Cosmology
Lecture 21

The intergalactic medium

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Mass fraction in haloes

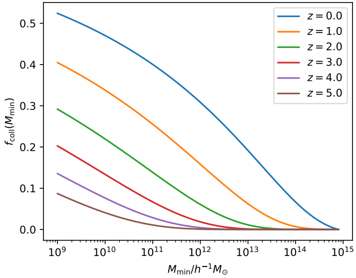
- We have already found the number of haloes per unit comoving volume in a mass range. The amount of mass contained in haloes of mass $> M_{\rm min}$ per unit volume is simply

$$\rho_{\rm coll}(M_{\rm min}) = \int_{M_{\rm min}}^{\infty} {\rm d}M \, n(M) \, M.$$

- The *fraction of mass* in haloes of mass $> M_{\rm min}$ will then be

$$f_{\rm coll}(M_{\rm min}) = \frac{\rho_{\rm coll}(M_{\rm min})}{\bar{\rho}_m} = \frac{1}{\bar{\rho}_m} \int_{M_{\rm min}}^{\infty} {\rm d}M \, n(M) \, M.$$

- It turns out that most of the matter, particularly at $z \gtrsim 2$, reside outside the haloes. This forms the **intergalactic medium (IGM)**.



The intergalactic medium

- The majority of the baryons reside in the diffuse IGM, particularly at high redshifts $z \gtrsim 2$. Only a few per cent of gas is in stars and the interstellar medium.
- The IGM is of low-density, hence requires less complicated physics to model.
- There is constant interaction between the galaxies and the IGM. The gas within galaxies were in the IGM at high redshifts. Also, the outflows from galaxies eject matter into the IGM.
- The IGM-galaxy connections are important for understanding galaxy formation and evolution.

Probing the IGM with quasar spectra

- This diffuse gas is best probed through the absorption spectra of distant quasars, where the light from these sources is absorbed by the intervening IGM.
- We start with the radiative transfer equation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\kappa_\nu I_\nu + j_\nu,$$

  where I_ν is the specific intensity, $\kappa_\nu \equiv n_{\mathrm{abs}}\sigma_\nu$ is the absorption coefficient and j_ν is the emission coefficient.
- In the expanding Universe, the equation becomes

$$\frac{\partial I_\nu}{\partial t} + \frac{c}{a}\hat{n}\cdot\vec{\nabla}_x I_\nu - \frac{\dot{a}}{a}\nu\frac{\partial I_\nu}{\partial \nu} + 3\frac{\dot{a}}{a}I_\nu = -c\kappa_\nu I_\nu + c j_\nu.$$

- Let us assume that there is *no emission* along the line of sight between the quasar and the observer.
- The integral solution along the line of sight can be obtained using the method of characteristics and is given by

$$I_{\nu(t)}(t) = I_{\nu(t_i)}\frac{a^3(t_i)}{a^3(t)}\exp\left(-c\int_{t_i}^{t}\mathrm{d}t'\ \kappa_{\nu(t')}\right),$$

  where we have assumed the initial condition $I_\nu = I_{\nu(t_i)}$ at $t = t_i$ (the intensity emitted by the quasar) and

$$\nu(t) = \nu(t_i)\frac{a_i}{a(t)}.$$

The optical depth

- We define the **optical depth** as

$$\tau(t, t'; \nu) = c \int_{t'}^{t} \mathrm{d}t'' \; \kappa_{\nu(t'')} = c \int_{t'}^{t} \mathrm{d}t'' \; \kappa_{\nu a(t)/a(t'')}.$$

  The solution of the radiative transfer equation is then written in terms of the optical depth

$$I_{\nu(t)}(t) = I_{\nu(t_i)} \frac{a^3(t_i)}{a^3(t)} \mathrm{e}^{-\tau(t, t_i; \nu)}$$

- Most of the absorption we are interested in is due to neutral hydrogen (HI), hence we write

$$\tau(t, t_i; \nu) = c \int_{t_i}^{t} \mathrm{d}t' \; n_{\mathrm{HI}}(t') \, \sigma_{\mathrm{abs}}[\nu a(t)/a(t')] = c \int_{a(t_i)}^{a(t)} \frac{\mathrm{d}a'}{a' H(a')} n_{\mathrm{HI}}(a') \, \sigma_{\mathrm{abs}}[\nu a(t)/a'].$$

- The cross section for line transitions are written in terms of the Voigt profile. For Lyman-α transition, we write

$$\sigma(\nu) = \sigma_\alpha V\left(\frac{\nu}{\nu_\alpha} - 1\right) \approx \sigma_\alpha \delta_D \left(\frac{\nu}{\nu_\alpha} - 1\right),$$

  where we have assumed the lines to be sharp. Note that $\lambda_\alpha = 1216$ Å.
- Hence the optical depth is

$$\tau_\alpha(t, t_i; \nu) \approx c \int_{a(t_i)}^{a(t)} \frac{\mathrm{d}a'}{a' H(a')} n_{\mathrm{HI}}(a') \, \sigma_\alpha \delta_D \left(\frac{\nu a(t)}{\nu_\alpha a'} - 1\right)$$

The observed intensity

- The integral

$$\tau_\alpha(t, t_i; \nu) \approx c \int_{a(t_i)}^{a(t)} \frac{\mathrm{d}a'}{a' H(a')} n_{\mathrm{HI}}(a') \, \sigma_\alpha \delta_D \left(\frac{\nu a(t)}{\nu_\alpha a'} - 1 \right),$$

  will be non-zero only when

$$a(t) \geq \frac{\nu a(t)}{\nu_\alpha} \geq a(t_i) \quad \Longrightarrow \quad \nu_\alpha \geq \nu \geq \nu_\alpha \frac{a(t_i)}{a(t)}.$$

- In that case, the optical depth is

$$\tau_\alpha(t, t_i; \nu) \approx \sigma_\alpha \frac{c}{H(\nu a(t)/\nu_\alpha)} n_{\mathrm{HI}}(\nu a(t)/\nu_\alpha).$$

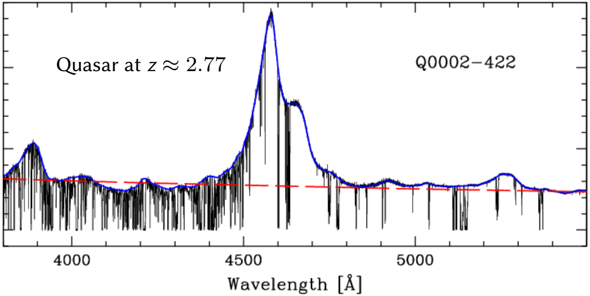
- The observed intensity (putting $a(t) = 1$) is

$$I_\nu(t_0) = I_{\nu/a(t_i)} \, a^3(t_i) \, \mathrm{e}^{-\tau(t, t_i; \nu)}.$$

- Clearly, there is a dilution factor of a^{-3} because of the expansion of the universe.

The observed intensity at $\nu < \nu_\alpha \, a(t_i)$

- We have $I_\nu(t_0) = I_{\nu/a(t_i)} \, a^3(t_i) \, e^{-\tau(t,t_i;\nu)}$, and $\tau = 0$ for $\nu < \nu_\alpha \, a(t_i) = \nu_\alpha/(1+z_i)$.
- In the absence of any absorption, the only other change in the spectrum would be the redshift, i.e., the intensity emitted at $\nu/a(t_i)$ would be observed at ν.



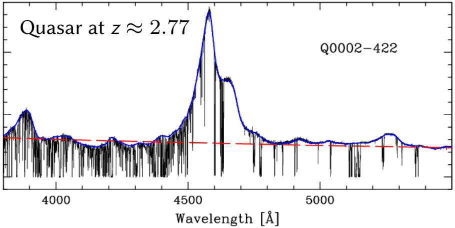
- For example, quasars have a sharp peak in their spectra at a rest wavelength of 1216 Å (arising from Lyα emission). This would be observed at a redshifted wavelength of $1216/a(t_i)$ Å $= 1216 \, (1+z_i)$ Å.
- Other absorption features at $\nu < \nu_\alpha \, a(t_i)$ are because of transitions of other elements (metals).

The Lyman-α forest

- At wavelengths blueward of λ_α, i.e, for $\nu > \nu_\alpha a_i, \ \lambda < 1216\,(1 + z_i)$ Å, we would observe Lyα absorption.
- The relevant relations for $\nu \geq \nu_\alpha \ a_i$ are

$$I_\nu(t_0) = I_{\nu/a(t_i)} \ a^3(t_i) \ \mathrm{e}^{-\tau(t_0, t_i; \nu)}, \quad \tau_\alpha(t_0, t_i; \nu) \approx \sigma_\alpha \left[c/H(a' = \nu/\nu_\alpha)\right] n_{\rm HI}(a' = \nu/\nu_\alpha)$$

Because of a delta function within the integral, the neutral hydrogen at $a' = \nu/\nu_\alpha$ produces an absorption signature at ν, which is given in terms of a' by $\nu = a'\nu_\alpha$.



- To understand this better, consider a photon packet of wavelength $\lambda = 1150$ Å emitted from the quasar at $a_i = 0.265, \ z_i = 2.77$. If there were no HI along the sightline, we would have observed the radiation at $\lambda = 4335.5$ Å.
- Now, as the photons travel, the wavelength increases because of the expansion, and at $a = 0.265 \times (1216/1150) = 0.28$, the wavelength becomes 1216 Å. At this point, depending on the amount of HI present, the photons will be absorbed. Hence, we will see an absorption feature at $\lambda = 4335.5$ Å, which directly maps out the HI content at $a' = \lambda_\alpha/\lambda = 0.28$, just what is expected!

Cosmology with Lyman-α forest

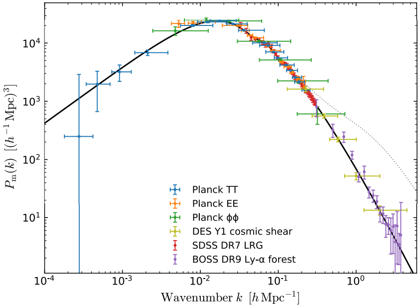
- The Lyman-α optical depth is

$$\tau_\alpha(t_0, t_i; \nu) = \sigma_\alpha \frac{c}{H(a' = \nu/\nu_\alpha)} n_{\rm HI}(a' = \nu/\nu_\alpha) \equiv \tau_\alpha(a').$$

- The neutral hydrogen density can be written as

$$n_{\rm HI}(a) = x_{\rm HI}(a)\; n_H(a) = x_{\rm HI}(a)\; \frac{\rho_b(a)}{m_p} = x_{\rm HI}(a)\; \frac{\bar{\rho}_b(a)\;(1+\delta_b(a))}{m_p} = x_{\rm HI}(a)\; \frac{\Omega_{b,0}\;\rho_c\;(1+\delta_b(a))}{m_p a^3}.$$

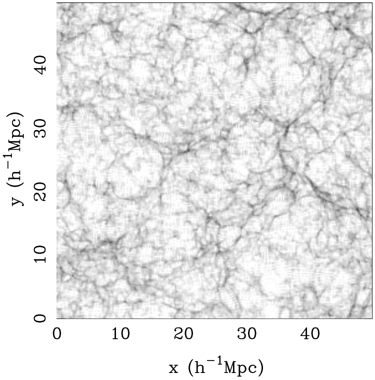
- Thus the optical depth $\tau_\alpha(a) \propto 1 + \delta_b(a)$. Since the observed fluctuations are directly related to δ_b, one can estimate the matter power spectrum using the Lyman-α forest.



Courtesy ESA and Planck Collaboration

Advantages of the Lyman-α forest

- Since high-density regions tend to occupy smaller volumes, the lines of sight to the quasars have low probability to pass through the high-density structures. They mostly trace the low and medium-density "cosmic web".



TRC, Haehnelt & Regan (2009)

- The Lyman-α forest can thus be modelled using quasi-linear theory or simulations which require much less resources.

The Lyman-α optical depth

- Let us now estimate the numerical value of the optical depth.
- We have

$$\tau_\alpha(a) = \sigma_\alpha \frac{c}{H(a = \nu/\nu_\alpha)}\ x_{\rm HI}(a)\ \frac{\Omega_{b,0}\ \rho_c\ (1 + \delta_b(a))}{m_p a^3}$$

- Use $H(a) \approx H_0 \sqrt{\Omega_{m,0}} a^{-3/2}$ to obtain

$$\tau_\alpha(a) = \sigma_\alpha \frac{c}{H_0} \frac{a^{3/2}}{\sqrt{\Omega_{m,0}}}\ x_{\rm HI}(a)\ \frac{\Omega_{b,0}\ \rho_c\ (1 + \delta_b(a))}{m_p a^3}$$

$$\approx 4.6 \times 10^5 \times x_{\rm HI}(a) \frac{\Omega_{b,0} h^2}{\sqrt{\Omega_{m,0} h^2}} \frac{1}{a^{3/2}} (1 + \delta_b(a)).$$

- Putting in the values $\Omega_{m,0} = 0.25$, $h = 0.7, \Omega_b h^2 = 0.02$, we get for $a = 0.25$, $\tau_\alpha(a) \approx 2.1 \times 10^5 x_{\rm HI}(a)(1 + \delta_b(a))$.

Ionized IGM

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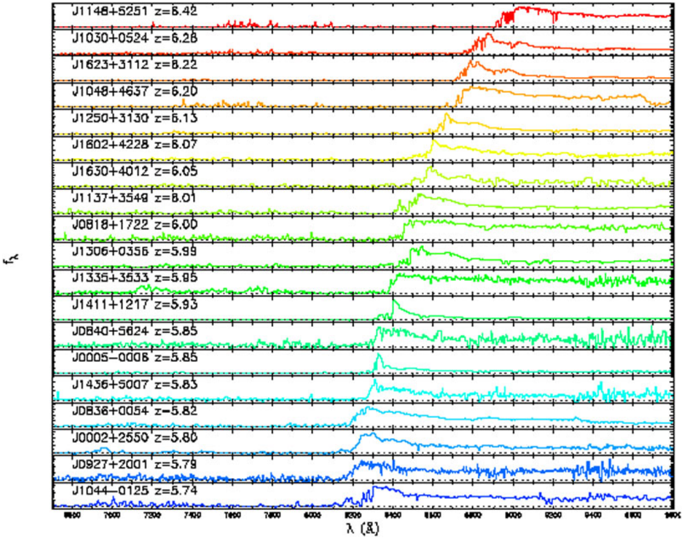
- Let us put $\delta_b = 0$ assuming an average-density universe.
- This then implies that the radiation would be completely absorbed whenever $x_{\mathrm{HI}} \gtrsim 10^{-5}$.
- The fact that we do not observe complete absoprtion of quasar spectrum at wavelengths blueward of the Lyα emission line implies that the universe is highly ionized at $z \approx 3$. This is known as the **Gunn-Peterson effect**.
- This conclusion is valid until $z \sim 6$.

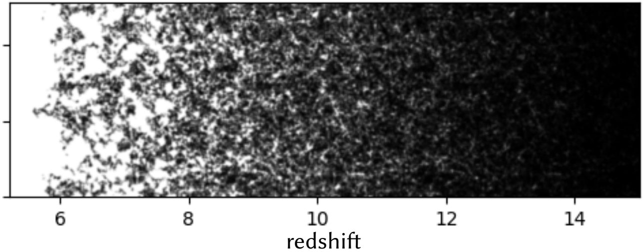
The Lyman-α forest at $z \sim 6$



Fan, Carilli & Keating (2006)

Reionization of the Universe

- The universe becomes neutral for the first time at $z \approx 1100$.
- However, quasar absorption spectra at $z \lesssim 6$ imply that the bulk of the universe is highly ionized.
- It is believed that ionizing photons from the early stars in galaxies ionized the IGM, known as **reionization**.



- Reionization can be studied using Lyman-α absorption, CMB anisotropies, and in the future 21 cm radiation.
- Reionization optical depth is one of the cosmological parameters in the concordance model of cosmology.