Astronomy & Astrophysics : An Introductory Survey
A lecture series by Prof. G. Srinivasan
A ‘Golden Jubilee Celebration’ Event of the Astronomical Society of India

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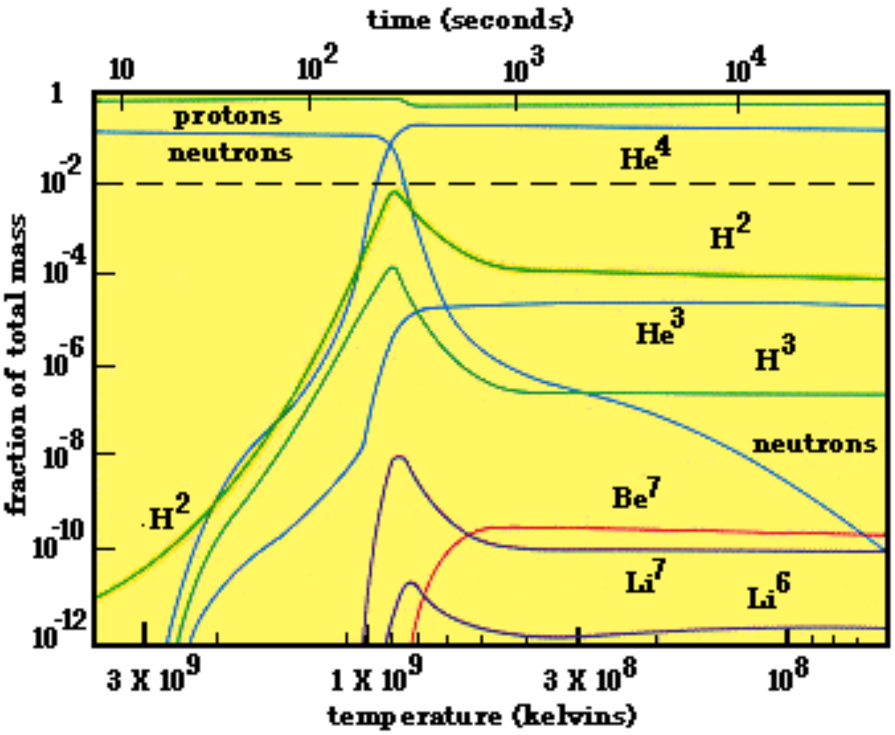
Lecture 35 : The Expanding Universe and the Synthesis of Elements

One could still imagine that God created the universe at the instant of the big bang, or even afterwards in just such a way as to make it look as though there had been a big bang, but it would be meaningless to suppose that it was created before the big bang. An expanding universe does not preclude a creator, but it does place limits on when he might have carried out his job! - A Brief History of Time, Stephen Hawking

In 1922, Alexander Friedmann proved that an isotropic, homogeneous universe cannot be static. By 1929, Hubble demonstrated that the clusters of galaxies are receding from us. Even prior to that, George Lemaitre had argued that if the universe is expanding, then it must have been very small and very hot in the beginning. In 1940, George Gamow conjectured that the elements may have been synthesized in the early universe. In this first of six lectures on Cosmology, This lecture explains the expanding universe scenario, and the synthesis of light elements such as Deuterium and Helium. The synthesis of heavy elements in the stars, as well as exotic scenarios like the coalescence of two neutron stars, is also discussed.



The mass fraction (abundance ratio) for various isotopes vs. time. Deuterium (H^2) peaks around 100 seconds after the Big Bang, and is then rapidly swept up into He^4 nuclei. A small fraction of the helium nuclei combine into heavier nuclei giving a small abundance of primordial Li^7. On the other hand, H^3 decays into He^3 with a 12-year half-life, and Be^7 decays into Li^7 with a 53-day half-life. Because of this no primordial H^3 or Be^7 survives to the present time.

[Figure Credit : Edward L. Wright]

Introductory Textbooks on Cosmology

1. J. V. Narlikar, 2002 (3rd Ed.), ***An Introduction to Cosmology***, Cambridge University Press
2. A. Liddle, 2015, ***An Introduction to Modern Cosmology***, Wiley

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Suggested Problems

1. Hubble's law occurs naturally in a Big Bang model for the Universe, where the density decreases and the distances between galaxies increase as the Universe expands. This model is not in agreement with the perfect cosmological principle, in which there are no privileged moments in time. The Big Bang itself is clearly a special moment. For this reason Bondi, Gold and Hoyle proposed the Steady State model in the 1940s. Interestingly, this model also gives rise to the Hubble law. In the Steady State model, the global properties of the Universe, such as H_0 and $\rho_m = \rho_0$, remain constant.
   (a) Show that the distance $r(t)$ increases with time t as $r(t) \propto e^{H_0 t}$.
   (b) For the Universe to remain in a steady state, the density of a volume V must remain constant, which means that matter must be created continuously at a rate M_{ss}. Express M_{ss} in terms of H_0, $_0$, and V. Calculate the rate with which matter would have to be created in our Universe, where $H_0 = 71$ km/s/Mpc and $0 = 3.01027$ kg.m^{-3}. Express the result in hydrogen atoms per cubic kilometer per year.
2. Using the Friedmann equation for a $k = 0$, radiation dominated universe, show that the age of the Universe at a time when the photon temperature is T is

$$t(T) = \frac{1}{2H} = 1.71 \left(\frac{1MeV}{k_B T} \right)^2 \; s \tag{1}$$

   The above equation would have been correct if the photons were the only relativistic species present. But, the cosmic neutrino background has an energy density that is 68% of the photon energy density, changing the normalization of this equation by a factor $1/\sqrt{1.68}$ to

$$t(T) = \frac{1}{2H} = 1.32 \left(\frac{1MeV}{k_B T} \right)^2 \; s \tag{2}$$

3. Primordial nucleosynthesis depends on a number of measured parameters. Consider the following changes in these parameters and qualitatively describe their effects on the predicted Helium abundance.
   (a) Assume the existence of an extra species of neutrinos.
   (b) Assume the weak interaction to be stronger (than in reality) so that thermal equilibrium distribution between neutrons and protons are maintained till $k_B T = 0.25$ MeV.
   (c) Assume the proton-neutron mass difference to be larger (than in reality).
   (d) The standard theory of primordial nucleosynthesis assumes that the matter in the universe was distributed homogeneously during the era of nucleosynthesis, but the alternative possibility of inhomogeneous nucleosynthesis has also been considered since the 1980s. Inhomogeneous nucleosynthesis is based on the hypothesis that baryons became clumped during a phase transition at $t \simeq 10^{-6}$ s, when the hot quark soup converted to a gas of mainly protons, neutrons, and in the early stages, pions. The baryons would then be concentrated in small nuggets, with a comparatively low density outside of these nuggets. After the phase transition but before nucleosynthesis, the neutrons would have the opportunity to diffuse away from these nuggets, becoming more or less uniformly distributed in space. The protons, however, since they are charged, interact electromagnetically with the plasma that fills the universe, and therefore have a much shorter mean free path than the neutrons. Most of the protons, therefore, remain concentrated in the nuggets.