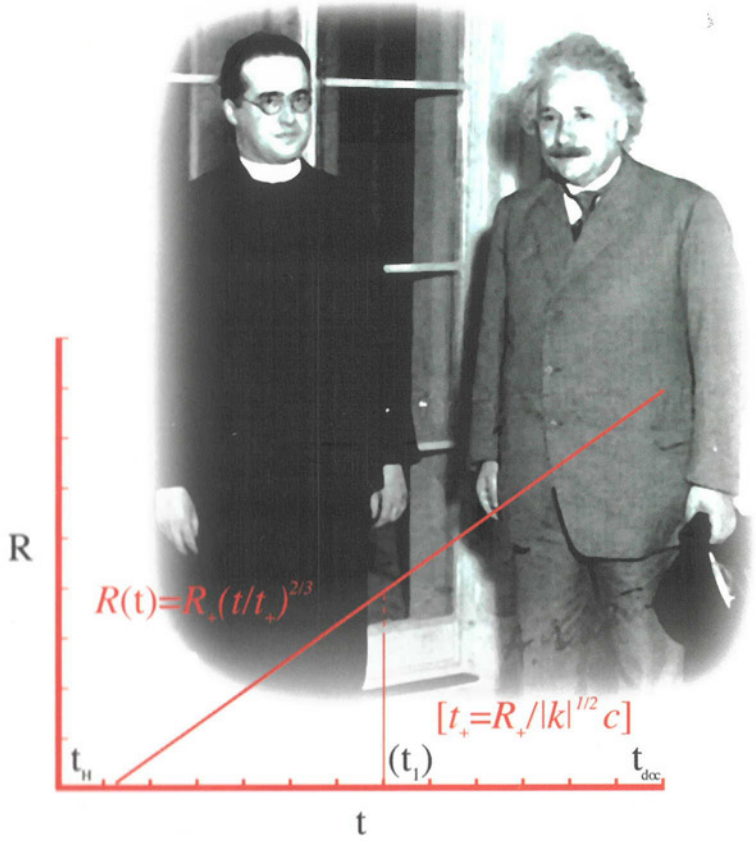
Julio A Gonzalo



Inflationary Cosmology Revisited

An Overview of Contemporary Scientific Cosmology After the Inflationary Proposal

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Julio A Gonzalo
Universidad Autonoma de Madrid, Spain

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To my parents

Inflationary Cosmology Revisited

"We are of course allowed to rearrange the matter of the universe... But in such rearrangement the experimenter *cannot*, and the theorist *must not*, violate the conservation of energy".

[Sir Arthur S. Eddington,
"Fundamental Theory",
Cambridge, 1949].

Foreword

INFLATION COSMOLOGY AND THE SCIENTIFIC METHOD

In the book *The End of Physics*, by David Lindley (Harper Collins Publishers, NY 1993) the author sums up his analysis of Inflation with the following words: "...the need for fine-tuning the initial conditions of the universe has been obviated by fine-tuning the Higgs mechanism instead. In this sense, inflation is not the greatest triumph of particle physics in cosmology but its greatest misapplication... with inflation, particle physicists have begun to design theories whose sole purpose is not to solve a problem in particle physics but to make cosmologists happy. Inflation is a nice idea; it would be pleasing if particle physics worked in such a way that it made the universe large and uniform. But there is no substantial evidence that inflation actually occurred... The argument is circular — cosmologists like inflation because particle physicists can provide it, and particle physicists provide it because cosmologists like it — and has proved, so far, immune to test" (p. 182).

Ten years later there is still no experimental proof of inflation; still less, of the Grand Unified Theory of fundamental forces used as a basis for postulating and describing the inflationary process. In the meantime, other ideas have been proposed that depart from conventional wisdom and that describe the universe and its evolution in drastically new terms: the MOND (Modified Newtonian Dynamics) of Mordehai Milgrom, that obviates the need for Dark Matter to explain the rotation curves of galaxies, and the varying speed of light in the vacuum as a function of time of Magueijo and others, with the possible answer to the uniformity of the universe in scales separated by distances unbridgeable by energy transfer at the present speed of light. Other data, implying possible distortions of the CBR due to galaxy clusters, might force a revision of the analysis of small fluctuations currently presented as "proofs" of Inflation. While these proposals need more study and the experimental verification of their consequences, they are, at present, just as valid as possible theories as inflation itself, which rests only upon unproven extrapolations of very abstract ideas.

In the present book, Dr. Julio Gonzalo analyzes with standard physics the main reasons for inflation, and finds them far from cogent. Actual calculations, without inflation or its concomitant postulates of Dark Matter and Dark Energy, lead to values of cosmic age and other parameters that are of the same order of magnitude as those derived from Inflation. Conservation of mass-energy is underlined as the basic scientific principle that should not be discarded in any acceptable theory. And the need for experimental checks, the lodestone of the scientific method, is correctly stressed at every point.

Much work needs to be done still in cosmology, as well as in particle physics. The present book is a welcome call for prudence and rigorous methodology. It will be worth reading and pondering by those interested in a critical view of standard "wisdom".

E. M. Carreira, Ph.D.

Prologue

In February 11th, 2003, the cosmic data, spectacularly precise, collected by the team in charge of the WMAP satellite were front page news in the New York Times. Next year will see the 25th anniversary of the revolutionary theory of cosmic inflation. As it is well known, Alan Guth postulated in this theory a short period of extraordinary cosmic expansion at constant density taking place 10^{-39}s after the Big Bang. The energy density at inflation should have been enormous compared with anything accessible with man made accelerators today.

In this book, the history of the twentieth century cosmology is viewed in perspective with the "inflationary" paradigm and with the new WMAP data in view. As it was to be expected, the cosmic data provided by WMAP in 2003 did vastly improve on the already spectacular data given by COBE in 1989.

Is there any alternative to "inflation" to cope with the increasingly precise cosmic data now available?

In a recent piece in "Physics Today" (August 2003, p. 50) Michel Riordan discusses fashions and facts in physics. He says: "I find difficult, however, to imagine how such a rigorous criterion of reality (experimental observation) could ever hold true for some of the fanciful ideas and constructs that have emerged in recent years from the minds of many theorists. How can we ever hope to work in everyday practice with such entities as superstrings, parallel universes, wormholes and phenomena (inflation?) that occurred before the Big Bang?" (Words in parenthesis are mine).

The word "paradigm" occurs frequently in the literature to describe "inflation". But a "paradigm" is not a fact. It could become a fact provided that conclusive observational or experimental evidence discard any simpler alternative.

The final chapter in the present book discusses "inflation" in the light of WMAP's data and rigorous criteria of reality. In fact, as shown in the Appendix, a quantitative estimate of the "age" of the universe as given by 13.7±0.2 Gyrs was anticipated (1998) within the framework of the pre-inflationary cosmological equations, in extremely good agreement with the "age" reported by WMAP (2003) as supported by "inflation" and "dark energy".

The "age" anticipated (N. Cereceda, G. Lifante, J. A. Gonzalo, "Acta Cosmologica" Krakow, 2003) was obtained using the time dependent dimensionless parameters $\Omega(t)=\rho(t)/\rho_c(t)$ and H(t).t. On the other hand Guth estimate (A. Guth, "The Inflationary Universe", 1997) was inconsistent, within error bars, with the "age" given by WMAP.

Inflation or no inflation, in physics "numbers decide" as Max Plank said in his Nobel Prize lecture, 2 June 1920. In the future, increased numerical precision will very likely decide between theoretical approaches of permanent value and merely fashionable theoretical approaches, as pointed out by Michael Riordan.

I am grateful to Gines Lifante (Universidad Autónoma de Madrid), Emmanuel M. Carreira S. J. (John Carrol University, Cleveland / Pontificia U. de Comillas, Madrid), Dermott Mullan (Bartol Research Institute, Newark), Ralph A. Alpher (Union College, Schenectady, N. Y.) and Anthony Hewish F. S. R. (University of Cambridge, U. K.) for reading the first version of the manuscript and/or for many helpful suggestions which contributed considerably to clarify things and to improve the final version. Prof. Hewish shared the 1974 Nobel Prize in Physics with Sir Martin Ryle for "their pioneering research in radio astrophysics" and was awarded that distinction for "his decisive role in the discovery of pulsars". In his letter to me commenting upon the first version of this book he is kind enough to say "Actually, here in Cambridge there is less attachment to the inflationary paradigm than you might believe".

I would like to thank also Miss Patricia López Vicente for her patience typing and retyping the manuscript and to Dr. Carmen Aragó Dr. Manuel I. Marques and Mr. Francisco Sánchez for useful comments.

Madrid, 28 January 2004
Julio A. Gonzalo

Contents

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 ($2\text{x}10^9$ 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 $t-t_i\approx t_0\approx 13.7\text{x}10^9\text{yrs}=4.32\text{x}10^{17}\text{s}$ 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 $t_i \approx 9.62 \mathrm{x} 10^{13}$s, the time at which the universe became transparent according to recent WMAP's data[8], and $t_0 = 4.32 \mathrm{x} 10^{17}$s (corresponding to $13.7 \mathrm{x} 10^9$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 $R=2$m. 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, $R(t) = \text{const} \times t^{2/3}$ (the pre-inflationary standard big bang equation) is sufficient to justify such a tremendous growth by itself at that very early epoch.

Chapter 2

The Microwave CBR

The discovery of the Cosmic Microwave Background Radiation (CMBR or simply CMB) played a decisive role in tilting the balance in favour of the big bang concept against the steady-state-theory. The CMB[1] comes clearly from the most distant and, therefore, the most ancient source of electromagnetic radiation in the whole spectral range directly observable from the Earth. The story of the CMB relevance to our theme deserves to be summarily recalled here.

In 1948, Ralph Alpher and Robert Herman[2], working then with George Gamow on the implications of the big bang theory for the creation of the elements, were investigating the existence and properties of an expanding cosmic fireball with a characteristic temperature, which was expected to cool throughout the expansion process. They anticipated that, at the beginning, the universe was very hot and was filled with radiation, which might be perceptible today in a weakened form. If the fireball radiation could be detected today, it would prove that the Universe began in an explosion. At that time, there were sensitive instruments adequate to investigate the remnant radiation. In fact, radar (radio detecting and ranging electromagnetic radiation) was available, as a result of work during the World War II. However those scientist who could have become interested in looking for the remnant cosmic back ground radiation either did not get to know the work of Alpher and Herman or did not pay serious attention to it. According to Herman, many years later, "There was no doubt in our minds that we had a very

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[1] See f.i. J. M. Lamarre and J. L. Puget, "The Cosmic Microwave Background", Europhysics News, November/ December 2001.

[2] R. Lastrow, "God and the Astronomers", p. 18. (W.W. Norton & Co.; New York, 1978).

interesting result, but the reaction of the astronomical community ranged from sceptical to hostile".

In 1965, Arno Penzias and Robert W. Wilson[3], two radio astronomers at Bell Telephone Laboratory on Crawford Hill, Holmdel, New Jersey, were using a huge antenna to test communications via the "Echo" satellite. The antenna characteristics, being a 20-feet horn reflector with ultralow noise, made it a perfect instrument for radio astronomical investigations. When they were testing their equipment, they noticed an unexplained static noise coming out in their radio receiver. After discarding possible sources, including pigeons litter in the rear of the antenna horn, the static persisted. They were forced to conclude that the static was some kind of radiation from space. After consultation with Robert Dicke and his younger colleagues at Princeton, they became aware of the possibility that the static radiation might be related to the radiation left over from the fireball which was filling the Universe all the way through billions of years.

Penzias and Wilson had measured the CMB radiation only at a certain wavelength but it was immediately anticipated that the spectral distribution of the cosmic radiation was of blackbody type.

The introduction of the concept of energy quanta to describe quantitatively the spectral distribution of blackbody radiation by Max Planck in 1900 marked the beginning of a new era in Physics. Planck had been born at Kiel in 1858. His father was professor of Constitutional Law at the university but he had chosen in due time Physics as his professional career. He did study at Munich, and then at Berlin, where he was taught by Kirchhoff (for whom he always professed a great admiration) whose chair Planck would occupy many years later, and also by Helmholtz. He began as a Privatdozen in Munich, continued as Associate Professor at Kiel, and then succeeded in 1889 to Kirchhoff at his chair in Berlin. In 1912, he was named Permanent Secretary of the Prussian Academy of Sciences.

His earliest work centred on various topics of thermodynamics, specially on the concept of entropy, introduced by R. Clausius and later

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[3] Steven Weinberg, "The First Three Minutes", p. 39 f.f. (Bantam New Age Books; New York, 1977).

given more direct physical meaning by Boltzmann. Soon, Planck's attention was addressed to the problem of how to explain the observed spectral distribution of the radiation emitted by a blackbody, a body in which energy in certain amount (depending on the equilibrium temperature) is trapped. The energy emitted though a small aperture in the surface has a very characteristic spectral distribution, with a peculiar temperature dependence, which is independent of the material which is making up the body in question. This spectral distribution does not respond to the predictions of classical physics. Planck's formula, on the other hand, sufficed to establish a relationship between the energy and the frequency (or the energy and the wavelength) of the emitted radiation, on the basis of a revolutionary concept: each oscillation mode in the blackbody could have only a discrete number of quanta of energy (hν), being h a universal constant (Planck's constant) and ν the frequency of the mode in question.

For some time the scientific community was reluctant to accept Planck's revolutionary proposal[4]: "Although Planck's formula was in the centre of discussion, one was nevertheless inclined to view Planck's proposal of the *quantum like oscillator energy* only as a provisional working hypothesis, and Einstein's light quanta were not taken seriously" (as recalled by Max Born about his meeting with Lummer and Pringsheim in 1906).

In summary Planck's quantum theory could be summarized as follows[5]:

(a) The *spectral distribution law* of blackbody radiation was given by

$$W_T(\omega) = \frac{\hbar\omega^3}{\pi^2 c^3} \cdot \frac{1}{e^{\hbar\omega/k_B T} - 1} \qquad [2.1]$$

where $W_T(\omega)$ is the thermal radiation energy density in the cavity per unit volume and per unit frequency interval, ω is the angular frequency

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[4] See f.i. S. L. Jaki, "Numbers decide or Planck's constant and some constants of philosophy", in Julio A. Gonzalo (Coord.) "Planck's constant: 1900-2000" (UAM; Madrid, 2000).

[5] See f.i. R. Loudon, "The Quantum Theory of Light", second ed. Chap. I (Clarendon Press; Oxford, 1983).

$2\pi\upsilon$ and T the absolute temperature. The dimensionless ratio $\hbar\omega/k_BT$ involves Planck's constant ($\hbar=h/2\pi$) and Boltzmann's constant (k_B).

(b) The *Wienn displacement law*

$$\hbar\omega_{\max} = 2.8\,k_B T \qquad [2.2]$$

which establishes a direct connection between the equilibrium temperature of the body and the frequency of the maximum of radiation emission ($\omega_{\max}$). In other words, known the frequency of maximum emission, we know automatically the absolute temperature of the emitter and vice versa. For instance, just by looking to the precision cosmic background spectra transmitted by the COBE data (see below) one could determine with excellent precision the characteristic temperature of the cosmic radiation.

And (c) The *Stefan-Boltzmann total radiation law*

$$\int_0^\infty W_T(\omega)d\omega = \left[\frac{\pi}{15}(\hbar c)^{-3}k_B^4\right]T^4 \equiv \sigma_{SB}T^4 \qquad [2.3]$$

which gives the total radiation emitted in the whole spectral frequency range from zero to infinity. Planck's work resulted in a direct physical meaning for σ_{SB}, the universal Stefan-Boltzmann's constant, in terms of $\hbar=6.885\text{x}10^{-27}/2\pi$ ergs.s, $c=3\text{x}10^{10}$cm/s and $k_B=1.38\text{x}10^{-16}$erg/K.

Planck immediately proposed a set of natural units of mass $m_p=(\hbar c/G)^{1/2}$, length $l_p=(\hbar G/c^3)^{1/2}$ and time $\tau_p=(\hbar G/c^5)^{1/2}$, in terms of h, c and Newton's gravitational constant $G=6.673\text{x}10^{-8}\text{cm}^3\text{g}^{-1}\text{s}^{-2}$.

In 1965, Penzias and Wilson had discovered the background cosmic radiation, a characteristic blackbody radiation confirmed later with the outmost precision by the COBE mission. Penzias and Wilson had noted that the cosmic radiation was isotropic or quasi-isotropic and that it looked the same from every spatial direction. The COBE mission would detect for the first time minute anisotropies, something of the order of 10^{-5} parts in one, which signalled the beginning of early cosmic structure, later to become the seeds of stars and galaxies. Ten years after COBE, another successful NASA satellite, the WMAP, did vastly improve on the measurement of the anisotropies and on a number of other basic cosmic parameters, reducing spectacularly the uncertainties of the main observable cosmic parameters.

The account of John C. Mather, the Principal Investigator of COBE project, telling in detail how the spectacular perfect blackbody character of the CBR was finally put together by its scientific team, deserves to be summarized here.

The satellite was launched southward on a Delta rocket at 6:34 am (Pacific Standard Time) on November 18, 1989 from the Western Space and Missile Centre at Vandenberg Air Force Base in California. From the launch site, after being confirmed that the satellite was O.K. and that all the solar panels and communication antennas were functioning properly, Mather and the other members of the scientific team travelled back to NASA's Goddard Space Centre, at the Atlantic side of the US.

Later[6] COBE's Principal Investigator would tell it vividly: One night after midnight, Ed Cheng and Rich Isaacman watched the satellite progress on computer screens. They were bored, Cheng had an idea "We've got the data pouring in", he said. "We just don't have the calibration yet. We have the ground-based calibration, though, and it should work fine..." They then pulled the original calibration, undertook some manoeuvring and, after a few minutes, the monitor started flashing "...the screen displayed an *absolutely perfect blackbody curve*, the slightly skewed arch that everybody desperately wanted to see".[7]

When John Mather presented the FIRAS (COBE) data showing the Planck's spectrum quality of the cosmic background radiation, Bob Wilson, discoverer of the CBR with Arno Penzias a quarter of a century earlier, was in the audience: "It was really, really spectacular. One of the most beautiful scientific results I've ever seen".

The FIRAS spectrum, perfect in its harmony with theoretical speculation, confirmed that the big bang theory really did explain how the universe began, something which was questioned to some extend by a mysterious bump in the curve reported by a Berkley-Nagoya team at the time.

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[6] John C. Mather & John Boslough, Chap. 15, "The Very First Light" (Penguins Books; London, 1998).

[7] Ibdem, p. 235.

Fig. 2.1. Ralph Alpher (left) and Robert Herman predicted the existence of the cosmic fireball in 1948 while they were working with George Gamow on the "Big Bang" theory of the creation of the elements.

Ten years after the first data from COBE were reported, at the meeting of the American Astronomical Society two balloon-borne experiments, BOOMERANG[8] and MAXIMA[9] gave the first view of the small scale anisotropy of the CBR, showing further peaks in the power spectrum of the angular distribution. The data did show clearly that, at the time the microwave background radiation was emitted, i.e. more than $13\mathrm{x}10^9$years ago, the picture was that of a flat universe ($\Omega=\rho/\rho_c$=ratio of the then actual density to the then critical density $\rho_c=3H^2/8\pi G$, very close to one), with well defined fluctuations (typically less than one part in 10^5), which were beginning to become the seeds for future protogalaxies. In February 2003, i.e. barely thirteen years after the FIRAS (COBE) did report the first findings, the "New York Times" (nytimes.com/2003/02/12/science) gave the news of the spectacular results from the WMAP satellite, the successor of COBE, which had been able to obtain vastly improved data on the CBR. A beautiful photo

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[8] P. de Bernardis et al, 2000, "A flat universe from high resolution maps of the CMBR", Nature 404, 955 (2000).

[9] A. T. Lee et al, "A high spatial resolution analysis of the MAXIMA-I cosmic microwave background anisotropy data", astro-ph/0104459.

of the anisotropies, copyright NASA via Agence France Press, had the following subtitle: "The universe, 13.7 billion years old, as an infant".

The cosmic microwaves, as pointed out in the New York Times article, give a snapshot of the universe as it was cooling down to the temperature at which atoms could first form at an age of about 380.000yrs after the big bang. Since COBE, continues the story, a series of smaller experiments have studied the observed lumps in cosmic sky, and have used them to study the CBR fundamental cosmic parameters at the time of the CBR emission, the "very first light". They concluded that then the universe was flat, and it was dominated (the NY Times report continues, but it is not the only possible interpretation) by "dark energy". The new satellite scans the whole sky every six months, and it is designed to operate for four years. The new sky map was based upon the first year's worth of data.

The ability to measure the polarization of the microwaves was crucial to the discovery of the formation era of the first stars, monsters many times larger and more massive than the sun, which did burn rapidly, and projected in all directions heavy elements, destined to become part of the later generation stars. Some of these stars could be fit to have rich heavy elements and so forth, according to Dr. Bennet, WMAP's Principal Investigator.

The theory of inflation, according to the NY Times report, hypothesizes that the universe underwent an enormous growth at an extremely early time, during a very brief period. A growth during which the overall density, surprisingly, remained constant. As Bennet noted, inflation "is often called a paradigm instead of a theory".

More on the birth of the inflationary theory in the next chapter.

Chapter 3

The Birth of Inflationary Cosmology

A number of theoretical physicists in the late 70's were able to complete a successful theory describing the main known results of high energy physics. These results had been obtained analysing violent collisions among elementary particles at a few large accelerators, in the US and in Europe. By then Feynman, Tomonaga and Swinger had developed in the 40's the theory called Quantum Electrodynamics (QED), which was spectacularly confirmed quantitatively in a fashion without precedent.

The interactions known to play a significant role in physical processes, from the microscopic world of the nuclei and its constituents to the macroscopic world of the galaxies and the groups of galaxies, are four: (a) the *gravitational* interaction, extremely weak but long range and always attractive; (b) the *weak* interaction, of short range, responsible for the radioactive decay of β emitting nuclei; (c) the *electromagnetic* interaction, responsible for attractive/repulsive forces between charged bodies, and for the ubiquitous electromagnetic waves all around (from microwaves, to radio, to X-rays, and γ-rays, all of them electromagnetic waves of increasing frequencies); (d) and the powerful *strong* interaction, of short range and very strong, capable of holding together the nucleons (protons and neutrons) within the closely packed and strongly positively charged atomic nuclei.

In 1964, Murray Gell-Mann[1] proposed a theory for the strong interactions which postulated the existence of certain strange elementary constituents, called by him "quarks", with strange masses and fractional charges. This theory did form later the basis for a "gauge" theory, called

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[1] M. Gell-Mann, "Physics Letters", vol. 8, 214 (1964).

Quantum Chromo Dynamics (QCD), which was designed to deal with the strong interactions in a similar way as QED delt with the electromagnetic interactions. Eventually QCD became an essential part of the so called "standard model" for elementary particles.

The basic elementary constituents of matter, discovered after strenuous efforts by high energy physicists through the years at various large accelerators, are classified in three "generations" of *Leptons* (non strongly interacting) and as many "generations" of *Quarks* (strongly interacting) as follows:

"Generation"	Leptons	Quarks
1st	e^- (electron)	d_R, d_G, d_B (down quarks)
	ν_e (electron neutrino)	u_R, u_G, u_B (up quarks)
2nd	μ^- (muon)	s_R, s_G, s_B (strange quarks)
	ν_μ (muon neutrino)	c_R, c_G, c_B (charmed quarks)
3rd	τ^- (tau)	b_R, b_G, b_B (bottom quarks)
	ν_τ (tau neutrino)	t_R, t_G, t_B (top quarks)

The number of particles in the three generations above is therefore 24, plus the respective antiparticles, resulting in 48 elementary particles (perhaps too many to be termed, all of them, elementary).

In particular, the neutron, which is unstable, is known to have a lifetime of about ten minutes when outside atomic nuclei. The neutron's decay is described by

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

This decay can be given in terms of quarks, characterized by sub indices denoting three colours, R (red), G (green) and B (blue), being each colour a property analogous to the electromagnetic charge, in other words, a property which plays a role similar to charge in the strong interactions.

The neutron decay thus, in QCD, is described by means of the following scheme

$$\begin{array}{lcl} d \rightarrow & u+W^{-} & \rightarrow u+e^{-}+\bar{\upsilon}_e \\ d \rightarrow & & \rightarrow d \\ u \rightarrow & & \rightarrow u \\ \hline \text{(ddu)} & & \text{(uud)}+\mathrm{e}^{-}+\bar{\upsilon}_e \end{array}$$

meaning that the neutron, composed of three quarks (ddu), decays into a proton, composed of three different quarks (uud), plus one electron, plus one antineutrino, as observed experimentally.

As a result of the 70's revolution in theoretical physics leading to the Standard Model (Quantum Chromodinamics + Electroweak Theory), physicists were lead to even more ambitious expectations.

Such expectations of arriving at Grand Unified Theories (GUT's), capable of unifying strong, electroweak and electromagnetic interactions, as well as dreams[2] of arriving at a final unified theory, including gravitation, were beginning to be considered as realistic by some theoretical physicists.

According to Alan Guth[3], the success of the Standard Model did produce a great impact on physicists in general, and theoretical physicists in particular due to the fast pace of developments, i.e. to the fact that some experimental confirmations had been obtained very rapidly, and (at least for theorists) it was also due to the shared impression that the whole thing looked very intuitive. By the late 70's, prominent theorists were announcing confidently that, within a short time, a full unification of all physical theory should be at hand. A note of caution however was

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[2] S. Weinberg, "Dreams of a Final Theory: The search for the fundamental Laws of Nature", (Phantheon Books; New York, 1992).

[3] Alan Guth, "The Inflationary Universe", p. 129. (Perseus Books: Cambridge, Mass. 1997).

put forward by S. L. Jaki[4], a noted historian of physics, as mentioned before, who pointed out that, from the experimental side, new relevant experimental data could come any time, to complicate the picture. And that, also, from the theoretical viewpoint, Gödel's incompleteness theorems, implying that no non-trivial mathematical system, including all non-trivial physico-mathematical theories, could have within them the final proof of their consistency.

To theoretical physicists, GUT's were attractive because they could be presented as the only theories which predicted that the charge of the proton must be exactly equal to the charge of the electron, and, specially, as the only theories which could provide an underlying relation between the strong (SU_3), the weak (SU_2) and the electromagnetic (U_1) interactions in such a way that all these interactions could finally become unified (symmetric) at energies of the order of 10^{16}GeV (i.e. at temperatures $T \sim E/k_B \sim 10^{29}$K). These theories, however, do not provide any justification, any hint, as to why it is so high the extremely high energy (temperature) at which this unification (symmetrization) should take place. It is said that the symmetry is "broken", and that the interactions become separated, distinct from one another, at $E \ll 10^{16}$GeV, encompassing all observable physical processes around us. We may note that the highest temperatures at the centre of very hot stars are estimated to be only $T \sim 10^7$K.

At energy scales of the order of $E \sim 10^{16}$GeV ($T \sim 10^{29}$K), the interactions become unified, according to the GUT's, and the differences between electrons, neutrinos and quarks disappear altogether.

At still higher temperatures ($T \sim 10^{31}$K), a *phase transition* is expected to take place, unifying finally with the rest the gravitational interaction. Such a *1st order* phase transition (*discontinuous*) as a function of temperature would be somewhat analogous to the vapour-liquid transition, with "supercooling", in the same way as real world vapour-liquid transitions occur either with "supercooling" or with "superheating". In other respects, this postulated phase transition would

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[4] S. L. Jaki, "The Chaos of Scientific Cosmology", pp. 83-112, in "The Nature of the Physical Universe", 1976 Nobel Conference, D. Huff and O. Prewett Eds. (Wiley; New York, 1979).

be, of course, very *different* from phase transitions in the real world, which *always conserve energy.*

Let us make now an order of magnitude estimate of the temperature at which the unification of gravity with all other interactions would occur. Let us assume that at these very high temperatures (and high densities) particles could be in existence in the early universe with a mass M_p and a charge e, however briefly. In them the gravitational attraction of the constituent mass should compensate the electrostatic repulsion of the charge in such a way that

$$\frac{GM_p^2}{l_p} \approx \alpha \frac{e^2}{l_p}, \qquad [3.1]$$

where l_p would be the particles radius, and α the fine structure constant, a purely dimensionless number ($\alpha = e^2/\hbar c \approx 1/137$). Using Heisemberg's uncertainty relation, l_p would be given by

$$l_p \approx \hbar / M_p c \qquad [3.2]$$

Then M_p, substituting α in terms of universal constants in [3.1], would became

$$M_p \approx \left(\frac{e^4}{G\hbar c} \right)^{1/2} \approx 1.58 \times 10^{-5} g \qquad [3.3]$$

with $e = 4.8 \times 10^{-10}$esu, $G = 6.67 \times 10^{-8} cm^3 g^{-1} s^{-2}$ (Newton's constant), $\hbar = 1.05 \times 10^{-27}$erg.s and $c = 3 \times 10^{10} cm.s^{-1}$ (all in cgs units). The corresponding energy scale would then be

$$E_p \approx M_p c^2 \approx 1.42 \times 10^{16} erg \approx 0.88 \times 10^{19} GeV\,. \qquad [3.4]$$

This would correspond precisely to a temperature $T_p \approx M_p c^2 / 2.8 k_B \approx 3.67 \times 10^{31}$K, as anticipated above, a temperature somewhat higher than the temperature at which the partially unifying first order transition could have taken place. The particle's radius, l_p, called Planck's length, given by equation [3.2], would be extremely small, $l_p \approx 2.2 \times 10^{-33}$cm, and it would have the peculiar property that, just for such a radius, a particle can exist in which its Compton's radius ($r_C \equiv \hbar / M_p c$) is exactly equal to its Schwarzschild radius ($r_S \equiv GM_p/c^2$), divided by the dimensionless quantity $\alpha^2 = (e^2/\hbar c)^2 \approx (1/137)^2$, i.e. by the squared fine structure constant. Particles with a mass $M>>M_p$ would have a Compton radius $r_C<<r_S$, substantially smaller than the corresponding Swarzschild radius, and the opposite would be true, for particles with $M<<M_p$, which is the case for elementary particles in general.

The Inflationary Theory was originally proposed by Alan Guth[5] to avoid the so called "monopole problem" (see below), appearing as a result of considering cosmic expansion from the viewpoint of Grand Unified Theories (GUT's). Inflationary Theory postulated that a spectacular first order phase transition must have taken place at a cosmic time between $t\approx10^{-37}$s and $t\approx10^{-35}$s, corresponding to temperatures just a few orders of magnitude below Planck's temperature, $T_p\approx M_pc^2/2.8k_B\approx3.61x10^{31}K$, associated with times of the order of $\tau_p\approx l_p/c\approx0.73x10^{-43}s$.

According to Guth, *cosmic inflation* must have taken place in a very quick succession of about 100 cosmic doublings in size ($2^{100}\approx10^{30}$ times) barely in 10^{-35}s, all the way at constant density. Guth's original motivation to postulate the first order phase transition was aimed at reducing the predictable cosmic abundance of "magnetic monopoles".

An initial first assumption[6] was that at very early cosmic times (high temperatures) the abundance of magnetic monopoles could have been of the order of the abundance of protons. But, since magnetic charge is expected to be conserved (like the electric charge) magnetic monopoles could not decay into ordinary matter particles. It was then conjectured that, due to monopole-antimonopole annihilation (analogous to the familiar electron-positron annihilation), the present abundance of monopoles would be 10^4 times that of nucleons (protons, neutrons), resulting still in an undesirable overproduction of monopoles.

Shortly afterwards there was (unconfirmed) a preliminary report by Blas Cabrera[7] suggesting that a cosmic magnetic monopole of the right mass had been detected at Sanford by means of a SQUID (Superconducting Quantum Interference Device). After some years of

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[5] Alan Guth, Ibidem, p. 167.

[6] Alan Guth, Ibidem, p. 147.

[7] B. Cabrera, Phys. Rev. Lett. 48, 1378 (1992).

intensive and systematic research the monopole event was still unconfirmed.

Guth's strategy at the time regarding the monopole problem was to postulate a phase transition in the high temperature cosmic matter-radiation primitive "ylem" (as Gamow had called it), in which the slow pace of bubble formation could solve the problem posed by too many magnetic monopoles. To this end he postulated a state of "false vacuum"[8] capable of undergoing a "supercooling" transition from a very high density ($\rho_{fv} \approx 10^{80} g/cm^3$) at $T \sim 10^{29}K$ to a more moderate density (nuclear density), in a relatively short time.

Taking into account that nuclear density is given by $\rho_{nm} \approx m_n / \frac{4\pi}{3} r_n^3 \approx 10^{14} g/cm^3$, the cosmic density at the end of inflation, which was the same as that at the beginning of inflation (when cosmic volume was 10^{30} times smaller), must have been $\rho_{fv} \approx (10^{14})^{6.5} g/cm^3 \approx 10^{80} g/cm^3$. (For comparison, the present cosmic density is $\rho_0 \approx 10^{-31} g/cm^3$).

The "monopole problem", now mainly of historical significance as a problem, is still given as one of the cosmological "problems" which justified the birth of the Inflationary Cosmology. Guth did postulate first the existence of a "false vacuum" and then predicted a phase transition, through which the "false vacuum" would decay forever, resulting in the familiar ordinary cosmic expansion we see now.

According to Guth, he had discovered the equations of de Sitter's Cosmology (1917), written in the form introduced somewhat later by Georges Lemaitre (1925), as part of his MIT Thesis[9], before introducing *inflation* as the starting point of his new cosmology.

After taking care, by means of *inflation* of the "monopole problem", Guth went one step further to solve the so called "flatness problem". This problem could be formulated as follows: since the available observational evidence indicates that $\Omega_0 = \rho_{m0}/\rho_{c0}$ (the ratio of actual cosmic density to critical cosmic density $\rho_{c0} = 3H_0^2/8\pi G$) is of order one, (in fact, it is much less than one, using data from our galactic neighbourhood for H_0) then he concluded that the density parameter *must*

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[8] Alan Guth, Ibidem p. 169.

[9] Alan Guth, Ibidem p. 175.

be exactly one. According to Guth, with inflation the flatness problem disappears because the effect of gravity is reversed. Instead of Ω being driven away from one, inflation drives it towards one "with exquisite accuracy". Something as obvious, he adds, as blowing up a balloon. He says further that we do not know the value of Λ (Einstein's cosmological constant), so it may be zero, but in any case, it could only complicate more the general picture without altering the result. In his account of the discovery, he says that, the following day, when he was explaining with much excitement to one colleague the advantages of his inflationary approach to cosmology, he did notice that his excitement failed to be contagious. His colleague said: "You know... the amazing thing is that they pay us for this".

Guth finally goes on[10] to explain how his theory of inflation solves the "horizon problem". Invoking the "zero law" of thermodynamics, (i.e. the general tendency of material objects to come to a uniform equilibrium temperature with the surrounding objects), he points out that *if* different parts of the universe were initially at very different temperatures, the cooling speed *could not* exceed c (velocity of light) and therefore, according to Guth, the present uniform (background) cosmic temperature could not have been achieved, except by invoking "cosmic inflation". (It may be noted, however that initially cosmic expansion proceeds at $\dot{R} >> c$, according to Einstein's cosmological equation, a fact which deserves careful consideration, specially if originally all parts of the exploding universe were at exactly the same temperature).

Fig.3.1 depicts the time evolution[11] of the scale factor R(t) according to Guth from the beginning of the inflationary period ($t \sim 10^{-37}$s) to the present. It must be noted that, after the end of the inflationary period, the time dependence of R(t) is fixed by Einstein's equations. When the universe became transparent (atom formation), the cosmic equation for a transparent universe should be $RT \approx$constant. This determines automatically the cosmic temperature T at a given time t. Prior to this time the time evolution of the cosmic temperature T requires a careful evaluation (See Chap. 8).

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[10] Alan Guth, Ibidem pp. 180-182.

[11] Alan Guth, Ibidem p. 185.

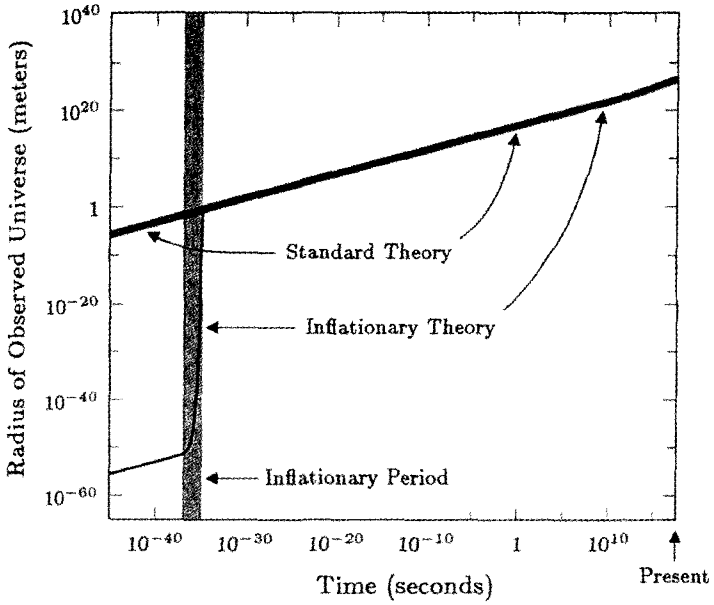

Fig. 3.1. Time evolution of the scale factor R(t) according to Guth from the beginning of the inflationary period ($t \sim 10^{-37}s$) to the present.

After reviewing the beautiful cosmic data obtained by the COBE mission (Chap. 4), examining the available evidence on dark mass, cosmic flatness and accelerated expansion (Chap. 5) and after looking at the spectacular data recently obtained by the WMAP (Chap. 6) we will analyse in some detail to what extent the "monopole problem", the "flatness problem" and the "horizon problem" require, or not, cosmic inflation as a problem solving "paradigm".

Chapter 4

The Cosmic Background Explorer (COBE)

Exactly on November 18, 1989, a Delta rocket was launched to space by a group of NASA scientist and engineers carrying within it a satellite with very special characteristics[1]. It had been christened COBE (Cosmic Background Explorer) and its mission was to measure, with unprecedented precision, the characteristics of the cosmic background radiation (CBR) predicted by Alpher and Herman in 1948 and first detected by Pencias and Wilson, in 1965.

Already in 1974, i.e. fifteen years before the COBE's launching, John C. Mather, then just graduated from the University of California at Berkeley, did respond to a call from NASA to present research projects which could be carried out using a satellite susceptible of being put in orbit by means of a Delta or a Scout rocket. To this end, Mather did produce a schematic diagram of the future satellite which included already, from the very beginning, three different instruments to carry on three different experiments:

DMR= Differential Microwave Radiometer,
DIRBE= Diffuse Infrared Background Experiment,
and FIRAS= Far Infrared Absolute Spectrometer.

All these experiments, eventually, were put in orbit at COBE's launching on November 18, 1989. Fifteen years is a long time, and many things had happened from the time of COBE's first proposal to the time of its actual launching, including the "Challenger" (1986) disaster, which did cost the lifes of a handful of young astronauts. Among the press and

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[1] John C. Mather & John Boslough, "The Very First Light", pp. 177-195, (Penguin Books; London, 1998).

within political circles questions had been raised on whether or not NASA was really necessary.

A number of experiments reported in the years preceding COBE's launching had raised some fundamental questions about the cosmic background radiation, which did require urgent clarification. Experiments in 1976-77, performed in an aeronautic balloon by Wilkinson and co-workers (Princeton University) and then confirmed by Miller and Smoot soon afterwards, had revealed that there was a "dipolar" anisotropy in the background radiation, probably related, it was assumed, to the fact that the Earth was moving in a certain spatial direction with respect to the cosmic background radiation. Two working teams, respectively based in Princeton and in Florence, had performed balloon experiments in 1981, which did seem to indicate the existence of an intrinsic "quadrupolar" anisotropy, unrelated to the Earth's motion. A few years later, in 1987, a Japanese-American (Nagoya-Berkeley) collaboration had taken measurements of the CBR at altitude of 200 miles from the Earth's surface by means of a small missile with measuring instruments aboard, with a result that indicated the presence of a 10% excess over the typical blackbody spectrum showing up at a certain spectral region. So, at the time of COBE's launching, there was considerable expectation in the astrophysicists international community.

John C. Mather, Scientific Director of the COBE Project and Principal Scientist of FIRAS, in his book "The Very Firs Light"[2], written in collaboration with John Boslough, tells the story of the rocket launching from Vandenberg Air Force Base in California in eloquent words:

"The launch crew stayed up all night conducting last-minute tests. I tried to sleep but could not, and gathered along with the two thousand other invited gests hours before dawn at several designated viewing sites safely removed a mile or two from the launch pad. Mike Hauser stood next to George Smoot at another site. They could not speak as they prepared to witness the spectacle they had been working toward for fifteen years. Other members of the COBE team watched on monitors at Goddard.

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[2] Ibidem, p. 223.

Top officials from NASA were there. As the final seconds of the countdown commenced, Len Fisk stood next to the Mc Donnell Douglas engineer who was to give the Delta its final command to launch. Fisk had authority to abort the procedure up to the last second if necessary. At approximately 6:34 a.m., the sky lit up and the rocket slowly and, at first, in eerie silence began lifting off the pad. Chunk Bennet, seeing the flash of light, thought at first that the rocket had exploded. Within seconds it was racing faster than the speed of sound, its coattails winding dramatically around a quarter Moon..."

"Within an hour the COBE was a satellite, circling the planet in almost perfectly circular north-south orbit with an altitude ranging from 899.3 km to 900.5 km that followed the moving dividing line between night and day, making a complete circuit every 103 minutes. Dennis McCarthy was elated... "That was quite a show..."

"Nancy (W. Bogges, Program Scientist, NASA) remained at Vandenberg... thanking the launch crew on behalf of the COBE team... Her gracious words meant a lot to the engineers, many of whom, their jobs suddenly and dramatically ended after years of strenuous effort, fell into a postlaunch emotional letdown..."

"In a very real sense, our work had just begun. We had to get back to Goddard and find out what kind of data COBE would generate about the beginning of the universe in the hope that the knowledge we would gain would justify its $160 million cost... The total cost, counting everything, was probably about $350 or 400 million."

Fig. 4.1 shows schematically the various components of the motion observed by COBE with respect to the background radiation[3]: COBE around the Earth at 7.4 km/s; Earth around the Sun, at 30 km/s; the Sun around the Via Lactea at 200 km/s; the Local Group around the Great Attractor at some 600 km/s... All these combined motions resulting in an overall velocity of about 360 km/s with respect to the cuasi isotropic cosmic radiation background.

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[3] J. A. Gonzalo, J. L. Sánchez Gómez, M. A. Alario (Eds), "Cosmología Astrofísica", pp. 88-89 (Alianza Universidad; Madrid, 1995).

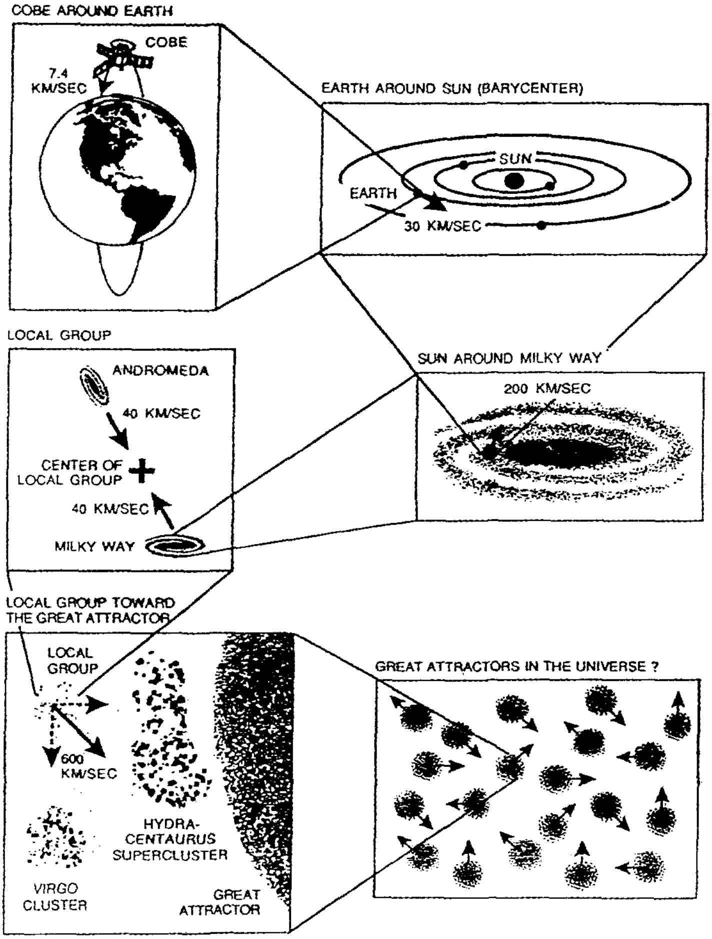

Fig. 4.1. Velocity components of the observed CMB Dipole.

Fig. 4.2 shows the microwave map of the sky obtained by the DMR-COBE instruments, showing the anticipated small anisotropies as they were at the time of atom formation, when the universe became transparent, and the very first light[4] began to travel almost freely in all

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[4] Ibidem, p. 90.

directions. The data accumulated after one year had an angular resolution substantially inferior to the resolution obtained with future experiments, but it was sufficient to identify for the first time the seeds of future galaxies in the CBR.

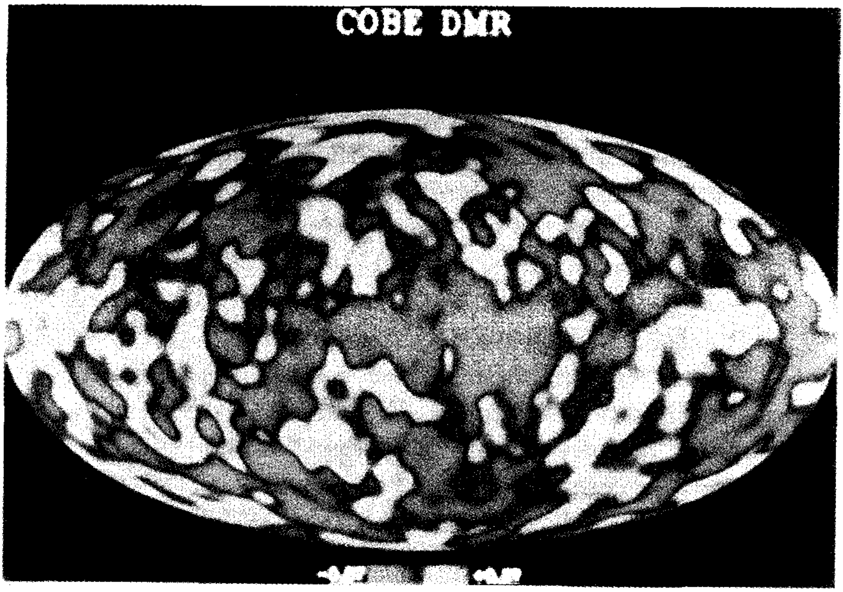

Fig. 4.2. COBE DMR one-year map showing anisotropy.

Fig. 4.3 presents the near infrared (~10 μm) map of the sky as given by the DIRBE-COBE experiment. It shows[5] the brightness of the interplanetary dust, dust grains in between planets, which are at a temperature of about 300 K. Some constellations, in which stars are forming, like Orion and Cygnus, can be clearly observed in this picture. This experiment provided considerable information on our galaxy, indicating that is not round, but rather asymmetrical, its brightness greater on the left than on the right. This could be interpreted as resulting from its barred character.

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[5] Ibidem, p. 93.

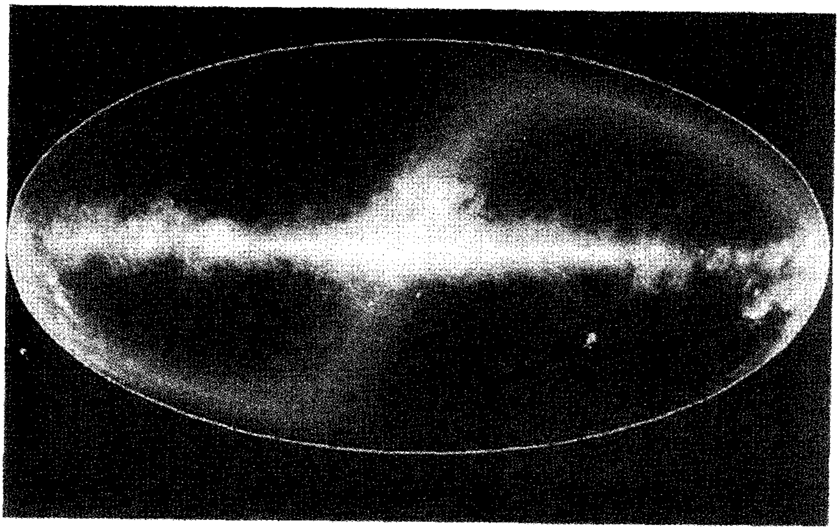

Fig. 4.3. DIRBE near infrared map.

Fig. 4.4 gives the FIRAS-COBE cosmic microwave background spectrum, based on only nine minutes of FIRAS data[6]. When it was shown at a plenary session of a meeting of the American Astronomical Society, on January 13, 1990, it brought a standing ovation from the participants. It can be seen that the theoretical prediction (Planck's formula) goes perfectly through the data (boxes).

It is worth summarizing the story in John Mather's words[7]:

"The day of our presentation had arrived. We were scheduled to speak after lunch in a large auditorium at the hotel near National Airport just outside Washington... Mike Hauser, George (Smoot), and I were dressed similarly for our presentation in what must have looked like the COBE uniform — blue blazers and khaki pants — even though I was certain we would be speaking to an empty hall.

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[6] John C. Mather & John Boslough, Ibidem p. 235.

[7] Ibidem pp. 233-234.

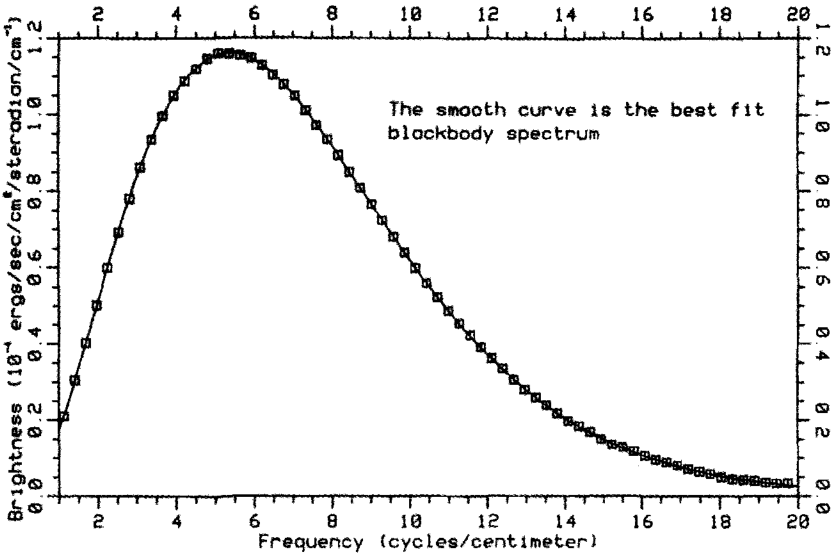

Fig. 4.4. FIRAS cosmic microwave background spectrum.

Our turn finally came. Ironically, the final session was chaired by Geoffrey Burbridge of the University of California who, along with Fred Hoyle, was a staunch opponent of the Big Bang Theory. As we walked into the large room, which I learned later could hold as many as two thousand people, I was astonished: the room was filled to overflowing. Nancy Boggess stood up and gave a summary overview of the COBE project.

Then I took the podium. After describing the instrument's principle of operation, I displayed a graph of the spectrum of the cosmic background radiation as revealed by the figure (see Fig. 4.4 in the present text). "Here is our spectrum." I said. "The little boxes are the points we measured and here is the blackbody curve going through them. As you can see, all our points lie on the curve." The theoretical curve predicted how the blackbody radiation should look if it had truly originated in the Big Bang.

There was a moment of silence as the other scientist there grasped the meaning of the data curve. Then the audience rose, breaking into spontaneous ovation. Blushing and with perspiration rising on my scalp, I stood there speechless before the big crowd. It had never occurred to me that so many scientists would be there or that they would think the preliminary FIRAS result was so important. I momentarily feared they were clapping for me, and thought about saying something about the team effort involved."...

In the summer of 1993, I had the privilege of coordinating with my good friends Ignacio Cantarell (recently deceased) and Rodolfo Nuñez de las Cuevas, as well as with José María Torroja, then Secretary of the Spanish Royal Society of Sciences (Exact, Physical and Natural being its full title), a course at El Escorial on "Astrophysical Cosmology" to which many distinguished scientist were invited to participate. Among them Ralph Alpher, George Smoot, Hans Elsaesser, Jerome Lejeune, Stanley Jaki... Six months earlier, I was busy faxing and phoning them to confirm their participation, their schedule and their talks titles. I had with me the APS Directory in which I found the telephone number of Dr. John C. Mather at NASA's Goddard Space Flight Centre and dialled direct from my office at UAM, expecting to get a secretary at the other end of the line. I was pleasantly surprised to be informed that I was talking with John Mather in person. I tried to tell him that our budget did allow a given maximum amount for very distinguished speakers... but he interrupted me quickly saying that as a US Government official he could take no fee for his lecture, only plain tickets, hotel and living expenses for the days of the conference. He agreed to come to Spain with his wife Jane, and told me that this way we, as organizers, would have more funds to take care of other expenses. I was delighted, of course, and when I met him and his wife at Hotel Felipe Segundo in El Escorial, the day before the opening of the Summer Course, I had a long and charming conversation with them, in spite of the very hot mid August day. The course went very smoothly and the CBR was a clear protagonist through the excellent lectures given there and then by Ralph Alpher ("The Big Bang in retrospect"), John Mather ("The COBE project achievements") and George Smoot ("COBE observations of the primitive universe") among others.

At the time some of the first COBE data were made public, the scientific reports addressed to physicists and cosmologists, as well as more general reports, did convey the message that COBE had found precisely just the CBR anisotropy predicted by the inflationary model. For instance, "Physics Today"[8], in the section on "Search and Discovery", reported that "proponents of the standard inflationary model of cosmology breathed a collective sigh of relief when members of the scientific team of NASA's Cosmic Background Explorer described their measurements of the microwave radiation at the APS spring meeting. The COBE satellite had provided the data necessary to keep the theory alive..."

It would be more fair, however, to say that standard cosmological models with no inflation, no dark matter or dark energy... did *not* exclude, evidently, thermal fluctuations at the time of atom formation. First, it was generally accepted that from the time of nucleosynthesis, (much earlier than atom formation) a substantial amount of ^{4}He and small amounts of other light nuclei were populating cosmic space, therefore introducing seeds of anisotropy in the mass distribution. In addition, one could use standard statistical mechanics[9] arguments to estimate the mean squared temperature fluctuation in the hot fluid made up by the cosmic matter/energy radiation just after atom formation. As it is well known, see f.i. Landau and Lifshitz[9], the fluctuations may be classical while, at the same time, the equation of state of the system may be given quantum mechanically. The probability of finding a fluctuation of ΔT in a system made up of N seeds of galaxies would be

$$W = \exp\left[-\frac{C_v}{2k_B T^2}(\Delta T)^2\right], \qquad [4.1]$$

where C_v is the heat capacity, k_B is Boltzman's constant and T the background temperature. For a gaussian distribution,

$$\left\langle (\Delta T)^2 \right\rangle = k_B T^2 / C_v \qquad [4.2]$$

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[8] "Physics Today" p. 17 (Jan 1992).

[9] E. M. Lifshitz and L. P. Pitaevski, "Statistical Physics" 3rd Ed. Part I (Landau and Lifsshitz Course of Theoretical Physics Vol. 5) p. 338 (Pergamon Press; Oxford, 1980).

and, substituting $C_v \approx N k_B$, one gets

$$\left\langle (\Delta T)^2 \right\rangle = T^2 / N \qquad [4.3]$$

which, using as the CMB temperature T~2.7K, and $N \sim 10^{11}$ as the total number of galaxies in the observed sky (which might be taken as the number of seeds of protogalaxies at atom formation), results in

$$\Delta T \cong \left[(2.7)^2 / 10^{11} \right]^{1/2} \cong 10^{-5} K \qquad [4.4]$$

which is of the same order as the anisotropy observed by the DMR-COBE instrument in 1990.

Chapter 5

Dark Matter, Cosmic Flatness & Accelerated Expansion

The inflation theory, which enjoyed considerable support among theoretical cosmologist from the very beginning, has been instrumental in providing a strong incentive among observational cosmologists and astrophysics to look for dark matter, i.e. for enough non-luminous matter as to render flat or quasi flat cosmic spaces. The astronomical record of luminous matter in the local neighbourhood of the Milky Way does not account[1] for more than 1% of the mass required for a flat universe, $\Omega=1$ ($k=0$). Baryonic matter, as determined mainly from the ^{4}He abundance, can account for 4% to 5% of the mass required (for $\Omega=1$). Dark matter estimated from observations of cosmic gravitational lensing estimates[2] give masses of $10^{15}M_\odot$ for groups of galaxies and much less for individual galaxies, like the Milky Way, as expected. But lensing has not[2] provided a definitive answer to the missing mass question.

F. Zwicky, almost seventy years ago[1] noted that rotation velocities of stellar bodies around the centre of mass are inconsistent with Keplerian motion. But the mass distribution in our galaxy, and more so in the class of the so called barred galaxies (of which our Milky Way is a candidate), is far from regular, and the motion of individual stars around the centre of the galaxy may be more alike one of rigid rotation than one purely Keplerian.

The intensive search for tangible material constituent of the dark matter has been so far unsuccessful. According to J. Silk[3], the most

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[1] Y. Ramachers, "Europhysicsnews", 32/6, p. 242 (2001).

[2] P. D. Sacket, "Europhysicnews", 32/6, p. 228 (2001).

[3] J. Silk, "Europhysicnews", 32/6, p. 211 (2001).

favoured candidate for cold dark matter is at present the neutralino, the lightest stable neutral supersymmetric particle with a mass in the range between fifty and a few thousand times the mass of the neutron. But, according to Silk[3], cold dark matter is seriously challenged.

Walter Baade[4], who worked closely with Fritz Zwicky in the late thirties, had pointed out that supernovae were very good candidates to measure cosmic distances due to the apparent uniformity of their peak brightness combined with the fact that they could be observed at very large distances, possessing extremely large intrinsic luminosity peaks. In the early eighties[5], supernovae with no hydrogen features in their spectra (type I) were subdivided in two classes, depending on the presence (Ia) or the absence (Ib) of a prominent silicon absorption feature in their spectrum at 6150Å. As pointed out by S. Perlmutter this refinement resulted in an amazing consistency among type Ia supernovae spectra. All the main features in their spectra begun to match, and their "light curves", consistent in plots showing how their brightness first increases and then disappears in the weeks that follow the supernovae explosion, did scale well. Measurements of "light curves" on a nearby low redshifted supernovae by Mario Hamuy and coworkers[6] did show spectacularly that simply by stretching the time scales of individual "light curves" to fit the norm, and then scaling the brightness by an amount determined by the required time stretch, all the type Ia light curves did mach almost perfectly. Thus one could hope use the supernovae light curve's time scale to predict the peak brightness and then refine the calibration of each supernovae.

Serious disadvantages to pursue cosmological measurements with type Ia supernovae must be, of course, overcome: they are rare (a couple of explosions per millennium in a typical galaxy); they are random, unpredictable, in principle (the largest world telescopes, the ones capable of observing distant type Ia supernovae properly, such as those in the Canary Islands, in Chile, California and Hawaii, devote scarce observing time to supernovae objects); and they are ephemeral, i.e. after exploding,

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[4] W. Baade, Astrophys. J. 88, 285 (1938).

[5] S. Perlmutter, Physics Today 56/4 p. 53 (2003).

[6] M. Hamuy et al. Astrn. J. 106, 2392 (1993); and 100, 1 (1995).

they must be detected immediately and be followed up for a few weeks, unless the peak brightness, so essential for calibration, is already gone forever. The ingenuity, competence and effective cooperation of dedicated astrophysicists in various parts of the world have produced a successful observing strategy, capable of sampling the expansion of the observable cosmos back to times without precedent, several billion years ago. The analysis of the results gave something unexpected. The supernovae type Ia data for redshifts up to $z=1$, which provided information of the cosmic expansion as it was more than $6\text{x}10^9$ years ago, was immediately interpreted (see below for an elementary critique of this interpretation) as indicative of an expansion speeding up rather than slowing down. A slowing down must be expected if it is in the end dominated by gravitational self-attraction. Einstein's cosmological constant Λ, which was invented precisely to counteract gravitation and to produce a static cosmos, was called back once again. Theoretical cosmologists, eager to justify cosmic flatness ($k=0$, $\Omega=1$) for all times, begun immediately to celebrate the beautiful observational findings, which were said to have been anticipated by them[7] as a kind of dark energy. It was concluded, confidently, that the cosmic density parameter $\Omega \equiv \rho/\rho_c$ was in fact given by $\Omega=\Omega_{DM}+\Omega_\Lambda+\Omega_m=1$, where Ω_{DM} (dark matter)≈ 0.26, Ω_Λ (dark energy)≈ 0.70, associated with the cosmological constant, and finally not completely excluded by the previous findings, Ω_m (ordinary matter)≈ 0.04. Fortunately (!).

Some amount of non-baryonic dark matter might possibly be homogenously distributed throughout cosmic spaces, but, to accept as undisputable that 26% to 96% of the matter mass of the universe is completely elusive and intangible, i.e. non-baryonic, and that all is made up of purely hypothetical particles or objects, is another thing. The list of candidates includes relatively massive neutrinos, WIMPS (Weakly Interactive Massive Particles, which remain undetected), MACHOS (Massive Compact Halo Objects) and massive neutron star binaries, considered responsible for GRB (Gamma-Ray Bursts). They might, however, account perhaps for a certain amount of dark matter, but not for

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[7] M. S. Turner, Physics Today 56/4 p. 10 (2003).

the enormous amount required to make flat the universe[8]. Otherwise some of those ubiquitous particles or objects should have been directly detected long ago.

In current analyses of cosmic dynamics, something very basic must have been missing. From the time dependence of the Friedmann-Lemaitre solutions to Einstein equations, as noted, as late as 1995, by R. A. Alpher and Herman[9] the following conclusion is undisputable for an open universe with Λ=0:

"We have evaluated Ω numerically and find, as expected, that at early times the value of Ω is extraordinarily close to unit and that the deviation from unity becomes increasingly small for earlier and earlier times".

Here it is not spelled out by Alpher and Hermann, but it is straightforward to check from the Friedmann–Lemaitre solutions, that H (Hubble's parameter) becomes, at earlier and earlier times, larger and larger. (Ht), the product of H by the universe age approaches exactly 2/3 at the same time that Ω approaches 1. Alpher and Hermann conclude "that it may not be necessary to invoke that consequence of an inflationary paradigm which requires that the value of Ω be unit throughout the history of the expansion..." Period.

As one can check directly in Eq. [1.1] (Einstein's Equation)

$$\frac{\dot{R}}{R}=\left\{\frac{8\pi}{3}G\rho-\frac{kc^2}{R^2}\right\}^{1/2} . \qquad [5.1]$$

For sufficient early time (sufficient small radius), the first term within the squared root, in which $\rho = M/({}^{4\pi}\!/_{3}R^3)$, becomes much larger than the second, containing as it does a more pronounced dependence on 1/R than the later. Therefore, the second term is at first irrelevant, which is equivalent to put k=0, making cosmic space apparently flat, even if it is actually either closed, with k>0 (which happens not to be the case) or open, with k<0 (which seems in all appearance to be the case), all throughout its entire history. In other words, it is perfectly compatible to

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[8] Y. Ramacheers, ibidem. pp. 242-244.

[9] R. A. Alpher and R. Herman, "Calculations of Cosmological Parameters and Their Approximations in the Standard Big Bang Model", February 1995. Meeting on Unified Symmetry in the Small and in the Large, Coral Gables, Florida.

have $\Omega(t)\approx1$ for $t<<t_+$ (a universe which looks flat at early times), and $\Omega(t)<<1$ for $t>>t_+$ (a universe which appears patently open at present times), being t_+ the time at which $R\approx R_+$, in other words, the time at which the second term, $-kc^2/R^2=|k|c^2/R^2$, is becoming of the same order of $\frac{8\pi}{3}G\rho=2GM/R^3$, before finally becoming larger for ever thereafter.

Let us look more closely to the proper interpretation of the cosmic expansion as resulting from recent type Ia supernovae findings, going from nearby supernovae (redshift z=0.01) to relatively distant supernovae (redshift z≈1), whose light is arriving *now* to our best telescopes, having been emitted some 6×10^9 years ago.

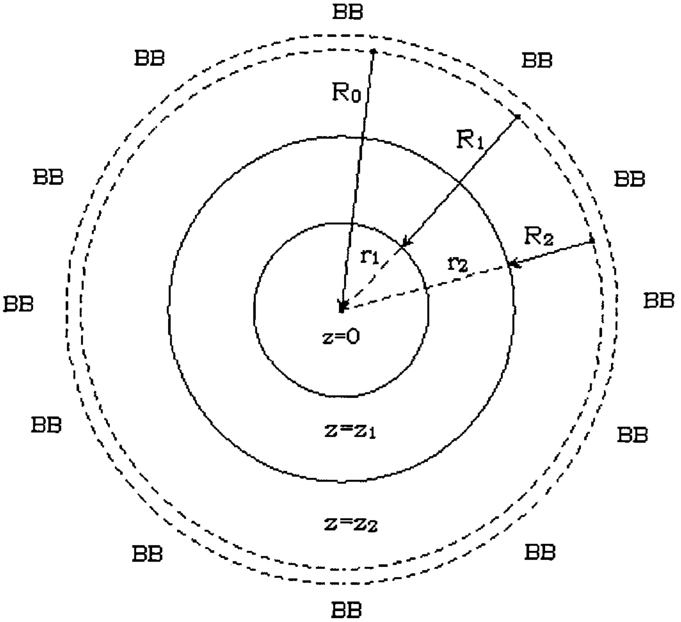

Fig. 5.1. Schematic plot of the expanding cosmos at present time, t_0, and radius, R_0, we view exploding supernovae at distance R and redshift z as they were speeding away from the outer circle corresponding to the Big Bang. Full cosmic sphere including the outer plasma portion corresponding to cosmic times $t<t_{af}$, i.e. before the universe became transparent. Exploding supernovae SN_1 at distance $r_1=R_0-R_1$ (redshift z_1) from us, and SN_2, at distance $r_2=R_0-R_2$ (redshift z_2) from us, are shown.

Fig. 5.1 shows a schematic picture[10] of the expanding cosmos: The Big Bang started at time t=0 with matter and energy enclosed within an infinitesimally small radius. The sphere, originally containing an incredibly dense and hot plasma of radiation and matter (later photons, protons and electrons, still later, also ^{4}He nuclei, and the corresponding electrons) continued its expansion at speeds much higher than the speed of light (as given by Friedman–Lemaitre solutions according to Eq. [1.1]-[5.1]). After having cooled sufficiently, the plasma constituents begun to form atoms at $t=t_{af}$ ($R=R_{af}$) about 10^6 years after the Big Bang and finally at $t_0=13.7\mathrm{x}10^9$ years, the cosmic sphere attained its present radius R_0 as the expansion kept going. Our galaxy has an almost negligible local motion with respect to the reference frame of the quasi-isotropic CBR[11]. Then, the origin of R (cosmic scale factor) is *not* to be taken at our galaxy, which is located relatively near the centre of the expanding cosmic sphere, but at *any point* on the spherical surface. Likewise $\dot{R}$ is the speed at which at any time the actual radius grows, with the origin at a point on the surface of the cosmic sphere corresponding to the moment of the Big Bang. When cosmic distances, say to a type Ia supernovae, are measured from our point of observation, the distance is given by $r=R_0\text{-}R$, where R is the cosmic radius corresponding to time t after the Big Bang, at which the light arriving at us now was originally emitted.

Fig. 5.2 shows a schematic plot of the supernovae magnitude, proportional to the logarithm of $r=R_0\text{-}R$, as a function of the redshift, which is, at first, approximately proportional to the recession speed $\dot{R}$. The plot gives data for type Ia supernovae depicting semiquantitatively the observed behaviour[12]. The slope of the curve at a point corresponding to a distance r (redshift z) from us is given by

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[10] M. J. Rees, in "Astrophysical Cosmology "Proceedings of the Study Week on Cosmology and Fundamental Physics (Sept. 28-Oct.2, 1981) pp. 7-20,

H. A. Brick, G. V. Coyne and M. S. Longair Eds. (Pontificae Academiae Scientiarum Scipta Varia; Vatican City, 1982).

[11] J. A. Gonzalo, J. L. Sânchez G6mez, M. A. Alario (EDS) "Cosmología Astrofísica" (Alianza Universidad; Madrid, 1995).

[12] S. Perlmutter, Ibidem, p. 56.

$$\tan\alpha \approx \frac{r}{\dot{R}} = \frac{R_0 - R}{\dot{R}} = \frac{R_0}{\dot{R}} - \frac{1}{H} \qquad [5.2]$$

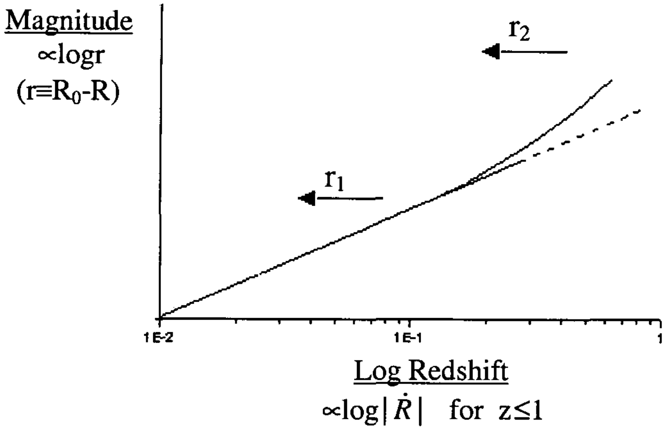

Fig. 5.2. Schematic plot of the magnitude of exploding type Ia supernovae as a function of redshift. Note that the evolution of $\Delta M/\Delta z$ corresponding to $\Delta r / \Delta \dot{R}$ does not imply that the cosmic expansion (viewed from the origin of space time) is accelerating. The opposite is true (See discussion in text; Eqs. [5.2] to [5.5].

When comparing the Hubble parameter ($\equiv \dot{R}/R$, by definition) for a nearby supernovae ($z_1 \approx 0.01$) and for a relatively distant one ($z_2 \approx 1$), we see, in Fig. 5.2, that

$$\frac{R_0}{\dot{R}_1} - \frac{1}{H_1} < \frac{R_0}{\dot{R}_2} - \frac{1}{H_2} \qquad (\tan\alpha_1 < \tan\alpha_2) \qquad [5.3]$$

or equivalently,

$$\frac{R_0}{\dot{R}_1} - \frac{R_0}{\dot{R}_2} < \frac{1}{H_1} - \frac{1}{H_2}\,. \qquad [5.4]$$

Here, $\tan\alpha_1 < \tan\alpha_2$, Eq. [5.3], implies that $\dot{R}_1 < \dot{R}_2$, and therefore that the cosmic expansion is *decelerating*, resulting in $H_1 < H_2$, in spite of the fact that a wrong interpretation of the same data shown in Fig. 5.2 can lead to the wrong conclusion that the cosmic expansion is *accelerating*. In other words,

$$\frac{\Delta M_1}{\Delta z_1} < \frac{\Delta M_2}{\Delta z_2} \rightarrow \frac{\dot{R}_1}{r_1} > \frac{\dot{R}_2}{r_2} \quad [5.5]$$

does *not* imply that $H_1 > H_2$. The *opposite* is true.

The cosmic radius R=R(t) at time t is related to the cosmic radius $R_0=R(t_0)$ at time t_0 (present) by

$$R = R_0/(1+z) \quad [5.6]$$

where z is the redshift. Eqs. [1.4] makes explicit the Friedman–Lemaitre open solution to Einstein's cosmological equation,

$$y = \sinh^{-1}(R/R_+)^{1/2}, \quad [5.7]$$

where R_+ is a constant, depending on G, M, k and c^2, and makes equal in absolute value the two terms within square brackets in Eq. [5.1]. Taking into account that in the present transparent phase of the cosmic expansion $R/R_+=T_+/T$,

$$y = \sinh^{-1}\left(\frac{R}{R_+}\right)^{1/2} = \sinh^{-1}\left(\frac{T_+}{T}\right)^{1/2} = \sinh^{-1}\left(\frac{[1+z_+]}{[1+z]}\right)^{1/2} . \quad [5.8]$$

Then we can calculate directly the Hubble's parameter $H(y)=\text{const}(\cosh y/\sinh^3 y)$, the cosmic time $t(y)=\text{const}[\sinh y\cosh y-y]$, their dimensionless product H(y)t(y), and the dimensionless density parameter $\Omega(y)=\rho(y)/\rho_c(y)=1/\cosh^2 y$ in terms of redshift z, spanning data from z=0.01 (nearby supernovae) to z=1 (relatively distant supernovae). Table 5.1 gives the corresponding values.

Table 5.1. Cosmic Parameters Ht (Hubble parameter times the time elapsed since big bang) and Ω (ratio of actual density to critical density) as a function of redshift z.

z	**0.01**	**0.1**	**1.0**
y (adimensional)	2.262	2.220	1.930
H(km/sec.Mpc)	67	73	135.6
t(yrs)	13.7×10^9	12.5×10^9	6.54×10^9
Ht(adimensional)	0.9416	0.9371	0.9107
Ω (adimensional)	0.042	0.058	0.080

These numbers, obtained using T_0=2.726K for the present microwave radiation background temperature, which implies T_+=62.17K, y_+=0.8813 and z_+=21.80 at $R=R_+$, as defined above, are compatible with a Hubble parameter twice as large as it is now at a time some six billion years ago (in accordance with Supernovae Type Ia observation[12]) and also with a density parameter Ω about twice as large as it is now approximately at that same time. This argument extrapolates to $\Omega \approx 1$ (only slightly lower than one) at the cosmic sphere of the CMB, corresponding to $z \approx 1000$, which is itself relatively close to the sphere of the big bang.

Chapter 6

The Microwave Anisotropy Probe (WMAP)

The WMAP (Microwave Anisotropy Probe) was launched in June 2001 in a Delta rocket, the same type of rocket in which the COBE had been launched in orbit in November 1989. The success of the COBE mission had established beautifully the blackbody character of the microwave background radiation and, in so doing, had detected unambiguously for the first time the small anisotropies which signal the formation of the first protogalaxies. The WMAP's results (rechristened with the initial W to the memory of Princeton University astrophysicists David Wilkinson, recently deceased, who was a founding member of the partnership between Princeton and NASA's Goddard Space Flight Centre) confirmed and complemented COBE's findings with unprecedented accuracy.

The Delta rocket did carry the WMAP satellite on a journey, which, within a few weeks, brought it to the vicinity of the L2 Lagrange point[1], a special point 1.5 million km antisunward of Earth. From that point of observation, remote and unobstructed, the instrument could map the sky continuously, with an unprecedented precision, measure the faint departures of the CBR from perfect anisotropy (Fig. 6.1), and detect (something which COBE was unable to do) the still fainter polarization carried by the quasi-isotropic cosmic background radiation. As shown below, this small polarization gave unexpected information on the first massive stars, about one hundred times the sun mass, which had formed in a relatively short time after the universe became transparent, and after

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[1] B. Schwarzschild, "Phys. Today", April 2003, p. 21;
WMAP Collaboration, http://arxiv.org/abs/astro-ph/0302207-09,13-15,17,18,20,22-25.

the cosmic plasma became a gas of neutral atoms, sometime before they begun to become gravitationally bound.

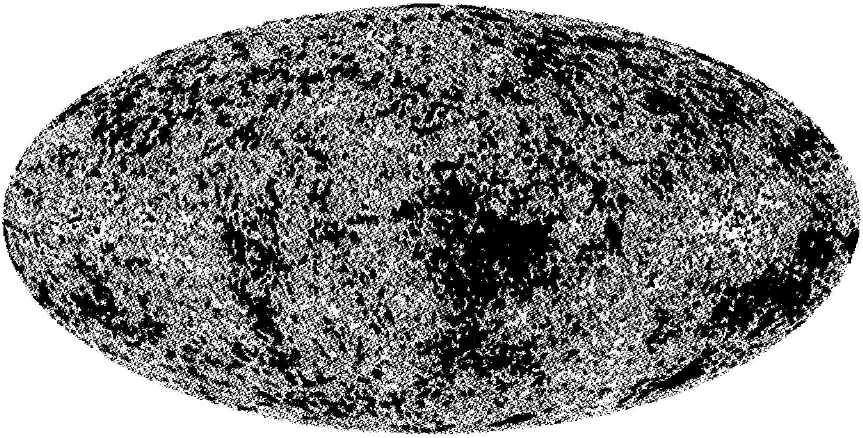

Fig. 6.1. All sky map of microkelvin departures from isotropy of the 2.725K cosmic microwave background, as given by WMAP (angular resolution about 12 arcminutes).

In February 11, 2003, the expected report of WMAP's first full year observations, was made public in the form of 13 separate preprints, full of data, accompanied by a wealth of preliminary analysis. The following day, The New York Times outlined the story: "For Astronomers, Big Bang Confirmation"[2]. The report pointed out right away that the task was to understand the *dark stuff* ("dark matter" and "dark energy") that "apparently makes up 96 percent of everything, and to investigate what happened in the Big Bang that gave birth to it all".

Cosmologists, according to the NY Times report, "do not know what *dark energy* is". They do not know either, in spite of a wealth of potential candidates, what *dark matter* is made of. One leading candidate, according to prestigious theoretical cosmologists, is the force associated with the cosmological constant, which Einstein introduced as a fudge factor in an attempt to keep the universe from collapsing, and later

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[2] See "New York Times", 02/12/2003 (Science Section).

disavowed. Alternative proposals include a force field named "quinta essence".

But apparently, cosmologists agree, the analysis performed has not solved the dark energy problem. Dr. Sperger, from WMAP's team said its data seemed to favour Einstein's fudge factor the whole thing remains, however, highly speculative.

The cosmic microwaves represent a snapshot of the universe as it was cooling through the temperature at which atoms begun to form from electrons and protons (and from a non negligible amount of α-particles, ^{4}He nuclei), at a time of about 380.000 years after the big bang.

After COBE had confirmed, in 1992, that tiny lumps were present in the almost isotropic cosmic background radiation, a series of smaller experiments investigating more closely the lumps had concluded that the geometry of the universe was flat (Euclidian), but they only glimpsed at small portions of sky for limited times. The new satellite, however, was scanning the whole sky every six months. The new map of the sky given in Fig. 1 was based upon the first year worth of data, but the satellite was designed to operate for four years. Improved accuracy should be expected after the completion of eight full scans of the entire sky or more.

The satellite's instruments were capable to measure, like a pair of Polaroid sunglasses, the polarization of the microwave radiation, in addition to measuring its brightness with an unprecedented precision and angular resolution. Those measurements were crucial to determine the era of formation of the first stars. In the same way, as light skipping off a lake's surface[2], the electric and magnetic fields that constitute electromagnetic radiation bounce off cosmic ionised gas, showing definitive preference to vibrate in a particular plane, and therefore, to become polarized. Recently, astronomers had shown that polarization was imparted to the microwaves right at the moment when the first neutral atoms were formed. A new different polarization event was expected by the astronomers when stars were first formed by gravitational collapse out of the gas of neutral atoms. In stars, the reionisation of the hydrogen and helium atoms takes place again, a process which is taking place now at the surface of our Sun (a second or third generation star). As in the Sun's surface, the free electrons at the surface of the newly formed stars polarize cosmic radiation again leaving an imprint in the CMB.

A majority of astronomers expected that the first stars would have been formed about the time of formation of the most distant quasars around 800 million years ago. But it was a surprise for them to find, from WMAP's data, that the first stars (probably monsters 100 times as massive as the Sun) formed so much earlier, as Dr. Bennet, WMAP's Principal Investigator, did explain in his interview for the New York Times. These early and massive stars did burn rapidly and violently, transmuting primordial hydrogen and helium into heavy elements, like carbon and oxygen, and sending them out to space, to form future generations of stars, including, eventually, our Sun and its planetary system.

The WMAP's data could shed light on what might have been going on during and after the Big Bang. The theory of inflation, however, which has been dominant among theoretical cosmologists for more than two decades now, as Dr. Bennet noted, is often called a paradigm instead of a theory. A physical theory is always accountable to test and experimental checks. A paradigm, however, not so well defined, might have, in principle, such a degree of flexibility that new observations could be accommodated within it, without excessive difficulty. Inflation seems to be available now in such number of versions that one or other is likely to account for most conceivable observational finding. Dr. Linde, from Stanford, inventor of one of the models ruled out by WMAP's data, said, according to the NY Times, that it was "great" that theories were getting "culled". Dr. Turner, another prominent cosmologist, was reported as saying: "This is the door to precision cosmology being opened. It's the first step in a long march".

The instrument's design[3] was tailored to improve by an order of magnitude the calibration of the previous probes used by the COBE, which were already extremely accurate. Due to its sensitivity and to its uninterrupted full-sky coverage the WMAP was able to measure, only with the first year's data, the first "acoustic" peak in the temperature of the cosmic background anisotropy, within very small errors (See Fig. 2).

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[3] B. Schwarzschild, Ibidem, p. 22.

The data provided a precise numerical value for the time elapsed since the Big Bang, as given by

$$t_0 = 13.7 \pm 0.2 \text{ billion years} = (4.32 \pm 0.06) \text{x} 10^{17} \text{ sec} \qquad [6.1]$$

and a specific time for the occurrence of atom formation, (triggering cosmic transparency) as

$$t_{af} = 379 \pm 8 \text{ thousand years} = (1.19 \pm 0.02) \text{x} 10^{13} \text{ sec} . \qquad [6.2]$$

WMAP's first year data provided also very accurate estimates of the Hubble constant at present time

$$H_0 = 71 \pm 4 \text{ Km/s.Mpc} = (2.31 \pm 0.13) \text{x} 10^{-18} \text{ sec}^{-1} . \qquad [6.3]$$

The dimensionless product $H_0 t_0$, obtained using the present value of H (which is time dependent) and t (obviously also time dependent) is given by

$$H_0 t_0 = 0.942 .$$

This dimensionless product corresponding to an open universe ($k<0$) must have evolved from an early value $H_{af} t_{af} \approx 2/3$, at $t = t_{af}$, as previously noted, and is growing at present towards one. This is a clear indication that the universe was expanding faster at earlier times as viewed from the Earth now. But, as noted in the previous chapter, it would be not only confusing but wrong to say that the universe is actually accelerating now.

Not so long ago[4,5] the value of Hubble's constant was known with a precision no better than 25%. In fact some estimates, in which the expansion of nearby galaxies counted more, suggested $H_0 \approx 50$Km/s.Mpc, while other estimates, perhaps relaying rather in farther away galaxies, favoured $H_0 \approx 100$ Km/s.Mpc. Having into account that the expression of Hubble's constant, as deduced from Einstein's cosmological equations (without the cosmological term) is strongly dependent on time (as it is the density parameter), both previous estimates, $H_0 \approx 50$Km/s.Mpc (from nearby galaxies) and $H_0 \approx 70$Km/s.Mpc (possibly from farther away galaxies), may not be as contradictory as they appear at first sight.

The slightly hot and cold spots in the all-sky map given by WMAP's first year data, signal local regions at the beginning of the transparent

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[4] M. S. Turner, Ibidem, p. 11.

[5] M. S. Turner, Ibidem, p. 10.

epoch, that show mass densities and energy densities only very slightly lower or slightly higher than the mean value. The expansions and contractions of such density fluctuations can be viewed as acoustic waves in the viscous elastic cosmic fluid in which, at the end of the plasma epoch, radiation pressure was competing against gravitational contraction. In fact, radiation pressure, dominant in the plasma epoch, can be viewed as the driving force for the cosmic expansion all the way since the Big Bang, at least since Planks epoch ($t \sim 10^{-44}s$) and conceivably even earlier. The sound speed, limiting how fast hot or cold spots grow in the plasma epoch, was relatively close to the speed of light, about $c/\sqrt{3}$.

To extract the best numerical values of cosmic parameters from the CMB radiation it is convenient to obtain the angular power spectrum of temperature fluctuations by decomposing the celestial map, giving ΔT departures from the mean CMB temperature, into a sum of spherical harmonics $Y_{l,m}(\theta,\phi)$. For a certain multipole l, the fluctuation power is given by the mean-square value of the expansion coefficients $a_{l,m}$, averaged over the $2l+1$ values of the azimutal index m. There is no preferred direction in the CMB sky after subtracting the dipole contribution. This contribution is due to the displacement of the probe in cosmic space with respect to the reference system defined by the CMB itself. (The distribution of power in m varies randomly with the observer's position in the cosmos). In Fig. 6.2, it is shown the angular spectrum of the temperature fluctuations. The variance (in μK^2) is indicated by a shaded region, which is widest at small l. According to the report by Bertram Schwarzschild in "Physics Today"[1], the extremely low quadrupole ($l=2$) power in the spectrum, which is outside the variance of the calculated best fit as a function of l, might or might not have cosmological significance, but the accumulation of further data in the next years could improve sufficiently the statistics to provide an answer to this open question. The power spectrum peaks correspond to those modes (characterized by definite l values), which happened to be maximally either *over* or *under-dense* at the moment when the universe became transparent.

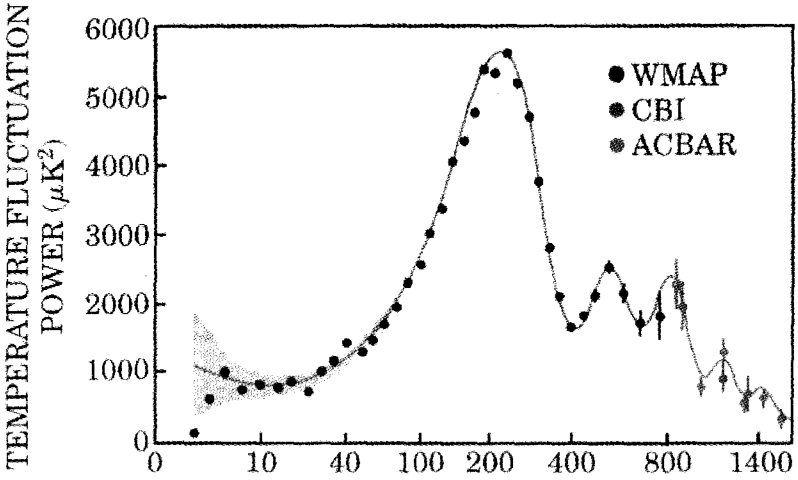

Fig. 6.2. Angular power spectrum of temperature fluctuations in the cosmic microwave background given by WMAP.

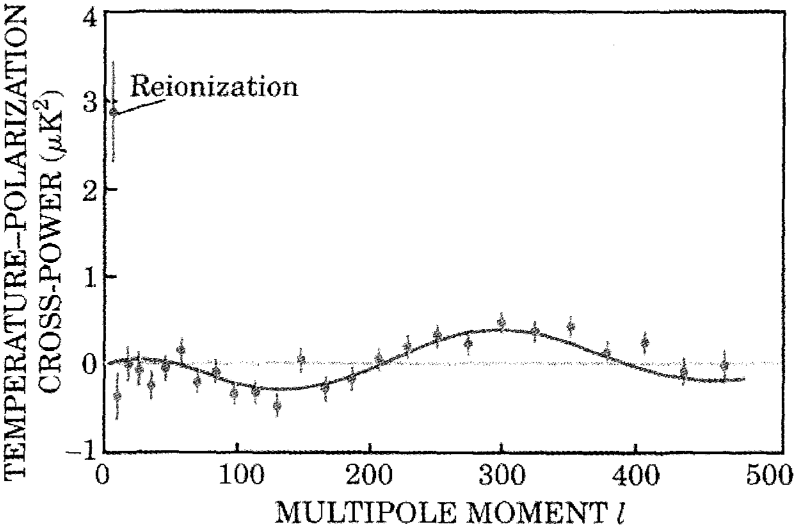

Fig. 6.3. Cross-power spectrum of correlation between CMB temperature fluctuation and polarization in the cosmic microwave background measured by WMAP. The point at the lowest multipole moment is attributed to the first stars, formed about 200 million years after the formation of the CMB according to WMAP's team.

The main surprise provided by the first year of WMAP's observations, as noted, was the definitive excess of temperature-polarization cross-power (in μK^2), about 3 for l of order ten compared with an oscillating background about ±0.5 as a function of increasing l up to $l \approx 460$ (see Fig. 6.3). This is attributed to the beginnings of cosmic gas reionization corresponding to the formation of the first stars, thought to have formed[1] about 200 million years after the original CMB temperature anisotropies were fixed in the microwave sky (at the time of atom formation) about 400 thousand years after the Big Bang.

Nearly twenty years ago[4], M. Turner, G. Steigman and L. M. Krauss, did try to reconcile "theoretical prejudice" (in their own words), implying Alan Guth inflationary theory (with k=0 as the cosmic curvature), with observational data, pointing out that the presence of mass smoothly distributed at scales >>199 Mpc could make compatible those data with $\Omega \approx 1$ (k=0), either by means of relativistic particles, which might contribute a relativistic mass density $\Omega = 1 - \Omega_{NR} >> \Omega_{NR}$, or else by reintroducing Λ (Einstein's cosmological constant) into the basic cosmic equation. It should be noted that Λ, by definition must be spatially constant. The contribution of a cosmological term into the density parameter would later be relabelled Ω_Λ.

A "Reference Frame" by Michael Turner in "Physics Today"[6] devoted to WMAP's findings is entitled: "Dark Energy: Just What Theorist Ordered". After referring to the problems for a flat universe considered most important at the 1990's he states: "To save a beautiful theory, theorists are willing to consider the implausible although not the impossible". (He does not explain why it should be considered so beautiful a theory which does not even attempt to respect energy conservation; a theory which is "the ultimate as a free lunch", according to Alan Guth). Then he reviews how Bondi, Gold and Hoyle used the cosmological constant to address the fact that the cosmic time back to the Big Bang appeared (then, half a century ago) to be less than the age of the Earth. Hints by the mid-1990 from the CMB anisotropy data could be

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[6] M. J. Rees, "Introductory Survey", pp. 3-20, in "Astrophysical Cosmology", Proceedings of the Study Week on Cosmology and Fundamental Physics (H. A. Bruck, G. V. Coyne sum Scripta Varia; Vatican City, 1982).

taken as indications that the universe is flat. However, our author points out, "there was a problem: Λ_{CDM} (standing for "cold dark matter with a cosmological constant") also predicts accelerated expansion, and the first supernovae results did not yet show acceleration. With the discovery of cosmic speed up in 1998, Turner continues, "everything quickly fell into place".

Theoretical estimates of the cosmological constant (made obligatory in the authors view, by quantum mechanics, as a sum of zero point energies) give $\Omega_\Lambda=10^{55}>>1$, somewhat embarrassing for theoretical physics, and to be left aside for the time being.

Let us stop here for a moment. As shown in the preceding Chapter, if counting distance (r) to supernovae from our vantage point implies *accelerated* cosmic expansion, counting the distance (R-r) from the Big Bang sphere (located behind the CMB radiation sphere, which is the right origin[5] for R), implies *decelerated* cosmic expansion.

After reviewing briefly the merits/demerits of the real or rhetorical problems which propelled cosmic inflation to the cosmologists attention (the monopole problem, the flatness problem and the horizon problem) we will show how a time dependent $\Omega(t)$ is compatible with $\Omega(z=0)=\Omega(t_0)\approx0.04$, $\Omega(z=1)=\Omega(t=6.5\mathrm{x}10^9 \text{ yrs})\approx0.08$ and $\Omega(t_{af})\approx 0.98$, and how an evolving $H(t)$ is compatible with $H(z=0)=H(t_0)\approx 67\pm4$ Km/s.Mpc, $H(z=1)=H(t=6.5\mathrm{x}10^9\text{yrs})\approx135\pm8$ Km/s.Mpc and $H(t_{af})\approx (4.96\pm0.30)\mathrm{x}10^5$ Km/s.Mpc at atom formation.

Chapter 7

On the Monopole, Flatness and Horizon Problems

Alan Guth[1], in his book "The Inflationary Universe", pays special attention to the role played by *three problems*: (1) the magnetic monopole problem (2) the flatness problem, and (3) the horizon problem. In this way he convinced distinguished theoretical cosmologists that the *concept of inflation* was *needed* (or at least very desirable, as a paradigm) to rescue Big Bang cosmology from grave dangers. In this Chapter, we will reproduce succinctly Alan Guth's words stating successively these three problems (P), and subsequently we will argue that these three problems do not need to be of overriding concern[2] (R).

P(1) Magnetic monopole problem: "A problem, discovered by John Preskill in 1979, concerning the compatibility of "grand unified theories" with standard cosmology. Preskill showed that if standard cosmology were combined with grand unified theories, far too many "magnetic monopoles" would have been produced in the early universe"[3].

R(1). This problem, now of little more than historical relevance, achieved considerable notoriety when Blas Cabrera at Stanford University did report the experimental finding of a candidate

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[1] Alan Guth, "The Inflationary Universe", (Perseus Books; Cambridge, Mass, 1997).

[2] See f.i. A. Lightman and R. Brawer, "Origins: The Lives and Works of Modern Cosmologists" (Harvard University Press; Harvard, Mass, 1990), quoted by R. A. Alpher and R. Herman in "Calculation of Cosmological Parameters and Their Approximations in the Standard Big Bang Model", presented at the 1995 meeting on "Unifies Symmetry in the Small and the Large", Coral Gables, Florida.

[3] Alan Guth, Ibidem, p. 337.

monopole event[4]. He did take a superconducting loop, placed it in a device at an ultralow magnetic field, and monitored the current with a superconducting Quantum Interface Device for months. On 14 Feb. 1982 (Saint Valentine's day) he detected a change in the flux through the superconducting circuit matching exactly the expected flux due to a Dirac monopole, with magnetic charge g=ħc/2e. The experiment was carried out with outmost care[4]. A noted theorist remarked: "One shouldn't be convinced by one event. But it is about as impressive as one event can be". Cabrera himself noted: "It is not yet a discovery. It's an interesting event". But many months of subsequent search with improved experimental systems did not find further monopole events. It is not clear whether the present situation regarding the available observational evidence now on magnetic monopoles is good or bad for grand unified theories. In any event this does not seem to be relevant to the case for or against standard Big Bang cosmology.

P(2) **Flatness Problem:** "A problem of the traditional big bang theory (without inflation) related to the precision required for the initial value of "omega", the ratio of the actual mass density to the critical mass density. If the description is started at one second after the big bang, for example, omega must have been equal to one to an accuracy of fifteen decimal places, or else the resulting universe would not resemble our own. Yet the traditional big bang theory offers no explanation for this special value, which must be incorporated as an arbitrary postulate about the initial conditions"[5].

R(2). Let us take a look to Einstein cosmological equation, Eq. [1.1], supplemented by a cosmological term,

$$\frac{\dot{R}}{R}=\left\{\frac{8\pi G}{3}\frac{M}{\frac{4\pi}{3}R^3}+\frac{|k|c^2}{R^2}+\frac{\Lambda c^2}{3}\right\}^{1/2} . \qquad [7.1]$$

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[4] See f.i. "Physics Today", June, 1982, "Cabrera counts flux quanta to find a Dirac monopole" in Search & Discovery, p. 17.

[5] Alan Guth, Ibidem p. 332.

Clearly, at R→0, the first term within the square root is dominant perforce. Then

$$\rho \equiv \frac{M}{\frac{4\pi}{3}R^3} = \frac{3(R/\dot{R})^2}{8\pi G}, \qquad [7.2]$$

but by definition, the critical density is

$$\rho_c \equiv \frac{3H^2}{8\pi G}, \qquad [7.3]$$

thus omega (the density parameter) has no choice but being

$$\Omega \equiv \rho/\rho_c \cong 1, \qquad \text{at } R \to 0 \qquad [7.4]$$

regardless of the value of k (space curvature).

There is no mystery in the fact that (for an open universe, with or without a positive cosmological constant) Ω is arbitrarily close to one at the beginning, a little less so at a time slightly later, and so forth. At a sufficiently small t (small R) Ω would be equal to one to an accuracy not of fifteen but of one hundred decimal places or more.

P(3) **Horizon problem:** "A problem of the traditional big bang theory (without inflation) related to the large scale uniformity of the observed universe. The problem is seen most clearly in the "cosmic background radiation", which is believed to have been released at about 300,00 years after the big bang, and has been observed to have the same temperature in all directions to an accuracy of one part in 100,000. Calculations in the traditional big bang theory show that the sources of the background radiation arriving today from two opposite directions in the sky were separated from each other, at 300,000 years after the big bang, by about 100 "horizon distances". Since no energy or information can be transported further than the horizon distance, the observed uniformity can be reconciled only by postulating that the universe began in a state of near perfect uniformity"[6].

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[6] Alan Guth, Ibidem p. 335.

R(3). If one substitutes “postulating” by “concluding” in the last sentence, the problem disappears. At the big bang (or an instant after, when R→0, t→0) the universe, which was then extremely hot and dense, was expanding at a speed incredibly faster than the speed of light. Then, two subnanoscopic regions separated by distances larger than *ct* could be either (a) assumed to be at wildly different temperatures or (b) at extremely close temperatures, which is the most reasonable expectation. In other words, at face value it seems much more artificial to postulate wildly different local initial conditions and then to introduce a complicated theory (inflationary theory *is* complicated) than to infer as a fact that local conditions were almost identical at $\Omega \approx 1$, and that only later, after baryon formation, electron formation, nucleosynthesis, atom formation etc, tiny fluctuations begun to be noticeable.

Would it be disappointing if inflationary cosmology were shown to be artificial and unnecessary? To physicists who have cast their vote for it early in the game, probably yes. As shown in Chap. 8 (Steady Growth vs. Inflation) Einstein’s equation implies

$$R(t) = const.t^{2/3} = R_+\left[|k|^{1/2} c/R_+\right]^{2/3} t^{2/3} \qquad [7.5]$$

regardless of the cosmic equation of state, which is given by RT=const after decoupling, and (not unlikely) by $RT^{4/3}$=const prior to decoupling. Using $M=c^2R_+/2G=4.10\text{x}10^{54}$g ($R_+=6.07\text{x}10^{26}$ cm) as an estimate of the total observed universe mass, the earliest meaningful cosmic time is

$$t_H \cong \frac{\hbar}{Mc^2} \cong 2.84\times10^{-103}\, s \qquad [7.6]$$

to be compared with Planck’s time

$$t_p \cong \left(\frac{\hbar G}{c^5}\right)^{1/2} \cong 5.37\times10^{-44}\, s\,. \qquad [7.7]$$

The steady growth in scale factor, according to Eq[7.5], is then

$$R(t_p)/R(t_H) = (t_p / t_H)^{2/3} \cong 3.29 \times 10^{39}, \qquad [7.8]$$

of the same order as the inflationary growth factor, given by Alan Guth ($\sim 10^{40}$).

Chapter 8

An Alternative to Inflation?

Guth's inflationary theory [1] postulates that the big bang was set into motion by a period of very rapid "inflation", lasting only about 10^{-35} seconds. During the last twenty years or so, as it is well known inflationary cosmology has enjoyed among cosmologists, specially among theoretical cosmologists an exalted status.

But, is it possible to consider an alternative cosmological model to inflation within the general relativistic framework of Big Bang cosmology?

As it is well known, half a century ago [2] the two main rival cosmological models were the big bang model, originally proposed by G. Lemaitre, and the steady-state model, supported at that time by Gold, Bondi and Hoyle. The discovery of the 3 K cosmic background radiation by Penzias and Wilson in 1965, difficult to reconcile with the steady state model, decided the matter in favour of the big bang model. The steady state model did postulate a steady expansion of the universe at constant density, with cosmic matter coming out of nowhere in a continuous way.

In August 1993, some time after the publication of the COBE results, at an International Summer School on Astrophysical Cosmology held at El Escorial, a question was raised as to whether or not the inflationary cosmology, which postulated a very large cosmic expansion at a conveniently early cosmic time of about 10^{-35} seconds after the big bang, could be considered a new version of the steady state theory dressed in new clothes. The answer of the speaker was that while there were analogies in the equations describing the constant density expansion in both cases, these analogies were only superficial.

Within the last few years, new and more accurate cosmic data begun to be available. Such cosmic parameters as the universe age, t_0, i.e. the time elapsed since the big bang, and the Hubble parameter H_0, characterizing the expansion rate of the universe, became known with uncertainties of only a few percent. It is well known, but often not sufficiently appreciated, on the other hand, that H and, of course, t are changing with time, as given by Einstein's cosmological equations. The observed data are putting more and more stringent limits on the compatibility of cosmic parameters obtained from different sets of raw data. For instance, given the fact that, for a universe evolving from a flat geometry to an open geometry (following Einstein's equations) the product Ht must be such that $2/3 \leq Ht \leq 1$, the graphic relations between the present age of the universe and the present value of Hubble's "constant" given by Alan Guth, Figures E.1 and E.2, in "*The Inflationary Universe*" [1] become inconsistent with recent observations (WMAP's data) because if $t_0 \cong 13.7 \times 10^9$ yrs, as given by WMAP data [3], H_0 should be less than 47 Km/s per Mpc (according to those graphs), which is considerably lower than $H_0 \cong 71 \pm 4$ Km/s per Mpc, given independently in the same WMAP's report.

Is this a possible indication that there is a simpler alternative to inflation? Perhaps, as shown below.

But first, let us quote at length from the recent article by Michel Riordan in "Physics Today" August 2003, p. 50, entitled "Science Fashions and Scientific Fact". In it Riordan shows that the case with "quarks" with fractional charge was very different from the case with "inflation". In the quarks, suggested by Gell-Mann and Zweig in the mid sixties, both theorists and experimenters were sceptical until a long series of results in the most powerful accelerators of the US and Europe clinched the case. In the case of inflation, received with acclaim as an extension "in the big bang cosmology of the standard model" of elementary particles, and only with a modicum of reservation by experimental cosmologists, there is not (and there will not be in the foreseeable future) experimental confirmation, because the energy density corresponding to 10^{-39} sec after the Big Bang is many orders of magnitude apart from anything attainable in the best accelerators.

It is worthwhile to reproduce Riordan discussion in detail:

"As an MIT graduate student and postdoc during the 1970s, I took part in a series of experiments that ended up discovering quarks. The leaders of the MIT-SLAC inelastic electron-scattering experiments — Jerome Friedman, Henry Kendall, and Richard Taylor — shared the 1990 Nobel Prize in Physics for this breakthrough, while collaboration members basked in reflected glory at an unforgettable Stockholm reunion.

In the late 1960s when those experiments began, the quark hypothesis stood far down the list of particle theories. Even Murray Gen-Mann, who conceived the idea along with George Zweig, did not think such fractionally charged entities could ever exist. For Gen-Mann, quarks had to be "mathematical", a convenient rubric for organizing the burgeoning zoo of baryons and mesons. As he wrote in 1964, "A search for stable quarks of charge -1/3 or +2/3... at the highest-energy accelerators would help to reassure us of the non-existence of real quarks."

Undeterred, experimenters still went hunting for these oddities. Some sought quarks at accelerators, where they would have shown up as faint tracks in bubble chambers; others searched in cosmic rays and Millikan-style experiments, hoping to observe fractional charges. By the late 1960s, after none of these experimenters had found anything, it appeared that Gen-Mann had been right. Quarks did not seem to exit. If they had any essence at all, it had to be mathematical. They could not be "real", red-blooded elementary particles.

Do quarks really exist?

Thus we did *not go* seeking quarks in the early MIT-SLAC experiments. Quarks had been largely dismissed by particle physicists, who were far more interested in the then-fashionable bootstrap models, Regge theories, and vector dominance to explain what happens within nuclei. Except for few stalwarts, theorists were abandoning field theories and constituent models of the strong force.

We went to Stanford instead to measure electromagnetic structure functions of the proton and neutron, which James Bjorken and Sidney Drell had suggested might show how the stuff inside is distributed. Much to our surprise, a fraction of the electrons fired into protons in the first experiment ricocheted off. Such deep-inelastic scattering was occurring far more often than expected. Bjorken and Richard Feynman proposed that the electrons might have bounced off tiny pits inside the protons, which Feynman dubbed "partons".

But those were only hints, not results. Nobody was booking a flight to Stockholm-or even drafting a press release. Instead, we went back to SLAC repeatedly during the next five years, to make much more detailed measurements. To check parton ideas against other explanations, we observed electrons rebounding at a wide range of angles from both protons and neutrons.

By 1973, when results of these second-generation experiments were in, everything seemed to be coming up quarks. All the fashionable "soft-scattering" theories had fallen by the wayside, despite desperate attempts to patch them up. But Feynman's partons remained in excellent condition; they indeed seemed to behave like fermions with fractional charges. Neutrino-scattering experiments at CERN, as well as proton-proton collisions in its new Intersecting Storage Rings, gave supporting evidence.

Yet one major problem persisted. The putative quarks never seemed to appear outside hadrons, no matter how hard one hit them! The resolution of that seeming paradox eventually emerged from the theory of the interquark force, quantum chromo-dynamics, which stipulates that the force *increases* as two quarks part: company. So you can never pry one out of a baryon or meson. But it took the rest of the 1970s for acceptance settle in.

Well before then, amazing results from an MIT experiment at Brookhaven National Laboratory and the SLAC-LBL experiment on the SPEAR electron-positron collider forced us to regard quarks as real. The 1974 discovery of the J/ψ particle in those experiments could be explained only by postulating a fourth quark, dubbed the charm quark. This surprising discovery was Nature's slap in the face, which finally made physicists sit up and admit that quarks truly existed. By 1976, when Burton Richter and Samuel Ting shared the Nobel Prize for the discovery, opposition to quarks had collapsed.

Count on experiments

This brief history of the quark discovery illustrates the crucial role that experiments play in making modern physics. It was not theory but experiment that plucked the quark idea from near oblivion. Aided and abetted by theory, experiments made quarks real, transforming them from a wayward hypothesis into concrete objects of experience. Experiments are what ultimately discarded the science fashions of the sixties and turned quarks into hard scientific fact.

That hallmark has indeed proved true for quarks, which form the bedrock of the standard model, the dominant paradigm of particle physics. Today we work with quarks almost unthinkingly, taking them for granted in high-energy experimentation. At Fermilab, physicists bash together bags of quarks and antiquarks, hunting for Higgs bosons and other exotica. Quarks have indeed become *things*.

I find it difficult, however, to imagine how such a rigorous criterion of reality could ever hold true for some of fanciful ideas and constructs that have emerged in recent years from the minds of many theorists. How can we ever hope to work in everyday practice with such entities as superstrings, parallel universes, wormholes, and phenomena that occurred before the Big Bang?

Some of these ideas may have great mathematical beauty and significant explanatory power, but so did many discarded physics fashions of the 1960s. Superstrings are in fact an outgrowth of one of those earlier ideas, the dual resonance model, which John Schwarz resurrected in the 1980s and applied at the Planck scale. But how can we ever hope to make meaningful measurements at this scale when we have such difficulty building particle colliders to work at the comparatively lowly Higgs scale?

One or more of the extra dimensions required in superstring theories may soon become observable at the energies accessible at Fermilab or CERN's future Large Hadron Collider. Such a phenomenal discovery, if it occurs, would be tantamount to bringing superstrings down to Earth. But for such large extra dimensions ever to become truly real, experiments would have to exclude *all other* possible explanations of what occurs. That will not be an easy task.

Cultivate skepticism

One of the great strengths of scientific practice is what can be called the "withering scepticism" that is usually applied to theoretical ideas, especially in physics. We subject hypotheses to observational tests and reject those that fail. It is a complicated process, with many ambiguities that arise because theory is almost always used to interpret measurements. Philosophers of science say that measurements are "theory laden", and they are. But good experimenters are irredeemable skeptics who thoroughly enjoy refuting the more speculative ideas of their theoretical colleagues. Through experience, they know how to exclude bias and make valid judgments that withstand the tests of time. Hypotheses that run this harrowing gauntlet and survive acquire a certain hardness — or reality — that mere fashions never achieve. This quality is what distinguishes science from the arts.

But many of today's practicing theorists seem to be unconcerned that their hypotheses should eventually confront objective, real-world observations. In a recent colloquium I attended, one young theorist presented a talk on his ideas about what had transpired before the Big Bang. When asked what observable consequences might obtain, he answered that there weren't any, for inflation washes away almost all preexisting features. Young theorists are encouraged in such reasoning by their senior colleagues, some of whom have recently become enamored of the possibility of operating time machines near cosmic strings or wormholes. Even granting the existence of cosmic strings, which is dubious, I have a difficult time imagining bow anyone could ever mount an expedition to test those ideas.

I like to call this way of theorizing "Platonic physics", because implicit within it is Plato's famous admonition that the mathematical forms of experience are somehow more real than the fuzzy shadows they cast on the walls of our dingy material caves.

And, in reaction to the seemingly insuperable problems of making measurements to test the increasingly abstract theories of today, some people have even begun to suggest that we relax our criteria for establishing scientific fact. Perhaps mathematical beauty, naturalness, or rigidity — that Nature couldn't possibly choose any other alternative — should suffice. Or maybe "computer experiments", as Stephen Wolfram intimated last year in *A New Kind of Science*, can replace measurements. According to a leading science historian, such a subtle but ultimately sweeping philosophical shift in theory justification may already be underway.

If so, I think it would be a terrible mistake. There would then be little to distinguish the practice of physics from, say, that of painting or printmaking — in which the criteria that distinguish the good from the bad are based largely on opinions of art critics and historians. There is something unique about scientific fact, and that uniqueness has much to do with the often tedious practice of making telling empirical observations. The primary criterion of good science must remain that it has been repeatedly tested by measurements — no matter how difficult they may prove to be — and found to be in excellent accord with them.

* * *

For nearly four centuries, reading the Book of Nature has been the foundation of an extremely powerful practice that has proved remarkably successful in extending cognition into the diverse corners of experience. It was by reading that book, in fact, that we stumbled upon quarks in the late 1960s. To abandon the practice now would be to risk a return to the chaos of opinion that preceded Bacon and Galileo. As physicists concerned about the future of our discipline, we must do everything we can to continue reading this rich and fascinating book."

We can see that in his "Physics Today" article, Riordan shows convincingly that, through the joint efforts of theoretical and experimental physicists during a period of about sixteen years "quarks were shown to be" real "entities". He is sceptical, however, that anything similar, after a period of nearly twenty five years, can be said about "inflation".

Only a few months before, in the pages of "Physics Today" too, April 2003, p. 10, a distinguished theoretical cosmologist Michael S. Turner, from the University of Chicago and Fermilab, presented an eloquent defence of "inflation", according to him a beautiful theory, in an article entitled "Dark Energy: Just What Theorists Ordered". According to him inflation was in peril some ten years before because problems for a flat universe, required by inflation, had been piling up. But according to Turner, recent observational results had come to the rescue. Let us quoted Turner at length:

"In the article on page 53, Saul Perlmutter describes how his team, and one led by Brian Schmidt, used distant supemovae to discover that the expansion of the universe is speeding up, not slowing down. At puzzling times like these, theorists are called upon to provide understanding and, in the process, to convince their audience that they actually anticipated the puzzling discovery (maybe even predicted it).

The discovery of cosmic speedup, perhaps one of the most important in all of science over the past 25 years, saved a beautiful theory — inflation — and presented theorists with a wonderful puzzle — "dark energy", the stuff causing cosmic speedup. What more could we ask for?

Since 1980, Alan Guth's cosmic inflation has been the driving idea in cosmology. Central to inflation is a very early, tremendous burst of expansion, powered by the potential energy associated with a hypothetical scalar field called the inflation. In a tiny fraction of a second, a small bit of the universe is blown up to a size that encompasses all that we can see today and much, much more. Any spatial curvature becomes flattened, and quantum fluctuations in the inflation field are stretched from subatomic to astrophysical size. The decay of the inflation produces the heat of the Big Bang, and the quantum fluctuations in it lead to the matter inhomogeneity that provides the seeds for all the structure in the universe, from galaxies to clusters of galaxies and beyond.

Inflation not only explains, it also predicts. Its predictions include: a spatially flat universe, a pattern of anisotropy in the cosmic microwave background (CMB) that arises from the quantum-produced density perturbations, and a sea of gravitational waves. Inflation was the inspiration for the very successful cold dark matter (CDM) scenario for how structure formed. CDM theory is based on a flat universe, dark matter made of slowly moving elementary particles, and density perturbations arising from quantum fluctuations.

From the beginning, inflation's signature prediction — a flat universe — was in trouble. According to Einstein's theory, the mean energy density ρ_0 determines the spatial curvature of the universe; for a flat universe; it must be equal to the critical energy density. In cosmology talk, $\Omega_0 = 1$, where Ω_0 is the ratio of the mean energy density in any and all forms to the critical energy density. In 1980, astronomers' measurements of Ω_0 indicated its value was something around 0.1.

Inflationists (like me) pinned our hopes on growing evidence for enormous amounts of dark matter that hold galaxies and clusters of galaxies together. This dark matter is distributed more diffusely than stars, making it harder to inventory. Estimates for Ω_0 rose, and for a while it appeared that enough dark matter would be found to meet the inflationary prediction".

Cosmic troubles

"By 1990, the problems for a flat universe were piling up. Estimates of the amount of dark matter were getting better and still falling short, and observations of large-scale structure suggested a CDM universe with a matter density that was one-third of the critical density, that is, $\Omega_M = \frac{1}{3}$. Several of us sheepishly made a suggestion to save inflation: Add a cosmological constant, Λ, for the missing two-thirds of the critical density, $\Omega_\Lambda = \frac{2}{3}$. Thus $\Omega_0 = \Omega_M + \Omega_\Lambda = 1$. The inflationary prediction is a flat universe, not necessarily $\Omega_M = 1$.

To save a beautiful theory, theorists are willing to consider the implausible, although not the impossible. With its checkered history in cosmology, the cosmological constant was certainly implausible. Albert Einstein used it to create a static model of the universe; Hermann Bondi, Thomas Gold, and Fred Hoyle used the cosmological constant to address the fact that the time back to the Big Bang appeared to be less than the age of Earth, and now it is invoked to save inflation.

By the mid-1990s, the observational evidence for the Λ version of CDM, including the first hints from CMB anisotropy measurements that the universe is flat, was becoming compelling, at least for theorists. However, there was a problem: Λ_{CDM} (CDM with a cosmological constant) also predicts accelerated expansion, and the first supernova results did not yet show acceleration.

With the discovery of cosmic speedup in 1998, everything quickly fell into place: The universe is flat, with one-third in matter and two-thirds in something like a cosmological constant. Overnight, skeptical astronomers became believers in inflation. Strange as it was, cosmic speedup was the missing piece in the puzzle. It saved inflation, but be careful what you wish for!

According to Isaac Newton, gravity is always attractive, because the strength of an object's gravity depends only on its mass. Einstein's theory, however, allows for repulsive gravity and cosmic speedup because the strength of gravity also depends on pressure, p, with $\rho + 3p$ acting as the source of gravity. Something that is *very* elastic (that is, negative pressure $p < -\rho/3$) has gravity that repels, rather than attracts.

Something with pressure comparable to its energy density is exotic. Matter, even at the center of a sun, has a pressure that is orders of magnitude smaller than its energy density. The ratio of pressure to energy density is characterized by the square of the internal velocity divided by c^2 .Thus dark energy is intrinsically relativistic and is more like energy than matter. Even though repulsive gravity sounds like fun, dark energy — as far as we know — can't be bottled up to create an object with antigravity.

Quantum mechanics provides a candidate for something that is very elastic: The virtual pairs that fill the vacuum have negative pressure. To see this, compute the pdV work done by an expanding piston that encloses quantum vacuum; you will find that $p_{\text{vac}} = -\rho_{\text{vac}}$ where ρ_{vac} is the quantum vacuum's energy density. Thus, quantum vacuum energy is very repulsive because $\rho + 3p = -2\rho_{\text{vac}}$. Mathematically, quantum vacuum energy is equivalent to Einstein's infamous cosmological constant.

Although Einstein dismissed the cosmological constant as a personal blunder, quantum mechanics makes it obligatory. Unfortunately, even the best quantum "mechanics" have failed to produce a sensible prediction for Λ. The sum of zero-point energies diverges due to short-wavelength modes. Truncating at an energy scale beyond which we can appeal to physics ignorance illustrates the enormity oft the problem: For a 100-GeV cutoff, $\Omega_\Lambda = 10^{55}$. This disparity is the greatest embarrassment in all of theoretical physics.

Many particle theorists believe that a correct calculation of Λ will yield precisely zero because of the utter implausibility of obtaining a number 55 or more orders of magnitude smaller than its "natural value". If quantum nothingness wighs nothing, what, then, is causing the universe to accelerate? Dark energy!"

Mystery deepens

"What do we know about dark energy and how can we learn more? It accounts for about two-thirds of the critical energy density and is much more smoothly distributed than matter. If it clumped, we would see its effects when, studying clusters and other gravitationally bound objects, and we do not. Dark energy is characterized by an "equation of state", which is the ratio w (pronounced "dubya") of its pressure to its energy density $w = p/\rho$. Although ω need not be constant, for simplicity I will assume that for now.

If dark energy is vacuum energy, $w = -1$ (for comparison, for nonrelativistic matter $w = 0$, and for radiation, $w = 1/3$). The ratio w determines how the energy density of dark energy changes as the universe expands: $\rho \sim 1/R^{3(1+w)}$, where R is the cosmic scale factor. Negative pressure ($w < 0$) leads to an energy density that decreases more slowly than matter ($\rho \sim 1/R^3$). Because of this fact, dark energy was less important in the past and will become more important in the future. Why dark energy is just becoming important today begs for explanation. I call this the Nancy Kerrigan problem — why me, why now?

That dark energy was unimportant in the past is good: This fact means the repulsive gravity of dark energy doesn't interfere with the attractive gravity of dark matter that drives the formation of cosmic structure. The lesser importance of dark energy in the past is also the root of an independent argument for cosmic acceleration. The "missing energy" needed in addition to matter to account for the flat universe determined from CMB measurements must have been unimportant in the past; otherwise its smooth distribution would have interfered with the formation of structure. To make the missing energy unimportant in the past requires that $w = 1/2$, which implies that it must have repulsive gravity.

Imaginative theorists have suggested an array of possibilities for dark energy. Many involve the existence of a new, scalar field and the idea that we are in a period of mild inflation while this field (called quintessence) rolls toward its ground state. Because quintessence and inflation both involve accelerated expansion and the underlying cause of each is poorly understood, it has been speculated that they might be related. Thus far, quintessence has raised new questions without shedding light on dark energy.

What we call dark energy could be the harbinger of exotic physics rather than a new, etherlike substance. Cosmic, acceleration could be signalling that Einstein's theory requires modification, perhaps due to the influence of unseen additional spatial dimensions. An interesting twist is, that some string theorists believe that cosmic speedup and string theory, which itself predicts extra dimensions, are incompatible. This will come as a relief to the less enthusiastic fans of string theory".

After this long quote, let us look at an alternative to inflation.

Inflation or Steadly Driven Expansion?

As it can be shown, Einstein cosmological equation at very early time, regardless of the equation of state, for zero cosmological constant, implies

$R(t)=\mathrm{const.}t^{2/3}$

Then between the earliest meaningful cosmic time $t_H \approx \hbar/Mc^2$, fixed by Heisemberg's uncertainty principle for the total matter mass M in the 10^{11} galaxies of the observable universe ($M \sim c^2 R_{+}/2G \approx 4.1 \mathrm{x} 10^{54}$ g), and the Plank's time, given by $t_p \approx (\hbar G/c^5)^{1/2}$, the resulting steady growth in scale factor is

$$R(t_p)/R(t_H)=(t_p/t_H)^{2/3} \approx 3.29 \mathrm{x} 10^{39},$$

with no need to invoke inflation.

Partisans of "inflationary" cosmology claim that cosmic mass density is given by $\Omega_0=\Omega_m+\Omega_\Lambda=1$, but, as shown above, Einstein's equations (with $\Lambda=0$) require $\Omega(t)$ evolving with time from $\Omega(0)\approx 1$ in such a way that $1 \leq \Omega(t) \leq 0$ for an open ($k<0$) universe, which is not incompatible with observations as discussed in previous chapters.

A number of important questions should be answered before accepting at face value that there is no viable alternative to the inflationary "paradigm":

Is matter mass density time independent or not? [$\Omega(t)$?]

Is the Hubble parameter time independent or is not? [$H(t)$?]

Is the total cosmic mass finite or not?

Is the cosmological constant zero or not?

Answering the above questions in the affirmative in accordance with Einstein, may be now controversial. But there is nothing wrong with being controversial in that company.

The rest of this final Chapter is devoted to put forward a summary of an alternative to inflation which may be called "Steadily driven expansion".

Fundamental equations

In what follows, we will first summarize the fundamental equations of dynamical cosmology[1], i.e. Einstein equations, the energy-conservation equation and the equation of state. Then we will make allowance for a change of equation of state at decoupling. Finally we will compare the inflationary and the non-inflationary estimates for cosmic time and cosmic radius at: (i) decoupling ($T=T_{\mathrm{dec}}$); (ii) nucleosynthesis ($T=T_{\mathrm{ns}}$); (iii) electron formation ($T=T_{\mathrm{e}}$); and (iv) baryogenesis ($T=T_{\mathrm{b}}$).

We will then comment briefly on the definite advantages of the results obtained with the traditional non-inflationary model using the two distinct equations of state respectively appropriate for the transparent and the opaque phases of cosmic expansion.

As explained by S. Weinberg in "*Gravitation and Cosmology*"[2], the fundamental equations of dynamic cosmology are

$$\dot{R}^2 + k^2 = \frac{8\pi G}{3}\rho R^2, \quad \text{[Einstein cosmological equation]}, \qquad [8.1]$$

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[1] A. H. Guth, "*The inflationary universe*" (Perseus Books, Cambridge, Massachusetts, 1997).

[2] See f.i. S. Weinberg, "*Gravitation and Cosmology*" (N.Y. Wiley and Sons, 1972), the fundamental equations of dynamical cosmology are discussed in pp. 470-475.

where R is the scale factor or radius of the universe, $\dot{R}$ its time derivative, k the space curvature, G Newton's gravitational constant, and ρ the density;

$$\frac{\mathrm{d}}{\mathrm{d}R}\left(\rho R^3\right) = -3pR^2, \text{ [Energy conservation equation],} \qquad [8.2]$$

where p is the pressure; and

$$p = p(\rho), \text{ [Equation of state].} \qquad [8.3]$$

The equation of state should result in a relationship between R (radius) and T (temperature) characterizing the expanding universe.

Equations of state

The state of cosmic matter goes through several successive phases as the expansion proceeds from the original state of an opaque plasma prior to decoupling, to the state of a transparent gas of neutral atoms immediately after decoupling, and to, finally, a transparent state at which largely quasi-empty space surrounds galaxies, made up of stars and cosmic dust, produced after the first reionization of massive chunks of matter. We may write, in general, $\rho = \rho_m$(matter mass density) + ρ_r(radiation mass density) and also, for the pressure acting upon matter, p_{rm}(radiation on matter) + p_{mm}(matter on matter), and, for the pressure acting upon radiation, p_{mr}(matter on radiation) + p_{rr}(radiation on radiation).

For the present, *transparent* phase of the universe, taking into account that in this case $p_{rm} = p_{mm} = 0$, $p_{mr} = -p_{rm}$ becomes zero and only $p_{rr} = \rho_r/3$ is non-zero, we have (after decoupling) that Equation [8.2], can be separated into two equations, one for ρ_m and one for ρ_r, as follows

$$\frac{\mathrm{d}}{\mathrm{d}R}\left(\rho_m R^3\right) \cong -3\left(p_{rm} + p_{mm}\right)R^2 \cong 0 \rightarrow \rho_m \cong const \cdot R^{-3} \qquad [8.4]$$

$$\frac{\mathrm{d}}{\mathrm{d}R}\left(\rho_r R^3\right) \cong -3\left(p_{mr} + p_{rr}\right)R^2 \cong -\frac{\left(\rho_r R^3\right)}{\mathrm{R}} \rightarrow \rho_r \cong const \cdot R^{-4}. \qquad [8.5]$$

Taking into account Stefan–Boltzmann's law

$$\rho_r = \sigma T^4 \cong const \cdot R^{-4} \rightarrow RT = const. \qquad [8.6]$$

As a direct consequence of Equations [8.4] to [8.6], for the present transparent universe, the ratio of radiation mass energy (ρ_r) to matter mass energy (ρ_m) is given by

$$\frac{\rho_\mathrm{r}}{\rho_\mathrm{m}} = \frac{const \cdot T^4}{const \cdot R^{-3}} = const \cdot T \qquad [8.7]$$

and, therefore, that

$$\frac{\rho_\mathrm{r}}{\rho_\mathrm{m}} = \left(\frac{\rho_\mathrm{r}}{\rho_\mathrm{m}}\right)_{dec} \left(\frac{T}{T_{dec}}\right), \text{ where } \left(\frac{\rho_\mathrm{r}}{\rho_\mathrm{m}}\right)_{dec} = 1 \text{ at decoupling}. \qquad [8.8]$$

This describes the fact that in the present transparent phase of cosmic expansion the *radiation* mass density ρ_r is decreasing proportionally to T with respect to the *matter* mass density ρ_m.

On the other hand the baryon to photon ratio in the present transparent phase (after decoupling) remains constant, and is given by

$$\frac{n_\mathrm{b}}{n_\mathrm{r}} = \frac{\rho_\mathrm{m}/m_\mathrm{b}}{\left(\rho_\mathrm{r}/c^2\right)/2.8k_BT} = \frac{2.8k_BT_{dec}}{m_\mathrm{b}c^2} = 5.47 \times 10^{-10} \qquad [8.9]$$

where, using WMAP's data, $T_{dec} \cong 2130$ K is the decoupling temperature shown above.

Thus, as the transparent phase of cosmic expansion proceeds, the ratio (ρ_r/ρ_m) tends to zero with the decreasing cosmic temperature, and the ratio (n_b/n_r) remains constant at the level given by Equation [8.9], after decoupling. As shown below this is not the case prior to decoupling.

For the phase of the expansion *previous to* decoupling, matter in the universe was in the form of a hot plasma made up of positive ions (protons and a significant amount of ^{4}He nuclei) and electrons. In this plasma, material particles and radiation scatter each other effectively in such a way that matter and radiation expand in unison ($p_{mr} + p_{rm} = 0$), and, given that $p_{rr} = \rho_r/3$, we have $p_{mr} = -\rho_r/3$. On the other hand, in the reference system co-moving with matter and radiation, $p_{rm} + p_{mm} = 0$, i.e. p_{rm}(action) = $-p_{mr}$(reaction) = $\rho_r/3$, which results in

$$\frac{\mathrm{d}}{\mathrm{d}R}\left(\rho_\mathrm{m}R^3\right) \cong 0 \quad \rightarrow \quad \rho_\mathrm{m} \cong const \cdot R^{-3} \qquad [8.10]$$

$$\frac{\mathrm{d}}{\mathrm{d}R}\left(\rho_{\mathrm{r}}R^{3}\right)\cong 0 \;\rightarrow\; \rho_{\mathrm{r}} \cong const\cdot R^{-4}. \qquad [8.11]$$

Then, taking into account again Stefan-Boltzmann law

$$\rho_{\mathrm{r}} = \sigma T^{4} \cong const\cdot R^{-3} \;\rightarrow\; RT^{4/3} \cong const \qquad [8.12]$$

instead of Equation [8.6].

In this *opaque* phase of the expansion prior to decoupling of radiation the ratio of radiation mass to matter mass energies becomes constant

$$\frac{\rho_{\mathrm{r}}}{\rho_{\mathrm{m}}} = \left(\frac{\rho_{\mathrm{r}}}{\rho_{\mathrm{m}}}\right)_{dec} = 1 \qquad [8.13]$$

while the baryon to photon ratio becomes variable

$$\frac{n_{\mathrm{b}}}{n_{\mathrm{r}}} = \frac{\rho_{\mathrm{m}}/m_{\mathrm{b}}}{\left(\rho_{\mathrm{r}}/c^{2}\right)/2.8k_{B}T} = \left(\frac{\rho_{\mathrm{m}}}{\rho_{\mathrm{r}}}\right)_{dec}\frac{T}{m_{\mathrm{b}}c^{2}/2.8k_{B}} = \frac{T}{T_{\mathrm{b}}}. \qquad [8.14]$$

It was one at $T = T_{\mathrm{b}}$ (baryogenesis temperature), while it became $(T_{\mathrm{dec}}/T_{\mathrm{b}}) \cong 5.47 \times 10^{-10}$ at decoupling, just before the universe became transparent, remaining constant thereafter.

The time dependent cosmic scale factor R(t)

Direct integration of Einstein's cosmologic equation, Equation [8.1],

$$\dot{R} = R^{-1/2}\left[\frac{8\pi G}{3}\rho R^{3} + c|k|^{2}R\right]^{1/2} \qquad [8.15]$$

where R_{+} is defined in such a way that

$$\frac{8\pi G}{3}\rho_{+}R_{+}{}^{3} \equiv c|k|^{1/2}R_{+} \qquad [8.16]$$

leads to

$$R(y) = R_{+}\sinh^{2}y\,, \qquad \left[y \equiv \sinh^{-1}\left(R/R_{+}\right)^{1/2}\right] \qquad [8.17]$$

$$t(y) \cong \frac{R_{+}}{c\,|\,k\,|^{1/2}}\left[\sinh y\cosh y - y\right]. \qquad [8.18]$$

From Equations [8.17] and [8.18] we get the dimensionless cosmic parameters:

$$Ht = (\dot{R}/R)\cdot t \cong \frac{1}{\tanh^2 y} - \frac{y}{\tanh y \sinh^2 y} \qquad [8.19]$$

$$\Omega = \rho \Big/ \left[\frac{3H^2}{8\pi G}\right] \cong \frac{1}{\cosh^2 y}. \qquad [8.20]$$

For a transparent universe, the auxiliary dimensionless cosmic parameter y is given, using Equation [8.6], by

$$y = \sinh^{-1}(R/R_+)^{1/2} = \sinh^{-1}(T_+/T)^{1/2}. \qquad [8.21]$$

[Note that for $T_{dec} >> T_+$, as it will be shown to be the case, and for the transparent phase of cosmic expansion, this expression alone determines the cosmic time and the cosmic scale factor for any T in the interval $T_{dec} \geq T \geq T_0$].

In general, for a universe, which undergoes a change from *opaque*, at $T \geq T_{dec}$ (prior to decoupling), to *transparent*, at $T \leq T_{dec}$ (after decoupling), the dimensionless parameter y can be written as

$$y = \sinh^{-1}(T_+/T)^{1/2} \quad \text{for } T \leq T_d \qquad [8.22]$$

after Equation [8.6], as long as the universe is in the *transparent* phase of cosmic expansion, and

$$y = \sinh^{-1}\left\{(T_+/T_d)^{1/2}(T_d/T)^{2/3}\right\} \quad \text{for } T \geq T_d \qquad [8.23]$$

after Equation [12], putting $T_{dec} \equiv T_d$, as long as the universe is in the *opaque* phase of cosmic expansion.

Cosmic background temperature (T_+) at reionization

At present, accurate observational values for $H_0 = 71 \pm 4$ Km/s·Mpc, $t_0 = 13.70 \pm 0.14$ Gyr, and for the present CBR temperature $T_0 = 2.726$ K, allow the determination[3] of T_+ by means of

$$H_0 t_0 = 0.942 \quad [\Omega_0 = 0.042 = \Omega_{bo}(\text{WMAP})] \qquad [8.24]$$

which implies, through Equations [8.19] and [8.20],

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[3] D. N. Sperger et al. "*First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters*". Preprint available at http://map.gsfc.nasa.gov.

$$y_0 = 2.267\,, \quad T_+ = T_0 \sinh^2 y_0 = 62.17\,\mathrm{K}\,. \qquad [8.25]$$

[It may be noted that this temperature is very close to the upper limit for the "reionization" temperature, according to WMAP's data a temperature at which the first supermassive stars formed, $T_R = (1+z_R)T_0$, at a redshift $z_R = 17 \pm 4$].

T_{eq}, the temperature at which ρ_r and ρ_m become equal, on the other hand, is given by

$$T_{eq} = T_0 \frac{\Omega_0 \left(\dfrac{3H_0}{8\pi G}\right)}{\left(\dfrac{\sigma T_0^4}{c^2}\right)} = 2135 \;\;\mathrm{K} \qquad [8.26]$$

which comes relatively close to $T_{dec} = (1+z_{dec})T_0 = 2968$ K, with $z_{dec} = 1088 \pm 2$ given by WMAP's data.

It should be underlined that present values ($z = 0$) for $H_0t_0 = 0.942$ and $\Omega_0 = 0.042$ corresponding all to an open universe, are fully compatible with decoupling values ($z_{dec} = 1088$) for $H_dt_d = 0.669$, $\Omega_{dec} \cong 0.979$, describing an almost flat ($\Omega_{dec} \sim 1$) universe at that time.

According to the general Equations [8.17] and [8.18], the dependence of cosmic scale factor (radius) with cosmic time is fully specified at all times. However, in particular for events prior to decoupling, i.e. at a cosmic temperature much higher that T_+, the approximations

$$R_q(y) \cong R_+ y^2\,, \qquad [8.27]$$

$$t(y) \cong \frac{R_+}{|k|^{1/2}\,c}\, y^3 \qquad [8.28]$$

become valid. They imply

$$R(t) = R_+ \left[|k|^{1/2} c/R_+\right]^{2/3} t^{2/3} \qquad [8.29]$$

which describes cosmic expansion regardless of the equation of state.

Steadily driven expansion (SDE)

For events *prior to* decoupling one must distinguish between the temperature dependence corresponding to a *steadily driven expansion*

(SDE) and the temperature dependence corresponding to a *transparent* expansion which would become an *inflationary expansion* (IE) at a given specific time ($t \cong 10^{-35}$ sec). In (SDE) the equation of state at $T < T_{\text{dec}}$ determines a dimensionless cosmic parameter depending on cosmic temperature as given by

$$y \cong (T_+/T_\text{d})^{1/2}(T_\text{d}/T)^{2/3} \quad \text{(plasma universe)} \qquad [8.30]$$

at any time prior to decoupling, while in (IE) the equation of state at $T < T_{\text{dec}}$ results in y as given by

$$y \cong (T_+/T)^{1/2} \quad \text{(transparent universe)} \qquad [8.31]$$

at all times above $t = t_\text{I} = 10^{-34}$, a time at which inflation would produce suddenly a 10^{45} fold increase in cosmic radius.

Table 8.1 gives numerical values for *cosmic time* (t) and *cosmic radius* (R) at various events *prior to decoupling* according to the equations describing:

(SDE) a *steadily driven* cosmic expansion (opaque universe) at all times below $t \leq t_{\text{dec}}$.

(IE) an inflationary cosmic expansion (transparent universe) at times $t \leq t_{\text{dec}}$, but only down to $t \gtrsim t_\text{I} \cong 10^{-34}$ sec.

(i) Between $T = T_0$ and $T = T_{\text{dec}}$ the universe is transparent and, therefore cosmic time and radius are identical in (SDE) and (IE).

(ii) At *nucleosynthesis*, fusion research data[4] gives for the ignition temperature $T_{\text{io}} \cong 39.8$ KeV $\cong 4.60 \times 10^8$ K, which can be taken as T_{ns}, the final temperature during cosmic expansion at which nucleosynthesis can take place.

Under steadily driven expansion (*opaque* universe) y_{ns} at nucleosynthesis becomes

$$(y_{\text{ns}})_{SDE} = \left(\frac{T_+}{T_\text{d}}\right)^{1/2}\left(\frac{T_\text{d}}{T_{\text{ns}}}\right)^{2/3} = 4.66 \times 10^{-5}$$

corresponding to a cosmic time

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[4] See f.i. J. G. Cordey, R. J. Goldston and R. R. Parker, "*Physics Today*", Jan. 1992 pp. 22-30; J. D. Callen, B. A. Carreras and R. D. Stanbaugh, *Ibid.* pp. 34-42; and references therein.

$$(t_{\rm ns})_{SDE} \cong \frac{R_+}{|k|^{1/2}c}(y_{\rm ns})_{SDE}{}^3 = 2.06\times10^3\,\sec$$

which, using τ_n = 887 sec for the free neutron half life[5], results in a neutron to proton ratio

$$(n/p)_{SDE} \cong e^{-t_{\rm ns}/\tau_n} = 0.098 \pm 0.035\,, \qquad [8.32]$$

compatible with the observed neutron to proton ratio deduced from the cosmic ^{4}He abundance[6] $n/p \cong 0.131$.

Inflationary expansion (IE)

On the other hand, under (IE) inflationary expansion (*transparent* universe at all times) $y_{\rm ns}$ at nucleosynthesis becomes

$$(y_{\rm ns})_{IE} = \left(\frac{T_+}{T_{\rm ns}}\right)^{1/2} = 3.61\times10^{-4}$$

resulting in a cosmic time

$$(t_{\rm ns})_{IE} \cong \frac{R_+}{|k|^{1/2}c}(y_{\rm ns})_{IE}{}^3 = 9.45\times10^5\,\sec$$

which, using again τ_n = 887 sec., leads to

$$(n/p)_{IE} \cong e^{-(t_{ns})_{IE}/\tau_n} \cong 0\,, \qquad [8.33]$$

which is incompatible with the observed neutron to proton ratio deduced from the cosmic ^{4}He abundance[6] quoted above.

Then at nucleosynthesis the agreement with observation obtained with an expanding *opaque* universe is clearly better than that obtained with a *transparent* universe as assumed in inflationary cosmologies.

(iii) At the equilibrium temperature for electron formation ($T_e = m_e c^2/2.8k_B = 2.11\times10^9$K), the electron to photon ratio is given for an opaque expanding universe (SDE), after Equation [8.14] by

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[5] E. J. Pagel, "*Physica Scripta*" Vol. **T36**, 7 (1991).

[6] R. A. Olive and G. Steigman, *Astroph. J. Suppl. Ser.* **97**, 49 (1995).

$$\left(\frac{n_e(T_e)}{n_\gamma(T_e)}\right)_{SDE}=\left(\frac{n_b(T_e)}{n_\gamma(T_e)}\right)_{SDE}=\frac{T_e}{T_b}=\frac{m_e}{m_b}=5.44\times10^{-4}, \qquad [8.34]$$

and for a *transparent* expanding universe at all times (IE), after Equation [8.9] by

$$\left(\frac{n_e(T_e)}{n_\gamma(T_e)}\right)_{IE}=\left(\frac{n_b(T_d)}{n_\gamma(T_d)}\right)_{IE}=\frac{T_d}{T_b}=5.47\times10^{-10}. \qquad [8.35]$$

(iv) Finally, at the equilibrium temperature for baryogenesis ($T_b=m_bc^2/2.8k_B=3.88\times10^{12}$K), the baryon to photon ratio for an *opaque* expanding universe (SDE), is given by

$$\left(\frac{n_b(T_b)}{n_\gamma(T_b)}\right)_{SDE}=\frac{T_b}{T_b}=1, \qquad [8.36]$$

while for a *transparent* expanding universe at all times (IE), is given again by

$$\left(\frac{n_b(T_b)}{n_\gamma(T_b)}\right)_{IE}=\frac{T_d}{T_b}=5.47\times10^{-10}. \qquad [8.37]$$

It may be noted[7] that "...the baryon number per photon might have started at some reasonable value, perhaps around one, and then dropped to its present low value...". If this were the case, it would be in accordance with Equation [8.36].

Comparison of cosmic numbers using SDE and IE

Under the steadily pressure driven expansion in an *opaque* plasma universe (SDE) the baryons come into existence closely packed, i.e. for $y=y_{SDE}=1.12\times10^{-7}$ corresponding to $T_b=3.88\times10^{12}$K, we get for the total number of baryons in the universe, with $r_{cb}=\hbar/m_bc\cong2.1\times10^{-14}$cm,

$$\left(\frac{R_{SDE}}{r_{cb}}\right)^3\cong4.79\times10^{79}\text{ baryons,}$$

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[7] See f.i. S. Weinberg, *"The first three minutes"*, p. 89 (Bantan Books, New York, 1979).

which is close enough to the ratio of the estimated universe mass to the baryon mass,

$$\frac{M_U}{m_b} \cong \frac{4.50\times10^{54}}{1.67\times10^{-24}} \cong 2.69\times10^{78} \text{ baryons}\,.$$

Under the expansion conditions corresponding on the other hand to a *transparent* universe at all times (IE) baryons would come into existence loosely packed, since

$$\left(\frac{R_{IE}}{r_{cb}}\right)^3 \cong 4.80\times10^{86} >> \frac{M_U}{m_b}\,.$$

Table 8.2 gives the numbers for cosmic time and cosmic radius at *very early times*. Under cosmic conditions corresponding to an *opaque* universe expanding without inflation (SDE), from $t_H \cong \hbar/Mc^2 \cong 2.84 \times 10^{-103}$ sec., (which is the shortest cosmic time with any physical meaning below which no horizon restriction of any sort on the thermal state of the different parts of the expanding microcosms is applicable), to $t_p \cong (\hbar G/c^5)^{1/2}$, (which is the time at which outwards radiation pressure

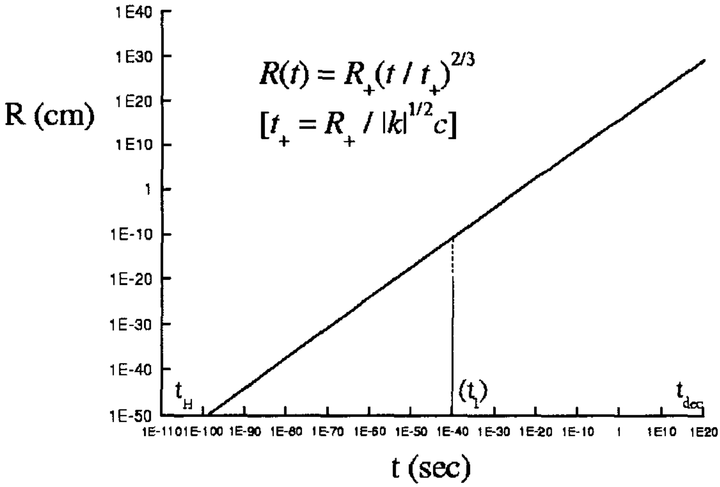

Fig. 8.1. Cosmic radius ***R*** (m) vs. cosmic time ***t*** (sec) ***without*** (——) & ***with*** (-----) inflation at $t \cong 10^{-39}$ sec.

Table 8.1. Cosmic time and cosmic radius prior to decoupling under an steadily driven expansion (SDE), and an inflationary expansion (IE).

Event	Decoupling	Nucleosynthesis	Electrons	Baryons
Temperature (K)	2.13×10^{3}	4.60×10^{8}	2.11×10^{9}	3.88×10^{12}

Steadily driven expansion (opaque universe at $t < t_{dec}$) (SDE)

$y=\left(\frac{T_+}{T_d}\right)^{1/2}\left(\frac{T_d}{T}\right)^{2/3}$	0.168	4.66×10^{-5}	1.69×10^{-5}	1.12×10^{-7}
$t=\frac{R_+}{\lvert k\rvert^{1/2}c}y^3$ (sec)	9.62×10^{13}	2.06×10^{3}	9.79×10^{2}	2.85×10^{-5}
$R=R_+y^2$ (cm)	1.72×10^{25}	1.32×10^{18}	1.74×10^{17}	7.63×10^{12}

Inflationary expansion (transparent universe at $t < t_{dec}$) (IE)

$y=\left(\frac{T_+}{T}\right)^{1/2}$	0.168	3.61×10^{-4}	1.69×10^{-4}	3.93×10^{-6}
$t=\frac{R_+}{\lvert k\rvert^{1/2}c}y^3$ (sec)	9.62×10^{13}	9.45×10^{5}	9.75×10^{4}	1.23
$R=R_+y^2$ (cm)	1.72×10^{25}	7.93×10^{19}	1.73×10^{19}	9.40×10^{15}

Table 8.2. Cosmic expansion at very early times:
SDE= Steadily Driven Expansion
IE= Inflationary Expansion.

Event	Inflation Ends	Inflation Begins	Planck	Uncertainty
Time (sec)	$\sim10^{-35}$	$\sim10^{-35}$	$t_p=(\hbar G/c^5)^{1/2}$	$t_H=\hbar/Mc^2$
***Early steadily driven expansion* (SDE)**				
$t=\frac{R_+}{\lvert k\rvert^{1/2}c}y^3$ (sec)	-	-	5.37×10^{-44}	2.84×10^{-103}
$R=R_+y^2$ (cm)	-	-	1.16×10^{-13}	3.53×10^{-53}
***Early inflationary expansion* (IE)**				
$t=\frac{R_+}{\lvert k\rvert^{1/2}c}y^3$ (sec)	$\sim10^{-35}$	$\sim10^{-35}$	-	-
$R=R_+y^2$ (cm)	3.80×10^{-8}	3.80×10^{-53}	-	-

compensates inwards gravitational pressure in Planck monopoles of mass $m_p=(\hbar c/G)^{1/2}=2.17\times10^{5}$g), the cosmic radius grows $R_{SDE}(t_p)/R_{SDE}(t_H)\cong3\times10^{39}$ times, which is comparable to the instantaneous growth postulated under *inflationary* expansion (IE) $R_{IE}(end)/R_{IE}(beginning)\cong10^{42}$ times.

Figure 8.1 depicts the growth with time of the cosmic radius $R(t)$ without (SDE) and with (IE) inflation from $t_H\cong2.84\times10^{-103}$ onwards.

Conclusion

We have pointed out the intrinsic time dependence of important cosmic parameters, including the density ratio $\Omega(t)$, something, which is often overlooked. We further have confirmed that the cosmological constant is unnecessary to describe the cosmic expansion. We conclude finally that the traditional big bang cosmology has definitive advantages over inflation regarding physical conditions at cosmic nucleosynthesis, bariogenesis and Planck's epoch.

Appendix

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How close are the cosmic times for matter/radiation equality and for atom formation?

Noé Cereceda, Ginés Lifante and Julio A. Gonzalo
Facultad de Ciencias, C-IV, Universidad Autónoma de Madrid

28049 Madrid, Spain

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Abstract

It is shown that the cosmic matter/radiation equality time ($\rho_r=\rho_m$) corresponding to $H_0t_0\cong 0.910$ and the atom formation time, as determined from Saha's law, appear to coincide almost exactly at a background radiation temperature about $T_{eq}\cong$Taf $\cong$3840 K. The resulting maximum amount of dark matter comes out to be of the order of that of ordinary baryonic matter, which is consistent approximately with the lower limit of Ω_0 estimated from gravitational lenses. We get $\Omega_0\cong 0.0824$ (total) to be compared with $\Omega_{bo}\cong 0.0355$ (baryonic).

1. Introduction

It is well known that radiation/matter equality ($\rho_r=\rho_m$) and atom formation (ions+electrons→atoms) occur at cosmic times (temperatures) relatively close to each other. How close are the radiation/matter equality (t_{eq}) and the atom formation (t_{af}) times? Is there an approximate coincidence between them or a nearly exact one? Is it fortuitous or is there a direct physical connection between both? Current estimates [1] give $t_{af}\sim 3x10^5$ yrs, not far, but substantially larger, than $t_{eq}\sim 1x10^4$ yrs. In this work, we argue that, in spite of the present uncertainties in our knowledge of H_0 (present value of the Hubble's constant) and t_0 (time elapsed since the big bang) their product is related by means of Einstein's equations [2] to Ω_0 (present value of the cosmic density parameter). This constrains the ranges of acceptable values for H_0, t_0 and Ω_0. From these considerations alone we show that the resulting time for matter/radiation equality is in almost perfect coincidence the atom formation time, given by $t_{eq}\cong t_{af}\cong 4.7x10^5$ yrs. The corresponding contemporary CBR temperature is $T\cong 3840$ K. After atom formation the universe is made up of atoms (transparent to radiation), and prior to it is made up of a plasma; of ions and electrons (opaque to radiation). In the present work, we put aside the dynamics of cosmic evolution prior to matter density/radiation density equality (t_{eq}) leaving it for future consideration elsewhere).

The solutions of Einstein equations, [2], relate parametrically the time (t) and the scale factor (R), which is in turn related to the temperature (T) by the appropriate equation of state. In the present, matter dominated era ($\rho r<<\rho m$) of the cosmic expansion, the cosmic equation of state is given by $RT\cong$const. Prior to atom formation the equation of state is generally assumed to be the same, but, as mentioned above, we will not be concerned here with this assumption.

We set the open solutions [3, 4] of Einstein cosmological equations in a convenient form to get (Ht) and (Ω) a function of $R/R_+=T_+/T$, using the equation of state for a transparent universe, where R_+, and T_+ are taken as the scale factor and temperature, respectively, at which the terms involving the total mass density and the space curvature in Einstein equation have the same value, i.e. at $(8\pi G/3)\rho R_+^3=c^2|k|R_+$. Then we use observational constraints on H_0, t_0 and T_0 (CBR temperature) to fix T_+, knowing very well, as we do, the present value of the CBR temperature T_0 [5]. From this starting point we will get the value of the radiation/matter equality temperature, T_{eq}, at which the mass densities of radiation (ρ_r) and matter (ρ_m) become equal. Next we evaluate the atom formation temperature, T_{af}, from Saha's law, under the assumption that the matter mass density ρ_m (related to the particle density $n_p \approx \rho_m/m_p^*$, where m_p^* is the effective ion mass) is equal to the radiation mass density, given by Stefan-Boltzmann law as $\rho_0 = \sigma T^4/c^2$. We show that the values for T_{eq} and $T_x = T_{af}$ thus obtained are in almost perfect coincidence with each other.

2. Radiation/matter equality temperature

In the time interval between t_0 (present) and t_x (atom formation), near to or equal to decoupling, the equation relating the change in internal energy of the cosmos with the work done in the expansion leads to

$$\rho = \rho_m + \rho_r = \rho_m\left(1 + \frac{R_x}{R}\right) \qquad [1]$$

where

$$\rho_r R^4 = \left(\frac{\sigma T^4}{c^2}\right) R^4 = const \qquad [2]$$

and

$$\rho_m R^3 = const, \qquad [3]$$

implying RT = const and $\rho_x = 2\rho_{mx} = 2\rho_{rx}$ (at t_{eq}).
Einstein's field equation [3, 4] for an open ($k < 0$) or flat ($k = 0$) universe is given by

$$\dot{R} = R^{-\frac{1}{2}}\left(\frac{8\pi G}{3}\rho R^3 + c^2|k|R\right)^{\frac{1}{2}} \qquad [4]$$

Using Eq.[1] for $t \geq t_x$ we get

$$\int dt = \int\left[\left(\frac{8\pi G}{3}\rho_{m+}R_+^3\right)(R_+ + R) + c^2|k|^2 R^2\right]^{-\frac{1}{2}} R\,dR, \qquad [5]$$

where, as stated before, R_+ is fixed at $(8\pi G/3)\rho_+ R_+^3 = c^2|k|R_+$, and $R=R_0(T_0/T)$ will be the scale factor at any time t in the interval $t_{eq} < t < t_0$.

Integration of Eq. [5] gives

$$R = R_+ \sinh^2 y,$$

$$t - t_x = \frac{R_+}{c\sqrt{|k|}}\left[\left\{\frac{R_x}{R_+} + \sinh^2 y \cosh^2 y\right\}^{\frac{1}{2}} - \left\{\frac{R_x}{R_+} + \sinh^2 y_x \cosh^2 y_x\right\}^{\frac{1}{2}}\right.$$

$$\left. - \frac{1}{2}\ln\left[\frac{1}{2} + \sinh^2 y + \left\{\frac{R_x}{R_y} + \sinh^2 y \cosh^2 y\right\}^{\frac{1}{2}}\right] \Big/ \left[\frac{1}{2} + \sinh^2 y_x + \left\{\frac{R_x}{R_+} + \sinh^2 y_x \cosh^2 y_x\right\}^{\frac{1}{2}}\right]\right].$$

For $R_x/R_+=T_+/T_x \ll 1$ the above time equation becomes,

$$t \cong \frac{R_+}{c\sqrt{|k|}}\left[\sinh y \cosh y - y\right] . \qquad [6]$$

Using R(y) and t(y) expressions for the Hubble parameter H, and the dimensionless cosmic parameters, (Ht) and Ω, are obtained, as

$$H = \frac{\dot{R}}{R} \cong \frac{c\sqrt{|k|}}{R_+}\frac{\cosh y}{\sinh^3 y}, \qquad [7]$$

$$Ht = \frac{\dot{R}}{R}t \cong \frac{1}{\tanh^2 y} - \frac{y}{\tanh y \sinh^2 y}, \qquad [8]$$

$$\Omega = \frac{\rho}{\frac{3H^2}{8\pi G}} \cong \frac{1}{\cosh^2 y}. \qquad [9]$$

Further, if at t_x (radiation/matter equality) the temperature T_x is $T_x \gg T+$,

$$y_x = \sinh^{-1}\left(\frac{R_x}{R_+}\right)^{\frac{1}{2}} = \sinh^{-1}\left(\frac{T_+}{T_x}\right)^{\frac{1}{2}} << 1. \qquad [10]$$

Eq. [6] for t_x becomes, to a very good approximation,

$$t_x \cong \frac{R_+}{c\sqrt{|k|}}\frac{2}{3}y^3, \qquad [11]$$

which can be put into the alternative form

$$t_x \cong \frac{2}{3}H_x^{-1}\Omega_x^{-\frac{1}{2}} = \frac{2}{3}H_0^{-1}\Omega_0^{-\frac{1}{2}}\left(\frac{R_x}{R_0}\right)^{\frac{3}{2}}$$

$$= \frac{2}{3}H_0^{-1}\Omega_0^{-\frac{1}{2}}\left(\frac{T_0}{T_x}\right)^{\frac{3}{2}}, \qquad [12]$$

where $(R_x/R_0) = (T_0/T_x) = (1+z_x)^{-1}$, being z_x the redshift at time t_x.

Basic known cosmic parameters at present times are the CBR temperature T_0=2.726 ± 0.01K, the lower limit to the Hubble constant H_0 > 65 km/s.Mpc from recent Hubble telescope data on classical Cepheid variables [6], and a lower bound to $t_0 \geq 13.7\text{x}10^9$ yrs [7] based upon a re-evaluation of the age of the oldest globular clusters (main sequence turn off). The above values of H_0 and t_0 imply.

$H_0t_0 \geq 65$ (km/s.Mpc) $\times 13.7 \times 10^9$yrs=0.910 (dimensionless). [13]

Eqs. [8] and [9] on the other hand connect (H_0t_0) and Ω_0 through the parameter $y_0=\sinh^{-1}(R_0/R_+)^{1/2}$ restricting H_0t_0 to be in the interval $(2/3) < H_0t_0 < 1$, with (2/3) for a flat universe ($k = 0$, $\Omega_0 = 1$) and $H_0t_0 \rightarrow 1$ for an open universe ($k < 0$, $\Omega_0 < 1$) with a vanishing amount of matter. We may note that a very recent report, (Phys. Today, Sept. 1997, pp. 19-21) of the careful analysis of data compiled on stars out to an unprecedented distance of about 500 light-years, taken by the European Space Agency Hipparcos Satellite, basically confirms that t_0 must be slightly larger than 13×10^9 years. This analysis appears to reconcile the estimated values of t_0 from globular stars clusters in our galaxy and from the Hubble's constant. Fig. 1 gives $\Omega_0 \cong 1/\cosh^2 y$ vs. $H_0t_0 \cong (\sinh y_0 \cosh y_0 - y_0)\cosh y_0/\sinh^3 y_0$ showing $(H_0t_0)_{\min} \cong 0.910$ and the estimated present baryonic mass density parameter Ω_{bo}=

$0.0355<(\Omega)_{max}\cong 0.0824$, taking $(\Omega_0)_{max}$ as fixed by Eq. [13]. Since observational estimates on the total matter mass density parameter [8] from gravitational lenses give $0.1<\Omega_0<0.3$, our upper bound to $(\Omega_0)_{max}\cong 0.084$ comes out to be close to $\Omega_0=0.1$, and we will use it in our analysis of cosmic evolution from radiation/matter equality/atom formation, t_x, to present times.

From the above value for $(H_0t_0)\cong 0.910$, using RT=const as the equation of state for a transparent universe ($t \geq t_x$), we get

$$y_0 = \sinh^{-1}\left(\frac{T_+}{T_0}\right)^{\frac{1}{2}} \geq 1.92, i.e. \mathrm{T}_+ \geq 30.4K. \qquad [14]$$

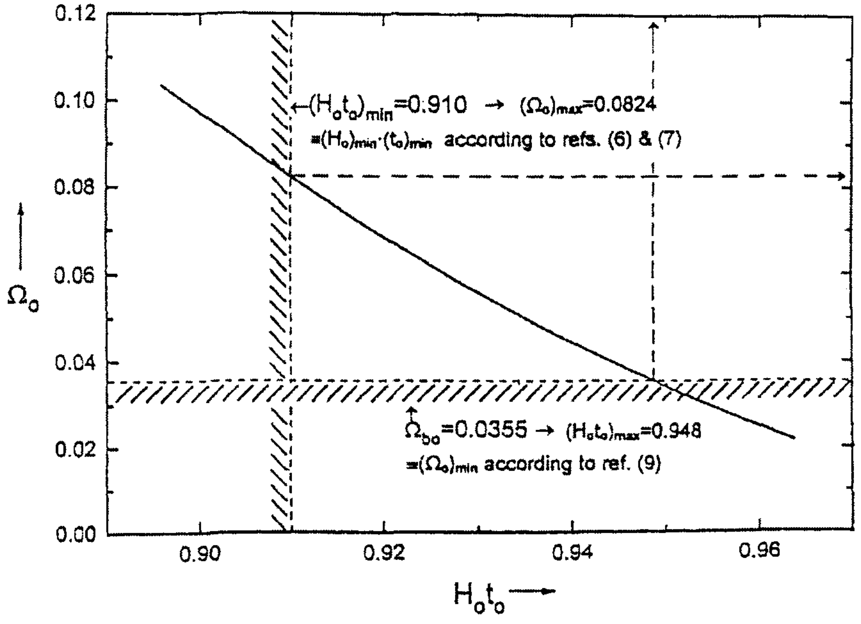

Fig. 1. $\Omega_0\cong 1/\cosh^2 y_0$ vs. $H_0t_0\cong[\sinh y_0 \cosh y_0 - y_0]\cosh y_0/\sinh^3 y_0$. Vertical dashed line gives constrain on the baryonic mass density $\Omega_{b0}\cong 0.0355$, from ^{4}He abundance fixed from the time of nucleosynthesis.

Once we have a numerical value for $T_+\cong 34.2K$ we are in a position to obtain numerical values for t(T), ρ_r(T), ρ_m(T) in terms of y(T) at any $T<T_x$.

At radiation/matter equality, $\rho_{req}=\rho_{meq}$, which implies

$$\frac{\sigma T_{eq}^4}{c^2}=\rho_{mo}\left(\frac{T_{eq}}{T_0}\right)^3, \qquad [15]$$

where $\rho_{mo} \cong \Omega_0 3H_0^2/8\pi G = 6.54\text{x}10^{-31}\text{g/cm}^3$, $\Omega_0 = 0.0824$ and $H_0 = 2.10\text{x}10^{-18}$, one gets

$$T_{eq}=\frac{\rho_{mo}}{\frac{\sigma T_0^3}{c^2}}=3.84x10^3K. \qquad [16]$$

This value becomes close to the temperature near the Sun's surface, where ionisation and recombination of electrons and positive hydrogen and helium ions are known to be taking place.

3. Atom formation

Now we can try to exploit Saha's law for ionization/recombination in a plasma to get independent estimate of T_x under the assumption that the radiation and the matter energy densities in the plasma are equal. Taking into account that the relative abundance of H and ^{4}He (ignoring other very scarce light elements) is well established, we can estimate the effective average mass per ion as $m^* = m_{eff} = 1.187\ m_p$ and the effective average ionization energy as $B_{eff} = 14.27$ eV. This is done by noting [9] that the cosmic neutron to proton. ratio (n/p) is determined by

$$(n/p)\cong\frac{1}{2}\frac{Y_p}{1-\frac{1}{2}Y_p}\cong 0.131, Y_p=0.232\pm 0.008, \qquad [17]$$

implying that the corresponding average fractions of protons and ^{4}He nuclei are given by

$$f_H\cong 0.9374, \qquad f_{^4He}\cong 0.0626, \qquad [18]$$

and that the average ionization energy is, therefore,

$$B_{eff}=f_H(13.6eV)+f_{^4He}(22.4eV)=14.27eV. \qquad [19]$$

Saha's equation [10] can be written as

$$\frac{x^2}{1-x}=\frac{1}{n_{eff}}\left(\frac{m_ek_BT}{2\pi\hbar^2}\right)^{3/2}e^{-B_{eff}/k_BT} \qquad [20]$$

where x is the fraction of ionised atoms, equal to 50% right at T_x (the ionisation/recombination temperature), n_{eff} is the effective average ion density, given for $\rho_{mx}=\rho_{rx}$ by

$$n_{eff}=\frac{\Omega_{bo}}{\Omega_o}\frac{\rho_{mx}}{1.187m_p}=\frac{\Omega_{bo}}{\Omega_o}\frac{\frac{\rho_{mx}\sigma T_x^4}{c^2}}{1.187m_p}, \qquad [21]$$

with $(\Omega_{bo}/\Omega_o)=0.0355/0.0824$, and B_{eff} is the effective average ion density, given by Eq. [19]. Rearranging terms we get

$$3.716x10^{-15}=\left(\frac{B_{eff}}{k_BT_x}\right)^{\frac{5}{2}}e^{-B_{eff}/k_BT_x}=\beta_x^{5/2}e^{-\beta_x}. \qquad [22]$$

This results in

$$\beta_x=\frac{B_{eff}}{k_BT_x}=42.88,$$

and therefore, using $B_{eff}=14.27$eV,

$$T_x=3880K, \qquad [23]$$

which is in excellent agreement with $T_{eq}=3840$K obtained above from purely cosmological quantities. The very good agreement is a little surprising, considering the inevitable approximations and guesswork involved in determine T_{eq}. It must be emphasized that the method used is simple and direct, and that use of the best available observational evidence, as far as we know, has been made. In Fig. 2 we have plotted x as a function of T according to Eq. [20] for $B_{eff}=14.27$eV (H, ^{4}He) and for B=13.6eV (H). The difference is small but significant. Note also that the transition between 90% ionisation and 10% ionisation occurs sharply within ±8.7% of $T_x=3880$K, disregarding other suggested possible complications [4].

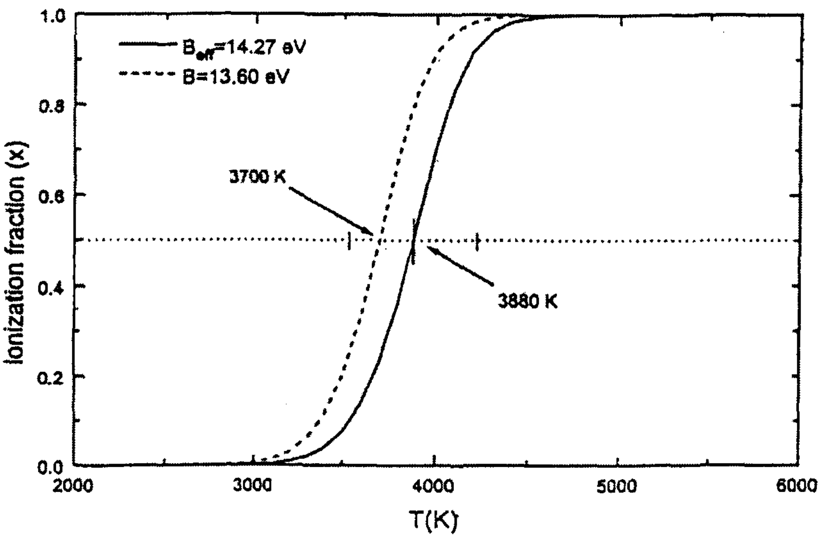

Fig. 2. x (ionisation fraction) vs. T (temperature) under the assumption $\rho_{mr}=\rho_{rx}$, for B_{eff}=14.27eV (H, ^{4}He) and for B=13.6eV, according to Saha's equation.

4. Concluding remarks

The coincidence found between radiation/matter equality temperature and atom formation temperature raises the question of the proper equation of state prior to the atom formation time. We will take up this point in future work elsewhere.

Table 1 gives the dimensionless cosmic parameters Ω=matter mass to critical mass ratio, (Ht)=Hubble's parameter times cosmic time, and (ρ_r/ρ_m)=radiation to matter densities ratio, all as function of the contemporary CBR radiation temperature. Note that in the inflationary paradigm Ω=1, Ht=2/3, at all T.

Table 1. Cosmic parameters as a function of CBR radiation temperature.

Temperature(K)	T_0=2.726	T_+=30.4	T_{eq}=3840	(T>>T_{eq})
Ω	0.0824	0.500	0.992	≈1
(Ht)	0.910	0.733	0.667	≈2/3
(ρ_r/ρ_m)	7.1×10^{-4}	7.31×10^{-3}	1	–

We conclude that a critical evaluation of the available observational evidence supports a close coincidence between the cosmic matter/ radiation equality time and the atom formation time.

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A Brief Glossary

Alpha particle: Particle composed of two protons and two neutrons bound together, corresponding to a helium (^{4}He) nucleus.

Antimatter: Matter consisting of antiprotons, antineutrons and positrons, i.e. of antiparticles which can annihilate with the corresponding normal matter particles, producing pure radiation (photons).

Baryogenesis: process by which a definite population of baryons (protons, neutrons) becomes well defined in the early universe. This requires that the cosmic matter density becomes equal or less than nuclear density, which occurs at a cosmic temperature $T_b \approx 3.88 \times 10^{12}$K. It must take place at $t \sim 10^{-5}$ sec or at $t \sim 1$ sec depending on the cosmic equation of state valid at $t(T_b)$.

Baryons: Protons and/or neutrons which make up overwhelmingly ordinary matter since the masses of electrons ($m_e << m_b$) and neutrinos ($m_v << m_e$) are much smaller than the *masses* of baryons ($m_b \sim 1836\ m_e$).

Big Bang nucleosynthesis: Primordial process by which cosmic protons and neutrons fuse together to form ^{4}He nuclei and traces of other light nuclei. This occurs at a temperature $T_{ns} \sim 4.60 \times 10^8$ K. It must take place at $t \sim 10^3$ sec or depending on the equation of state valid at $t(T_{ns})$.

Blackbody radiation: A blackbody is an object which is in thermal equilibrium at a given temperature and emits radiation according to Planck's formula. The intensity of the emitted radiation depends smoothly on frequency at any given fixed temperature and presents a characteristic maximum. (See Chapter 2).

Black hole: A physical system so massive and compact that in it the strong gravitational field prevents even light from escaping. The primordial cosmos could not have been a black hole because in that case the big bang could not have taken place.

Blue shift: If a star or galaxy moves towards us the radiation emitted observed from the Earth appears shifted towards shorter wavelength (towards the blue) (See Doppler shift).

Chaotic inflationary universe theory: A version of the inflationary universe (Linde, 1983) in which the energy density of the hypothetic inflationary field has a unique minimum at the centre.

Closed universe: A homogeneous and isotropic universe in which the gravity associated to the matter density is strong enough to eventually reverse an initial process of expansion.

COBE: Cosmic Background Explorer, an orbiting satellite with three scientific instruments on board.

Cosmic background radiation: See blackbody radiation.

Cosmic distance ladder: A sequence of calibrated distances to remote galaxies which allows astronomers to extend the range of distance measurements to greater and greater distances.

Cosmic accelerated expansion: Recent observations of magnitude (related to distance) vs. redshift (relate to recession speed) from far away galaxies indicate that these distant galaxies are receding from us (or we are receding from them) relatively faster than expected from the observed motion of nearby galaxies. If we take the local space-time origin at our galaxy now this can be viewed as cosmic *accelerated* expansion, which would require a cosmological constant (see below). But if we tale the local space-time origin behind the surface of "last scattering", at $13.7\text{x}10^9$ light years from us, the same observations are viewed as cosmic *decelerated* expansion, requiring no cosmological constant (See Chapter 5).

Cosmic parameter (Ω): dimensionless parameter giving the ratio between actual mass density (ρ_m) and critical mass density (ρ_c), corresponding to cosmic matter moving barely at escape velocity. $\Omega(t)=\rho_m(t)/\rho_c(t)$ is time dependent, and, at present, using local data $\Omega(t_0)=\rho_m(t_0)/\rho_c(t_0)\approx0.04$, very small in comparison with $\Omega(t_{af})\approx 0.99$, corresponding to the time of atom formation ($t_{af}\approx300.000$ yrs) (See Appendix).

Cosmic time parameter (Ht): Cosmic parameter (dimensionless) giving the product of the Hubble's parameter $H \equiv \dot{R} / R$ and the cosmic time at any moment in the cosmic expansion. For an open universe Ht is less than one and more than two thirds (2/3). This parameter is time dependent, because H(t) is time dependent and, of course, t is also time dependent. At present, using local data Ht≈0.9, substantially larger than $H_{af}t_{af}$≈0.667≈2/3 corresponding to the time of atom formation (t_{af}≈300.000 yrs) (See Appendix).

Cosmological constant: A term in Einstein's cosmological equations of general relativity which results in repulsive interaction with opposite sign to the gravitational attraction. Inflationary theories interpret this term as a measure of the energy density of the vacuum.

Density perturbations: Fluctuations of the density of matter or radiation in the early universe which can be later amplified by gravity resulting in proto galaxies at early cosmic times.

DIRBE: Diffuse Infrared Background Experiment. One of the three COBE instruments, cooled at 1.5 °K by liquid helium and designed to measure any cosmic primordial infrared radiation as well as any other infrared radiation from stars and dust in the Milky Way and other galaxies. It works at 10 different wavelengths from 1.2 to 240 micrometers.

DMR: Differential Microwave Radiometer. One of the three COBE instruments designed to look for small anisotropies in the cosmic microwave background radiation; it works at 3 wavelengths, 3.3, 5.7 and 9.6 mm. The 3.3 and 5.7 mm receivers operate at 140°K, and the 9.6 mm works at room temperature.

Doppler shift: Shift in the receiver frequency (and wavelength) of a wave (sound or electromagnetic radiation) due to the relative motion of source and observer. Depending on the approach or recession, for light, i.e. electromagnetic radiation, results in a blueshift or a redshift, respectively.

Electromagnetic interactions: Interactions due to electric charges. Static charges give rise to electric fields, while accelerated / decelerated charges produce electromagnetic waves, including radio, microwave, infrared, visible, ultraviolet light and X-rays, as well as γ-rays.

Electroweak interactions: Unified description of weak interactions (responsible for nuclear beta decay) and electromagnetic interactions, due to Glashow, Weinberg and Aldous Salam (1967-1970).

FIRAS: Far Infrared Absolute Spectrometer. One of the three COBE instruments, designed to measure the spectrum of the cosmic background radiation and to compare it with the predicted blackbody Planck distribution curve; it is cooled at 1.5 °K by liquid helium and measures wavelengths from 0.1 to 10 mm by means of a very precise interferometer.

Flat universe: a homogeneous, isotropic universe just at the borderline between spatially *closed* (with a halt in the expansion followed by contraction) and spatially *open* (expanding for ever with non zero acceleration). The geometry for a flat universe is precisely Euclidean. The general relativity cosmological equations are consistent with a flat universe only if the total mass of the universe is infinity, which brings forth the spectre of Olbers gravitational paradox.

Flatness problem: A problem, real or rhetorical, of traditional big bang theory pointed out by proponents of cosmic inflation which requires that k=0 (Ω=1) always, regardless of observational evidence to the contrary in our local neighbourhood ($R \sim R_0$, $t \sim t_0$).

Gauge theories: Theories which allow transformations in the dynamical equations leaving invariant the scalar and vector potentials describing physical interactions. The theoretical equations describing electromagnetic interactions (QED) are an example of gauge theory. The theoretical equations describing the strong nuclear forces, i.e. quantum crhomodynamics (QCD) equations, are an example of gauge or Yang-Mills theory resulting in the so called asymptotic freedom for the way quarks are bound within the nucleons.

Gluons: Particles which play a role in the strong interactions analogous to that of photons in electromagnetic interactions.

Grand unified theories: A speculative class of theories of particle interactions which attempts a unified description of the electromagnetic, weak and strong interactions, leaving aside the gravitational interaction.

Gravitation: The mutual attraction between any two massive particles. In a cosmic scale gravity appears as strong because it has an infinite range, like the electromagnetic interaction, and unlike the weak and strong nuclear forces, but is always attractive. Only in inflationary theory a cosmic false vacuum is postulated that results in a repulsive force resembling a negative gravitation.

Horizon problem: A problem, real or rhetorical, of traditional big bang cosmology pointed out by proponents of cosmic inflation. If at very early times after the big bang the universe was homogeneous and isotropic to start with, the horizon problem disappears altogether.

Hubble parameter: The ratio of recession velocity of galaxies ($\dot{R}$) to distance (R), improperly called Hubble's constant, because for nearby galaxies $H_0 \approx \dot{R}_0 / R_0$ is approximately constant, but, in principle, it is time dependent, being $H(t) \approx \dot{R}(t) / R(t) >> H(t_0)$ for early times. The presently accepted value of the Hubble parameter is $H_0 \approx 67$(km/s)/Mpc, being 1 Mpc (Megaparsec)$\approx 3.26 \times 10^6$ lightyears.

Inflationary cosmology: The cosmological theory which assumes a very early ($\sim 10^{-35}$sec after the big bang) exponential expansion *at constant density* during which the total mass of the universe increases by many orders of magnitude. In the inflationary process the new matter comes out of the vacuum itself. The process is somewhat analogous to the continuous creation of matter out of nothing in the steady-state-cosmology of Bondi, Gold and Hoyle, which was popular in the 50's and early 60's, before the cosmic background microwave radiation was discovered by Penzias and Wilson in 1965.

Ionised atoms: Atoms under physical conditions (f.i. high radiation pressure) such that one or more electrons have been taken apart. At times below 300.000 years and temperatures higher than 3880 K the universe consisted in a *plasma* of ionised atoms, mainly hydrogen (76%) and a substantial amount of ^{4}He (23%). Later, when the temperature was cooling progressively, the universe begun to consist in a gas of neutral atoms. Substantially later, the gravitational interaction begun to pull atoms together to form protostars within protogalaxies. Finally, the universe evolved towards its present, slowly changing, overall physical conditions.

Leptons: A class of non-strongly interacting particles which includes the electron, the muon, the tau particle, and their associated neutrinos (See Chapter 3).

Local group: A group formed by about twenty galaxies surrounding our Via Lactea (Milky Way).

Local supercluster: An assembly of about 100 clusters of galaxies including our local group.

Magnetic monopole: An isolated pole (north or south) of a hipotetic magnet. An infinitely long magnet in which the two poles are so far apart than they do not affect each other would act as a pair of monopoles. Dirac predicted the existence of particles with properties of magnetic monopoles, and so did some grand unified theories. But they have never been observed.

Magnetic monopole problem: A problem, real or rhetorical, of traditional big bang cosmology originally pointed out by the proponents of cosmic inflation. Since the observation of real magnetic monopoles has not been confirmed, this problem appears to have faded away.

Meson: A strongly interacting particle consistent in a quark and an antiquark.

Microwave: An electromagnetic wave with wavelength between one millimetre and about 30 centimetres.

Neutrino: An elementary particle of very small rest mass which is electrically neutral and very weakly interacting with other material particles. It was predicted in 1931 by Pauli and detected experimentally in 1956 by Cowan and Raines.

Observed cosmic mass: Einstein's cosmic general relativistic equations are consistent with a very large but finite mass for the entire universe. Present cosmic dynamics allows one to estimate the total cosmic mass as $M_U \approx 4.5 \times 10^{54}$ g. Note that this number if of the order of $N_G N_S M_{sun}$, where $N_G \sim 10^{11}$ (galaxies) times $N_S \sim 10^{11}$ (stars) times $M_{sun} \sim 2 \times 10^{33}$ g, the mass of a typical star (the Sun).

Open universe: A homogeneous isotropic universe in which gravity is not strong enough to stop the expansion. So an open universe goes on expanding for ever. Local cosmic dynamics data support an open universe with a cosmic space curvature $k<0$ (See Appendix 1 and 2).

Phase transition: A sudden change in the properties of a material system produced by varying temperature, pressure or other physical parameter. Inflationary theory postulates a cosmic phase transition at about 10^{-37} seconds after the big bang.

Photon: A quantum (discrete) minimum of electromagnetic energy consisting essentially in a localized particle of light after the quantum theory of radiation put forward by Max Planck in 1900.

Planck's time: A "natural" unit of time proposed by Max Plank in terms of universal constants: $t_{pl} \approx (\hbar G / c^5)^{1/2} \approx 5.4\times10^{-44}$ sec .

Quark: Elementary constituents of protons, neutrons and other strongly interacting particles (baryons and mesons).

Red giant: A phase in the life cycle of a typical star (not very heavy, like our Sun) in which the size of the stars increases tremendously and then blows up into space, leaving as a remnant a white dwarf.

Redshift: Shift towards longer wavelength (smaller frequency) in the light emitted by stars or galaxies moving away from us (See Doppler Shift).

Relativity: The special theory of relativity, proposed by Albert Einstein in 1905, assumes that all light propagates at a constant (invariant) speed c in free space, regardless of the relative motion of source and observer. The general theory of relativity, produced by Einstein in 1915, constitutes a general theory of gravity consistent with special relativity, and therefore, with the invariance of c. It predicts that light rays are deflected in their path when coming close to large masses. The observation of this effect taking advantage of a Solar eclipse in an expedition headed by Eddington in 1919, did make Einstein instantly famous all over the world, and confirmed the theory of relativity.

Renormalization: A theory such as quantum electrodynamics (QED) which in first approximation gives answers in agreement with experiment, in a second approximation, however, may give divergent answers (infinity) which are unrealistic. Renormalization is a mathematical transformation on the theoretical equations to avoid the unwanted infinities.

Singularity: When the standard big bang theory is extrapolated back to time zero, a number of cosmic physical parameters become infinity, f.i. the density, the pressure, the temperature. It is physically meaningful to tray to investigate what happens as $t \to 0$ and $R \to 0$, but there is always a limit, imposed by Heisemberg uncertainty principle which sets a minimum conceivable cosmic time ($t_H \approx \hbar / M_U c^2 \approx 2.8\text{x}10^{-103}$ sec) beyond which it is pointless to speculate within the realm of physical theory.

Standard model of particle physics: A general theory of particle interactions which describes successfully the electromagnetic, the weak and (to a large extent) the strong interactions. This theory was developed in the early 1970's and leaves out the gravitational interaction.

Steadily driven expansion (SDE): An alternative to inflationary theory based upon the traditional big bang theory in which the large increase in cosmic radius from very early cosmic times ($t_H \approx 2.8x10^{-103}$sec) to times beyond Planck's time ($t_{pl} \approx 5.4x10^{-44}$ sec) takes place steadily instead of instantly.

Strong interactions: The interactions which bind together quarks to form protons, neutrons, etc.

Thermal equilibrium: Physical conditions which imply that photons (radiation) have a characteristic spectral distribution, the so called blackbody spectral distribution. COBE confirmed that cosmic thermal equilibrium prevailed at the time of atom formation (T~3880 K), and presumably much earlier, f.i. at nucleosynthesis, baryon formation, Plank epoch, and even before.

Uncertainty time: The earliest conceivable cosmic time allowed to be considered by the uncertainty principle ($t_H \approx 2.8x10^{-103}$ sec).

Weak interactions: Short range nuclear interactions responsible for beta decay. Neutrinos are subject only to this type of interactions.

White dwarf: Final phase in the life of a typical star after it went through the phase of red giant.

Ylem: The primordial cosmic material after Gamov and collaborators. When the cosmic density was incredibly high, matter density, which then could have been present in an amount comparable to that of radiation or not, was so incredibly high that far exceeded that in ordinary baryons or electrons.

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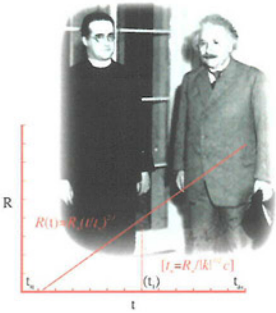
Inflationary Cosmology Revisited

An Overview of Contemporary Scientific Cosmology After the Inflationary Proposal



Scientific Cosmology is clearly one of the most active physics research fields at present, and likely to remain so in the near future. Shortly after the pioneering cosmological work of Einstein, Georges Lemaitre proposed a model which some years later to be known as the big-bang model. In the early fifties an alternative proposal, the so called steady-state (expansion at constant density) model, became the fashionable model in prominent academic circles. The discovery of the cosmic background microwave radiation (Penzias & Wilson, 1965) made the steady-state model almost untenable. A quarter of a century later the inflationary model was proposed, becoming extraordinarily popular almost immediately. For some it seemed to combine attractive features of both the steady-state and the big-bang models, by postulating a very early violent (constant density) expansion during a very tiny fraction of a second.

The book makes use of the best and most recent observational data, from the Cosmic Background Explorer (COBE, 1992) to the Microwave Anisotropy Probe (WMAP, 2003), to discuss the merits and demerits of inflationary cosmology for a general readership acquainted with the basic facts of scientific cosmology. A complete Glossary and a detailed Index help the reader to follow controversial topics, such as dark matter, dark energy, cosmic flatness and accelerated expansion.

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