of Lyα clouds

Absorption line studies suffer from the limitation that in general only one-dimensional information along the line-of-sight is available. From the absorption line itself we measure the temperature and column density of the gas, and from observations of the QSO luminosity function we can compute an estimate of the ionizing background radiation, but to obtain the density and the ionized fraction of the gas an additional independent estimate of the size of the absorbing gas cloud is needed.

Observations of close lines-of-sight to groups of QSOs or to multiple images of gravitationally lensed QSOs can restore to some degree the missing second dimension and provide a measurement of the cloud sizes, at least as projected in the plane of the sky. Imagine that we had two lines of sight with a known separation. For Lyα 'clouds' with a given size, some of the clouds will intersect both lines-of-sight, others only one of them. In a statistical sense, the typical size of Lyα forest absorbers can be determined from the numbers of 'hits' and 'misses', i.e., from knowing how often an absorption system seen in one of the lines-of-sight also appears in the second one. Such estimates have yielded astonishingly large transverse sizes on the order of 0.1–1 Mpc proper separation. These sizes enable us to compute rough estimates of the ionization fraction and density of the gas.

Assuming that the neutral fraction x of hydrogen is determined by photoionization equilibrium (cf equation (1)), we have

$$x = 3.9 \times 10^{-6} \left(\frac{T}{3 \times 10^4}\right)^{-0.35} \left(\frac{I}{10^{-21}}\right)^{-0.5} \times \left(\frac{N}{10^{14}}\right)^{0.5} \left(\frac{D}{100\ \mathrm{kpc}}\right)^{-0.5}, \qquad (7)$$

where T is the gas temperature in K, I is the intensity of the ionizing UV background in units of ergs Hz^{-1} sr^{-1} s^{-1} cm^{-2}, N the H I column density in cm^{-2}, and D the thickness of the cloud (or the path length of our line of sight through it).

Likewise, the total number density of the gas (the number of protons per cm^3) is given by

$$n = x^{-1} N D^{-1} = 8.3 \times 10^{-5} \left(\frac{T}{3 \times 10^4}\right)^{0.35} \left(\frac{I}{10^{-21}}\right)^{0.5} \times \left(\frac{N}{10^{14}}\right)^{0.5} \left(\frac{D}{100\ \mathrm{kpc}}\right)^{-0.5}. \qquad (8)$$

This is about four orders of magnitude less dense than the gas in the disk of our Galaxy. Even if the clouds are not spherical but flattened (so they would appear more extended across than along the line-of-sight) the conclusion is inescapable that the gas is highly ionized and the density in the typical cloud is within a factor of a few from the mean density of the universe, far less than the average density in a galaxy.

The intergalactic medium as a cosmic fluid

So far we have used only simple astrophysical arguments to infer the basic physical properties of the Lyα absorbers, without explicit reference to a model of structure formation. The decomposition into Voigt profiles had originally been justified by the assumption that Lyα absorption systems are discrete, pressure-confined gas clouds in hydrostatic, thermal and ionization equilibrium, floating in intergalactic space. This picture provided an analytically tractable model which made a host of observationally testable predictions, several of which unfortunately contradicted the observational evidence. For example, the large range in column densities observed, and the evolution of the number of absorption systems with redshift are difficult to reproduce in that model. Moreover, observations of the spectral shape of the cosmic microwave background radiation with the COBE satellite have provided arguments against the existence of a hot intercloud medium necessary to provide the confinement pressure for the Lyα clouds.

The pressure-confinement model finally fell from grace because of its lack of a convincing theory of the formation of the cloudlets, and the rise (in popularity) of structure formation cosmogonies dominated by the presence of large amounts of weakly interacting dark matter. The gravitational collapse of dark matter would have trapped large amounts of baryonic gas as well. The most popular, cold dark matter (CDM) structure formation scenario predicts a large abundance of collapsed CDM halos with individual masses too small to form stars and turn into galaxies. Warm photoionized intergalactic gas sinks into these 'mini'-halos or accretes onto dark matter filaments and sheets. The thermal gas pressure prevents the gas from further collapse; relatively stable gaseous configurations are formed. These structures are visible only in absorption since there are no stars which could produce any light.

A breakthrough in cosmology occured in the early 1990s when hydrodynamic cosmological simulations became available. As far as the comparison with data is concerned the hydrodynamics simulations represent an advance over pure dark matter (so-called N-body) simulations, as they attempt to directly predict observable astrophysical quantities. The hydro-codes include, in a simplified way, gas dynamics, elementary radiative processes, heating and cooling, and some schematic stellar feedback, all of which are essential to an understanding of the formation of structure for ordinary (baryonic) matter like galaxies, stars and intergalactic gas clouds. The ultimate hope of the hydro-simulations is to reproduce realistic galaxies, but at the current level of detail and spatial resolution possible the intergalactic medium with its simple physics is perhaps the most promising target for quantitative modelling.

The cosmic web

If the underlying cosmological picture (a universe dominated by cold dark matter) is correct, then the hydro-simulations are telling us that the spatial distribution and physical state of the Lyα forest gas is more complex than previously thought. The gas is arranged in filaments and sheets, in what has been called the 'cosmic web', closely tracing the dark matter distribution on large scales (figure 3). Low column density absorption systems ($N \lesssim 10^{14}$ cm^{-2}) are associated with sheet-like structures or pancakes of gas (length scale $\sim$ a few hundred kpc to 1 Mpc proper). The gas accretes through weak shocks (developing a double humped temperature profile), and settles in a dense, central cooling layer, presumably to form stars in some of the denser regions. At the lowest column densities gas remains unshocked and just bounces back because of the hydrostatic pressure. The gas is partly confined by dark matter gravity and partly by ram-pressure. Higher column density clouds arise in more filamentary structures, with column density contours of $N \sim 10^{14}$ cm^{-2} extending continuously and at relatively constant thickness ($\sim$ 40–100 kpc proper) over Mpc distances. With increasing column density the absorber geometry becomes rounder; column density contours at $N \gtrsim 10^{16}$cm^{-2} invariably are spherical. Such absorbers more closely correspond to the aforementioned minihalos; there the enclosed gas column is high enough to make the absorption system appear as a Lyman limit or damped Lyα system. Looking at the higher column density, optically thick gas on scales of several Mpc one gets a somewhat different impression of chains of mini- or larger halos, lining up like pearls on a string, quite similar to the structure seen in N-body simulations of the dark matter distribution. To produce as much absorption as observed, a large fraction of all baryons (80–90%) is required to reside in the low column density Lyα forest, mostly in the column density range $10^{14} < N < 10^{15.5}$ cm^{-2}.

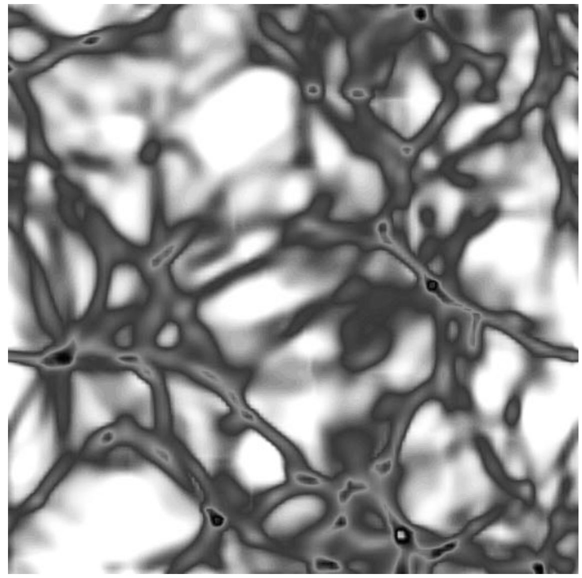

Figure 3. Cosmological hydro-simulation: projection of the baryonic density distribution in a simulated box at $z = 3$ (same spatial extent as for figure 2) showing the 'cosmic web' filamentary structure of the Lyα forest (image courtesy Michael Norman, University of Illinois).

In general this theoretical picture very well reproduces the observational properties mentioned earlier. The column density distribution is in excellent agreement, as are the large transverse sizes measured in projection, and the clustering along the line-of-sight. In this model the rapid evolution of the number of the absorption systems with redshift is largely a consequence of the expansion of the gas with the Hubble flow. The statistical distribution of the flux level $I = e^{-\tau}$ in the Lyα forest is extremely well matched by these models, as can be seen from a comparison of the observed distribution with one from a simulated ΛCDM universe (figure 4). The spatial correlations as evident from the flux power-spectrum are equally well reproduced. The most complex piece of observational information, the distribution of Doppler parameters is qualitatively understood, but as it depends on a variety of initial conditions (epoch of reionization, baryonic density of the universe, cosmological model) and possible stellar energy feedback, several of these parameters need to be tuned carefully to get acceptable quantitative agreement.

Perhaps most importantly, the successes of the hydromodels show that the majority of the Lyα absorbers are consistent with being low density condensations formed by gravitational collapse of the intergalactic medium. In this picture the gas seen as Lyα forest *is* the original reservoir of matter from which galaxies are condensing.

Conversely, the success in reproducing the observations of the Lyα forest provides perhaps the best observational evidence for *hierarchical* structure formation we have to date.

Cosmology with the Lyα forest

Most of the intergalactic gas observed at high redshift has experienced only mild gravitational collapse. A typical region of space has undergone little processing other than heating by photoionization and compression, in competition with adiabatic cooling by the Hubble expansion. It turns out that the weaker, unsaturated absorption lines ($N < 10^{14}$ cm^{-2}) are still on or near the linear regime of gravitational collapse. Even for lines close to saturation the overdensities with respect to the mean density of the universe are less than about a factor $\delta \sim 10$–15. On spatial scales on the order of one Mpc and larger where the thermal pressure of the gas is not important the intergalactic medium traces the underlying mass distribution much more closely than the stellar light of galaxies observed in emission. This fact and the simple astrophysics involved should make the intergalactic medium an ideal cosmological laboratory.

Recently there have been various attempts at tapping the cosmological potential of the Lyα forest. The link between the observable appearance of the Lyα forest and the various cosmological input parameters can be described approximately by the Gunn–Peterson relation for the H I optical depth τ, generalized to include an inhomogenous density and velocity field. As long as the gas is highly ionized and in photoionization equilibrium (not necessarily thermal equilibrium), and the gas is unshocked, the optical depth for Lyα absorption at redshift z is proportional to

$$\tau(z) \propto \frac{(\Omega_b h_{50}^2)^2}{\Gamma} \left(\frac{H(0)}{h_{50} H(z)}\right) T^{-0.7} \times \left(\frac{\rho}{\bar{\rho}}\right)^{\alpha} (1+z)^6 \left(1 + \frac{\mathrm{d}v_{\mathrm{pec}}}{H(z)\mathrm{d}r}\right)^{-1} \quad (9)$$

This equation relates the optical depth to the mean baryonic density (in gas) in units of the critical density, Ω_b, the Hubble constant at redshift z, $H(z)$, the average gas temperature T, the proper baryon density ρ, the photoionization rate Γ, and the gradient of the local peculiar velocity $\mathrm{d}v_{\mathrm{pec}}/\mathrm{d}r$ along the line-of-sight. A further convolution with a Voigt profile is necessary to include the proper thermal velocity broadening. The exponent α ($\alpha = 2$ for an isothermal gas) takes account of the fact that in denser regions of the universe the gas is typically warmer because it is more effectively heated by photoionization, but α also depends on the reionization history of the gas and the amount of adiabatic expansion/compression. Values of $\alpha \approx 1.6$–1.8 are given in the literature.

To turn this relation into a complete description of the observed Lyα forest, cosmology has to predict the cosmic density and velocity fields, the fraction of the closure density in the form of gas, the equation of state of the intergalactic medium, and the ionizing radiation field. Measuring cosmological parameters then boils down to creating Lyα forest spectra according to a given cosmological prescription, and iterating with varying input parameters until good agreement between observed and predicted properties is obtained. At the time of writing these techniques are just beginning to be explored, but it has become obvious that there are at least three main areas to benefit from such studies.

From equation (9) the optical depth is directly proportional to the ratio $(\Omega_b h_{50}^2)^2/\Gamma$. In other words, a higher density produces stronger absorption, but a higher photoionization rate reduces the neutral fraction of the gas and decreases the absorption. With a suitable hypothesis for or an independent measurement of the photoionization rate Γ (e.g. estimating the density of ionizing photons from QSO surveys) the baryon density Ω_b of the universe may be constrained.

The 'equation of state' of the intergalactic medium, as the statistical distribution of the gas volume elements in temperature-density ($T - \rho$) space has become known, has a more complex and subtle influence on the optical depth distribution: a change in the slope $\mathrm{d}T/\mathrm{d}\rho$ changes the value of the temperature of a given volume element and thus the recombination coefficient $\alpha(T)$, the neutral fraction and column density, and the absorption line width. It appears that the distribution of the Lyα forest lines in Doppler parameter–column density ($b - N$) space is a distorted map of the density–temperature relation, and can be used to constrain the latter. $T(\rho)$, in turn, contains information on the epoch of reionization and reheating and on the sources of ionizing radiation.

Finally, it is clear that the fluctuation properties (amplitude, spatial correlation) of the density ρ and peculiar velocity v_{pec} fields propagate through to the optical depth (cf equation (9)). At least in the regime where the Lyα lines are strong enough to be detected but not yet too strong to be saturated, the spectra provide a record of the initial conditions of gravitational structure

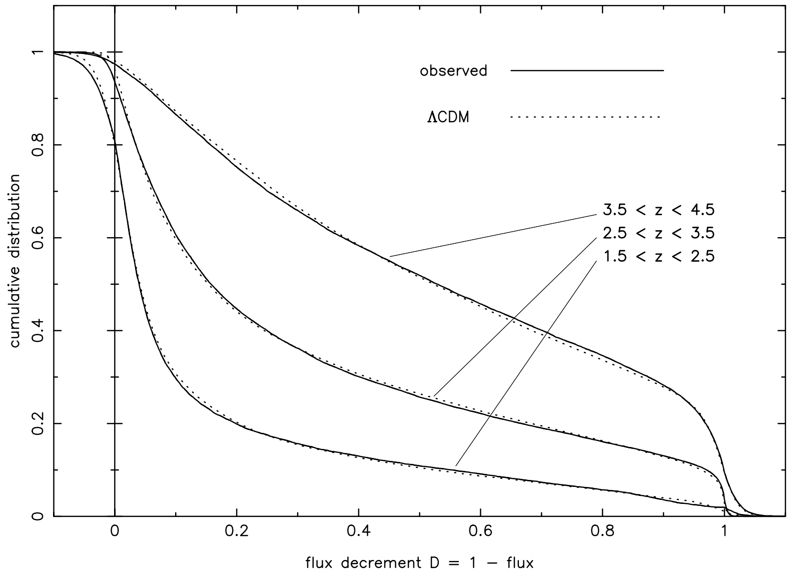

Figure 4. Observed and simulated statistical distributions of the absorbed flux level in the Lyα forest, for three different mean redshifts. The solid lines show the distribution for a sample of QSOs observed with the Keck telescope, the dotted lines are from a simulation of a ΛCDM universe (performed by Renyue Cen *et al* at Princeton University). The good agreement in the shape of the distributions lends observational support to the Lyα forest being a by-product of hierarchical structure formation.

formation. In principle the Lyα forest spectra can be inverted to provide a measurement of the power spectrum shape and amplitude of the initial fluctuations.

The helium Lyα forest

We conclude with a glance at one of the most intriguing new topics of research, the Lyα forest absorption due to singly ionized helium (He II). The He II forest has only recently become acessible as the transition is in the far ultraviolet (304 Å) and even if redshifted out to $z \sim 3$ still needs to be observed with a UV spectrograph from space. In addition, it is very difficult to find a QSO with its UV continuum intact, as the Lyman limit continuum absorption from higher redshift systems tends to obliterate the far UV in most QSOs. Nevertheless, there are potentially big scientific rewards to be gained: (1) since He II and H I have different ionization potentials, looking at the ratio of the column densities from their respective Lyα forests one can constrain the shape of the UV spectrum ionizing the two species. (2) Helium and hydrogen atomic masses differ sufficiently that a comparison of the Doppler parameters of both can measure the amount of non-thermal line broadening. (3) The first observations of He II forests are showing that He II ionization appears to be patchy and not fully developed by redshift 3–4. This observation could help us to understand how and when the universe was first ionized.

There are many other topics related to the rapidly growing field of QSO absorption lines for which we refer the interested reader to the literature given below (see also QUASISTELLAR OBJECTS: INTERVENING ABSORPTION LINES; INTRINSIC AGN ABSORPTION LINES). These include metal absorption systems in general, and the correspondence between absorption systems and various galactic or interstellar environments, as seen in local galaxies. Damped Lyα systems, the absorbers most relevant to high redshift galaxy formation, are treated in the separate article LYMAN ALPHA ABSORPTION: THE DAMPED SYSTEMS.

Bibliography

Reviews of the subject at a level accessible to students, and detailed references to the literature are given in

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The scientific literature on the subject begins with the first measurement of the Gunn–Peterson effect, published as

Gunn J E and Peterson B A 1965 On the density of neutral hydrogen in intergalactic space *Astrophys. J.* **142** 1633

A number of conference proceedings give very useful overviews at a somewhat more technical level than the reviews; they are indispensible as guides to the many topics related to QSO absorption lines which could not be treated here:

Blades J C, Turnshek D A and Norman C (eds) 1988 *QSO Absorption Lines: Probing the Universe (Proc. QSO*

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