Physics 224 **Fall 2000**

Discoveries and Inventions of Modern Physics **due 11:00 am Thursday Nov. 30**

PROBLEM SET 9

Use the lecture notes (including the appendix to lecture 14) to answer these questions. Note that the gravitational constant $G = 6.67 \times 10^{-8}$ cm^3/gm–sec^2.

1. The galaxies of the Virgo cluster are moving away from our galaxy at a speed of 1000 km/s. What is the redshift parameter z? (The doppler shift was covered in lecture 9.)

2. The current value of the Hubble constant is $H_o = 67$ km/sec-Mpc. 1Mpc = 1 mega-parsec $=3.09\times10^{24}$ cm $\simeq$ 3 million light years. What is the critical density ρ_c in gm^2/cm^3?

3. (15 pts–3 pts each)

   (a) Using the Stefan–Boltzmann law from lecture 4, what is the photon energy density u_γ at a temperature T measured in Kelvin?

   (b) In the radiation–dominated era after the annihilation of electrons and positrons, the energy density is dominated by photons and neutrinos. The ratio of the energy density u_ν of neutrinos and antineutrinos to that of photons is

   $$\frac{u_\nu}{u_\gamma} = 0.4542 \qquad (1)$$

   Use your answer to part (a) to calculate the total energy density $u = u_\nu + u_\gamma$. Find the equivalent mass density ρ using $u = \rho c^2$.

   (c) Use the answer to part (b) to find the time (in days) required for the universe to cool from 10^8 K to 10^7 K in the radiation dominated era.

   (d) Use your answer to part (c) to find the ratio by which the cosmic scale factor $R(t)$ has increased as the universe cools from 10^8 K to 10^7 K.

(e) Use the answer from part (b) find the time (in years) required for the universe to cool from very high early temperatures to 3000 K. Assume that this occurs in the radiation dominated era and that the density at very early time is such that $1/\rho(t = \text{very early universe}) \ll 1/\rho(T = 3000K)$.