Cosmic Microwave Background Radiation

After end of e^+e^- creation-annihilation leave the **lepton era**; since neutrinos decouple about the same time (also nucleosynthesis), enter **photon era**.

Photon gas in thermal equilibrium from $X\bar{X} \to \gamma\gamma$ and remains so from **free-free** and **bremsstrahlung**: $e\gamma \to e\gamma$.

Processes freeze out at $z \approx 10^6$ ($t \approx 1500$ y), leaving only equilibrium scattering (no energy change), so spectrum fixed by **thermalization epoch = cosmic photosphere** (analogy to star).

Spectrum

Thermal equilibrium $\Rightarrow$ **Planck** or **blackbody** spectrum

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1},$$

characterized by temperature T, with energy density ρ, number density n,

$$\rho = \frac{\pi^2}{15}\frac{k^4}{c^5\hbar^3}T^4 = 4.7\times 10^{-34}\,(T/2.73\,K)^4\,\mathrm{g\,cm^{-3}}$$

$$n = \frac{2\zeta(3)}{\pi^2}\frac{k^3}{c^3\hbar^3}T^3 = 410\,(T/2.73\,K)^3\,\mathrm{cm^{-3}}$$

$$\nu_{peak} = 160\,(T/2.73\,K)\,\mathrm{GHz}$$

$$\lambda_{peak} = 1.9\,(T/2.73\,K)^{-1}\,\mathrm{mm}$$

With expansion $\nu \sim a^{-1}$, $T \sim a^{-1}$ so spectrum remains blackbody.

Peaks today in microwave region.

Spectral distortion

Arise if out of equilibrium energy inputs (e.g. decaying particles, explosions). At $z > 4000$ energy shared by many photons so photon number $\approx$conserved $\rightarrow$ like chemical potential:

$$\textbf{Bose}-\textbf{Einstein}\ \text{distortion}:\quad \mu = 1.4\Delta E/E \quad < \quad 9\times 10^{-5}.$$

At $z < 4000$ no time to Compton cool ($e\gamma \rightarrow e\gamma$) so get

$$\textbf{Comptonization}:\quad \Delta E/E = e^{4y} - 1 \approx 4y$$

$$y = \int \Gamma\, dt = \sigma_T \int dt\, n_e (T_e/m_e) \quad < 1.5\times 10^{-5}$$

FIGURE of Planck and distortions

FIGURE of FIRAS spectrum

Last Scattering Surface

After decoupling ($\Gamma_{e\gamma} < H$) photons **free stream** since last interactions (electron scattering) done.

Not instantaneous though. **Optical depth** from scattering

$$\tau = \int_t^{t_0} n_e \sigma_T \, dt.$$

Since Poisson process then probability for scatter is $1 - e^{-\tau}$.

Visibility function gives probability of scattering between z, $z + dz$

$$p(z) = \frac{d}{dz}(1 - e^{-\tau}) = e^{-\tau} \frac{d\tau}{dz},$$

defining the last scattering surface. Well fit by Gaussian with mean $z_{lss} = 1055$ and thickness $\Delta z = 150$.

FIGURE 7.1 showing X, tau, p vs. z

Summary of Recombination Epochs

- Equality: energy density of matter and radiation equal; transition from radiation to matter dominated expansion behavior

• Recombination: (hydrogen) atoms form as ionization-recombination reactions fall out of equilibrium; free electron abundance freezes out

• Decoupling: electron-photon (Thomson) scattering reactions freeze out; matter and radiation lose contact

• Last Scattering: photons free stream

Recombination Epoch Parameters

$z_{eq} = 23900\,\Omega_m h^2$	$t_{eq} = 1500(\Omega_m h^2)^{-3/2}\,\mathrm{y}$	$T_{eq} = 10\,\mathrm{eV} = 10^5\,K$
$z_{rec} = 1300$	$t_{rec} = 2 \times 10^5\,\mathrm{y}$	$T_{rec} = 0.3\,\mathrm{eV} = 3600\,K$
$z_{dec} = 1100$	$t_{dec} = 3 \times 10^5\,\mathrm{y}$	$T_{dec} = 0.25\,\mathrm{eV} = 3000\,K$
$z_{lss} = 1055 \pm 75$		

Reionization

If electrons reheat after decoupling epoch ($z \approx 1100$) then get Compton distortion – probe of galaxy/star formation energetics.

$$y = 2.3 \times 10^{-5} \left(\frac{T_e}{5000\,K}\right) \left(\frac{z_{heat}}{1000}\right)^{3/2} .$$

Optical depth from scattering

$$\tau(z) = \sigma_T \int_{t(z)}^{t_0} dt\, n_e = \sigma_T \int_0^z dz\, (dt/dz) n_\gamma (n_e/n_\gamma)$$

$$= \sigma_T H_0^{-1} \eta\, n_{\gamma,0} \int dz (1+z)(1+\Omega z)^{-1/2}$$

$$\to \left(\frac{1+z}{121} \right)^{3/2} h^{-1} \quad (\Omega = 1)$$

So universe unlikely to have significant optical depth after decoupling.

(Local version called *Sunyaev-Zel'dovich effect*).

Cosmological Origin of Blackbody Radiation

- 5 times the energy density of galactic light
- Would require $10^9 n_{gal}$ in discrete sources to match isotropy
- Direct detection at $z > 0.54$ from SZ effect; indirect out to $z = 1.97$ by atomic excitation
- Predicted by Big Bang; consistent with nucleosynthesis

Temperature, Expansion, and Velocity

Expansion gives scaling

$$T(z) = T_0 \, (1+z)$$

Observed to 13% at $z < 1.97$ (upper limits at $z < 4.38$) from radiative excitations of CI, CII, CO.

Velocity gives Doppler shift

$$T = T_0 \, (1 + v \cos\theta) \qquad \textbf{dipole anisotropy}$$

Motion with respect to isotropic CMB frame. Detected

$$\Delta T/T = 1.23 \times 10^{-3} \qquad \Delta T = 3.356 \, mK$$

$$v_{\oplus} = 369 \, \mathrm{km \, s^{-1}} \qquad v_{gal} = 550 \, \mathrm{km \, s^{-1}}$$

This motion gives probe of mass distribution. **Dipole offset** of CMB from local peculiar velocity field depends on $\Omega_m^{0.6}$.