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A b s t r a c t

A review of the fundamental cosmological problems is given; possible ways of their solution are discussed. A considerable attention is paid to inflationary universe models.

1. Introduction

Modern cosmology was born after Einstein [1] formulated gravitational theory based on General Relativity and Friedman [2] found nonstationary solution of the Einstein equations. Einstein being the first who put forward the idea of cosmological application of his equations was however discouraged by the absence of stationary solutions in cosmological situation. To get rid of this "shortcoming" Einstein proposed to generalize the equations by adding so called cosmological term [3] which could stabilize the universe. However it soon became clear that the universe indeed expanded in accordance with Friedman's predictions. This was announced by Hubble [4] who discovered the flowing away of distant astronomical objects with the speed proportional to the distance to them. The next natural step, stimulated by the theory of primordial nucleosynthesis, was the formulation by Gamow [5] of the hot universe model. The latter became a respectful and well established cosmological model after discovery of the relic electromagnetic background made by Penzias and Wilson [6]. The detailed calculations of light nuclei synthesis made by Fowler, Hoyle and Wagoner [7] greatly supported the status of the hot model since the results were in excellent agreement with astronomical observations. The most impressive of these was the coincidence with the data of He^4 abundance which was a difficult point for other cosmological models.

The triumphal success of the Friedman cosmology even more emphasizes the fact that the underlying hypotheses are completely weird. I do not mean of course the theoretical foundations (mainly General Relativity); there are few of them and they are very beautiful. The specific values of the model parameters and the initial conditions which determines the evolution of our world that is what makes one feel uneasy. Namely the initial state looked very much like vacuum and the parameters were chosen with an extremely high precision. If this were not the case the universe would look quite different with no condition for life at least in our understanding of the world. One could think that the Creator took special care to make comfortable conditions for our existence looking after almost all from 10^{80} particles in the visible part of the world. The circumstance gives rise to the so called anthropic principle which in its strong form reads: the very our existence is the answer to the question on the properties of our universe. If the universe were slightly different such a question could not be put because no curious (as well as noncurious) creature would exist to put it. The anthropic principle being true, no job is left for a physicist. That's why one seeks for another explanation of these eternal cosmological problems. trying to find a model in which the universe evolves to the present state more ot less independently from the initial conditions obeying only laws of fundamental physics. In recent years a considerable progress in elementary particle physics opened a way to do that. Correspondingly cosmology is reaching a new and higher level: fundamental cosmological parameters formerly taken from observations or considered as a result of specific initial conditions now hopefully can be calculated. One should not think of course that all cosmological problems are solved. There are plenty of difficulties on the way and probably the final solution will be quite different from the variants which are considered now. Anyway the possibility to understand the specific initial conditions in our "best of all possible worlds" seems to be at hand now.

The paper is organised as follows. In section II a short review of cosmological data, which are of interest in what follows, is presented. In section III the fundamental cosmological problems are considered and possible ways of their solutions are outlined. In sectionIV the inflationary universe model, with which the bulk of the recent progress is connected, is discussed in some detail. The results of this presentation are summarised in conclusion.

II. The universe today (mainly observational data)

1. The universe expansion is undoubtful now. Probably undoubtful is also the Hubble law /4/ i.e. proportionality between the velocity v of a remote astronomical object and the distance to it r :

$$v = Hr \qquad (1)$$

Perturbations of these general law due to peculiar motion of separate galaxies or their clasters are of course possible. Less reliable is the numerical value of the Hubble constant H.

Majority of recent observations /8/ give H around 100 km/sec. •Mpc but twice lower value is also presented /9/ . Claims in favour of larger value of H seem impressive and, if not the data on the universe age (see below subsection 6), they could dominate the public opinion pool.

2. Whether the universe expansion will last forever or stop and turn into contraction is determined by the ratio of the average energy density in the universe to the so called critical density:

$$\Omega = \frac{\rho}{\rho_c}, \quad \rho_c = \frac{3H^2}{8\pi G} = 1.86 \cdot 10^{-29} h_{100}^2 \frac{g}{cm^3} \tag{2}$$

where G is the gravitational constant, $G \equiv m_{Pl}^{-2} = (1{,}22 \cdot 10^{19}\ \mathrm{GeV})^{-2}$ *), and $h_{100} = H/(100\ \mathrm{km \cdot sec^{-1} mps^{-1}})$. If $\Omega > 1$, the universe is closed, and somewhen in future it will start to contract. If $\Omega \leq 1$ the universe is open and the expansion will never stop. The special case of $\Omega = 1$ corresponds to the spatially flat, euclidean universe.

The value of energy density, measured through its gravitational effects, now is believed to be more or less around $0{,}3\ \rho_c$ /10/ giving evidence in favour of the open universe the accuracy being not sufficient however. Surprisingly the directly observed amount of luminous matter and of the matter in intergalactic gas is an order of magnitude smaller: $\Omega_B \approx 0.03$.

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*) We use here the natural system of inits where the speed of light, the Planck constant, and the Boltzman constant are equal to unity: $c = h = k = 1$. With this convention temperature, mass, and energy have the same dimensionality of inverse length or, which is the same, inverse time. For example the proton mass m_N is equal: $m_N = 940\ \mathrm{MeV} = 10^{13}\mathrm{K} = (2 \cdot 10^{-14}\mathrm{cm})^{-1} = (7 \cdot 10^{-25}\mathrm{sec})^{-1}$.

Index B here shows that this value of Ω corresponds to the usual baryonic (that is made of protons and neutrons) matter. The discrepancy between Ω found by the dynamics of galaxies and Ω_B is known as the problem of a hidden mass of the universe /11/. One could think that by some unknown reason a considerable part of the usual baryonic matter escaped modern observations. However the data on deuterium abundance in the universe as well as the theory of galaxy formation make it hardly probable. The most popular now is the point of view that the invisible matter is either in the form of massive neutrino or some other not yet discovered particles (e.g. axions, photinos, or gravitinos). The discussion of these topics and references to the relevant literature can be found in papers /12/. In connection with the problem of the hidden mass one cannot exclude also the possibility of a modification of the gravitational interaction at large scales.

The invisible matter could in principle raise the value of Ω up to 1 or even higher but only if this matter is more unifirmly distributed over the space than galaxies and their clusters /13/. The value of Ω is of crucial importance for the inflationary universe model discussed in what follows.

3. As is known the equations of general relativity can be generalised by introducing tho so called cosmological term /3/:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu} \qquad (3)$$

where $T_{\mu\nu}$ is the stress tensor of matter and the term proportional to Λ can be considered as contribution of gravitating vacuum and correspondingly rewritten in the form: $\Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu}^{vac} = -8\pi G \rho^{vac} g_{\mu\nu}$. In the standard cosmology it is assumed that $\Lambda = 0$. Observational bounds [14], if expressed in terms of critical density, are rather weak however:

$$|\rho_{vac}| < 5\cdot 10^{-47} m_N^4 \approx 10^{-29} \frac{g}{cm^3} \approx \rho_c \qquad (4)$$

On the other hand, if compared with a characteristic scale in elementary particle physics as well as with values of energy density in the very early universe, ρ_{vac} is enormously small. This smallness is the basic reason for the assumption that ρ_{vac} is identically zero.

4. The matter density in the universe averaged over large scale looks to a high degree homogeneous. Of course fluctuations are large on the galactic scales but for distances exceeding 100 Mpc relative variation of the density are pretty small:

$$\frac{\Delta\rho}{\rho} < 10^{-3} \qquad (5)$$

Homogeneity of the universe is confirmed also by the isotropy of the microwave electromagnetic background which directional variation does not exceed $10^{-3} \div 10^{-4}$.

5. Practically no antimatter (i.e. positrons, antiprotons, antineutrons) in the universe is observed. Theory predicts however that the number density of antineutrino is not small. Strictly speaking it is possible that some galaxies are made of antimatter but in all known cases of colliding galaxies or the galaxies covered with the same cloud of interstellar gas, it is seen that these regions are filled with the matter of the same type. This fact as well as a low flux of antiprotons

in cosmic rays make one to think that there is no noticeable amount of antimatter in the universe. The presence of only one type of matter is called charge or baryonic asymmetry of the universe.

An important cosmological quantity is the ratio of the average number density of baryons N_B to that of relic photons N_γ,

$$N_\gamma = 550(T/3K)^3 cm^{-3} \qquad (6)$$

In accordance with the modern data this ratio is equal to

$$\beta = N_B / N_\gamma = 10^{-9} - 10^{-10} \qquad (7)$$

6. The time that passed from the initial hot period is called the universe age, t_u. It is definitely larger than $5.10^9 y$ because we know for sure that the Earth is so old. Radioactive isotope chronometry and also observations of old globular clusters demand the larger value /15/ :

$$t_u = 15.10^9 y \qquad (8)$$

The universe age t_u can be expressed through the modern value of the Hubble constant H and the parameter Ω. Since the universe spent almost all life in the state when nonrelativistic matter dominated energy density, the following approximate formula is valid:

$$t_u = 10.8 \cdot 10^9 y \cdot \left[h_{100} \left(1 + \frac{1}{2}\sqrt{\Omega}\right)\right]^{-1} \qquad (9)$$

(under assumption of vanishing cosmological term).

Evidently value (8) does not agree with $h_{100} = 1$ (i.e. $H = 100$ km.sec^{-1} Mpc^{-1}) and we are to choose among the following possibilities:

a) the Hubble constant is smaller than it is claimed in recent papers, $h_{100} < 0,6$;

b) the theories of nucleosynthesis and star evolution are not very accurate, so a smaller value of t_u is permissible (e. g. $t_u \simeq 10.10^9 y$);

c) The cosmological constant is nonvanishing and close to its upper bound (4).

Let us note in advance that in the inflationary universe model the above mentioned contradiction is slightly worse because this model demands $\Omega = 1$ and correspondingly t_u is smaller than for $\Omega = 0,3$.

III. Fundamental cosmological problems

The Einstein equations on which most of modern cosmological models are based, for the case of homogeneous and isotropic matter distribution have the very simple form:

$$\ddot{a} = -\frac{4\pi G}{3} a (\rho + 3p) \tag{10}$$

$$\dot{a}^2 = \frac{8\pi G}{3} \rho a^2 - k \tag{11}$$

where dot means time derivative, ρ and p are respectively energy density and pressure of matter (with possible taking into account vacuum term), a is a scale factor, and k is a numerical constant which value can be chosen as ± 1 or 0 with a suitable redefinition of a.

Eq. (11) can be rewritten in the form

$$\rho = \rho_c - \frac{k}{a^2}, \quad \rho_c = \frac{3\dot{a}^2}{8\pi G a^2} \tag{12}$$

Hence $k < 0$ xorresponds to the closed universe and $k > 0$ corresponds to the open universe. The regime of expansion depends on equation of state $p = p(\rho)$. We write down here some interesting specific examples for the special case ($k = 0$):

Relativistic gas	$p = \frac{\rho}{3}, \quad \rho(a) \sim a^{-4}, \quad a \sim t^{1/2}$	(13a)
Nonrelativistic matter	$p = 0, \quad \rho(a) \sim a^{-3}, \quad a \sim t^{2/3}$	(13b)
Strings	$p = -\frac{\rho}{3}, \quad \rho(a) \sim a^{-2}, \quad a \sim t$	(13c)
Domain walls	$p = -\frac{2\rho}{3}, \quad \rho(a) \sim a^{-1}, \quad a \sim t^{2}$	(13d)
Gravitating vacuum	$p = -\rho, \quad \rho(a) = const, \quad a \sim \exp\left\{\left(\frac{8\pi G}{3}\rho\right)^{1/2} t\right\}$	(13e)

Today the universe is dominated by nonrelativistic matter and the expansion law is close to (13b) (if ρ is not too far from ρ_c). The change of the regime from relativistic to nonrelativistic one took place at the following value of the red shift factor $z = 4\,\Omega \cdot h_{100}^2 \cdot 10^4$. We do not know whether strings or domain walls dominated energy density in early universe; it is often assumed that there was a period when the cosmological term was dominating. The possible role of domain walls in the universe was considered in ref. /16/ where it was argued that the walls born by the spontaneous breakdown of a discrete symmetry would spoil the observed homogeneity of the universe. Cosmological effects due to strings are discussed in papers /17/. It is shown that the inhomogeneities caused by possible string production in the very early universe are acceptably small and, what's more, the strings that exist in some unified theories of strong and electroweak interaction with a characteristic scale of the order of $10^{14} - 10^{15}$ GeV can explain the large scale structure of the universe (galaxies and/or their clusters).

How far can one travel backward in time depends on our knowledge of particle interactions at high energies and densities. Relativistic expansion law (13a) is surely valid up to temperatures of several tens or even hundreds MeV. Somewhere in this energy region the equation of state of the primeval plasma could change due to quantum chromodynamical phase transition to hadrons from free quarks and gluons. Before the phase transition the equation of state was also close to that of the ideal relativistic gas of elementary particles. And we believe that this continued starting at least from the temperatures of 100 GeV. Roughly up to this energy we have information on particle interactions confirmed by experiment. Extrapolation into region of higher temperatures is not so reliable because for $E > 100$ GeV there exist almost no experimental data on elementary particles. There is however a theory which in a inified manner describes strong and electroweak interaction, has also some other attractive features, and states that nothing unusual happens up to the Planck energy $E = 10^{19}$ GeV, when effects of quantum gravitation were of importance. Unfortunately no theory of the latter is yet established. In the frameworks of Grand Unified models one can hope to describe the universe history till the quantum gravitational era as definitely as a concrete model (which is in fact not singled out) permits. If all the phase transitions happened in the course of the universe expansion and cooling down were that of the II order or weak I order then the influence of them on the expansion regime were not much important and equations (13a) were approximately valid till the Planck energy. If a phase transition was strong I order one and the stress tensor was dominated by the cosmological term then for some time the expansion was exponential (13e). The statement about phase transitions with changing temperature in field theories with a spontaneously broken symmetry was made in papers /18/ and since is used in cosmological models.

Returning to eq. (12) let rewrite it in the form

$$\Omega_2^{-1} - 1 = \left(\Omega_1^{-1} - 1\right) \frac{\rho_1 a_1^2}{\rho_2 a_2^2} \tag{14}$$

where indices 1 and 2 mean that the corresponding quantities are taken at time moments t_1 and t_2 respectively. Choosing t_1 and t_2 to be the today's moment and the moment of the change from the relativistic expansion regime to the nonrelativistic one we find $\Omega_2^{-1} - 1 = (\Omega_1^{-1} - 1) z_1^{-1} \approx 10^{-4}$. If t_2 is taken as a moment when the primordial nucleosynthesis started ($t_2 \approx 1$ sec, $T_2 \simeq 1$ MeV) - one can be sure that the universe was in this state since it is confirmed by the observational data on the abundances of light elements, then $\Omega_2^{-1} - 1 \simeq 10^{-16}$. If one travels even farther in time till $t_2 = 10^{-43}$ sec and $T_2 = T_p = 10^{19}$GeV then $\Omega_2^{-1} - 1 \simeq 10^{-59}$. In other words if a universe created at the Planck moment is to survive to the present state the value of the cosmological parameter Ω must be very well tuned. This fine tuning reflects the huge difference between the Planck time and the modern universe age. Indeed if $\Omega - 1 = O(1)$ at $t = t_p$ then the characteristic expansion time would be of order 10^{-43}sec, i.e. for the closed universe the expansion would turn into contraction in about that time and the open universe would expand so fast that no galaxies, stars, and planets could form. Thus the very our existence gives evidence in favour of very special initial condition, of almost spatially flat early universe.

This mysterious fact is one of the most important cosmological problems which is called

1) the flatness problem.

There are some other important cosmological problems without solving which we cannot hope to understand how our world was created.

2) Isotropy and homogeneity problem.

These also suggest some very specific initial conditions, large violation of which are not forbidden even by antropic principle. So a natural expansion of this fact is even more desirable.

Isotropy of the microwave background supporting the isotropy of the universe gives rise to another problem

3) the horizon problem which is due to the slow rise of the scale factor a in regimes (13a) and (13b) in comparison with the sise of the causally connected region (horizon) $h \sim t$.

The relic electromagnetic quanta became free, i.e. stoped to interact with the matter in the universe when the temperautre fell lower than the hydrogen recombination temperature $T_r \simeq 3000$ K. From that time the scale factor rose $Z_r = \frac{T_r}{3K} = 1000$-fold. For standard expansion regime (13a) the horizon size was about 10^{13} sec at that moment and correspondingly the physical processes forming electromagnetic background could occur only in a smaller domain. Nowadays the size of this region became $R = Z \cdot 10^{13}$ sec. The radiation having ceased to interact with matter 10^{10} years ago, regions with the angular size larger than 0.03 are disconnected physically. Meantime relic radiation coming from different directions on the sky is the same. This shows that some deviation from the standard expansion regime must exist which made possible signal (interaction) exchange between different parts in the sky.

4) <u>The problem of the cosmological constant</u>. As was mentioned before $|\rho_{vac}| < 10^{-46} m^4$. It is fantastically small in comparison with standards of elementary particle physics /19/. Indeed quantum field theory predicts that vacuum fluctuations of quantum fields give some contribution into vacuum energy. This contribution is infinite for any particle type but there is a hope based on supersymmetric models that these infinities cancell when summed over all boson and fermion species. However supersymmetry being not exact, a finite part in this sum does not generally vanish and is of the order of m_o^4 where m_o is a characteristic mass scale of supersymmetry breaking. Besides in gauge theories which describe elementary particle interactions phase transitions with changing temperatures are possible /18/. During such transitions vacuum energy changes its value. For example the change of vacuum energy due to phase transition in QCD is about $\Delta\rho_{vac} = (10^{-3} - 10^{-4})\, m_N^4$, in electroweak interaction $\Delta\rho_{vac} \simeq 10^{8} m_N^4$, and in grand unified theories $\Delta\rho_{vac} = 10^{60} m_N^4$. Since the today's value of vacuum energy is known to be zero (vacuum does not gravitate now) these phase transitions which took place during the cooling down of the universe imply that initially the vacuum

energy was nonvanishing and prepared with the fantastic accuracy of not less than 10^{-106} if a more natural mechanism of eating up the cosmological term will not be found.

5. The problem of singularity and universe creation seems to be most difficult of all we encounter now. Recently the hypothesis of universe creation from "nothing" as a result of quantum jump became popular /20/. Such a universe is necessarily closed with vanishing all net conserved quantum numbers. From the infinite multitude of universe created in this way only those are suitable for life which do not much differ from ours. This gives an answer to the question of the specific initial conditions mentioned above. Unfortunately we have no reliable theory for description of such a quantum jump.

The idea of ever existing closed oscillating universe encounters difficulties because of infinite entropy generation. To avoid this a crucial alteration of physical laws at small distances is necessary. An attempt of this kind based on the aaumption of a limiting value of energy density was made in ref. /21/. The question of entropy generation in the frameworks of this model is not yet clear however.

6) The long standing problem of charge asymmetry of the universe i.e. of dominance particles over antiparticles can be considered as resolved now /22/. In the frameworks of Grand Unified Models not only qualitative but also reasonable quantitative agreement with the astronomical data for N_B/N_γ is obtained. Let describe briefly how one understends today the mechanism of generation of an excess of particles over antiparticles so that we need not to return to this in what follows giving the bulk of the paper to other not so well

understood puzzles. A more detailed discussion can be found in review /23/ or in popular paper /24/.

The basic point is the hypothesis of baryonic charge nonconservation which is in fact inherent to the Grand Unification Models. Some of these models predict the existence of superheavy particles (H and X bosons) with masses about 10^{14} - 10^{15} GeV. These particles can decay into states with different values of baryonic charge B. Two other essential ingredients of the mechanism are a violation of charge symmetry (i.e. different interactions of particles and antiparticles) and violation of thermodynamical equilibrium caused by the universe expansion. It can be shown that in these conditions decays and inverse decays of H and X bosons produce an excess of particles over antiparticles (or vice versa) and the latter is not compensated by other processes because of nonequilibrium. The exact value of this excess can not be calculated because we do not know much about X and H meson decays but an order of magnitude estimates are in reasonable agreement with observations. It is especially attractive that for some models the result does not depend upon initial conditions i.e. upon initial excess of baryons or antibaryons. An important feature of the considered mechanism in its classical form is the presence in the primeval plasma of large amount of X and/or H bosons and correspondingly a high temperature of the plasma, $T \gtrsim 10^{15}$ GeV. at the period of charge excess generation.

7) The problem of magnetic monopoles stands apart from those enumerated above. It is not a specific cosmological problem but emerging because of the prediction /25/ of magnetic monopole existence in gauge field theories. Monopoles born during phase transition from symmetric to nonsymmetric state

of a Grand Unification Model, as the universe expanded and cooled down, survived up to now and their residual concentration calculated in the frameworks of the standard cosmological scenario proves to be inacceptably large [26].

Problems 1, 2, 3 and 7 can be resolved in a beautiful and unified way in the inflationary universe model [27,28] but the problem of cosmological term becomes even deeper. The starting point of the inflationary universe model is the dominance of the vacuum term in the stress tensor $T_{\mu\nu} \simeq \rho_{vac} g_{\mu\nu}$ during some period in the universe history. In accordance with eq. (13e) the scale factor rises exponentially during this period and the energy density quickly tends to its critical value, so that $\Omega \to 1$ (see eq. (14)). In this model the universe looked for some time as an expanding empty space (the density of initially present matter exponentially tended to zero). During this fast expansion all the initial conditions became forgotten and the universe became so homogeneous as only vacuum could be. However this was not a real vacuum but false and it exploded bearing particles [23] which filled the universe and thermolised. After that the expansion regime became the Friedman's one. The necessary duration of the inflation τ depends upon the temperature of the produced particles. To insure the contemporary value $\Omega = O(1)$ the condition $\exp(H\tau) > 10^{30}(T/m_p)$ must be fulfilled, i.e.

$$H\tau > 0 - \ln \frac{m_p}{T} \qquad (15)$$

So τ is not unreasonably large.

If the exponential (de Sitter) stage indeed existed in the universe history, the initial value of Ω could be almost arbitrary. If the universe is open and $\Omega \leqslant 1$ then in the course of expansion the energy density of matter ρ_m decreased and correspondingly vacuum term ρ_{vac} began to dominate generating exponential expansion. If the universe is closed, $\Omega > 1$, then generally the contraction began when $\rho_m > \rho_{vac}$ and no exponential stage took place. However, as was noted by L.B.Okun, in an oscillating universe the amplitude of the oscillations rises due to entropy generation and correspondingly ρ_m in the point of maximal expansion becomes smaller. Thus sooner or later a closed universe starts to have an exponential period in its life. (of course if $\rho_{vac} \neq 0$, $\rho_{vac} < 0$). So the flatness of our universe can be explained without assumption of a fine tuning of initial values of the parameters. If one takes this point of view however then for a resolution of the problem of flatness for the closed universe no inflationary scenario is needed. Indeed the universe oscillating with an increasing amplitude comes ultimately into the present state and we could be in it only when the conditions for life became bearable.

The horizon problem is also naturally solved in an inflationary scenario because the scale factor is proportional to exp(Ht) and rises faster than the horizon.

It is noteworthy that value of Ω in this model should be very close to unity because almost any excess of τ over its lower bound (15) will lead to the universe which almost absolutely flat and deviation of Ω from 1 is in fact determined by density fluctuations. Astronomical data however tend against this value rather giving $\Omega \simeq 0.3$ if only the universe is not filled by a uniforly distributed matter /13/

e.g. in form of weakly interacting massive particles (neutrino, gravitino, etc.). In this connection a more reliable determination of the Hubble constant is of importance. In particular for $\Omega = 1$ $h_{100} = (7,2.10^9 y/t_u)$. This might be the only way to verify inflationary models.

Inflationary model presents also a natural solution to the magnetic momopole problem, if after the phase transition which generates the monopoles, a considerable exponential expansion takes place. This is also necessary for suppression of inhomogeneities (see below). In this case one could hardly expect to find more than one monopole in all the visible part of the universe and the registration of the second one (after that of ref. /30/) would demand a modification of this simple version of the model. Let us note in this connection that in supersymmetric inflationary models /31/ the problem of monopoles comes to life again. With more complicated models however it is possible to have variants in which the monopole density does not contradict observation and at the same time is not negligibly small.

As for the homogeneity problem the originality formulated model /27/ was far from satisfactory. The point is that the inflation proceeded in a symmetric state before the phase transition. Later bubbles of new asymmetric phase were born, inflation ended and these bubbles filled all the space. Generally in models of this type the inhomogeneities due to the bubble's walls should be lerge (in ref. /32/ a mechanism of vacuum burning was considerdd which might give rise to small inhomogeneities). Much smaller inhomogeneities appears in the new inflationary universe scenario /28/ in which a considerable exponential expansion takes place not only before and also after the phase transition because the vacuum expection value of the scalar field (order parameter) tends to its limit in the symmetric state slowly in comparison with the expansion rate. Inhomogeneities in the new inflationary universe scenario were discussed in ref. /33/ where it was shown that in the simplest version based on SU(5) model of Coleman and Weinberg (see below) the inhomogeneities would be acceptably small if very restrictive and unnatural conditions were imposed on the underlying theory. This made one to consider supersymmetric models /31/ which may not suffer from the mentioned shortcoming. However in supersymmetric approach other difficulties (with magnetic monopoles, particle production at the end of inflation, etc) can arise. To get rid of them more complicated models is to be constructed. Thus inflationary scenatio in principle beautifully solves many of enumerated above cosmological problems, however no final, worked out in detail, and free of all the shortcomings model is not yet found.

What makes one feel especially uneasy in connection with the inflationary scenario is the problem of the cosmological term. The point is that the inflation is driven by a nonzero vacuum energy which is to be absolutely cancelled after phase transitions*). It seems to be quite a difference either one

*) Recently Linde proposed a model of inflation without a first order phase transition. It is discussed in some detail in the next section.

assumes ρ_{vac} = 0 identically or $\rho_{vac} = -\delta\rho \neq 0$ at thebeginning (here $\delta\rho$ is the change of vacuum energy under phase transitions). Advocates of inflationary models can however reasonably object that the cosmological term problem exists independently of inflation. An exception is the model of ref. /34/ where inflation takes place in the planckian (or ever earlier) epoch and is driven by vacuum polarisation corrections to the Einstein equations. It is possible also that there exist alternatives to the inflationary scenario opening other ways for resolution of the above mentioned problems; for example in ref. /35/ an attempt is made to explain large entropy stored in our universe by large amount of phase transitions in the very early universe. In any event the inflationary model is the first cosmological model which gives a solution to several eternal cosmological problems which were earlier considered as a fancy of initial conditions. In more detail this model is described in the following section.

Returning to the cosmological term problem let us note that taken by their face values quantities t_u, H, and Ω give evidence in favour of $\rho_{vac} \neq 0$. If an inflationary model is valid and hence $\Omega = 1$ then for $h_{100} = 1$ and $t_u = 15.10^9 y$ the vacuum energy should be positive and be about $0.95\rho_c$. Since ρ_c varies with time (roughly as $m_p^2 t^{-2}$) and ρ_{vac} = = const, this means that the influence of ρ_{vac} is noticeable only in the present epoch and in earlier time it can be neglected. This reveals one more mysterious coincidence. At the moment no absolutely satisfactory model explaining the smallness of the cosmological term is known, but if the presented above values of H and t_u are confirmed, it seems more natural to demand from such models not absolute concellation of ρ_{vac} but only up to terms of the order of m_p^2/t^2. The noncompensated part of ρ_{vac} which is not necessarily proportional to $g_{\mu\nu}$ could be noticeable in all the history of the universe; it could influence the primordial nucleosynthesis, galaxy formation, give its contribution into the missing mass, etc. In ref. /36/ a dynamical model of killing a vacuum energy was considered. The idea is to organise a cancellation of the vacuum energy by a condensate of a scalar field interacting with gravity. The condensate generation is driven by the cosmological term itself. In this sence the model uses the well known in radiotechnique feedback effect. The compensation of a vacuum energy, being made by gravitational interaction, proceeds rather slow so that the noncompensated term is always of order of ρ_c. The concrete model however is based on a quantum field theory on which very restrictive and unnatural conditions are imposed.

It seems that the cosmological term problem is now the central cosmological problem and without its solution no cosmological model can be considered as absolutely satisfactory.

As for the problem of initial singularity and universe creation there exist some crazy ideas in the literature. I would like to add to them an extra one. Assume that there exist, say, a scalar field δ with an effective potential unbounded from below and with infinite amount of local minima separated from each other by a potential barier, each minima deeper and deeper as δ increases. By-hand examples of such a potential are $m^2\delta^2 \cos(\delta/\sigma)$ or

$m\delta^3[1-\varepsilon\cos(\delta/\sigma)]$. Universe once created (may he infinitely long ago) would stuck in one of these local minima for some, generically very large time, then after quantum channel transition through the potential barier goes into other lower vacuum state and so on infinitely many times. The energy released through these quantum jumps eventually turns into elementary particles and the latter would be very much dissolved in space due to universe expansion especially if the latter was exponential. The cosmological term (or to be more exact terms) appearing in this model could be compensated by the mechanism of the type proposed in ref. /38/. The model describes an ever expanding universe infinitely cooling down practically to vacuum and infinitely bursting into flare again, demostrating an infinite number of big-bangs. A suitable name for such a universe is the Phoenix universe. Unfortunately (or better to say, fortunately) this conception is impossible to verify because in case of the next big-bang an observer would disappear before observe anything.

IV. Inflationary universe models

Inflationary universe models are mostly based on the assumption that the phase transition from symmetric to nonsymmetric state is strong first order. In a symmetric state there is no condensate of a scalar field, $\langle\varphi\rangle = 0$, and vacuum energy is nonzero:

$$T_{\mu\nu}^{vac} = -g_{\mu\nu}V(\sigma) \qquad (16)$$

where V is the effective potential of field φ and σ is the vacuum expectation value of φ after the phase transition. Important assumption (16) has no natural grounds and is imposed on the model just to ensure the vanishing of the cosmological term in the nonsymmetric phase.

Primarily there could be a matter in the universe with energy density ρ_m but in the course of expansion $\rho_m \to 0$ and ρ_{vac} = const (if a mechanism which kills cosmological term proceeds slowly). If ρ_{vac} became larger than ρ_m before the phase transition occured, the universe would exponentially expand till the transition ended:

$$a \sim \exp(Ht), \quad H = \left[\frac{8\pi}{3M_\varphi^2} V(\sigma)\right]^{1/2} \qquad (17)$$

The value of $V(\sigma)$ is typically of the order of $(10^{15}\,\text{GeV})^4$ in Grand Unified Models, hence $H \approx 10^{11}$ GeV.

As a simplified model of phase transition let consider scalar field theory described by the Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \ldots \qquad (18)$$

where dots denote terms which describe interaction with other particles: gauge bosons, fermions, other scalar fields. The Lagrangian possesses symmetry with respect to transformation $\varphi \to -\varphi$ and maybe a higher symmetry if φ is a multicomponent field. In the standard model of spontaneous symmetry breaking it is assumed that $m^2 < 0$ and thus the stable extremum of the potential is the point $\varphi_0^2 = -m_0^2/\lambda$. For nonzero temperature the extra term $\alpha T^2\varphi^2$ is added to the potential. If the temprature is sufficiently high, the equilibrium point is shifted to $\varphi = 0$ /18/. Hence the behaviour of φ when the universe cools down should be the following. At high temperature vacuum expectation value of φ is vanishing, $\langle\varphi\rangle = 0$. This corresponds to unbroken symmetry. With falling temperature the sum ($m^2 + \alpha T^2$) becomes negative and $\langle\varphi\rangle^2 = -(m^2+\alpha T^2) \neq 0$. The symmetry is spontaneously broken, particles interacting with φ obtain masses proportional to $\langle\varphi\rangle$. The phase transition in this model is evidently of the second order and this is not what we need. However in more complicated models e.g. based on SU(5) symmetry group quantum corrections make possible first order phase transitions for a rather wide range of parameters. For details and references to the original papers one can adress to reviews /37, 38/. It can be shown that in a class of theories the effective potential calculated with the account of one loop diagrams is of the form /18, 39/

$$V(\varphi,T) = \frac{1}{2}(m^2+\alpha T^2)\varphi^2 + \frac{\lambda}{4}\varphi^4 \ln\frac{\varphi^2}{\sigma^2\sqrt{e}} + aT^4\int_0^\infty dx\, x^2 \ln\left\{\frac{1-e^{-\sqrt{x^2+b\varphi^2/T^2}}}{1-e^{-x}}\right\} \quad (19)$$

where $\sigma = 10^{14} - 10^{15}$ GeV; α, λ, and b are numerical constants depending on interaction strength; value of a does not depend on interaction, the contribution of the corresponding term gives for $\varphi = 0$ just the thermal energy of particles. Let neglect the last term in eq. (19) assuming that the temperature is small. This does not qualitatively change our conclusion. Potential (19) has a minimum at $\varphi = 0$ if $m^2 + \alpha T^2 > 0$. If $m^2 + \alpha T^2 < \lambda\sigma^2 e^{-1}$ then except for the first minimum there is another one at $\varphi \simeq \sigma$. This minimum is deeper than the first one for $m^2 + \alpha T^2 \lesssim \lambda\sigma^2/4$. Hence stable at high temperature minimum at $\varphi = 0$ becomes quasistable separated from the new stable minimum (real vacuum of the theory at T = 0) by a potential barrier. As a rule, quantum transition through a potential barier is exponentially suppressed. Thus the system under consideration can be in the quasistable state for a very long time. The tunnel transition in quantum field theory was first considered in ref. /40/. Technically more elegant approach was proposed in papers /41/. It was shown in these papers that the transition probability is determined by the action calculated on solution of classical equation of motion in imaginary time. An approximate result can be obtained in a simpler way by calculating extremum of the action variationally. In particular the probability of tunnel transition per unit of time and volume in potential (19) at zero temperature is approximately equal to

$$\frac{dW}{dV dt} \approx M^4 \exp\left\{-\frac{8\pi^2}{3\lambda} \frac{1}{\ln\frac{\lambda\sigma^2}{m^2}}\right\} \tag{20}$$

where M is an unknown parameter with dimension of mass; its value probably is of the order of the inverse size of the bubble of new phase, i.e. $M \simeq m$. Since $\lambda < 1$ the transition time is enormously large and the universe could indeed exponentially expand so that no trace of the primary matter would be left. One should keep in mind however that due to event horizon in the de Sitter space the temperature in it does not vanish but tends to $H/2\pi$ in the comoving frame /42/.

RThe state with $\langle\varphi\rangle = 0$ being unstable the transition to the new phase with $\langle\varphi\rangle \neq 0$ should take place sooner or later. Immediately after the phase transition the value of classical field φ inside the bubble of new phase is of order $m/\sqrt{\lambda}$. It follows from the dependence (19) of effective potential on φ. For natural parameters values φ tends to its limit σ quickly in comparison with H. Indeed after the quantal jump giving origin to the phase transition the time evolution of φ is described by the equation

$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{\partial V}{\partial \varphi} \qquad (21)$$

with the initial conditions $\varphi(0) \approx m/\sqrt{\lambda}$ and $\dot{\varphi}(0) = 0$. Here the space derivatives of φ were neglected because their contribution is divided by the scale factor and quickly vanishes. The value of $\partial V/\partial\varphi$ at $\varphi = m/\sqrt{\lambda}$ can be estimated with the help of eq. (19) as $m_1^2\varphi$, where m_1 is a parameter with the dimension of mass. Generically in Grand Unification Theories $m_1 \gg H$ and thus φ increases with time as exp ($m_1 t$). Consequently after the bubble is born the phase transition terminates in much smaller time than H^{-1} so no exponential expansion of the bubble take place. If it were the case there would be many bubbles in the visible part of the universe and the inhomogeneities would be too large. A more detailed discussion and references to the original papers can be found in ref. /37/.

In the modified inflationary scenario [28] restrictive condition $m^2(T) \equiv \partial^2 V(0,T)/\partial \varphi^2 \ll H^2$ is imposed on the potential. This condition, which does not naturally follow from the theory, is specially invented to ensure a slow rise of $\varphi(t)$ after a bubble of new phase was born: $\varphi(t) \sim \exp\,(m^2 t/3H)$. The problems we encounter can be solved if $m^2 < H^2/25$. The bubble in this case quickly inflates so that all visible part of the universe is the inner part of a single bubble which was at the moment of its birth of the size $\sim m^{-1}$ and to the present time became as large as

$$R \gtrsim \frac{1}{m} \exp\left\{\frac{3H^2}{m^2}\right\} \cdot \frac{T}{3K} \tag{22}$$

Here T is the temperature of the primeval plasma after the end of phase transition. The total universe expansion in this scenario is much larger and differs from that given by eq. (22) by the exponential factor in expression (20). The inhomogeneities size in this version of the model are of course considerably smaller than in the original one. Nevertheless calculations made in frameworks of the standard SU(5) theory show that the inhomogeneities are about two orders of magnitude larger than we see in reality [33]. Note that in contrast to the previous case the inhomogeneities are connected with the rise of quantum fluctuations of φ in de Sitter space and not with the bubble's walls. It is noteworthy that in the standard universe scenario (i.e. without a de Sitter phase) the evaluation of inhomogeneity size due to quantum fluctuations gives the result about two orders of magnitude smaller than it is necessary for galaxy formation.

To ensure small inhomogeneities effective potential $V(\varphi)$ should be very flat in a rather large range of values of φ beginning from φ near zero. However the rate of particle production by external field $\varphi(t)$ is proportional to the speed of φ variation and correspondingly in a model of the discussed type the particles that should fill the expanding vacuum and serve as a building material for our world are produced too slowly, their density and temperature, if they have enough of time to thermolize, are low and the baryonic asymmetry of the universe could not be generated. A detailed review of these problems as well as discussion of the role played by gravitation and temperature in such a scenario are given in papers /38/. We note only that usually gravitational effects are not important when the energies are small in comparison with the Planck energy. In the considered model however a new hierarchy of mass is introduced $m^2 \ll H^2$ or $m^2 \ll R$ where R is the four dimensional curvature. Because of this condition gravitational corrections to the effective potential are not small. In particular it is known that to a Lagrangian of a scalar field the term $\frac{1}{2}\xi R\varphi^2$ can be added, which considerably changes the effective mass of φ in de Sitter space.

The smallness of effective mass m^2 in comparison with H^2 mentioned above presumes the smallness or cancellation of different terms contributing into the coefficient of $\frac{1}{2}\varphi^2$ in the effective Lagrangian:

$$m^2 = m_0^2 + \alpha T^2 + \xi R + \lambda \langle\varphi\rangle^2 + \dots \tag{23}$$

Here m_o is the mass of φ in the symmetric state in flat space with zero temperature. Natural value of m_0 in Grand Unification Models is about 10^{14} GeV. An exception is the Coleman-Weinberg model [43] which is in fact defined by the condition $m_0 = 0$ imposed on $V(\varphi)$. Maybe there is a hidden beauty, but strictly speaking no arguments are found to keep $m_0 = 0$. Moreover the Coleman-Weinberg model was originally formulated in flat space-time and the condition $m_0 = 0$ meant

$$\frac{\partial^2 V}{\partial \varphi^2}\Big|_{\varphi=0,\ R=0} = 0 \tag{24}$$

where R is the space-time curvature. However the condition R = 0 at $\varphi = 0$ is not fulllfilled in the inflationary model and instead $R = -8\pi G T^\mu_\mu = 32\pi G V(\sigma)$. Hence it was proposed [38] to change condition (24) to the following

$$\frac{d^2 V}{d\varphi^2}\Big|_{\varphi=0,\ R=32\pi G V(\varphi)} = 0 \tag{25}$$

Since we do not understand the cosmological term puzzle, this equality is not very well based. For example in the model of ref.[36] the condition $R = 32\pi G V(\sigma)$ is generally not valid and consequently a selfconsistent version of the Coleman-Weimberg model in a curved space should be different.

The second term in eq. (23) comes from interaction of φ with heat bath. The value of α is of the order of Ng^2 where $g \approx 0.5$ is the gauge coupling and N is the number of vector field species in the symmetry group under consideration. Due to existence of lower limit for temperature in a De-Sitter space, $T_H = H/2\pi$ /42/, this term by itself can violate the condition $m^2 < H^2/25$. To prevent from such a violation it was proposed in papers /31/ where supersymmetric inflation was considered that φ is a gauge singlet not interacting with vector fields. As for couplings to other dields they can be made arbitrarily small and with them constant α. Such field with the only "reason d'etre" to ensure inflation is called inflation.

Conformal invariance if imposed on the scalar field theory demands $\xi = 1/6$. In this case the third term in expression (23) give too big contribution: $\xi R = 12\xi H^2 = 2H^2$. It is known however that conformal invariance in a field theory is as a rule violated and so no grounds for the condition $\xi = 1/6$ exist. In particular it can be shown /44/ that for Goldstone bosons ξ is zero.

The last explicitely written down term in eq. (23) is generated by quantum fluctuations of φ in curved space-time /45/. It can be negligible if constant λ which determines the selfinteraction of field φ is chosen sufficiently small.

Thus putting aside naturalness the necessary duration of inflation after the phase transition can be achieved. It is more difficult to solve the homogeneity and baryon asymmetry problems. The effective potential in this case should be extremely flat for $\varphi < H$ so that $V''(\varphi) \ll H^2$ and rather steep for large φ. One can construct models giving potentials of this kind but they seem to be rather complicated and at the moment no concrete mechanism of inflation is generally accepted.

Now let discuss briefly particle production at the end of inflation. Immediately after the phase transition the universe was "without form and void; and darkness was upon the face of the deep". No usual matter in form of elementary particles was present. Classical field φ was rising in accordance with eq. (21) and the stress tensor in the right hand side of the equations of General Relativity was changing in accordance with equations:

$$\rho = \rho_{vac} + V(\varphi) + \frac{1}{2}\dot{\varphi}^2$$
$$p = -\rho_{vac} - V(\varphi) + \frac{1}{2}\dot{\varphi}^2 \qquad (26)$$

Potential $V(\varphi)$ satisfies the conditions $V(0) = 0$ and $V(\sigma)$ is connected with ρ_{vac} by eq. (16). Here σ is the value of φ at the stable minimum of the potential.

In the new inflationary scenario /28/ the value of φ after the phase transition φ_0 is small so that $V(\varphi_0) \ll \rho_{vac}$. Besides the variation of φ with time is assumed to be slow, $\dot{\varphi}/\varphi \ll H$. Hence at the beginning the expansion is not noticeably changed being almost the same (exponential) as it was before the phase transition. Practically no particles are produced during this period. Then for larger φ $V(\varphi)$ becomes steeper and φ starts to oscillate around its equilibrium point σ. The oscillation damping is caused by two factors. The first is the universe expansion which gives rise to the friction term $3H\dot{\varphi}$ in eq. (21) and the second is the particle production. The latter is not taken into account in eq. (21). The oscillation frequency being rather high, $\omega \approx m(\varphi = \sigma) = 10^{14} - 10^{15}$ GeV, particle production becomes essential. The expansion regime abruptly changes from exponential (13e) to nonrelativistic (13b). Indeed for harmonic oscillations the pressure determined by eq. (26) vanishes which just corresponds to equation of state (13b). Deviations from pure harmonicity are not very much important. Estimations made in concrete models show that the rate of particle production $\dot{N}/N$ during the period under consideration is as a rule larger than the universe expansion rate $H = 2/3t$. It is assumed in the standard model that φ is a Higgs field and so its coupling to other field is proportional to their masses. Correspondingly oscillating field φ produces mostly the heaviest particles with the condition however that their mass does not considerably exceed oscillation frequency ω. As a result of this process the universe became filled up with superheavy bosons which were far out of equilibrium. This favoured the baryoproduction. The decay of these superheavy particles produced lighter species such as leptons, quarks, gluons, photons, etc. Shortly after the decay the primeval plasma thermalized and the expansion law become relativistic (13a). The temporary dominance of heavy particles in the energy-momentum tensor and a smaller-than-equilibrium density of the superheavy particles led to some dilution of the baryon asymmetry:

$$\beta = 3\beta_0 \frac{T_1}{m(\varphi \to \sigma)} \qquad (27)$$

where β_0 is the baryon asymmetry originally generated by the superheavy boson decay, T_1 is the temperature of the primeval plasma after thermolization, and $m(\varphi=\sigma)$ is the mass of field φ at the stable equilibrium point σ. Thus the models in which the primeval plasma is too cold to the moment of thermolization are forbidden.

Besides the difficulties with the inflationary scenario described above which are rather of technical character there are some more important problems connected with quantum tunneling in curved space-time. The theory of tunneling in flat space-time proposed in ref. /40,41/ was generalized for a de Sitter space in papers /46/. The latter can not be directly applied to our case however because the results obtained by the imaginary time method for an exact de Sitter space are not necessarily valid for the real universe which only approximately was a de Sitter one. The reason for this is that analytic continuation (from real to imaginary time) of an approximate function can differ very much from the analytically continued exact one.

One may try here the Hamiltonian formalism*) and solve quasiclassically the functional Schroedinger equation for the state vector of the considered field theory in a given gravitational background. The condition that the inflation period is sufficiently long demands that the vacuum energy after the phase transition does not noticeably change. This justifies the neglect of back reaction of φ on gravity.

Assuming that the metric is of the form $ds^2 = dt^2 - e^{2Ht} dz^2$

*) Analogous arguments were also presented by A.Goncharov and A.Linde (private communication).

we obtain

$$\left\{ 2i\frac{\partial}{\partial\tau}+\frac{\delta^2}{\delta\varphi^2}-\frac{2}{9H^2\tau^2}\int d^3x\left[\frac{1}{2}(3H\tau)^{2/3}(\nabla\varphi)^2+V(\varphi)\right]\right\}\Psi=0 \quad (28)$$

where $\Psi(\varphi, t)$ is the state vector, $\tau=(3H)^{-1}\exp(-3Ht)$, and $V(\varphi)$ is the effective potential

$$V(\varphi)=\frac{1}{2}m^2\varphi^2+\frac{\lambda}{4}\varphi^4\ln\frac{\varphi^2}{\sigma^2}+\dots \quad (29)$$

So we encounter the problem of tunneling through time-dependent potential.

An essentially simpler one dimensional (not infinitely dimensional as eq. (28)) quantum nechanical example with the potential $U=\tau^{-n}V(x)$ shows that the usual expression for the transition probability

$$\Gamma\sim\exp\left\{-\int\sqrt{2mU}\,dx\right\} \quad (30)$$

is valid as $\tau\to 0$ if $n>2$ and invalid if $n<2$. In the boundary case $n=2$ the result depends upon the values of the parameters of the potential. In particular expression (30) proves to be valid if the coefficient before x^2 in $V(x)$ is sufficiently large. This result directly transferred to eq. (28) shows that transition probability cannot be calculated quasiclassically just in the conditions of the new inflationary scenario, i.e. $m^2 \ll H^2$. Of course in the opposite case of small H^2 the quasiclassical result of flat space is valid.

Solution of one dimensional Schroedinger equation with time dependent potential $U\sim\tau^{-2}V(x)$ shows that in the nonquasiclassical case i.e. in the case of slowly rising with χ potential $V(\chi)$ the tunnel probability is considerably larger than that given by expression (30), and what's more, it reveels no $1/\tau$ dependence when $\tau \to 0$ but much milder one. If this results can be applied to the case of infinitely dimensional eq. (28) than it follows that the probability of small bubble formation is large because the kinetic term effectively vanishes and the action is proportional to the volume of the bubble. Thus bubble formation in quickly expanding universe is not exponentially suppressed.

The value φ_0 of field φ immediately after the phase transition is very much of importance for the realization of the new inflationary scenario. For potential (29) in flat space-time $\varphi_0 = m/\sqrt{\lambda}$ which is small enough for the slow rolling down of φ towards σ and the exponential period is sufficiently long. If on the opposite φ_0 is large then the equilibrium point is quickly reached and the expansion quickly becomes of a power law. It can be shown that if the bubble size is τ, the value of the field inside it is about $(\sqrt{\lambda}\tau)^{-1}$. Hence for the prosperity of the inflationary model large bubbles are necessary. However in the theory described by eq. (28) the bubble size is unknown. In the case considered in ref. /46/ it is shown that the bubble size is not larger than H^{-1} what is rather natural because it is the horizon size in the de Sitter space. It is not clear however how much this result depends on the thin wall approximation used in papers /46/ and, what is more important, the assumption that the universe is strictly a de Sitter one. The point is that a de Sitter space in imaginary time becomes a four dimensional sphere of the radius H^{-1}. It is evident that in three dimentional space the bubble size at the moment of its formation can not be larger than this value (at least in the frameworks of imaginary time method). If this result proves to be true in the real case, the inflationary model is seriously jeapardised because φ_0 is to be large and the bubble does not inflate.

Another point which might be also of importance is that the effective Lagrangian is calculated under assumption of slow variating fields. In reality the speed of field variation is not small, generally $\dot{\varphi}/\varphi \simeq H$. Thus it is somehow necessary (but how?) to take quantum loop corrections without assuming φ = const. It is not yet clear how all these influence the tunnel transition probability and the value of φ_0.

The fantastically small region from which our universe (its visible part) started to expand is also worrisome. In accordance with eqs. (22) and (20) the size of that region was definitely smaller than 10^{-100}cm even for the modest value $\lambda \simeq 0.1$. It is difficult to believe that at such small distances known physical laws do not undergo serious modifications (even in vacuum which as we know is very complicated). Maybe however one should not worry about it because sufficiently large regions of space could always be considered for which no surprises in vacuum structure arose. Even if new phenomena could take place in the inflation of a tiny valume, they disappeared when the latter became large.

Recently a very interesting version of the inflationary scenario for which no phase transition was necessary was proposed by Linde /47/. The starting point of the model is the assumption that initially scalar field φ was very large, $\varphi > m_{\varphi}$, in some region of space. It is also assumed that space variation of φ was small in the scale of inverse Planck mass, and also small was initial value of $\dot{\varphi}$. Such a situation could be realized in the case of chaotic initial conditions if the selfcoupling of φ is weak so that $V = \frac{1}{4}\lambda\varphi^4 \ll m_{\varphi}^4$. In this case the term proportional to $H\dot{\varphi}$ dominates in the r.h.s. of eq. (21), where $H = (\frac{8\pi}{3}\rho m_{\varphi}^{-2})^{1/2} \simeq (2\pi\lambda/3)^{1/2}\varphi^2 m_{\varphi}^{-1}$. Correspondingly eq. (21) has the solution

$$\varphi = \varphi_i \exp\left\{-\frac{\sqrt{\lambda}}{\sqrt{6\pi}} m_{\varphi} t\right\} \tag{31}$$

In these circumstances the rate of the universe expansion, $\dot{a}/a = H$ is much larger than the speed of the decrease of φ (this is due to the condition $\varphi_i / m_{\varphi} > 1$) and the region of the universe where (simply by chance) the above mentioned initial conditions were realised underwent the exponential expansion

$$\frac{a}{a_0} = \exp\left\{2\pi \frac{\varphi_i^2}{m_{\varphi}^2}\right\} \tag{32}$$

This expansion could be sufficient for solving the problems discussed in the previous section if $\varphi_0^2/m_{\varphi}^2 > 10$. In the initially chaotic infinite universe where all configurations of field φ were possible, region (or regions) where φ satisfied the conditions discussed above surely existed.

These regions inflated and turned into universes suitable for our existence. As for other not so comfortable regions they flew away far beyond any possibility of observation.

This model to be realized not many special restrictions on the theory are necessary. Weakly interacting and self-interacting field φ, if exists, could generate sufficient inflation and in this sence create our world. There are some problems however which are not yet worked out, in particular the problem of quantum corrections to the classical equation of motion for large values of φ.

Of course the problem of the naturalness of the initial conditions exists as before. In contrast to the classical Friedman cosmology for which an extreme fine tuning of the initial conditions is necessary, this model is operative if the universe is chaotic initially with all values of φ (including very large) and its first derivatives (including small) reached. The latter possibility seems more appealing, though the origin of the initial chaos remains mysterious.

V. Conclusion

There are nowadays two principally different approaches to the problem of the universe creation and evolution. One of them is based to some extent on the anthropic principle claiming that the very fact of life existence makes senseless putting the question why the universe is such as it is. This approach has a right to exist especially if an infinite set of different universes were (or are being) created. Then only few of these universes are acceptable for us. Life can exist however if only the Sun with the Earth were present or at any rate only our Galaxy does. From the point of view of the anthropic principle the colossal abundancy of other galaxies is absolutely weird.

The other approach presumes that the universe is single with more or less arbitrary initial conditions. But the point is that the universe evolution based on the fundamental physical laws eventually results in our very nontrivial world.

The inflationary model satisfies these creteria; the modified chaotic version discussed at the end of the last section is intermediate between the two extreme approaches. Of course the inflationary model cannot be considered as a final one. First, some problems inside the model are not yet solved (e.g. the problem of the tunnel transition in an expanding universe). Second, the underlying field theory is not established. One cannot hope to answer the last question before the particle theory applicable up to the Planck energy is formulated. Sooner just the opposite, if the inflationary model based on the strong first order phase transition is to be operative, very strong restriction on the particle theory can be found.

What reasons have we now to believe that the inflationary universe model is indeed true. First of all it is beautiful. It is based on a single assumption that in the history of the universe a period of exponential expansion once existed. If it was sufficiently long the problems of homogeneity, isotropy, horizon, flatness, and relic monopoles could be solved in a unified manner. This is in favour of the model. Against it is the cosmological term problem and, to a lesser degree, the absence (in the meanwhile) of a consistent and worked out in detail theoretical basis. The status of the inflationary model will of couse strengthen if it is observed that the cosmological parameter $\Omega = \rho/\rho_c$ is equal to unity. Unfortunately no way is seen to do it in the near future with a decent accuracy. On the contrary it seems easier to refute the model by finding reliable bounds on Ω.

Even if weighty arguments are found in favour of the inflationary model (they sooner will be based on a theory but not on observations), there will be nevethaless a long way to the total happiness till the problems of the cosmological term and the universe creation are not solved. One should not forget however that "the appetite comes with eating" - the fundamental cosmological problems which now due to the inflationary model can be considered as solved (or more modestly, a possibility to solve these problems became visible) looked absolutely impregnable, and the importance of this achievement should not be underestimated.

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