Lecture 16:
Baryons and Photons

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1 Reionisation

1.1 When did reionisation happen?

- Prior to reionisation, CMB photons will stream through the Universe uninhibited by baryons (since they're too low energy to ioinise hydrogen).
- After reionisation, however, they will interact with the free electrons.
- The rate at which they will interact with the free electrons will depend on the number density of free electrons, n_e and the interaction cross-section, σ_e:

$$\Gamma = n_e \sigma_e c \tag{1}$$

- If baryonic matter is reionised at time t_*, then the optical depth for scattering is:

$$\tau_* = \int_{t_*}^{t_0} \Gamma(t) dt = c\sigma_e \int_{t_*}^{t_0} n_e(t) dt \tag{2}$$

- Which, since $n_e(t) = n_e(t_0)a^{-3}$, we can re-write as:

$$\tau_* = \Gamma_0 \int_{t_*}^{t_0} \frac{dt}{a(t)^3} \tag{3}$$

  where $\Gamma_0 = c\sigma_e n_e(t_0) = c\sigma_e n_{\text{Bary}}(t_0) = 1.58 \times 10^{-4}$ Gyr

- Since $da/dt = \dot{a}$, meaning $dt = da/\dot{a}$, this can be written as:

$$\tau_* = \Gamma_0 \int_{a(t_*)}^{1} \frac{da}{\dot{a}a(t)^3} = \Gamma_0 \int_{a(t_*)}^{1} \frac{da}{H(a)a(t)^4} \tag{4}$$

- And using $a = (1+z)^{-1}$, so $da/dz = -(1+z)^{-2}$ and thus $da = (1+z)^{-2}dz$ gives:

$$\tau_* = \Gamma_0 \int_{0}^{z_*} \frac{(1+z)^2 dz}{H(z)} \tag{5}$$

- In a universe dominated by Dark Energy and matter:

$$H(z) = H_0(\Omega_{m,0}(1+z)^3 + \Omega_{D,0}))^{1/2} \tag{6}$$

- Meaning the integral can be solved analytically to give:

$$\tau_* = \frac{2}{3\Omega_{m,0}}\frac{\Gamma_0}{H_0}((\Omega_{m,0}(1+z_*)^3 + \Omega_{D,0})^{1/2} - 1) \tag{7}$$

which, in the Benchmark Model, is:

$$\tau_* = 0.00485(0.31(1+z_*)^3 + 0.69)^{1/2} - 1) \tag{8}$$

- Observations of the CMB are consistent with $\tau = 0.066 \pm 0.016$, which, using the above formula, corresponds to $z_* = 7.8 \pm 1.3$.

- In the Benchmark Model, this corresponds to when the Universe was $t_* \sim 650$ Myr old.

2 How many ionising photons do we need?

- We can gain insights into what reionised the Universe by considering how many photons we need.

- On average, there are 0.25 baryons per cubic metre in the Universe:

$$n_{\mathrm{Bary}} = 0.25\ \mathrm{m}^{-3} = 7.3 \times 10^{66}\ \mathrm{Mpc}^{-3} \tag{9}$$

- Assuming 20% of all ionising photons that are emitted actually make it out of their galaxies, then we need:

$$n_{\mathrm{Bary}} = \frac{7.3 \times 10^{66}}{0.2}\ \mathrm{Mpc}^{-3} = 3.7 \times 10^{67}\ \mathrm{Mpc}^{-3} \tag{10}$$

ionising photons.

3 Can stars reionised the Universe?

- The star formation rate per comoving Mpc was around $20,000\ \mathrm{M}\odot\ \mathrm{Mpc}^{-1}\ \mathrm{Myr}^{-1}$. Considering the initial mass function, about 2000 $M\odot$-worth of these will be O-stars.

- Since an O-star has a mass of around 30 $M\odot$, this corresponds to a rate of O-star production of:

$$\dot{n}_{\mathrm{O-star}} = \frac{2000\ \mathrm{M}\odot\ \mathrm{yr}^{-1}}{30\ \mathrm{M}\odot} = 67\ \mathrm{yr}^{-1} \tag{11}$$

- And since each O-star lives for around 6 million years, it means that there are around 6 = 400 O-stars per megaparsec in existence at any time.

- With each O-star emitting 5×10^{48} ionising photons per second, this corresponds to a rate of ionising photon production of:

$$\dot{n}_* \approx (5 \times 10^{48}\ \mathrm{s}^{-1})(400\ \mathrm{Mpc}^{-3}) \approx 2 \times 10^{51}\ \mathrm{s}^{-1}\ \mathrm{Mpc}^{-1} = 6 \times 10^{64}\ \mathrm{Myr}^{-1}\ \mathrm{Mpc}^{-3} \tag{12}$$

- Comparing this to the number of photons needed, gives a timescale for reionisation of:

$$t = \frac{n_*}{\dot{n}_*} = \frac{3.7 \times 10^{67}\ \mathrm{Mpc}^{-3}}{6 \times 10^{64}\ \mathrm{Myr}^{-1}\ \mathrm{Mpc}^{-3}} \approx 600\ \mathrm{Myr} \tag{13}$$

compared to an age of the Universe of ~ 650 Myr at the time of reionisation.

- So, providing the first stars formed within the first few tens of Myr, then the Universe had time make sufficient numbers of stars to reionised the Universe.