Particle Physics and Cosmology

New Aspects of an Old Relationship

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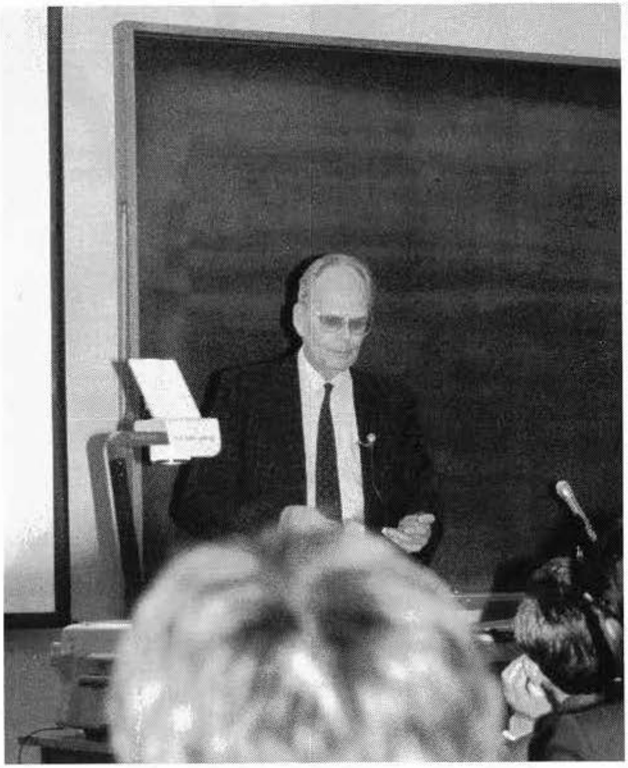

Prof. L. Van Hove giving the lecture at Faculty of Science, University of Tokyo on April 11, 1990

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1. Introduction.

It has been a great pleasure to visit Japan as a guest of the Nishina Memorial Foundation, and I am deeply honoured to deliver the Memorial Lecture dedicated to the illustrious Japanese physicist Yoshio Nishina. I have chosen to speak on the relationship between physics and cosmology, not a new subject but one that experienced in the last decade a flurry of exciting developments triggered by the new results and speculations which marked the rapid progress in particle physics in the 70's and 80's.

The aim of cosmology is to study the large-scale structure of the Universe and to reconstruct its early history on the basis of the astronomical observations and of the laws of physics. The historical element is crucial in the study. When astronomers observe distant objects, the signals they detect have travelled a long time and therefore reflect the state of these objects in the deep past. Furthermore, astronomers cannot look very far in space nor very deep in the past. During the early and most interesting phase of its expansion, the Universe was presumably filled with very hot and dense matter which absorbed and thermalized all electromagnetic radiation including all information-carrying signals.

Cosmology is therefore an historical discipline condemned to work with highly incomplete records. Using the laws of physics, the cosmologist can only speculate on how the Universe could have evolved and what its large-scale structure could be. Consistency with observations and logical consistency are of course demanded, but plausibility arguments and assumptions play a big role despite their unavoidable lack of objectivity. The deepest one goes into the past, the largest is the dependence on theoretical speculations. In the last decade such speculations have proliferated to an amazing degree, throwing into doubt at one time or another almost everything that seemed generally accepted in the cosmological models of the 60's and 70's, and inventing for the expansion of the Universe a variety of possible "scenarios" which compete for scientific recognition.

A striking impression of the change in cosmological thinking is given by contrasting S. Weinberg's classic "The First Three Minutes" (1977) [1)] with A. Linde's very recent "Particle Physics and Inflationary Cosmology" (1990) [2)]. A closer appreciation of the highly diversified evolution of cosmological thinking in the 80's can be gained from the successive Proceedings of the ESO-CERN Symposia on "Astronomy, Cosmology and Fundamental Physics" (Geneva 1983, Garching bei

München 1986, Bologna 1988) [3,4,5].

My aim in this lecture is not to review those many speculative developments. I shall concentrate on general features common to most of them, on items where knowledge has advanced reliably (although usually not enough to give unique answers) and on some unsolved problems for which progress can be expected in the coming decade or so.

2. Matter in the Expanding Universe.

As evidenced by all observations, the spatial distribution of "visible", i.e., electromagnetically detectable matter in the Universe is extremely inhomogeneous, with many sorts of clustering (stars, galaxies, clusters and superclusters of galaxies, voids, filaments and / or sheets, gas clouds, etc, etc). So far, attempts to define a characteristic length for the space structure are inconclusive because they tend to give results of the order of the largest distances observed. Despite the inhomogeneities, the very simple Hubble expansion law continues to hold on the average up to the largest observed distances.

In amazing contrast with the high degree of inhomogeneity of visible matter, the microwave background radiation (MBR) must have an extremely homogeneous space distribution. As recently measured by the COBE satellite, its spectrum is blackbody to very high precision (T=2.7 K). Apart from the dipole anisotropy due to our "peculiar" motion with respect to the local average comoving frame, the MBR is highly isotropic (to a level of 10^{-4}, soon to be improved by COBE). All this is only understandable if the space distribution of the MBR is very homogeneous.

To form a theoretical picture of this contrasting situation, one usually assumes that, despite the observed inhomogeneity of visible matter, there is an average homogeneity of all matter over very large, as yet unobserved distances. Averaging over such distances one can assume the expanding Universe to be described by an homogeneous (Robertson-Walter) metric with a time-dependent scale factor a(t) [a(t) represents the distance at time t between two comoving local frames; choosing two other such frames only multiplies a(t) by a constant]. The Einstein equations of General Relativity then give

$$H^2 = 8\pi G \rho/3 + k/a^2 + \Lambda , \qquad H \equiv a^{-1} da/dt \tag{1}$$

with H(t) the Hubble "constant" (constant in space, not in time), G Newton's constant, $\rho(t)$ the non-gravitational energy density including all mass contributions, k the curvature constant and Λ the cosmological constant (currently the latter is the subject of wide-ranging discussions and speculations). The units used in eq.(1) are such that $h/2\pi = c = 1$.

At present the estimated value of ρ for visible matter (of order of $0.1 \div 1$ GeV/m^3, i.e., $0.1 \div 1$ nucleon / m^3 on the average) gives for the first term of (1), $8\pi G\rho / 3$, no more then a few percent of the observed value $H^2 \sim 4 \times 10^{-36}$ sec^{-2}, which itself is still very uncertain (at least by a factor 2) whereas k/a^2 and Λ are believed to be $\lesssim H^2$ in absolute value. Unless we live in a special era of the expansion, one expects $8\pi G\rho / 3$ to be very close to H^2, and the popular "inflationary" scenarios of the early expansion have made this an attractive prediction. Hence the current strong belief that our present Universe contains lots of "dark", i.e., invisible matter, and the multitude of attempts to try to detect and identify it. Dark matter could come in many sorts: ordinary matter (protons, nuclei, electrons) too cold to emit visible light (as is the case for the planets), and / or massive neutrinos (masses of a few tens eV are of interest), and / or so far unknown types of particles for which many candidates have been proposed in the last 15 years by theorists trying to extend and improve the Standard Model of particle physics.

The usual basis for the reconstruction of the history of the expanding Universe is eq.(1) supplemented by

$$d(\rho\, a^3)/dt \,\Big/\, p\, da^3/dt = 0 \qquad (2)$$

(p = pressure) which expresses energy conservation for a comoving domain of volume a^3 under the simplest thermodynamic assumption, namely adiabatic expansion (no entropy creation). Eqs. (1) and (2) can be solved for $a(t)$ and $\rho(t)$ if the pressure p is a known function of the energy density ρ. Before the dark matter issue came up, this was straightforward for the present Universe where ρ. was supposed to be the mass density of visible matter (protons, nuclei, electrons, all with non-relativistic velocities in the comoving frame) plus very small contributions due to photons and massless neutrinos. If this were the whole story, or if most dark matter consisted of neutrinos, the pressure term in eq.(2) would be negligible, ($p \ll a^3$), ρ would be $\propto a^{-3}$ and eq.(1) would give $a \propto t^{2/3}$, at t early enough for k/a^2 and Λ to be negligible. Another extreme case of great simplicity obtains if most dark matter consists of (almost) massless particles having extremely weak non-gravitational interactions. The pressure is then $p \sim \rho/3$ and eqs.(1,2) give $\rho \propto a^{-4}$, $a \propto t^{1/2}$ (the latter again when k/a^2 and Λ are negligible).

The dark matter problem illustrates the great importance of neutrino physics for cosmology. As is well known, another case in point concerns primordial nucleosynthesis. A major step forward has been taken last year, when the new e^+e^- colliders (SLC at SLAC, LEP at CERN) operating on the Z^0 peak established that the number of neutrino species produced with standard electroweak coupling is three. This number corresponds to the species known from earlier experiments and agrees with the number needed to account for primordial nucleosynthesis. Unfortunately, progress is much slower on the equally important problem of neutrino masses. The 1988 Particle Data Table report the upper bounds 18 eV, 250 eV and 35 MeV for the electron -, muon - and tau - neutrinos respectively. After an ITEP group (Moscow) reported some years ago a non-vanishing ν_e mass in tritium decay (their present value is 26 ± 5 eV), a number of new experiments were undertaken with results so far compatible with zero mass. Regarding the muon - and tau - neutrinos, the experimental problems are even much more formidable, and it will at best be a long time before the neutrino side of the dark matter problem is solved.

3. The Visible and Invisible Parts of the Universe.

Our large-scale astronomical observations are entirely based on electromagnetic radiation, mostly visible light and radio waves (one day, perhaps, gravitational waves will be detected, widening immensely our cosmological horizon !). At present, electromagnetic radiation travels almost undisturbed through intergalactic space because there is very little ionized matter to absorb it. But this was not so in the past, when the MBR, instead of its present $T = 2.7$ K $= 2.3 \times 10^{-4}$ eV (we put Boltzmann's constant =1), was blackbody radiation at temperatures $T \gtrsim 3000$ K $= 0.26$ eV and was able to ionize matter. The latter was then an electron-ion plasma, in thermal equilibrium with the photons and opaque to electromagnetic radiation on astronomical scales. By the Hubble redshift, the temperature of the photon blackbody spectrum scales like $1/a(t)$. We must therefore conclude that we have no astronomical observations on the state of the Universe at times $t < t_{dec}$ when $a(t)$ was $< a(t_{dec}) \sim (2.7/3000)\ a(t_{pres})$, where t_{pres} refers to the present and the "decoupling time" t_{dec} refers to the period where matter became electrically neutral and the photons decoupled from it. Consequently, since in our units light travels with velocity 1, the visible part of the Universe has a diameter $D_{vis} \sim t_{pres} - t_{dec}$.

To estimate D_{vis} we must solve eqs.(1,2) between t_{dec} and t_{pres}, which requires assumptions concerning dark matter. The two simple cases considered in section 2 give

$$\rho \sim C\, a^{-n}, \qquad C = \text{constant} \tag{3}$$

with n = 3 and 4. As long as one avoids recent times so that the k/a^2 and Λ terms can be neglected, eqs. (1) and (3) give

$$n^{-1}\, d\rho^{-1/2}/dt = L \tag{4}$$

$$\begin{aligned} L \equiv (8\pi G / 3)^{1/2} &= 1.2 \times 10^{-19}\ \mathrm{GeV}^{-1} \\ &= 7.8 \times 10^{-44}\ \mathrm{sec} \end{aligned} \tag{5}$$

(4) is integrable. It gives the time interval $t_2 - t_1$ between an early and a later phase of the expansion ($t_1 < t_2$) in terms of the corresponding energy densities ρ_1, ρ_2 :

$$t_2 - t_1 = (\rho_2^{-1/2} - \rho_1^{-1/2}) \,/\, n\, L \tag{6}$$

The uncertainties on the ρ values are much larger than the uncertainties on n (n = 3 or 4) and the difference between our crude approximation (4) and the full equations (1,2). Eq.(6) is therefore good enough to estimate the time development of the expansion. For example, for $t_1 = t_{dec}$ and $t_2 = t_{pres}$, (6) gives

$$D_{vis} \sim t_{pres} - t_{dec} \sim (\rho_{pres}{}^{1/2}\, n\, L)^{-1} \tag{7}$$

because $\rho_{dec} \gg \rho_{pres}$. We adopt

$$\rho_{pres} \sim 10 \div 50 \text{ GeV} / \text{m}^3 \tag{8}$$

which would correspond to some 10 to 50 nucleons per cubic meter if all the matter is nucleonic, instead of the estimated 0.1÷1 nucleon/m^3 of visible matter. Eq.(7) then gives

$$D_{vis} \sim (1 \div 2)\ 10^{23} \text{ Km} \tag{9}$$

$$t_{pres} - t_{dec} \sim (1 \div 2)\ 10^{10} \text{ years} \tag{10}$$

Eq.(9) gives the estimated size of the visible part of the Universe.

Up to a few years ago, most cosmologists assumed the visible and invisible parts of the Universe to have the same properties (assumption of overall homogeneity). Recent considerations on the possible effects of quantum fluctuations at very early times have led to a change in attitude, and a popular trend of theoretical cosmology is now to discuss highly inhomogeneous scenarios for the invisible part of the Universe (see section 7). The vast array of current speculations encompasses changes not only in the state of matter, but in the fundamental physical constants, the laws of physics, and even in the dimensionality of spacetime ! Needless to say, there are no observational indications for such dramatic effects.

Let us now discuss times before t_{dec} and in particular what is commonly called the "age of the Universe", widely quoted to have a value of order (10). For $t < t_{dec}$, and as long as the Standard Model of particle physics applies (i.e. for temperatures up to ~ 1 TeV = 10^3 GeV, the highest energy attained by an existing accelerator, the Fermilab Tevatron), the pressure in eq.(2) can be taken $\sim \rho / 3$, so that eq.(3) applies whith $n = 4$. As mentioned in section 5, there is a phase transition at $T \sim 200$ MeV, which causes a sudden change in the coefficient C of (3). Taking this change into account shortens the estimate (6) by an amount of order 10^{-5} sec, totally negligible for our present discussion. We therefore apply (6) with $n = 4$ to the interval $t_{dec} - t_{TeV}$ where t_{TeV} is the time where the temperature was 1 TeV

$$t_{dec} - t_{TeV} \sim (\rho_{dec}{}^{-1/2} - \rho_{TeV}{}^{-1/2})/4\,L \sim (4\rho_{dec}{}^{1/2}\,L)^{-1} \qquad (11)$$

ρ_{dec} is of order 1 GeV/cm^3 and $\rho_{TeV} \sim 10$ TeV^4 $\sim 2 \times 10^{50}$ TeV/cm^3. Hence

$$t_{dec} - t_{TeV} \sim 3 \times 10^{13} \text{ sec} = 0.95 \times 10^5 \text{ years} \qquad (12)$$

and adding to (10) we have

$$t_{pres} - t_{TeV} \sim (1 \div 2)\ 10^{10} \text{ years} \qquad (13)$$

The latter estimates would not be affected if t_{TeV} is replaced by any earlier time t_1 such that $\rho \propto a^{-4}$ holds between t_1 and t_{TeV} because

$$t_{TeV} - t_1 \sim (\rho_{TeV}{}^{-1/2} - \rho_1{}^{-1/2})/4\,L \leq$$
$$\leq (4\,\rho_{TeV}{}^{1/2}\,L)^{-1} \sim 4 \times 10^{-13} \text{ sec} \qquad (14)$$

a totally negligible time compared to (12) and (13).

In the present cosmological discussions, it is the early epoch, of duration $\lesssim 10^{-13}$ sec and characterized by temperatures $\gtrsim 1$ TeV but presumably already with a $\rho \propto a^{-4}$ type expansion, which best deserves the name of Hot Big Bang (HBB), whereas the so called "age of the Universe" is the time elapsed since then, of order $(1 \div 2)\, 10^{10}$ years. The present trend is to abandon the view, very popular in the last decades, according to which that epoch started with a space-time singularity [$\rho_1 = \infty$ and $a(t_1) = 0$ in the above equations] marking the "beginning" of the Universe. The main reason for this change of attitude is the difficulty to understand in such a scenario the observed isotropy of the MBR. As explained in section 7, a radically different $\rho(t)$ versus $a(t)$ behaviour is needed to account for this property. There are undoubtedly many theoretical possibilities, including scenarios where the Universe pre-existed and the HBB relevant to the part visible to us resulted from a local quantum fluctuation .[6]

This completes our discussion of the limited space-time domain of the Universe about which we can claim to have a fair degree of knowledge. Our main aim was to point out the uncertainties still affecting what many regard to be the standard, i.e., well established part of cosmology. We did not even discuss the inhomogeneity of all visible matter, simply because no convincing solution is yet known to the problem of explaining its origin.

4. Production of Exergy.

From now on we take t to be the time after the Hot Big Bang (HBB) as defined in the previous section. At time $t \sim 1$ sec, the temperature of matter and of radiation (photon gas) in the Universe had dropped to $T \sim 1$ MeV = 1.2×10^{10} K and departures from thermal equilibrium began to appear. Matter was then composed of nucleons (protons and neutrons), electrons, positrons, (anti-) neutrinos, and possibly exotic particles now belonging to dark matter. At $T \sim 1$ MeV the rate of collisions controlled by the weak interactions, i.e., those involving neutrinos, dropped below the expansion rate and very rapidly these collisions became so rare as to be negligible. The neutrinos became in effect a non-interacting gas, each of them with a momentum redshifted by the expansion proportionally to a^{-1} with $a = a(t)$ the scale parameter. Also the neutron to proton ratio ceased to be given by the ratio of the Boltzmann factors, $\exp(-\Delta m/T)$ with $\Delta m = m_n - m_p = 1.3$ MeV. The n/p ratio became constant, except for a small initial decrease due to the decay of free neutrons which stopped at t ~ 3 min when all remaining neutrons were stabilized by being bound in light nuclei, mainly ^4He (about 25 % of nucleons were then bound in nuclei, the others being free protons), the so-called primordial or big bang nucleosynthesis. The formation of heavier nuclei was negligible because of the very low densities and reaction rates; it could only occur at much later times ($t > 10^5$ to 10^6 years) when stars had formed and high reaction rates became possible in their dense and hot interior.

While the neutrinos and nucleons were falling out of equilibrium from t ~ 1 sec onward, the electromagnetic interaction maintained thermal equilibrium much longer between photons, electrons and positrons and it also maintained the protons and light nuclei in kinetic equilibrium with them, i.e., the velocity distribution of protons and nuclei remained the equilibrium one for the same temperature T. This situation persisted until the formation of neutral atoms at $t \sim 10^5$ years. Most positrons had disappeared by annihilation with electrons as early as t ~ 15 sec ($T \sim 0.3 \times 10^9$ K). From then on the remaining electrons were as numerous as the protons (electric neutrality), about one electron and one free or bound proton per 10^9 to 10^{10} photons.

Although in kinetic equilibrium as mentioned above, the nucleons after t ~ 1 sec were out of chemical equilibrium, i.e., their distribution in nuclei differed from the equilibrium one for the photon temperature T. As explained by Eriksson et al. [7] chemical equilibrium of the nucleons would have corresponded to almost 100 % free protons at $T > 3.3 \times 10^9$ K, almost 100 % ^{4}He at $3.0 \times 10^9\ \mathrm{K} > T > 2.5 \times 10^9$ K and almost 100 % ^{56}Fe at $T < 2.2 \times 10^9$ K, in each case with the appropriate numbers of electrons to have electric neutrality. The changes between these equilibrium compositions would have taken place in very narrow temperature intervals, but this would have required nuclear fusion rates faster than the expansion rate $a^{-1}\, da/dt$ of the Universe, and the actual fusion rates were very much slower. This is the cause of the non-equilibrium feature which preserved free protons and delayed the synthesis of heavy nuclei until the late times ($t > 10^6$ years) when stars formed and started to burn.

As was done in Ref.7, it is interesting to determine quantitatively the amount of non-thermalized energy which became available after t ~ 1 sec due to the non-equilibrium feature just discussed. This quantity is a special case of what has been called exergy, the maximum amount of non-thermal energy (mechanical work) which can be extracted from a physical system (in our case the nucleons in the

Universe) under the prevailing conditions (here the photon gas as heat bath), without violating the laws of thermodynamics. Eriksson and al. [7] find that the nuclear exergy, i.e.,the exergy related to the strong, electromagnetic and weak interactions of the nucleons, amounts to 7.8 MeV per nucleon, and this reserve of non-thermalized energy was formed in the first day of the expansion (1 sec $<$ t $<$ 24 hours). It increased steadily during this interval, mainly during the first minutes, except for a small drop of $\sim$ 0.6 MeV/nucleon at helium formation (t $\sim$ 3 min). A very small decrease of 10 eV/nucleon took place much later, at t $\sim$ 10^5 years when atoms formed. Of course, gravitation provides another source of exergy. It is not important in normal stars but is large if neutron stars or black holes are formed.

5. Hadronic Phase Transition.

According to general considerations and Quantum Chromodynamics lattice calculations, hadronic (i.e. strongly interacting) matter at high temperature (T $\gtrsim$ 200 MeV) takes the form of a quark-gluon plasma, whereas at low temperature and net quark number density it takes the form of a gas of well-separated hadrons inside which the (anti) quarks and gluons are confined. The lattice calculations predict that the phase transition is probably of 1st order and occurs at $T_c \sim 200 \pm 50$ MeV. Furthermore, the discontinuities $\Delta\rho_h$, Δs_h of the hadronic energy density ρ_h and entropy density s_h are probably large, perhaps of the order of the values of ρ_h, s_h on the low, hadron gas side of the transition. This is for small or vanishing net quark number density, the case appropriate to the early Universe. The transition temperature $T_c \sim 200$ MeV was reached at a time $t_c \sim 10^{-5}$sec after HBB. It is probable that the hadronic transition took place through nucleation, i.e., formation and growth of bubbles of hadron gas in the quark-gluon plasma, a smooth process described by eqs.(1) and (2) with constant pressure p, and taking place in a time interval from t_c to a time of order $(1.5 \div 2)t_c$. While it is now generally regarded to be unlikely that the hadronic phase transition had any lasting consequence on the expansion of the Universe, the discussion of possible effects led to some interesting considerations, two of which will be briefly mentioned.

Due to our ignorance of the non-perturbative aspects of Quantum Chromodynamics (the field theory of quarks and gluons, and hence of all hadronic phenomena), we cannot exclude the possibility that the hadronic phase transition could have been violent, for example with strong supercooling and sudden release of large amounts of latent heat over times of microsecond order. This could generate chaotic pulses of gravitational waves which would have travelled through space since time t_c, with very little damping but with the strong redshift resulting from the Hubble expansion. The present frequency range of the pulses would then be $\lesssim 1$ year^{-1}. Quite remarkably, high-precision timing measurements of millisecond pulsars can probe this range of gravitational wave frequencies, although detection of a signal would of course not yet mean that it would have originated from the hadronic phase transition. Other explanations would exist, e.g., "cosmic strings" as postulated by some models of galaxy formation. [8)]

Another possible consequence of nucleation in the hadronic phase transition could be the occurrence of large inhomogeneities in the space distribution of nucleons, persisting as long as the neutron-to-proton ratio was in thermal equilibrium with the electron-neutrinos, i.e., until $t \sim 1$ sec ($T \sim 1$ MeV). Up to that time, the nucleons oscillated very rapidly between the proton and the neutron states, their oscillating electric charge preventing them from diffusing through the dense electron plasma from the nucleon-rich to the nucleon-poor regions. After $t \sim 1$ sec, the neutrons could only become protons by the very slow process of beta decay (lifetime 891 ± 5 sec, another particle property of great importance for cosmology). Being electrically neutral, they could then diffuse to the nucleon-poor regions, leaving the protons behind. These curious phenomena have been modelled in considerable detail in the last few years, the most remarkable finding being that among the nuclides produced by primordial nucleosynthesis, the very rare lithium-7 turns out to be very sensitive to inhomogeneities in the nucleon distribution. The primordial ^{7}Li abundance can in fact be related to the actual parameters of the hadronic phase transition, especially its critical temperature T_c. [9)]

It should also be recalled, of course, that the ultra-relativistic heavy ion beams available at Brookhaven and CERN (now up to sulphur, in a few year's time lead at CERN and gold at Brookhaven) provide a more direct access to the study of the hadronic phase transition through the detailed experimental and theoretical investigation of nucleus-nucleus collisions.[10)]

6. Baryon Asymmetry and Standard Model.

Modern particle physics suggests that the observed asymmetry between matter and antimatter in the present Universe (much less antimatter than matter) can have originated from a symmetric situation at early times, under a variety of conditions including non-equilibrium features of the early expansion. This has become an very active domain of research, and many different models have been explored. Quite a few gave an asymmetry compatible with the observed sign and magnitude (1 nucleon and 0 antinucleon per 10^9 to 10^{10} photons in the present Universe), but none makes definite predictions, not even for the sign. In fact the present situation is that the existing asymmetry is used as one among several constraints which astrophysics imposes upon modern unified theories of particles and interactions. The common premise in this work is that the net baryon number B (number of baryons minus number of antibaryons) was originally negligible and evolved to the present value during an early phase of the expansion. It should be realized that from $t \sim 10^{-12}$ sec ($T \sim 1$ TeV) onward B was conserved in good approximation and the baryon asymmetry had the form $n_q - n_{\bar{q}} \sim (10^{-10}$ to $10^{-9}) \, n_{all}$ with the n's the number densities for quarks, antiquarks and all particles. Now $n_{all} \simeq n_{photons}$ and $n_{\bar{q}} \ll n_q$, but at $t \lesssim 10^{-5}$ sec one had $n_q + n_{\bar{q}} \sim n_{all}$ and hence $n_q - n_{\bar{q}} \ll n_q$.

If the observed baryon asymmetry of the Universe is to have evolved out of a symmetric situation, various conditions must be fulfilled. Firstly, of course, the basic interactions must violate B conservation, and this is the point discussed below. Secondly , both C and CP invariance must also be violated (C is charge conjugation which exchanges matter with antimatter, P is space reflection); indeed since C and CP reverse the sign of B, the appearance of $B \neq 0$ in a Universe which started with $B = 0$ can only result from interactions violating B, C and CP. As is well known both C and CP are violated in particle physics.

The third condition is a consequence of the CPT theorem, which holds for all relativistic field theories with local interactions and asserts exact invariance for the combined CPT transformation (T is time reversal). A consequence of the CPT theorem is that a system in thermodynamical equilibrium with vanishing chemical potentials is CPT-symmetric , and therefore symmetric between matter and antimatter. Indeed, the hamiltonian is CPT-symmetric by the theorem, and the sum over states covers equally states which differ by space reflection (P), by time reversal (T), and in case of zero chemical potentials by charge symmetry (C). This remains true (by definition) for any adiabatic, i.e., reversible evolution of such a system. The appearance of a CPT-asymmetric situation out of a symmetric one therefore requires departure from equilibrium.

In the 80's, most work on the baryon asymmetry of the Universe (BAU) consisted in going beyond the Standard Model of particle physics and inventing new field theories with lagrangians implying baryon number violation (BNV). Typically such theories are able to produce the BAU at very high temperatures ($T \lesssim 10^7$ TeV). They disregard the fact that 't Hooft had shown already in 1976 the existence of BNV in the Standard Model as an exceedingly weak non-perturbative effect (proton lifetime poorly predicted but much longer than anything measurable). More recently, it was noted that this Standard Model BNV, which is due to tunnelling between topologically inequivalent vacua through a potential barrier of the order ~ 10 TeV (tunnelling probability $\sim 10^{-173}$ at temperatures $T < 20$ GeV), could have been much stronger when the Universe was at temperatures $T \gtrsim 10$ TeV. [11)]

There is so far no reliable way to calculate high temperature BNV in the Standard Model, the difficuty lying in the non-perturbative, topological source of the violation. Progress is being made, however. Thus, Ringwald has recently estimated the increase with energy of the Standard Model BNV effects in quark-quark collisions.[12)] It turns out to be very rapid, but the strongest BNV effects appear in channels with large numbers of W and Z bosons. This problem is one of the most interesting challenges for positive temperature field theory, and its importance for cosmology is obvious. If Standard Model BNV is important at $T \gtrsim 10$ TeV, it is clear that the whole problem of the occurrence of the BAU must be reconsidered. Any BAU created by non-Standard-Model interactions at higher T could be erased by the time T drops below 10 TeV. Conversely, a baryon symmetric Universe at very high T could develop a baryon asymmetry, perhaps the observed one, by purely Standard Model effects in the $T \sim 10$ TeV range.

7. New Physics in the Early Expansion.

As mentioned at the end of section 3, the old HBB scenario in which the Universe began at a time t_1 where $\rho_1 = \infty$, $a(t_1) = 0$ is now generally rejected, the main reason being its failure to explain the observed isotropy of the MBR. This isotropy is only understandable if the MBR is very homogeneous over the whole visible part of the Universe. This homogeneity must have existed for the photons and the electron-ion plasma at the decoupling time t_{dec}, when the size of the now visible part of the Universe was

$$D_{dec} = D_{vis}\ a(t_{dec})\ /\ a(t_{vis}) \tag{15}$$

With the estimates of section 3 we find (remember c = 1)

$$D_{dec} \sim (0.6 \div 3)\ 10^7 \text{ years} \tag{16}$$

The large uncertainty is again due to the dark matter problem.

Before t_{dec}, the photons and the charged particles were in thermal equilibrium, at least locally. Their homogeneity over the distance D_{dec} at time t_{dec} can be understood if interactions had time to act over D_{dec} before t_{dec}. The effects of interactions cannot propagate faster than light, so that D_{dec} must be smaller than the maximum distance $D_{max}(t_{dec})$ which can be covered before t_{dec} by a signal travelling with light velocity (the so-called horizon distance). An elementary calculation based on the Robertson-Walker metric gives

$$D_{max}(t_{dec}) = a(t_{dec}) \int^{t_{dec}} dt\ /\ a(t) \tag{17}$$

where the integral extends over all times before t_{dec} (i.e., from $-\infty$ or from any finite initial time as the case may be). With (16) the condition $D_{dec} < D_{max}(t_{dec})$ gives $D_{max}(t_{dec}) \gtrsim 6 \times 10^6$ years. With (17) this can also be written

$$\dot{a}(t_{dec})\int^{t_{dec}} dt\,/a(t) \gtrsim 30 \quad , \qquad \dot{a} = da/dt \tag{18}$$

where we have used the value of $\dot{a}(t_{dec})\,/\,a(t_{dec})$ given by eq.(1) with $\rho = \rho_{dec} \sim 1\text{GeV}/\text{cm}^3$ and $k = \Lambda = 0$.

As explained in section 3 we can rely on the Standard Model to describe the expansion between the time t_{TeV} when the temperature was 1 TeV and the decoupling time t_{dec} . Neglecting the small correction due to the hadronic phase transition we have $\rho \propto a^{-n}$, $n = 4$. We use eq. (6) with $t_2 = t > t_1 = t_{TeV}$ and we choose the origin of time so that

$$t_{TeV} = (4\,L\,\rho^{1/2}_{TeV})^{-1} \tag{19}$$

(this is a more precise definition of the choice mentioned at the beginning of section 4). Solving for $a(t) \propto [\rho(t)]^{-1/4}$ we get

$$a(t) \propto t^{1/2}, \qquad t_{TeV} < t < t_{dec} \tag{20}$$

Hence

$$\dot{a}(t_{dec}) \int_{t_{TeV}}^{t_{dec}} dt / a(t) = 1 - (t_{TeV} / t_{dec})^{1/2} < 1$$

and the bulk of the inequality (18) must come from $t < t_{TeV}$:

$$\dot{a}(t_{dec}) \int^{t_{TeV}} dt / a(t) \gtrsim 29$$

or equivalently

$$\dot{a}(t_{TeV}) \int^{t_{TeV}} dt / a(t) > N \tag{21}$$

$$N \sim 29 \, (\rho_{TeV} / \rho_{dec})^{1/4} \sim 6 \times 10^{14} \gg 1 \tag{22}$$

This very large value of the bound N signals how deeply different the pre-t_{TeV} expansion must have been from the law $a \propto t^{1/2}$ extrapolated back to $t = a = \rho^{-1} = 0$, for which the lefthand side of (21) is = 1 ! The fact that $N \gg 1$ is the celebrated "horizon problem" of early cosmology (this denomination refers to the the "horizon distance" D_{max} mentioned above).

We now discuss model-independent aspects of the "horizon condition" $N \gg 1$, before mentioning briefly two popular approaches to its solution. We first ask : can the condition be fulfilled by a power law $a \propto t^q$ $(q > 0)$ beginning at $t = 0$? The answer is of course yes, the condition on q being $q > N / (1 + N)$. From $\rho \propto (\dot{a}/a)^2$ we deduce $\rho \propto a^{-n}$ with $n = 2/q < 2(N + 1) / N$. The adiabatic expansion condition, eq. (2), then gives

$$p = (n - 3)\, \rho/3 < -(1 - 2/N)\, \rho/3 \sim -\rho/3$$

i.e., a negative pressure, unusual physics indeed ! The same feature holds if the pre-t_{TeV} expansion is exponential, $a \propto \exp(H_o t)$ with H_o a positive constant (this is a so-called inflationary expansion scenario which could have started at $t = -\infty$; ρ is then constant, $\rho = 3\, H_o^2 / 8\, \pi\, G$, and

$p = -\rho$ is again negative).

More generally, even without the adiabatic assumption and under the sole condition of continuous expansion ($\dot{a} > 0$), we now show that the horizon condition (21) with $N \gg 1$ implies the very unexpected property that the non-gravitational energy contents of comoving volumes increases dramatically in the pre-t_{TeV} period. This energy varies as ρa^3. It decreases with time or is essentially constant under normal conditions ($\rho a^3 \propto t^{-1/2}$ for $a \propto t^{1/2}$, ρa^3 constant for $a \propto t^{2/3}$). The argument is very simple. Using eq. (1) with $k = \Lambda = 0$, we can write the lefthand side of (21) as follows (we abreviate t_{TeV} and the corresponding values of ρ, a, $\dot{a}$, by $\tilde{t}$, $\tilde{\rho}$, $\tilde{a}$, $\dot{\tilde{a}}$) :

$$\dot{\tilde{a}}\int^{\tilde{t}} dt/a = \dot{\tilde{a}}\int_{a_{in}}^{\tilde{a}} da/(a\dot{a}) = \int_{a_{in}}^{\tilde{a}} (\tilde{\rho}\,\tilde{a}^2/\rho\, a^2)^{1/2}\, da/a \qquad (23)$$

a_{in} is the initial value of a(t) taken at $t = -\infty$ or at a finite initial time as the case may be. The horizon condition (21, 22) implies that the quantity (23) is $\gg 1$. This can only be realized in essentially two ways which are not exclusive :

i) Either there was in the pre-t_{TeV} expansion a phase with $\rho a^2 \ll \tilde{\rho}\tilde{a}^2$ and *a fortiori* $\rho a^3 \ll \tilde{\rho}\tilde{a}^3$.

ii) Or a_{in} was $\ll a$ and ρa^2 was of order $\tilde{\rho}\tilde{a}^2$ for a range of a-values $\ll \tilde{a}$, so that $\rho a^3 \ll \tilde{\rho}\tilde{a}^3$ in that range.

In Ref. 13, where the above argument was first published, it is shown to hold also in presence of the curvature term k/a^2 of eq. (1).

Under the adiabatic expansion assumption, eq. (2), the strong increase of ρa^3 of course means negative pressure at pre-t_{TeV} times. If this assumption is discarded, eq. (2) is replaced by

$$d(\rho a^3) / dt = -p \; da^3 / dt + T \, d(s \, a^3) / dt + dE_g / dt \qquad (24)$$

where s represents the entropy density and the term containing it corresponds to irreversible production of heat. The term dE_g/dt represents any conversion of gravitational into non-gravitational energy not covered by the previous terms. Equation (24) shows that the "new physics" causing the increase of ρa^3 is not necessarily related to negative pressure. Strong irreversible processes creating large amounts of entropy, perhaps at the cost of gravitational energy, could equally well dominate the pre-t_{TeV} expansion.

We end this section with a few remarks on specific models proposed so far for the pre-t_{TeV} expansion. In the first half of the 80's, theoretical cosmologists favoured extensions of the Standard Model with a strong first-order phase transition at temperatures $\gtrsim 10^{10}$ TeV, the high temperature phase being caracterized by a very large positive value ρ_0 of ρ and a pressure $p = -\rho_0$. This high temperature phase created a period of exponential expansion $a \propto \exp(H_0 t)$ with $H_0 = (8\pi G \rho_0 / 3)^{1/2}$. These were the first inflationary scenarios; they ran into considerable difficulties and became very complicated, with a corresponding loss of popularity.

More recently a simpler class of models emerged, based on the assumption that the early expansion was controlled by the interaction of gravitation with one or preferably several scalar fields having very large expectation values at pre-t_{TeV} times. Many scenarios are possible (see for example Ref. 2) and current work explores their possibilities without claims to produce realistic models. When the scalar-field expectation values A_1, A_2,... are constant over a sufficiently large space domain, one adopts a Robertson-Walker metric for the domain, and all one has to solve is a simple system of differential equations for the time variation of the A_i and of the scale factor a(t). The masses and initial values can easily be selected to obtain a pre-t_{TeV} expansion with the desired properties. There is no built-in initial singularity of spacetime, and the interactions of the scalar fields do not play an essential role.

While such models have a strong *ad hoc* character, a nice feature is that they permit a simple discussion of the long-wavelength fluctuations of the scalar fields. Being redshifted by the expansion, these fluctuations can get "frozen", with the result that random differences appear between the expectation values of the A_i in widely separated space domains. This is called "chaotic inflation" and can generate , beyond the limits of the part of the Universe visible to us, large scale inhomogeneities in the spatial distribution of matter and in some of its physical properties.

Concluding Remarks.

Some sixty years ago, Cosmology was revolutionized by the discovery of the Hubble expansion, Friedmann's homogeneous expanding solutions of the Einstein equations became the basis for physical models of the Universe (remarkably enough, the pioneer in this respect was a young priest, G.Lemaître, see the historical account of Ref.14, especially pp. 57 and 58). This led to the Hot Big Bang "orthodoxy" of the 60's and 70's, with microwave background radiation and the Big Bang nucleosynthesis as splendid successes.

Are we experiencing a similar revolution with the tremendous increase of cosmological research in the 80's ? In absence of major breakthroughs it is certainly too early to say, but great intellectual excitement is created by the emergence of many new lines of speculation confronting the accumulation of extremely impressive observational results. Whereas maximum homogeneity and, more generally , basic simplicity (at the cost of incompleteness) characterized most of the cosmological models up to the 70's, the scene is now dominated by the opposite characteristics of complexity and inhomogeneity at the largest dimensions. Furthermore, the theoretical situation is in a constant state of flux, many of yesterday's proposals being overshadowed by new, equally tentative ideas.

In the meantime - and this is in my opinion a most important redeeming feature in the midst of so much speculation - slow but tenacious, high quality work is being done by observational cosmologists and experimental physicists, while phenomenological theorists carefully evaluate their results and confront the various interpretations, the only way to advance in the difficult quest for new cosmological knowledge of lasting significance.

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