1. The cosmic microwave background (CMB) photons are in the frequency range between 10^9Hz to 10^{12}Hz. Meanwhile, the electromagnetic spectrum ranges from radio-waves (frequency $\sim 10^4$Hz) to gamma rays (frequency $\sim 10^{24}$ Hz). When the background photons first decoupled after the recombination, in which region of the electromagnetic spectrum did their frequency lie? Justify you answer. [2]

photons freq is between $10^9 Hz$ to $10^{12} Hz$,

after decoupling the cosmic microwaves are redshifted hence:

$\frac{n\nu}{n\nu_0} = (1+z)^3$; the $n\nu = n\nu_0 (1+z)^3$; $\nu = \nu_0 (1+z)^3$

so the redshift waves lie in ~~microwave~~ range.

gamma rays.

2

2. If the scattering rate of photons with electrons is 5×10^{-6}/s and the Hubble constant is 2×10^{-10}/s, then are the photons still coupled to the electrons? Give reasons. [1]

$H = 2\times10^{-10}/s$ and Thomson's scattering $= 5\times10^{-6}/s$

The photons are ~~not~~ coupled because of the huge number density and high temperature.

and since $T < T_{freeze}$ the reaction rate is higher and

hence $H + \nu \rightleftharpoons p + e$ reaction is in equilibrium

1

4. The number density of photons in the present universe is $n_{\gamma 0}=400/\text{cm}^3$. A photon emitted from a star is observed with redshift $z = 500$. What was the number density n_γ when the photon was emitted. [4]

$n_{\gamma 0} = 400/\text{cm}^3$

$z = 500$

n_γ

$\frac{n_\gamma}{n_{\gamma_0}} = (1+z)^3$

$\therefore n_\gamma = 400 \times (501)^3$

$= n_\gamma = 400 \times 1.25 \times 10^8$

$= [illegible] = 5 \times 10^{10} /\text{cm}^3$

4

photon emitted from a star is
photon was emitted. [4]

5. Calculate the redshift of the universe at the transition from radiation to matter domination. Assume that $\Omega_M^0 = 0.3, \Omega_R^0 = 3 \times 10^{-5}$, and $\Omega_\Lambda = 0, \Omega_K^0 = 0$. [8]

at transition,

$$\rho_R = \rho_M$$

$$\rho_R \propto \frac{1}{a^4} \quad \rho_M \propto \frac{1}{a^3}$$

$$\rho_R = \frac{\Omega_R}{a^4}$$

$$\rho_M = \frac{\Omega_M}{a^3}$$

$$\Omega_R (1+z)^4 = \Omega_M (1+z)^3$$

8

$$1+z = \frac{\Omega_M}{\Omega_R}$$

$$= \frac{0.3}{3\times10^{-5}}$$

$$= \frac{3\times10^4}{3}$$

$$1+z = 10000$$

$$z = 999$$