Lecture 13 : The intergalactic medium

We have seen that diffuse gas is an important part of galaxy clusters. It turns out that there is also a large amount of gas left in the intergalactic space, since the galaxy formation process has not yet made all matter in the universe to collapse into bound objects. The study of this **Intergalactic medium (IGM** offers various clues to the formation and evolution of galaxies in the universe.

1 Lyman-α clouds

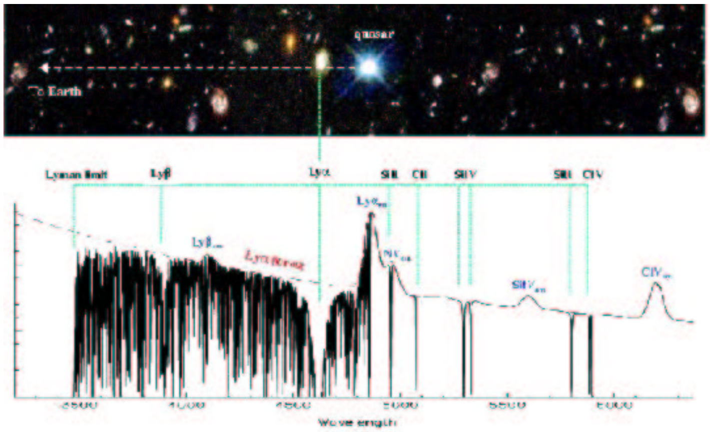

Figure 1: Cartoon to explain the Lyman alpha absorption feature.

The primary method of detecting the IGM is with the help of absorption by neutral hydrogen in the line of sight of distant quasars. The dominant absorption is at the Lyman-α line in the restframe of the atom. The mapping between redshift and space in the line of sight then means that the photons from the quasar with $\lambda \leq \lambda_{Ly\alpha}$ (in the restframe of QSO) is liable to be absorbed by intervening HI atoms, if any. It is found that there are a number of discrete absorption lines in this range of QSO spectra, first reported by Lynds (1971, ApJL, 164, L73), and are called the Lyman-α forest lines (see Rauch 1998, ARAA 36, 267 for a review).

The presence of these absorption line readily shows that the IGM is not uniformly distributed. The traditional practise is to identify distinct features as physical clouds, but this is somewhat misleading. The statistics of these absorption

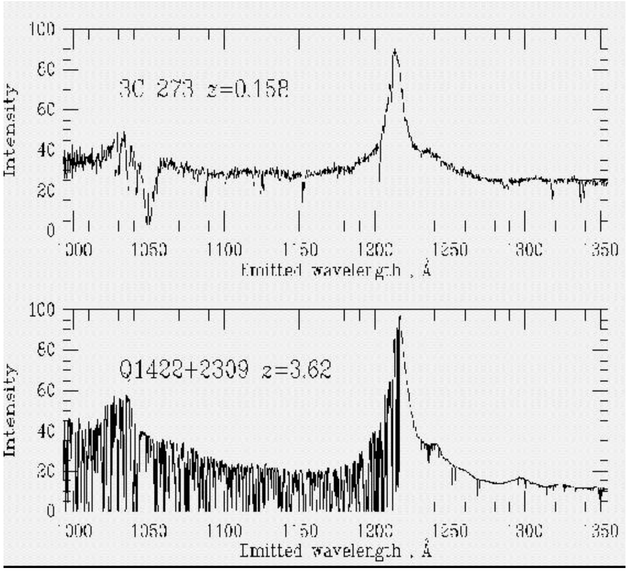

Figure 2: Comparison of Lyman alpha forest at different redshifts.

features are described in terms of the HI column density, N_{HI} as determined by Voigt profile fitting of the feature.

The distribution of column densities has a wide range, $10^{13}\,cm^{-2} \leq N_{HI} \geq 10^{22}\ \mathrm{cm}^{-2}$. The distribution in column densities is found to be roughly $dN/dN_{HI} \propto N_{HI}^{-1.5}$, almost independent of redshift. The number of the lines (per unit redshift) changes dramatically with redshift, however (as shown by the figure),

$$\frac{dN}{dz} \propto (1+z)^{2.3\pm0.4}\,. \tag{1}$$

Lines with HI column densities larger than 10^{17} cm^{-2}, which can absorb out all UV photons falling on it, are called **Lyman limit systems (LSS)**. Absorption systems with $N_{HI} \geq 10^{21}$ cm^{-2} are called **Damped Lyman Alpha systems (DLA)**, since the wings of these absorption lines are heavily damped.

It has been attempted to determine their sizes (actually the correlation scales between lines) by looking at lens pairs of QSOs and studying the coincident absorption systems. This has suggested a typical dimension of tens of kpc.

There is evidence that Lyman-α lines are underabundant close to the emission redshift of the background quasar, which is known as the **proximity effect**. This shows that the quasar ionizes the gas close to it (within a Mpc) to a large degree to produce any absorption. Since the QSO radiation spectrum is well known, one

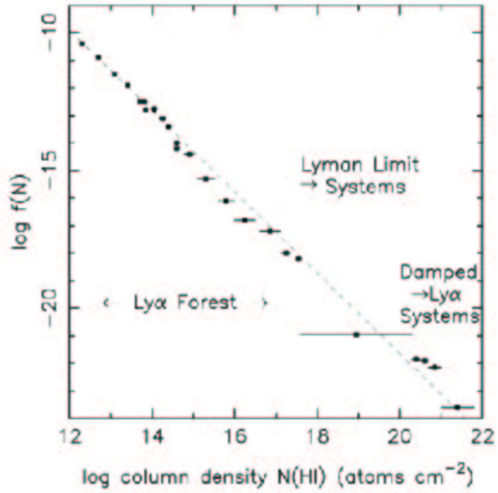

Figure 3: Column density distribution of lyman alpha clouds.

can use the observed decrease in the abundance of absorption lines to estimate the UV background radiation of the universe.

If the quasar has an observed luminosity per unit frequency L_ν, so that the flux of photons at a distance r (corresponding to a particular part in its spectrum) is $F_Q = L_\nu/4\pi r^2$. Now suppose the UV background radiation has a flux J_ν (erg/s cm^2 Hz sr). In ionization equilibrium, the neutral density would be inversely proportional to the radiation incident at frequencies greater than the lyman limit. If there were no quasar, then the HI column density would be

$$N_{HI} = \frac{N}{\int_{\nu_{LL}}^{\infty} 4\pi J_\nu} \tag{2}$$

where N is some hypothetical column density. In the presence of the QSO, the column density would drop to

$$N_{HI} = \frac{N}{\int_{\nu_{LL}}^{\infty} [F_Q + 4\pi J_\nu]} \tag{3}$$

If one assumes that J and F_Q have similar frequency dependence, and has a ratio $w = F_Q(\nu)/J_\nu$ between them, then

$$N_{HI} = \frac{N_o}{1+w} \tag{4}$$

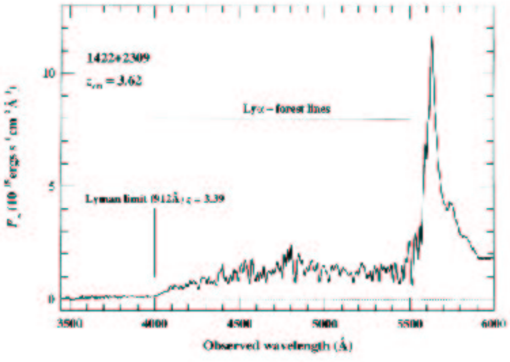

Figure 4: The presence of a LSS.

where N_o is the column density at $r \rightarrow \infty$ from the quasar. This can ben modeled to estimate J_ν.

It has been found that the flux of this background at 912 $\AA$ is of order 10^{-21} cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $z \sim 2-4$ which decreases at lower redshifts. Both quasars and star forming galaxies contribute to the production of these UV photons.

Determination of deuterium abundance in high redshift Lyman-α lines has recently led to another confirmation of the big bang nucleosynthesis model, with D/H $\sim 10^{-4.5\pm0.03}$ implying a baryonic density of $\omega_b \sim 0.02 \pm 0.002$ (Burles et al 2001).

Recent numerical simulations (Cen et al 1997, ApJ, 437, L9; Miralda-Escude et al 1996, ApJ, 471, 582) suggest that the IGM would suffer growth of small scale fluctuations, as a part of the structure formation process in the universe, clumping the matter into intersecting filaments, and HI in the intervening filaments in the line of sight would give rise to the Lyman-α forest lines. The IGM is thought to be photo-ionized by the background UV radiation. Numerical simulations have been able to match the observed column density distribution and the redshift dependence. The temperature of this gas is mostly around 10^4 K, although a small fraction of gas can also be heated more than 10^6 K giving rise to OVI-OVIII absorption lines (see Tripp et al 2000 ApJ, 534, L1).

Imaging of Damped Lyman alpha systems, whenever possible, has led to the conclusion that this population is a mixture of different kinds of objects, with a relatively large fraction of low surface brightness galaxies (Bouche' et al 2001) as well as some normal spirals (Boissier et al 2002). The metallicity variation in DLAs with redshift show little variation, consistent with the idea that low surface

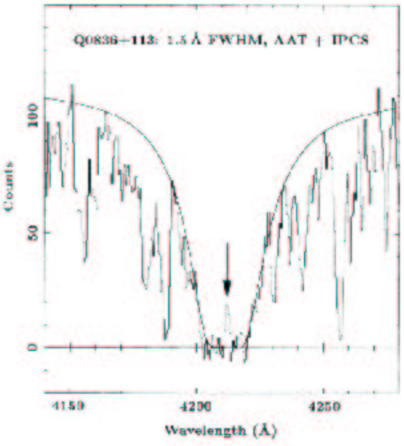

Figure 5: Damped lyman alpha system.

brightness galaxies, with low star formation rates, dominate this population, while the large scatter signifies the diverse nature of its population. In fact, it is believed that DLAs and LBGs occupy the two opposite ends of a distribution, with low/high SFR, PopI/PopII type metallicities and so on.

Lyman-α lines with very low HI column densities also have been found to be associated with metal lines, with metallicities of order $10^{-2.5}$ solar. This enrichment of the IGM is thought to be due to galactic winds at high redshift, perhaps from smaller, dwarf galaxies, which have shallow potentials and which were more numerous at an early phase.

2 Gunn-Peterson test

Soon after the discovery of the first QSOs, it was realised that the HI in the intervening gas would produce some distortion to the spectrum of distant quasars. Gunn and Peterson (1965, ApJ, 142, 1633) predicted that the opacity due to Lyman-α line absorption at z would be

$$\tau = \int_0^z \sigma(\nu) n(z) c (dt/dz) dz \,, \tag{5}$$

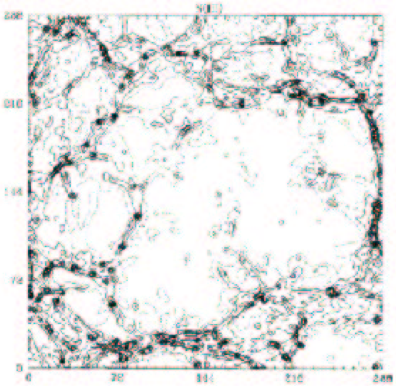

Figure 6: A typical slice of the IGM showing the HI density contours (miralda-Escude et al).

where the redshift can be identified as $1+z = \nu/\nu_0$, ν_0 being the observed frequency. Let ν_α be the frequency of Lyman-α transition. The cross-section is

$$\sigma(\nu) = \frac{\pi e^2}{m_e c} f \delta_D(\nu - \nu_\alpha)\,, \tag{6}$$

with an oscillator strength of $f = 0.416$. One then gets (using $dt/dz = (1/H_0)(1+z)^{-5/2}$ for $\Omega = 1$ universe),

$$\begin{aligned} \tau(z) \quad &= \int (\pi e^2 f/m_e c) n_{HI}(z)\,(c/H_0)(1+z)^{-5/2}\,\delta_D(\nu - \nu_\alpha)\frac{d\nu}{\nu_0} \\ &= (\pi e^2 f/m_e c\nu_\alpha) n_{HI}(z)(c/H_0)(1+z)^{-3/2}\,. \end{aligned} \tag{7}$$

Putting the numbers, one has

$$\tau(z) = 1.7 \times 10^{11} \frac{n_H(z)}{(1+z)^{3/2}}) \sim 6.6 \times 10^3 h^{-1} \left(\frac{\Omega_B h^2}{0.02}\right) f_{HI}(1+z)^{3/2}\,, \tag{8}$$

where $f_{HI} = n_{HI}/n_H$ is the neutral fraction, and $n_H(z) = \frac{\rho_c}{m_p}(1-Y)\Omega_B(1+z)^3 \sim 1.6 \times 10^{-7}\left(\frac{\Omega_B h^2}{0.02}\right)(1+z)^3$ cm^{-3}. This shows that even a small fraction of neutral atoms in the intergalactic medium (assumed to have the same mass density as all baryons put together; see later) would produce a large optical depth. This should cause a absorption trough for $\lambda \leq \lambda_{LY\alpha}$ in the rest frame of the QSO.

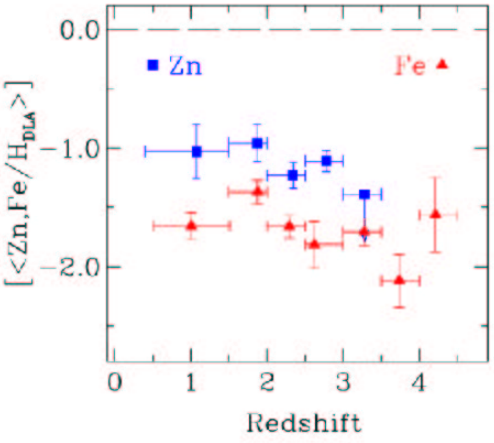

Figure 7: Metallicity variation (weighted by HI column density) with time in DLAs.

This absorption trough was not seen for all QSOs with $z \leq 6$, and only recently it has been discovered in a few large redshift quasars. This means that the universe got **reionized** sometime before this redshift. It is still not very clear how long was the reionization process and what were the sources of reionization, but it is generally believed that the first luminous structures in the universe were the culprit. It is believed that these first galaxies ionized the region surrounding them and slowly these ionized volume (cosmological HII regions) expanded to overlap one another and reionize the whole universe. The rate of expansion of these HII regions depend on the ionizing luminosity (and spectrum) and density distribution of neutral gas. It is expected that the ionizing source would be at very high density regions. The ionization process would be fastest in the low density voids in the web of IGM and the dense filaments would be ionized late. Therefore one expects, in the last stages of overlapping HII regions, some neutral fraction to still exist close to the ionizing sources (Loeb and Barakana, 2001, ARAA, 39, 19).

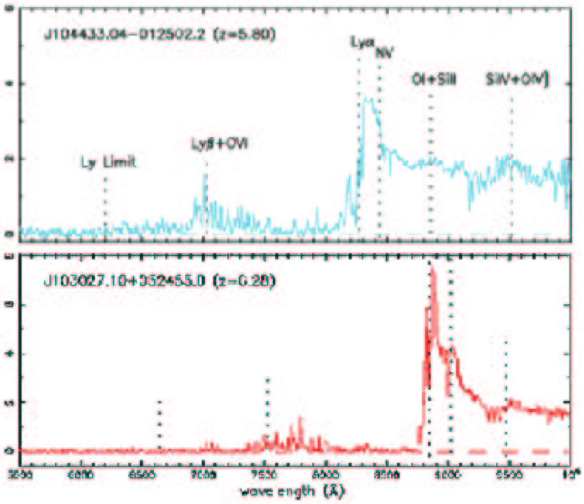

Figure 8: The lower spectrum of a quasar at $z = 6.28$ shows the GP absorption trough, whereas spectra of lower redshift quasars (like the upper one) does not show any.