Course: Introductory Astroparticle Physics

Code: PH7999

Credit: 1

Hours: 14

Instructor: Subir Sarkar (Professor, University of Oxford, UK)

Course Content: The universe observed, Relativistic world models, Reconstructing our thermal history, Big bang nucleosynthesis, Dark matter: astrophysical observations, Dark matter: relic particles, Dark matter: direct detection, Dark matter: indirect detection.

The course will be offered daily, starting 29$^{\text{th}}$ August and ending 11$^{\text{th}}$ September, from 13:30 to 15:00 in Room B-115 and B-114.

Brief CV: Subir Sarkar is Head of the Particle Theory Group, Rudolf Peierls Centre for Theoretical Physics at the University of Oxford. Subir was educated at the Indian Institute of Technology, Kharagpur and obtained his PhD (1982) at the Tata Institute of Fundamental Research, Bombay, where he was a staff member (1979–84). Subsequently, he held visiting positions at Oxford Astrophysics, Rutherford Appleton Laboratory, CERN Geneva, and also worked in science education & outreach at Eklavya, Bhopal.

Since 1990 he has been at Oxford — first as Glasstone Research Fellow, then Ernest Rutherford Fellow, appointed University Lecturer (1998-) and Professor (2006-). Presently he is an Affiliate Professor of the Niels Bohr Institute, Copenhagen and Adjunct Professor at the Raman Research Institute, Bangalore.

His main research interests are at the interface between cosmology and fundamental physics and he also works on astroparticle experiments: the IceCube Neutrino Observatory and the Cherenkov Telescope Array. Among other recognitions, he has been awarded the Niels Bohr Professorship (2013–18) and the IUPAP-TIFR Homi Bhabha Medal & Prize (2017).

PROBLEMS CLASS: WEDNESDAY 4 SEPT 2019, 13:30–14:30
(Solutions will be discussed on Wed 11 Sept 2019, 13:30–14:30)

1) **Olber's Paradox:** Calculate the likelihood that in a random direction in an isotropic, infinite, static universe uniformly filled with stars which have radius R and spatial density n, our view will be blocked by a star at distance r. (Assume that a typical star is like our Sun with radius $R_\odot \sim 7 \times 10^{10}$ cm and mass $M_\odot \sim 2 \times 10^{33}$ gm, and that the average density if luminous matter in the universe is $\sim 1\%$ of the critical density i.e. $\rho_{\text{lum}} \sim 2 \times 10^{-31}$ gm cm^{-3}.)

Given that the sky is dark at night, what bound can be inferred on the age of such an universe (and/or of the stars contained in it)? Discuss the resolution of Olber's Paradox in the universe we inhabit.

For comparison, calculate the brightness of the night sky for a matter-dominated Friedmann cosmology (with $k = 0$) expanding presently at a rate H_0.

In reality stars are not uniformly distributed in space but are clustered in galaxies (of typical radius $\sim 10h^{-1}$ kpc and present number density $\sim 0.02h^3$ Mpc^{-3}, where $h \equiv H_0/100$ km/s/Mpc is the Hubble parameter. Calculate the optical depth due to galaxies up to a redshift z, assuming their comoving number is conserved. At what redshift would it become unity?

2) **Eppur si muove:** The Cosmic Microwave Background (CMB) is observed to have a blackbody spectrum, i.e. the number of photons per unit volume with (angular) frequency ω in the range dω and moving in any direction (the solid angle dΩ integrated to 4π) is

$$n(\omega)\mathrm{d}\omega = \frac{1}{\pi^2 c^3}\frac{\omega^2 \mathrm{d}\omega}{\exp\left(\hbar\omega/kT_0\right) - 1} \tag{1}$$

where the present temperature is measured to be $T_0 = 2.7255 \pm 0.0006$ K.

In the standard cosmological model this radiation should be isotropic over the sky in the 'cosmic rest frame' (CRF). Show that an inertial observer moving at velocity v $(= \beta c)$ with respect to this frame, the radiation will still have the blackbody form but with a temperature

$$T(\theta) = T_0\frac{\sqrt{1 - \beta^2}}{1 - \beta \cos\theta}, \tag{2}$$

where θ is the angle between the direction of motion and the line-of-sight.

Expand this to show that the leading term in v/c is a dipole anisotropy. If the maximum change in the temperature we observe is $\Delta T = 3.352$ mK then how does our velocity with respect to the CRF compare with the expected 'peculiar' (non-Hubble) velocity due to the growth of inhomogeneities?

Elaborate on whether the existence of the CRF conflicts with the principle of relativity and generally on the possible cosmological implications of our motion with respect to this frame.