Chapter 1

Steady State versus Big Bang Cosmology

One hundred years ago[1], at the beginning of the twentieth century, it was not clear to observers of the sky whether the 'nebulae' detected by their telescopes were diffuse matter within our galaxy or 'extended galaxies', analogous to the Milky Way and located at very large distances from it. Vesto Melvin Slipher[2], an American astronomer, discovered around 1913 that the Andromeda nebula (not known then yet to be a spiral galaxy similar to ours) was moving away from us at about one thousand kms per hour. The following year he found that nearly a dozen nearby galaxies were rapidly moving away from the Milky Way at very large speeds, as deducted from the systematic redshifts observed in the light coming from them. True, few galaxies were moving in the opposite direction at lower speeds, but this was correctly interpreted to be due to local motions rather than to the general pattern of galaxy motion. He did not realize then that he had stumbled upon the first piece of evidence for the general expansion of the universe.

Around 1928 Hubble and Humason, using the new 100" telescope at Mount Wilson and, using as yardsticks a certain kind of stars, the Cepheid variables easily identifiable in nebulae far from us, whose intrinsic brightness was known from studies in our own galaxy, undertook the arduous task of determining the distances and the recession velocities (obtained using their measured redshifts) of more and more distant galaxies. Later, in 1948, Hubble and Humason, using the 200" telescope at the Palomar Mountain (then the largest in the

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[1] Herman Bondi, "Europhysicsnews", p. 209 (Nov/Dec 2001).

[2] Robert Jastrow, "God and the Astronomers", p. 30 (W.W. Norton & Co.; New York, 1978).

world) were able to infer from their data that there was a rough universal proportionality between distance and recession speed for all galaxies, the so called Hubble's law. Subsequently, much later, it was found that the distance scale had to be upgraded by a factor of ten, but this is another story.

The first attempt[3] of an answer to the question "Why the expansion?" came from a Belgian priest, George Lemaitre (1894-1966), who, before becoming a priest, had served in the Belgian army as an artillery man during World War I. As an artillery officer he had a good mathematical training and in 1927 he published a paper[4] in a local journal, "Annales de la Societe Scientifique de Bruxells", in which (unaware of Friedmann's articles published in 1922[5]) he did the connection between the Einstenian General Relativity Theory and cosmic expansion. At that time Einstein had achieved already world wide fame, after the expedition organized by Eddington had confirmed the curvature induced by the sun's gravitational field in the path of starlight rays, observed taking advantage of the 1919 solar eclipse visible from the southern hemisphere.

At the fifth Solvary conference[6], the same year, 1927, Lemaitre tried to contact Einstein in Bruxells to tell him about the general solutions to the relativistic cosmological equations he had obtained. Apparently, Einstein disliked very much these solutions, which entailed an expanding universe with a very specific origin in time for the expansion. He said: "Vos calculs sont correct, mais votre physique est abominable". But this did not discourage Lemaitre, who thought that the universe must have originated in a primordial explosion, coming from an extremely dense and hot point of spacetime which he called the "primeval atom". This was the true conceptual origin of what later would be known as the *Big Bang*. He later got the attention of Sir Arthur Eddington, who was a great

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[3] John C. Mather & John Bosloungh, "The Very First Light", p. 41 (Penguin Books; London, 1998).

[4] G. Lemaitre, Ann Soc. Sci. Brux, A47, 49 (1927), quoted in Steve Weinberg Gravitation and Cosmology, p. 632 (John Wiley & Sons; New York, 1972).

[5] A. Friedmann, p. 10. "Zeitschsift für Physik" (1922).

[6] Andre Deprit, "Monsignor Georges Lemaitre", in "The Big Bang and Georges Lemaitre", p. 370, ed. A. Berger (D. Reidel Publishing Co., 1984).

mathematician and did appreciate immediately the quality and originality of Lemaitre's work and invited him to talk at a large gathering of the British Association for the Advancement of Science.

The idea of a primordial explosion tied to the cosmic expansion, was later taken up by the Russian scientist emigrated to the U.S. George Gamow, and by his two younger collaborators, Ralph Alpher and Robert Herman, who were motivated by the search of an explanation to how the heavier chemical elements could have been synthesised at very high temperatures starting from the primordial hydrogen. Much later it would be shown that only D (unstable), ^{3}He (unstable), ^{4}He(stable) and traces of a few other light elements could have been originated from the primordial cosmic soup, the "ylem", as Gamow baptized it, and all the other heavier elements could only be originated later, at the core of massive stars after they were formed.

Then, the theory did not explain well the cosmic origin of the elements (except helium) and it had the drawback also that Hubble's estimate of the parameter describing cosmic expansion, Hubble's parameter $H = \dot{R}/R$, implied an "age" for the universe of only two billion years (2x10^9 yrs), much less than the ages (dated radioactively already, with relative accuracy, in the early fifties) of some old rocks from the surface of the earth.

By this time three young Cambridge scientist, Fred Hoyle, Herman Bondi and Thomas Gold, proposed a daring idea to get rid of the apparent conflicts entailed by an universe originated in a primordial explosion: what they called the *steady-state-theory*. The idea, according to them, was simple enough, a universe with no beginning and no end. The galaxies were expanding, but, all the way, matter (coming up from nowhere in particular) was pouring into intergalactic space, giving rise eventually to newborn galaxies, and keeping constant in the way the overall density of cosmic matter. This universe would look approximately the same to any observer at any time in the universe's history. In other words, it would have no history, no beginning and no end.

Einstein cosmological equations[7] with zero cosmological constant, $\Lambda=0$, reduce to

$$\frac{\dot{R}}{R}=\left\{\frac{8\pi}{3}G\rho-\frac{kc^2}{R^2}\right\}^{\frac{1}{2}} \qquad [1.1]$$

where R is the scale factor or radius of the universe, $\dot{R}$ is its time derivative, G Newton's gravitational constant, ρ the cosmic density (assumed to be roughly homogenous and isotropic), k a constant directly related to the three-dimensional curvature scalar (with k=|k| for closed solutions and k=-|k| for open solutions), and c the speed of light in free space.

In the steady-state-theory $\dot{R}/R=H$ is a constant for all t, k is set equal to zero, and the density is given by $\rho=3H^3/8\pi G$ always. Consequently

$$\frac{\dot{R}}{R}=H=\text{constant, (steady-state-theory)} \qquad [1.2]$$

which results in a solution

$$R(t)=R(t)e^{-H(t-t_i)}, \qquad [1.3]$$

in which t_i is any time $t_i<t$ previous to t. For instance, if we take $t-t_i\approx t_0\approx 13.7\text{x}10^9yrs=4.32\text{x}10^{17}$s and the actually observed present value for $H_0=65$ km/s.Mpc$=4.32\text{x}10^{-17}\text{s}^{-1}$, the resulting growth factor from $t=t_i$ to $t=t_0-t_i$ would be given by $e^{H_0t_0}\approx 2.484$, certainly not too large for such a long period of growth.

On the other hand, in the standard big bang model (without inflation) with k=-|k| (open solution), the general solution of Eq. [1] (see below, chapt 8) is given parametrically by

$$R(y)=R_+\sinh^2 y\,,\ t(y)=\frac{R_+}{c\,|k|^{\frac{1}{2}}}[\sinh y\cosh y-y] \qquad [1.4]$$

where the parameter $y\equiv\sinh^{-1}(R/R_+)^{1/2}$ can be related to the cosmic background temperature through the appropriate equation of state. For

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[7] Steve Weinberg, "Gravitation and Cosmology", p. 472 (John Wiley & Sons; New York, 1972).

early times, prior to the atom formation, (i.e. before the universe became transparent) the above solution corresponds to y<<1 and therefore

$$R(t) = R_+ \left[|k|^{1/2} \frac{c}{R_+} \right]^{2/3} t^{2/3} \qquad [1.5]$$

where R_+, $|k|$ and c are constants. If we take $t_i \approx 9.62 x 10^{13}$s, the time at which the universe became transparent according to recent WMAP's data[8], and $t_0 = 4.32 x 10^{17}$s (corresponding to $13.7 x 10^9$yrs), the growth factor between t_i and t_0 according to the big bang model would be $(t_i/t_0) \approx 272$, a factor one hundred times larger than that obtained above using the steady-state-theory for the same interval of time.

Before concluding this introductory presentation, in which we contrast the steady-state-theory with the original big bang theory as originally proposed by Lemaitre, Gamow and collaborators, it is informative to note, already at this early stage, that the inflationary theory first proposed by A. Guth and collaborators to solve the so called "monopole" problem, a theory proposed much later in the twentieth century, involves a tremendous growth in size at constant density (i.e. in exactly the same way as in the steady-state-theory) with the important difference that in the inflationary case this tremendous growth at constant density takes place at a very early time, and only during a very short period. According to Guth[9], inflation, i.e. growth at constant density, takes place roughly between 10^{-37}s and 10^{-35}s, during which time the cosmic scale factors grows from $R=10^{-52}$m to R=2m. This implies an extremely large Hubble parameter

$$H = \frac{\ln 10^{52}}{10^{-35}} = 1.19 \times 10^{37} s^{-1} \qquad [1.6]$$

which is more than 10^{54} times the presently known parameter as given above and as determined from the ratio between the actual recession speed and the actual distance of the galaxies moving away from us.

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[8] See f.i. http://www.nytimes.com/2003/02/12/science

[9] Alan Guth, "The Inflationary Universe", p. 187, (Perseus Books; Cambridge, Mars, 1997).

Why did inflationary take place exactly at such an early time, why did it last only for such a short time, why inflationary growth was of such proportion, not more, not less? All these are questions the inflationary theory leaves unanswered for the moment. On this and related questions, more in successive chapters.

But returning to the first reactions to the original expanding solution proposed by Lemaitre, which did in fact constitute the primitive version of the big bang theory, we must come back to the time of the discovery[10] of this solution by Eddington in 1930. He came quickly to the idea that the expanding solution brought one face to face with the concept of an absolute cosmic beginning, noting immediately that "the initial small disturbance can happen without supernatural interference". He added: "Unless a theory is invented which provides some force opposing this recession, there is no evading the rapid departure of nebulae from our neighbourhood". In his address to a meeting to the Mathematical Association[11], on January 5, 1931, he noted that in addition to the one-way expansion there had to take place a one way increase in the amount of cosmic entropy.

According to the noted historian of science Stanley L. Jaki[12], "Lemaitre, both a scientist and a priest, carefully avoided presenting his hypothesis of the primitive atom as the state of the world in which it came out from the Creator's hands".

However, Fred Hoyle, perhaps the most expressive of the proponents of the steady-state-theory[13], a theory which by 1948 looked as a very good alternative to the big bang proposal, criticized the big bang, (a derogative term coined by him) with the following words: "What kind of scientific theory is this that was conceived by a priest and endorsed by a pope?" He did refer to Pope Pious XII, who, aware of the serious consideration given by noted scientists to the big bang concept, said[14],

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[10] See f.i. S. L. Jaki, "Science and Creation", p. 338 (Lanham; New York, 1990).

[11] S. L. Jaki, Ibidem (p. 339).

[12] S. L. Jaki, Ibidem (p. 346).

[13] H. Bondi and T. Gold, "Monthly Notice of the Royal Astronomical Society", p. 252, 108 (1948).

[14] Quoted by John C. Mather & John Boslough, Ibidem (p. 48).

"True science to an ever increasing degree discovers God as though God were waiting behind each door opened by science".

Later in chapter 8, it will be shown that no inflation is required to justify a continuous growth of $\sim 10^{50}$ in the scale factor. It can be achieved smoothly starting at a very early time (in fact much earlier than Planck's time) and moving forward up to Planck's time, $t \approx 10^{-44}$s. In other words, $R(t) = const \times t^{2/3}$ (the pre-inflationary standard big bang equation) is sufficient to justify such a tremendous growth by itself at that very early epoch.