Physics – Uspekhi **40** (8) 763 – 772 (1997)

REVIEWS OF TOPICAL PROBLEMS PACS number: **98.80.–k**

Elementary particles and cosmology (Metagalaxy and Universe)

I L Rozental'

Contents

Abstract. The close relation between cosmology and the theory of elementary particles is analyzed in the light of prospects of a unified field theory. The unity of their respective problems and solution methodologies is indicated. The difference between the concepts of 'Metagalaxy' and 'Universe' is emphasized and some possible schemes for estimating the size of the Universe are pointed out.

1. Introduction

Our perceptions of the surrounding world develop dramatically. Yet two or three thousand years ago, for harbingers of Western civilization, the world was restricted by the basin of the Mediterranean (Hercule Pillars) and the sphere of static stars, the Sun, and the planets. The true size of the African continent was determined only on the order of Egyptian pharaohs. The size of Earth ($\sim 10^9$ cm) was established only after the expeditions of Columbus and Magellan (at the transition from the XV to the XVI century). The revolutionary ideas of Galileo and Copernicus did not change the concepts of the size of the Universe, but only introduced a new element into the concept of the 'centre' of everything (Earth $\rightarrow$ Sun). It was only at the end of the XVIII century that Hershel drew attention to the peculiarities of nebulae and stellar clusters and inferred preliminary conclusions that nebulae consist of many stars. However, a complete understanding of the nature of nebulae, the base of concept of the island universe, came about only at the beginning of the XX century through technical progress, namely, the development of the photography, allowing a reliable interpretation of nebulae (later named galaxies) as a collection of stars. Subsequently, due to further technical progress and the modernization of statistical methods of observational data processing, it was established that galaxies group into clusters, and recently (about 30 years ago) that galactic clusters collect, in turn, into superclusters. The conglomeration of all objects observed in the sky was called the Metagalaxy; however, the term 'Universe' was often for this conglomeration. (In what follows we will try to strictly separate these two notions). Table 1 summarizes the average characteristics of the main classes of celestial objects.

I L Rozental' Institute for Space Research, Russian Academy of Sciences
Profsoyuznaya ul. 84/32, 117810 Moscow, Russia
Tel. (7-095) 333-53 35, 134-53 40

Received 16 January 1997, revised 21 April 1997
Uspekhi Fizicheskikh Nauk **167** (8) 801 – 810 (1997)
Translated by K A Postnov; edited by S D Danilov

Table 1. The mean characteristics of celestial objects ($M_{\odot} \sim 10^{33}$ g is the mass of the Sun; 1 pc $\simeq 3 \times 10^{18}$ cm)

System	Mass, $10^{10} M_{\odot}$	Size, pc
Galaxies	1	10^4
Poor clusters	40	10^6
Reach clusters	270	2×10^6
Superclusters	1500	2×10^7
Metagalaxy	6×10^9	4×10^9

2. The Universe as an agglomeration of cognizable objects

One may conclude from the Introduction that the size of the Universe has notably increased with progress in research techniques and observations. Consequently, the concept of the Universe cannot be equivalent to 'all that is', it only reflects our knowledge about the world at the present time.

Nevertheless both in popular editions and in serious monographs an identity was rooted that the Universe is the total existence. There are two reasons for this fallacy. One is not scientific: 'The Universe' sounds much more effective than, for example, supercluster or Metagalaxy. There is, however, a second, scientific argument. A proposition has existed for many decades that the size of the Metagalaxy ($\sim 10^{28}$ cm) is identical to the border of everything, so it should be identified with the Universe. However, in recent time a point of view affirmed in cosmology is that the Metagalaxy is only a small part of everything and so the identification of the Metagalaxy with the Universe is far from being justified.

In connection with the subject of this paper it seems worthwhile giving a more precise definition of both concepts. We will call the Metagalaxy the collection of objects located at present inside the volume of space with radius $\sim 10^{28}$ cm. In this definition we neglect evolution of the Metagalaxy with time for simplicity.

The Universe is the collection of objects which can be perceived at a given time. This concept reflects the level of our knowledge. Only the coincidence of both concepts over some decades has led to their atavistic identification.

One note to conclude. Cosmology and the physics of elementary particles have so far been considered as different fields of physics. In recent time a tendency to their unification has arisen (see, for example, Ref. [1]). The purpose of the present paper is to canonize this tendency. However, one obstacle emerges in the way: a strict representation of both branches of physics within the framework of one paper is impossible. It is therefore often necessary to sacrifice strictness for generality. A full description of the different stages in cosmology is given in monographs [1 – 4].

3. The Metagalaxy and its main characteristics

3.1 Cosmological postulates

The principal assumption of classical cosmology is the admittance that the evolution of the Metagalaxy is determined by gravitational forces. This idea was first realized by Einstein (1917), who started from traditional concepts of the stability of the world. Since the equations of general relativity (GR), which generalize Newtonian gravity, have no stationary solution, Einstein introduced *ad hoc* a λ-term into the equations, which was essentially equivalent to introducing repulsion forces to balance gravitational attraction.

In 1922, Friedman found a solution to the GR equations under very general initial and boundary conditions (see Section 3.2), which turned out non-stationary. After a short polemic between the founders of modern cosmology, Friedman's solution gained its rights for existence. The main physical corollary of Friedman's model has been expansion of the Metagalaxy, which was confirmed by Hubble (1929), and since then this theory became largely recognized.

It was established afterwards that the main conclusion of the expansion of the Metagalaxy follows not only from GR, but is a natural consequence of the Newtonian theory of gravity, within whose framework there is also no steady state for a gravitating sphere with a uniform mass distribution. Here it is useful to make a small turn. In addition to the equations of the theory of gravitation, one needs to postulate initial and boundary conditions. Friedman formulated them in the following form: during evolution, the Metagalaxy is always homogeneous and isotropic. These hypotheses, which subsequently were called the 'basic cosmological postulates', have been well confirmed by observations. For example, the homogeneity is met to an accuracy of $\sim 10^{-2}$, and the isotropy to better than 5×10^{-1}. In any case, no reliable deviation from isotropy has been observed.

3.2 Friedman cosmology

The basic cosmological postulates are very strong hypotheses. For example, one may infer, using very simple kinematic considerations, that since the centre of the Metagalaxy is absent, only the relative distance between two arbitrary points r_{12} and their relative velocity v_{12} have any physical sense. Both characteristics are related as

$$v_{12} = H(t_{\mathrm{M}}) r_{12} \,, \tag{1}$$

where $H(t_{\mathrm{M}})$ is the Hubble constant, and t_{M} is time, counted from the beginning of expansion. From dimensional considerations it follows that the relative distance

$$r_{12} \propto t_{\mathrm{M}}^{a} \,, \tag{2}$$

where $a = \mathrm{const}(t_{\mathrm{M}})$, which coincides with the results of GR.

When deriving Eqn (2) we postulated $H(t) \propto t^{-1}$. There is, however, another interpretation of relationship (1). The factor $H(t)$ can be a constant with the dimension of inverse time. As such a global object as the Metagalaxy is considered, it appears natural to admit that this constant is determined by universal constants $\hbar$, c, and G. In this case the characteristic time is the Planck time $t_{\mathrm{P}} = G^{1/2} \sim 10^{-43}$ s. Here and below we use $\hbar = c = 1$. Then the solution of Eqn (1) is

$$r_{12} \propto \exp\left(\frac{t_{\mathrm{M}}}{t_{\mathrm{P}}}\right) . \tag{3}$$

The model, in which the expansion has an exponential form, is named after De Sitter. Relationships (2) and (3) include the relative distance r_{12}. Clearly, as a particular case these relationships describe the evolution of the size of the Metagalaxy r_{12}.

Solutions (2) and (3), obtained from dimensional considerations and basic cosmological postulates, approximately describe the evolution of the Metagalaxy, but, of course, do not give a full representation of the process. First of all, simple considerations indicate that in Friedman cosmology there are two classes of solutions depending on what determines the Metagalaxy expansion: kinetic energy or the potential energy of gravitation. The corresponding conditions per unit mass read:

$$\frac{v^2}{2} > \frac{G M_{\mathrm{M}}}{R_{\mathrm{M}}} \,, \qquad \frac{v^2}{2} < \frac{G M_{\mathrm{M}}}{R_{\mathrm{M}}} \,, \tag{4}$$

where M_{M} is the mass of Metagalaxy.

Using condition (1), these inequalities can be recast in the form

$$H^2 > \frac{8\pi}{3} G\rho \,, \tag{5}$$

$$H^2 < \frac{8\pi}{3} G\rho \,, \tag{6}$$

where ρ is the mean density of matter.

Clearly, if condition (5) were fulfilled, the Metagalaxy would expand unlimitedly; under condition (6), the expansion would eventually become a contraction. If the equation

$$\rho = \rho_c = \frac{3}{8} \frac{H^2}{\pi G}, \tag{7}$$

is realized, the expansion is never bounded, and the value ρ_c is called the critical density. Note that all the preceding analysis was made within the framework of Euclidean geometry. In GR it is necessary to take into account space curvature. If condition (5) is met, space is characterized by a negative curvature; if condition (6) is satisfied the curvature is positive. Relationship (7) corresponds to Euclidean space.

3.3 The Hubble constant

Now we pass on to juxtaposing the main theoretical and observable characteristics of the Metagalaxy. The main characteristic of the evolution of the Metagalaxy is the Hubble constant $H(t)$. At the present time t_{M0} it has been experimentally measured to a factor of $\simeq 2$:

$$H_0(t_{M0}) = 100h \text{ km s}^{-1} \text{ Mps}^{-1}, \tag{8}$$

$h \simeq 0.5-1$ (see, for example, Refs [5, 6]).

For simple estimates, if the distance $R < 10^{28}$ cm, one may use the relationship

$$H(t_{M0}) \sim 10^{-18} \text{ s}^{-1}.$$

$$t_{M0} \sim \frac{1}{H_0} \sim 3 \times 10^{17} \text{ c} \sim 10^{10} \text{ years}. \tag{9}$$

This equation is accurate to a factor of ~ 1.5.

It is important to note that the value t_{M0} determined from relationship (9), agrees well with the age of the oldest stars in our galaxy. A few decades ago, when observations gave the value of $H_o(t_{M0})$ to be an order of magnitude larger than (8), the discrepancy between the age of the stars and the Metagalaxy was the principal argument against Friedman's theory. An important parameter of the model is the power law index in relationship (2). The value of this index depends upon the form of material dominating in the Universe. For matter the index is $a = 2/3$, for radiation $a = 1/2$.

3.4 Cosmic microwave background

Gamow (1949) postulated that at $t_M = 0$ radiation dominated. Due to different laws for density change $\rho_m \propto R^{-3}$ (for matter) and $\rho_r \propto R^{-4}$ (for radiation) matter begins prevailing at $t_M \sim 10^6$ years. The most epochal, however, was the prediction by Gamow of the existence of an isotropic radiation with a temperature of $T \sim 10$ K. It was indeed discovered in 1965 and was called the cosmic microwave background or relic radiation. Since then the microwave background has been intensively studied. The recent data, obtained by the COBE satellite [7, 8], are as follows.

The temperature is $T_0 = 2.726 \pm 0.005$ K; the deviation from a black body energy spectrum is less than 0.03%. The isotropy of the cosmic microwave background has been confirmed to a high accuracy. To a lesser accuracy one can calculate the temperature of the relic background. The point is that the theoretical value of T_0 depends upon the number of degrees of freedom of matter, which in turn depends on the time t_M and the temperature T_0. To the best of the author's knowledge, accurate theoretical calculations of the temperature T_0 have not been performed. Rough estimates of this parameter [9] lead to the following expression:

$$kT \sim \frac{2 \times 10^{-6} g^{-1/2}}{t} \text{ [GeV]}, \tag{10}$$

where g is the number of degrees of freedom. The dependence of g on T is shown in Fig. 1. For $g \simeq 4$ and $t_0 \simeq 3 \times 10^{17}$ s, we may obtain that $T_0 \sim 10$ K. Considering the roughness of the estimate and uncertainties in parameters H_0 and Ω_0 ($\Omega_0 = \rho_M/\rho_c$), one may believe that this value conforms with observations.

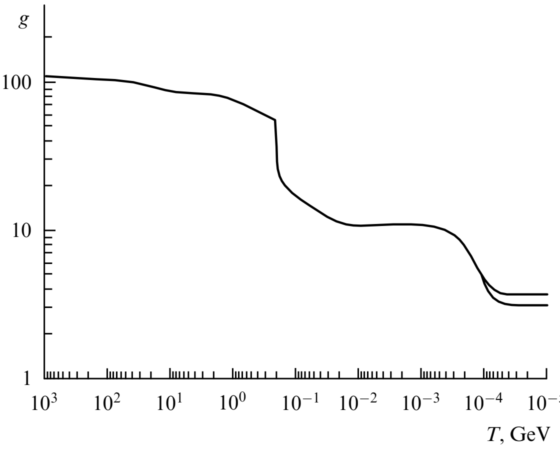

Figure 1. The number of degrees of freedom vs. temperature [9].

3.5 Relative abundance of light elements

The next important test for Friedman cosmology is the calculation of the relative abundance of light elements ($A \leqslant 4$) in the Metagalaxy. Qualitatively, the theory of the origin of light elements can be presented as consisting of several stages:

1. At $T_M \sim 10^{12}$ K ($t_M \sim 10^{-2}$ s) nucleons, neutrinos, $e^{\pm}$ and γ are in thermodynamic equilibrium.

2. At $T_M \sim 10^{11}$ K ($t_M \sim 10^{-1}$ s) the relative abundance of protons increases due to the mass difference between neutrons and protons.

3. At $T_M \leqslant 5 \times 10^9$ K ($t_M \sim 4$ s) the reaction $e^+ + e^- \to 2\gamma$ starts; the ratio of numbers of protons and neutrons is frozen at the level 5:1.

4. At $T_M \sim 10^9$ K ($t_M \sim 200$ s) d, ^{3}He, and ^{4}He are formed. At this time a free outflow of photons and (anti) neutrinos begins, which practically stop interacting.

Many papers have been devoted to calculation the relative abundance of light elements (see Refs [2, 3] for a review). The results of the calculations depend upon the parameter $\Omega_B = \rho_B/\rho_c$, where ρ_B is the mean baryonic density in the Metagalaxy. A good correspondence between the calculated data and observations is obtained for

$$\Omega_B h^2 = 0.01-0.02 \tag{11}$$

(see Ref. [10]).

The relative abundances of light elements in the Metagalaxy can be found in Ref. [11] (Table 2).

Within error ($\sim 1\%$), the theoretical and observable relative abundances of light elements in the Metagalaxy coincide.

Table 2. Relative abundance of light elements

Element	H by mass	^{4}He by mass	^{7}Li/H
Abundance	76 %	24 %	10^{-10}

3.6 Dark matter problem

Next we must consider one important question. The ratio Ω_B accounts for the total mass of atomic protons, nuclei, and electrons generating optical photons. There are, however, solid arguments (see, for example, Refs [5, 6, 11]) (first of all the virial theorem that provides the stability of cosmic objects) that the true matter density in the Metagalaxy far exceeds that of Eqn (11). For example, if one takes into account our galactic halo, which is typical, then $\Omega \sim 0.1$. The virial theorem applied to clusters of galaxies yields Ω close to 0.5 – 1.0, and here a very serious problem emerges, to which a lot of papers are devoted that, unfortunately, have not clarified the obvious question on the nature of the matter with mass which exceeds that of luminous material by about two orders of magnitude.

The simplest hypothesis that the dark matter consists of the well-studied electron neutrino gives no answer to this question. The mass of ν_e is less than 5.1 eV [12]; in order to provide the relation $\Omega \sim 0.1$, the mass of a neutrino must be $m_\nu \sim 90h^2$ eV [6], which far exceeds the experimental upper limit to m_ν. Mass limits for μ- and τ-neutrinos are significantly higher, however massive neutrinos must decay into three lighter neutrinos (decay into two neutrinos is prohibited by the lepton number conservation law). So to solve the hidden mass (dark matter) problem one admits the existence of particles with relatively exotic characteristics making their detection on modern accelerators difficult. For example, one postulates the existence of axions with masses of 10^{-6} – 10^{-4} eV or heavy neutralinos (10 GeV – 2 TeV) [6].

We recall that an axion is a neutral particle with a zero spin weakly interacting with matter. The axion was 'invented' to solve the problem of CP-parity conservation in strong interactions.

Unfortunately, the particles mentioned above have not been detected on accelerators (for supersymmetry and experiments on its detection see the Conclusions). See Refs [13, 14] for more details on the dark matter problem and its possible solutions.

3.7 Baryonic asymmetry of the Metagalaxy

As is well known, our Galaxy (and apparently the entire Metagalaxy) consists of protons, electrons, and neutral particles. In nature antiprotons and positrons rarely occur, and only in cosmic rays. Considering a flux ratio of antiprotons and protons in cosmic rays of $\sim 10^{-5}$, one can obtain a concentration ratio of antiprotons and protons of $\sim 10^{-20}$. Such a precise charge symmetry requires a justified explanation. Some decades ago it was admitted that isolated regions exist inside the Galaxy which contain exclusively protons and electrons or antiprotons and positrons. However, with the development of gamma-ray astronomy, this hypothesis died out, since at the boundaries of these regions annihilation processes should violently occur thereby generating photons that can be easily detected.

In this situation, Sakharov (1967) put forward two ideas to explain the baryonic asymmetry: (1) baryonic charge may not be conserved, and (2) due to CP-parity violation, the lifetime of baryons and anti-baryons are different, which would lead to the asymmetry.

At first this hypothesis was met with great scepticism. However, with progress in the grand unification theory the hypothesis of non-conservation of baryon charge began to dominate in elementary particle physics, since it led to an epochal prediction: the decay of the proton over the characteristic time-scale $t_p \geqslant 10^{30}$ years (see Ref. [15] and the Appendix). Estimates made on the basis of baryon decay hypotheses allowed a correct evaluation of one of the main characteristics of the Metagalaxy: the ratio $n_\gamma/n_p \sim 10^8$ (n_γ, n_p are the photon and proton concentrations).

Note in conclusion that when analyzing the kinetics of the origin of baryon asymmetry, a major role is played by the non-stationarity of the Metagalaxy, its expansion.

3.8 Problems of Friedman cosmology

Thus, Friedman cosmology well explains almost all the global characteristics of the Metagalaxy. An exception is revealing the nature of dark matter; this issue, however, relates more to elementary particle physics than to cosmology.

Nonetheless one cannot assert that the cosmology of the Metagalaxy is a completed science. Despite its successes, there are some serious internal contradictions pointing to its incompleteness. We note only the principal ones (see Ref. [1] for full analysis).

1. The singularity. Equation (2) implies that at $t_M = 0$ the density ρ tends to infinity. The existence of a physical singularity points to incompleteness.

2. The problem of the horizon. As mentioned above, the value $R_{M0} \sim 10^{28}$ cm $\sim t_{M0}$ means that the Metagalaxy has expanded with a velocity ~ 1. Consider the situation at $t_M \ll t_{M0} \sim 10^{10}$ years. Since in relationship (2) parameter a lies within the range $0 < a < 1$, the expansion velocity of the external 'boundaries' of the Metagalaxy at t_M is $v_M = (t_{m0}/t_M)^{1-a} > 1$ or $R_M > t_M$, which contradicts special relativity. The simplest attempt to resolve this contradiction, viz. the conjecture that at early stages the Metagalaxy was separated into many causally disconnected regions, would contradict the striking isotropy of the Metagalaxy.

3. The problem of flatness. As is well known, the curvature of the Metagalaxy is zero, which conforms to a Euclidean geometry of space and the fact that $\rho \sim \rho_c$. The question emerges: why, among the infinite number of possible geometries with non-zero curvature radius, did nature 'choose' the Euclidean one?

4. Inflationary cosmology and its experimental testing

4.1 Basic ideas of inflationary cosmology

The hypothesis underlying inflationary cosmology is that the primordial matter in Universe is physical vacuum. This idea, suggested as one possibility [16, 17], gained large popularity after paper [18], in which an attempt to solve the problems of Friedman cosmology was made using this hypothesis. The physical attractiveness of the idea is due to the main feature of vacuum being considered as a macroscopic relativistic form of matter. In this case a free particle passing through vacuum must conserve velocity. In the opposite case (the particle slows) vacuum would be an ether, which has been refuted by special relativity for many years. But such a feature of matter to preserve the velocity of a particle is possible only for a unique equation of state: $\varepsilon_v = -p_v$ (ε_v is the energy density of vacuum, p_v its pressure). Then the slowing of a particle would be strictly compensated by the acceleration caused by pressure.

But such an equation of state is characteristic of a metastability of matter. To imagine rapid vacuum decay one needs to suppose the existence of a potential barrier. In quantum language this means that the dependence $V(\varphi)$ of the potential energy on the vacuum wave function φ would have a minimum (Fig. 2). This minimum at $\varphi = 0$ corresponds to the main state of vacuum. Metastability, i.e. the possibility of slow vacuum decay, is provided by quantum-mechanical tunneling through the potential barrier. Vacuum fluctuations at $\varphi = 0$ may leak through the potential barrier and propagate away through the vacuum (this process is symbolically shown by lines $C'O$, $B'O$, $A'O$ in the figure). In order that the vacuum stage of perturbation would last long enough, it is needed that the dependence $V(\varphi)$ after the maximum would be quasi-flat (part MO on the curve $V(\varphi)$). At the moment C a phase transition occurs in the vacuum and the perturbation (which is sometimes called a bubble) decays into smaller regions, which determine the original expansion for the Friedman stage. The origin and evolution of the Metagalaxy is schematically shown in Fig. 3. Clearly, since the size of the regions is non-zero, the main shortcoming of the Friedman model, the singularity, disappears. During evolution the 'bubble' expands into a vacuum whose density remains practically unchanged. Such an expansion would correspond to an exponential law (3) (the De Sitter model). The main feature of this stage, called inflationary, is its duration t_i. This time can be estimated (very qualitatively) using dimensional considerations and modern concepts of the great unification theory. The beginning of the 'bubble' expansion must proceed from a region of Planck size $R_P \sim G^{1/2} \sim 10^{-33}$ cm. At this stage the evolution is determined by the unified interaction including gravitation. At the moment t_f a phase transition occurs and the interaction splits into gravitation and all the others (the so-called grand unification).

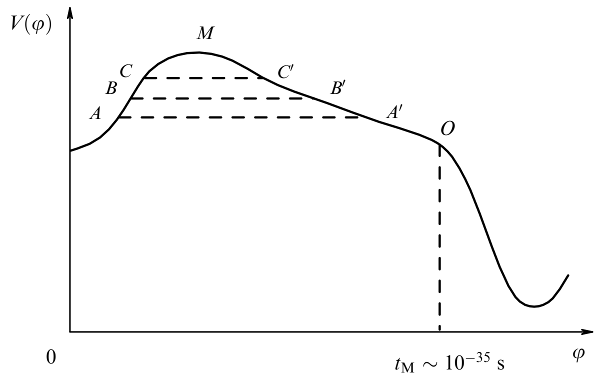

Figure 2. The potential energy of vacuum as a function of its wave function. The distances $C'O$, $B'O$, $A'O$ symbolize possible differences in the characteristics of transitions vacuum – inflationary stage – Friedman expansion. The point $O(t_M \sim 10^{-35}$ s) corresponds to phase transitions.

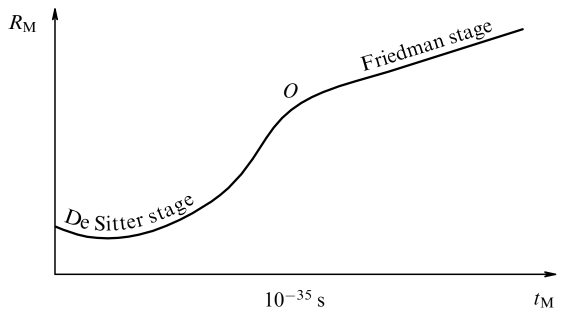

Figure 3. The scheme of formation and evolution of the Metagalaxy.

Grand unification is characterized by the mass of X-boson: $m_X \sim 10^{15}$ GeV (see Appendix). The time corresponding to the mass m_X is $t_f \sim 1/m_X$. Using (3) we derive the final size of the 'bubble' $\sim 10^{10^4}$ cm, which exceeds the size of Metagalaxy by many orders.

The inflationary stage explains other problems of Friedman cosmology too. All regions of the 'bubble' are causally-connected, so the part of it that would give rise to the Metagalaxy would also consist of causally-connected elements. The problem of flatness is simply solved by the inflationary scenario. The size of the 'bubble' far exceeds that of the Metagalaxy. From differential geometry it is known that a small portion of any smooth function can be approximated by a corresponding flat space.

Thus the introduction of inflationary space alleviates the difficulties of Friedman cosmology. However the question arises as to whether the *ad hoc* introduction of the inflationary stage is too high a price for solving some incompletenesses of a good cosmology? In our opinion, the answer should be negative, because in addition to interpreting the defects of the Friedman model the inflationary stage makes an important prediction. To formulate it, let us return to Fig. 2. Very strong vacuum fluctuations should exist in the main state $\varphi = 0$ [19]. Although precise calculations appear impossible here, this conclusion seems very likely. One can deduce a very important prediction: the probability of tunneling and the duration of the inflationary stage must also be fluctuating [20, 21], which could result in different physical laws operating inside the 'bubbles', and hence in metagalaxies. This important conclusion, which may be connected with experimental data, is well (although indirectly) confirmed by observations (see Section 4.2).

Some additional comments are in order. The qualitative approach to the inflationary scenario delineated above could seem to be oversimplified. However the function $V(\varphi)$ determining the inflation unfortunately cannot be calculated from general principles. So at present there co-exist many models of the inflationary scenario (words liked mostly by modern cosmologists) which use fields corresponding to massless scalar electrodynamics [21], tensor gravity [22], string theory [23], exponential potentials [24], superstring theory [25, 26], etc. So at the present stage a simplified representation of inflationary cosmology seems to be justified.

4.2 Experimental confirmation of the inflationary scenario

Now we wish to demonstrate, using simple examples, a principle (called the principle of determination [27] or the anthropic principle [28]) stating that physical laws in the Metagalaxy are not only sufficient for the existence of the main stable states (atomic nuclei, atoms, stars and galaxies), but are also necessary.

Specifically, we consider the stability of the structure of the Metagalaxy regarding the numerical values of the fundamental constants α of four interactions, the masses m_p and m_e, and the dimensionality of space N.

The proof of the principles mentioned above is based on the standard method for studying stability. Let us give some examples of the correctness of these principles.

1. Hydrogen atom — an absolutely stable element. The reaction

$$p + e^- \to n + \nu \tag{12}$$

(p, e^-, n, ν are proton, electron, neutron, neutrino) is absolutely prohibited at low energies (temperatures) since

$$\Delta m_N = m_n - m_p \simeq 1.3 \text{ MeV} > m_e \simeq 0.5 \text{ MeV}. \tag{13}$$

However, if one (thinkingly) increases the mass m_e, reaction (12) becomes possible, which would have catastrophic consequences — the impossibility of galaxy and, hence, star formation since in order to form a galaxy one needs neutral hydrogen [2–4]. On this background, the fact that a three-fold increase in m_e makes the main reaction of thermonuclear synthesis

$$p + p \to d + e^+ + \nu. \tag{14}$$

impossible seems relatively harmless.

Note that a three-fold increase in m_e is small compared to the ratio $\langle m \rangle / m_e \sim 10^3$, where $\langle m \rangle \simeq 1$ GeV is the average mass of elementary particles.

2. The biproton ^{2}He is an unstable particle. This instability is due to a Coulomb repulsion of the protons (its potential energy is $\simeq 2$ MeV). However, as estimates show, if the potential energy of nuclear attraction were higher by 50 keV, the nucleus of ^{2}He would be stable, which would lead to the reaction

$$p + p \to {}^2\text{He} + \gamma. \tag{15}$$

In this case reaction (15) would be caused by the electromagnetic interaction, instead of the weak, as in (14), and all the protons would have burnt out during the primordial (cosmological) nucleosynthesis. The effective constant α_s of the strong (nuclear) interaction cannot be appreciably decreased. In this case the condition $\Delta m_N < \varepsilon_d$ ($\varepsilon_d \sim 2.2$ MeV is the binding energy of deuterium) would be broken and deuterium would be unstable, which would disrupt the whole chain of primordial nucleosynthesis.

3. In order to synthesize elements with atomic number $A > 4$, a triple coalescence

$$3\alpha \to {}^{12}\text{C} \tag{16}$$

needs to be possible. However, the triple coalescence is effective only in resonance, i.e. when the condition $m_{3\alpha} = m_C$ is met. However, in fact we have $m_{3\alpha} = m_C + 7.7$ MeV. Reaction (16) is thus possible only when an excited level with energy 7.7 MeV exists. Such a level actually exists. However, with a small shift of this level (changes in α_s) the reaction of triple coalescence becomes ineffective. The dramatic history of the discovery of this level is described in book [29] and paper [30]. The number of such examples can be increased (see Refs [27, 28]). However, in our view, even the examples cited above are sufficient to prove the reality of the determination principle, which may have only two interpretations.

1. Fundamental constants change with time t_M. We are living in the epoch when the combination of constants is favorable for the existence of complex structures. This point of view was suggested by Dirac [31] and for a long time was a subject of numerous studies which found that the four fundamental interaction constants and the ratio m_p/m_e have practically not changed during the expansion of the Metagalaxy. For example, according to Ref. [32], over the last 10^9 years before our time,

$$\left|\frac{\dot\alpha_e}{\alpha_e}\right| < 10^{-17}\ \text{yr}^{-1}, \quad \left|\frac{\dot\alpha_s}{\alpha_s}\right| < 5\times 10^{-19}\ \text{yr}^{-1},$$
$$\left|\frac{\dot\alpha_w}{\alpha_w}\right| < 10^{-12}\ \text{yr}^{-1}, \quad \left|\frac{\dot\alpha_g}{\alpha_g}\right| < 10^{-10}\ \text{yr}^{-1}.$$

Paper [33] reported the following upper limits on the rate of change of constants over 10^{10} years:

$$\left|\frac{\Delta\alpha_e}{\alpha_e}\right| < 2\times 10^{-3}, \quad \frac{\Delta(m_e/m_p)}{m_e/m_p} < 2\times 10^{-3}.$$

In paper [34], similar limits have the form

$$\left|\frac{\dot\alpha_e}{\alpha_e}\right| < 5\times 10^{-14}\ \text{yr}^{-1}, \quad \left(\frac{\dot m_e}{m_p}\right)\left(\frac{m_e}{m_p}\right)^{-1} < 10^{-13}\ \text{yr}^{-1}$$

(α_e, α_s, α_w, α_g are the dimensionless constants of the electromagnetic, strong, weak, and gravitational interactions).

Also very impressive is the proof that the constants have not changed since the time $t_M \sim 1$ s, which is based on the agreement between theoretical and observed abundances of light elements in the Metagalaxy.

Thus Dirac's hypothesis contradicts experimental data.

2. The only possibility for interpreting the instability of the structure of the Metagalaxy with respect to fundamental constant changes is to suppose, in agreement with the chaotic inflationary cosmology scenario, a multiplicity of metagalaxies, each with its own fundamental constants. The complexity of the structure of Metagalaxy has itself chosen, among many possibilities, those constants that would cause its appearance.

4.3 On the fundamental constants

In the previous section we listed the constants, to change of which the structure of Metagalaxy is most sensitive. One may wonder why this list does not contain the velocity of light c, Planck's constant $\hbar$, and Newton's gravitational constant G.

Kinematics in an imaginary world with a changed value of the velocity of light was considered by Gamow. This approach was critically analyzed by Okun' [30]. This paper considered not only kinematical, but also dynamical effects connected with the variation of the speed of light while the other constants $\hbar$, e, m_e, m_p are unchanged. A significant change in the speed of light would lead to a cardinal change in the laws of physics.

In our opinion, this fact should be treated as a prohibition (even thought) of varying the velocity of light. This conclusion agrees with a fundamental non-trivial postulate of grand unification: the intersection of three running constants of the electroweak and strong interactions (see Ref. [15] and the Appendix).

However, in our view, there is a stronger argument favoring a cautious treatment of the constants c, $\hbar$ and G. If the conclusion of the inflationary cosmology on the existence of many metagalaxies is correct, there is no prohibition of their collision. It is not difficult to analyze, for example, the interaction of particles belonging to different metagalaxies with different values of m_e or m_p. But how can one imagine the dynamics of particles within the framework of special relativity with different values of the velocity of light, within

GR with two values of the constant G, or a self-consistent quantum mechanics with two values of $\hbar$. It appears very likely that constants c, G, and $\hbar$ are superconstants characteristic of not only the Metagalaxy, but of the entire Universe.

4.4 On the stage of formation of fundamental constants

As noted above, the fundamental constants remain unchanged from now back to the time $t_M \sim 1$ s. It is natural to assume that these constants were unchanged during all the Friedman stage. Since the vacuum in inflationary cosmology is not determined by the characteristics of real particles, one should admit that the fundamental constants α, m, N arose at the inflationary stage.

5. Interpretation of fundamental problems of elementary particle physics

5.1 List of problems

1. The elementary particle mass hierarchy.

According to the grand unification theory, an X-boson with a mass of $\sim 10^{14}-10^{15}$ GeV should exist which carries electromagnetic, weak, and strong interactions. The X-boson determines the unified interaction (see Ref. [15] and the Appendix). The masses of the W and Z-bosons determining the electroweak interaction are many orders smaller ($m_W = 80.22$ Gev, $m_Z = 91.2$ GeV). A question emerges: why is the ratio $m_X/m_{W,Z} \sim 10^{13}$ so large? Dirac [31] was the first to postulate that dimensionless fundamental constants should be of the order of unity. Attempts to interpret the mass hierarchy using the standard models all failed due to significant divergences [35]. A supersymmetry-based approach turned out to be more productive [36]. But in the last case, apparently, one cannot fully obviate the contradictions [37]. Here we put aside the lack of experimental confirmations of supersymmetry (see the Conclusions). Thus the important problem of the mass hierarchy remains unsolved.

2. The problem of three lepton generations.

Why do three generations of leptons (e, μ, and τ) exist in our Metagalaxy? This is not at all a new question. As early as after the discovery of muons in cosmic rays (1937) the question emerged: what are they needed for? Thus, after the very first publication about muons some doubts were put forward regarding its actual existence. The discovery of the τ-meson aggravated the riddle.

3. The problem of interaction constants.

Why are the interaction constants $\alpha_e \sim 1/137$, $\alpha_w \sim 10^{-5}$, $\alpha_g \sim 10^{-38}$ much smaller than unity? (The problem formulated by Dirac).

4. The problem of interactions.

Why are four interactions realized in the Metagalaxy?

5. The problem of vacuum.

Vacuum, being a form of matter, must gravitate. However the total matter density $\rho_t < \rho_c < 10^{-29}$ g cm^{-3}. Clearly, $\rho_v < \rho_t$. But the natural vacuum density should be the Planck density, $\rho_v = G^{-2} \sim 10^{94}$ g cm^{-3}. How can one explain the disagreement by 120 orders of magnitude?

6. The problem of N space dimensions.

All existing experimental data conform with the assumption that our space is tridimensional within the distance range 10^{-16} cm $< r < 10^{28}$ cm. Among integer numbers, special values (in terms of group theory) are 0 and 1. Why should we have $N = 3$?

5.2 Interpretation of the problems

1. The mass hierarchy problem

The mass of an X-boson m_X is very large. However, it could not be significantly smaller in a metagalaxy with a complex structure. Indeed, the experimental lifetime of a proton $t_p > 2 \times 10^{32}$ years for the decay $p \to e^+\pi^0$ [15]. The theoretical value is not well known, but falls within the range $10^{30}-10^{35}$ years. It is essential, however, that the time $t_p \propto m_X^4$ (see the Appendix). So if $m_X < 10^{10}$ GeV, all protons would decay over the life time of the Metagalaxy 10^{10} years. It is impossible to solve the mass hierarchy problem at the expense of increasing the mass m_W. This mass predetermines the process of cosmological nucleosynthesis and hence the entire evolution of matter in the Metagalaxy.

2. The three lepton generation problem.

As noted in Section 3, baryonic asymmetry of the Metagalaxy is determined by the non-conservation of baryonic number and CP-violation. Within the framework of grand unification, CP-violation appears if the number of lepton and quark generations $n \geqslant 3$ [38]. Three lepton generations meet this condition and hence are sufficient for baryon asymmetry to appear.

3, 4. The problems of the constants α and their numerical values.

All four interactions and numerical values of constants are necessary for the complex structure in Metagalaxy to exist.

5. The problem of vacuum.

The energy density of vacuum cannot be large ($\sim \rho_c$) for many reasons. First of all, this is because the age of the Metagalaxy t_{ex} is determined by its matter density and is approximately $t_{ex} \propto \rho^{-1/2}$ [3]. So if $\rho_v \gg \rho_c$ were fulfilled, one would have $t_{ex} \ll t_{M0}$ and consequently galaxies and stars would have no time to form.

A deeper reason for the smallness of ρ_v probably exists. To realize the inflationary scenario the condition $\rho_v \leqslant \rho_c$ is required, which also explains the smallness of ρ_v.

6. The dimensionality of space.

Far-acting forces in N-dimensional Euclidean space are determined by its dimension [39]. For example, the analog of the Newton and Coulomb laws in N-dimensional space reads

$$F \propto \frac{1}{r^{N-1}} . \qquad (17)$$

Ehrenfest (1917) studied the two-body problem in a Euclidean space of arbitrary dimensionality and showed that steady states a the two-body system can exist only when $N \leqslant 3$. Since for $N = 1, 2$ complex structures are impossible, $N = 3$ is the only dimension for which steady bound states exist. For example, for $N > 3$ no analogies to the solar system can exist. Ehrenfest performed his analysis within the framework of classical physics. Later on, his conclusion was generalized to quantum systems [40]. For $N < 3$ stable atoms cannot exist either.

Thus, using the determination principle, important problems of elementary particle physics can be interpreted.

6. On the size of the Universe

It is impossible to make measurements outside the Metagalaxy. However, experience allows us to make some extrapolations into this region.

First of all, it is necessary to separate the extrapolation of physical laws and numerical values of physical constants. Equations of dynamics are largely determined by the characteristics of space, first of all by its dimension (see, for example, Ref. [39]). It is useful to recall the direction of research fashionable in the late 60s — the axiomatic field theory, when it was tried to deduce all the consequences of relativistic quantum mechanics from a minimal number of axioms. Although these attempts all failed, nevertheless some conclusions can be inferred (of course, not unique) about the dynamics of the Metagalaxy as a whole. A different situation regarding the numerical values of the four fundamental interaction constants has appeared. First of all this relates to the constants of the four interactions representing a set of numbers that are impossible to decipher at present. Apparently, the only exception is the elementary particle mass distribution. Presently, data on (approximately) 300 particles exist [12], so their mass distribution can be reproduced accurately enough. Further it may be supposed that this distribution is the same everywhere in the Universe and draw some rough conclusions on the size of the Universe [41].

In this paper the experimental elementary particle mass distribution m [12] is fitted by the function

$$\frac{\Delta n}{\Delta \log(m/m_{\mathrm{p}})} \sim 300\left(\frac{m}{m_{\mathrm{p}}}\right)^{-2}, \tag{18}$$

if $m > 2m_{\mathrm{p}}$, and by

$$\frac{\Delta n}{\Delta \log(m/m_{\mathrm{p}})} \sim 30\left(\frac{m}{m_{\mathrm{p}}}\right)^{1.5},$$

for $m < 2m_{\mathrm{p}}$.

Approximation (18) shown in Fig. 4 was derived without the electron and X-boson. However it is these particles that play a deterministic role in the formation of the structure of Metagalaxy. Using distribution (18) one can estimate the probability w for particles having masses within the interval $0 - m_{\mathrm{e}}$ and $m_{\mathrm{X}} - \infty$. It turns out to be $w < 10^{-50}$. According to the inflationary scenario, metagalaxies can be born with their proper quantum numbers (see Section 4). The mass m_{X} determining the unification of interactions can be significantly smaller than 10^{15} GeV. In this case the proton lifetime would be close to the age of Metagalaxy, which would lead to a dramatic change in its structure. So the inequality obtained should be treated as a characteristic of the number n of metagalaxies in which elementary particle masses are distributed according to (17), (18). The number $n = 1/w > 10^{50}$.

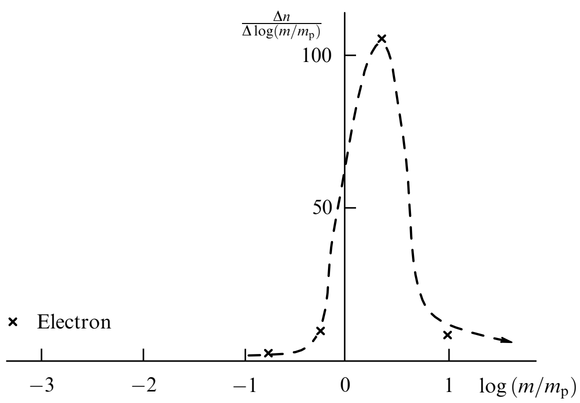

Figure 4. Elementary particle mass distribution.

In this derivation we extrapolated the distributions (17), (18) by about 12 orders of magnitude, which may cause natural doubts. The only justification of this is the very popular extrapolation of physical laws by 12 orders when constructing a grand unification theory.

7. Conclusions

In book [42] Ginzburg noted about 10 directions that pretended to be a universal theory of elementary particles in the post-war era and that all passed quietly away. The only very fruitful theory which survived is the renormalization method. But this is how its founder, Feynman, comments on it, "I personally think that the renormalization theory is one of the ways to hide the difficulties of electrodynamics connected with divergences under the carpet" [43].

The present hopes to construct a unified field theory are connected with very elegant (in the mathematical sense) directions: supersymmetry and its generalization, superstrings.

Supersymmetry makes one very important experimental prediction: the existence of supersymmetrical partners of elementary particles which have the same characteristics of the existing particles except spin. For example, s-electrons with integer spin should exist. However, despite large experimental efforts, s-particles have not so far been discovered. For example, the mass of s-neutrino (if it really exists) is > 40 GeV, of an s-electron is $> 50 - 60$ GeV, and of an s-photon is > 20 GeV [12]. An even higher lower limit was obtained for exotic particle masses, for instance s-gluons: $m_{\mathrm{g}} > 230$ GeV. The absence of s-particles does not totally refute supersymmetry (it may exist, but is violated).

The theory of superstrings includes supersymmetry; its fundamental object, a superstring, has a length of $l \sim l_{\mathrm{P}} \sim 10^{-33}$ cm. Basically, the main idea of this direction is the replacement of the concept of a point-like object by the concept of a small one-dimensional object. As is known, it is the assumption of truly elementary particles (leptons and quarks) being point-like that leads to the main divergences in quantum field theory.

The principal aim of the theory of superstrings is, by building upon the mathematical achievements of supersymmetry, to construct a unified quantum field theory, which would be free of divergences and anomalies (negative probabilities). For this purpose a small one-dimensional object, a superstring, is provided with many characteristics: tension (playing the role of the interaction constant) and different spins and symmetries. Superstrings may be treated as one-dimensional objects in 4-dimensional Minkowsky space or as compact layers in a split space (in the spirit of Kaluza – Klein's ideas). The main criterion of a superstring theory is the absence of intrinsic contradictions in the theory. This task is presently solved in the first (one-loop) approximation. The complexity of constructions appearing in superstring theory is demonstrated by the fact that in one of its most widely spread variants the dimensionality of compact space is 502. The reviews [37, 45, 46] and books [39, 47, 48] may be cited among many papers devoted to superstring theory.

In spite of a relatively long history (~ 25 years), supersymmetry has failed to solve the main problem, the construction of an anomaly-free and divergence-free theory. It appears plausible that this problem is not an isolated one and is connected with fundamental problems of elementary particle physics and cosmology. While the interpretation of supersymmetry violation at scales of ~ 100 GeV seems to belong to supersymmetry theory, the explanation of the dynamics of compactification and hence of the dimensionality of space is tightly related to cosmology (see Section 5). Clearly, this relation also appears in the formation of the Metagalaxy in inflationary cosmology and superstring theory being determined by processes occurring at Planck scales.

It seems essential that some fundamental characteristics of the Metagalaxy (vacuum parameters, elementary particle mass distribution) relate to the Universe as well (see Sections 5, 6). So a Theory of Everything (TOE) is impossible without interpreting these characteristics. Clearly, the problems pointed out belong not only to elementary particle theory, but to cosmology as well.

The construction of the theory of the evolution of the Metagalaxy, Universe, and the complete theory of elementary particles are different aspects of one problem.

Appendix

Grand unification and proton decay

The unification of interactions is possible if there is a general coupling constant α_u. It is known [15] that constants of the weak, electromagnetic, and strong interactions depend on the transferred 4-momentum q (i.e., on the corresponding mass). So the constants α are called running constants. The main hope that grand unification exists is connected with the existence of a very non-trivial intersection of running constants α_e, α_w, and α_s at $q \sim 10^{15}$ GeV. When at the beginning of the 90s a report [49] appeared on the absence of the intersection, a slight panic emerged between specialists. Fortunately, the data published in [49] have not been confirmed. The existence of the intersection means in field theory terms that a certain X-boson with a mass of $m_X \sim 10^{15}$ eV should be present that carries electromagnetic, weak, and strong interactions. Therefore the following reactions are possible:

$$p \to uud \to e^+ \bar{d}\, d \to e^+ \pi^0 ,$$

where u, $\bar{d}$ and d are quarks.

One of the channels of this chain is shown in Fig. 5. From this figure one can easily estimate the lifetime of the proton t_p. The main idea of the estimate is that once m_X is large, X-boson emission and absorption cross sections are always $\sigma \sim 1/m_X^2$. So the probability w of the process presented in Fig. 5 is $w \propto \alpha_u^2/m_X^4$ ($\alpha_u \sim 1/40$ is the unified interaction constant). From dimensional analysis the lifetime is $t_p \sim m_X^4/\alpha_u^2 m_p^5 \sim 10^{32}$ years for $m_X = 10^{15}$ GeV.

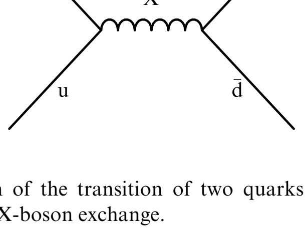

Figure 5. Diagram of the transition of two quarks into a lepton and antiquark with an X-boson exchange.

References

1. Linde A D *Particle Physics and Inflationary Cosmology* (New York: Harwood Acad. Publ., 1990) [Translated into Russia (Moscow: Nauka, 1990)]
2. Weinberg S *Gravitation and Cosmology* (New York: Wiley, 1972)
3. Zel'dovich Ya B, Novikov I D *Struktura i Evolyutsiya Vselennoiÿ* (Structure and Evolution of Universe) (Moscow: Nauka, 1975)
4. Gurevich L E, Chernin A D *Vvedenie v Kosmologiuy* (Introduction to Cosmology) (Moscow: Nauka, 1978)
5. Gelb J, Bertschinger E, Preprint Fermilab. 92/73 (December 1992)
6. Turner M, Preprint Fermilab. 92/382 (January 1993)
7. Mather J et al. *Astrophys. J.* **420** 439 (1994)
8. Turner M, Preprint Fermilab. Conf. 95-125A
9. Turner M, Preprint Fermilab. Conf. 92/313
10. Walker T et al. *Astrophys. J.* **376** 393 (1991)
11. Schramm D, Preprint Fermilab. Conf. 93/022-A (January 1993)
12. Summary Tables of Particle Properties *Phys. Rev. D* **50** 1193 (1994)
13. Turner M, in *The Early Universe* (Eds W Unruh, G Semenoff) (Boston: Reidel Publ. Com., 1988) p. 19
14. Gelmini G, in *The Early Universe* (Eds W Unruh, G Semenoff) (Boston: Reidel Publ. Com., 1988) p. 351
15. Okun' L B *Leptony i Kvarki* (Leptons and Quarks) (Moscow: Nauka, 1990) [Translated into English (Amsterdam: North Holland, 1982)]
16. Gliner E B *Zh. Eksp. Teor. Fiz.* **49** 542 (1965) [*Sov. Phys. JETP* **22** 378 (1966)]
17. Starobinskiĭ A A *Pis'ma Zh. Eksp. Teor. Fiz.* **30** 719 (1979) [*JETP Lett.* **30** 682 (1979)]
18. Guth A H *Phys. Rev. D* **23** 347 (1981)
19. Hawking S W *Nucl. Phys. B* **144** 349 (1978)
20. Linde A D *Phys. Lett. B* **129** 177 (1983)
21. Linde A D *Phys. Lett. B* **175** 395 (1986)
22. Copeland E J et al. Preprint Fermilab. 93/029-A (March 1993)
23. Barrow J D *Nucl. Phys. B* **310** 743 (1988)
24. Burd A B , Barrow J D *Nucl. Phys. B* **308** 929 (1988)
25. Ellis J et al. *Nucl. Phys. B* **277** 231 (1986)
26. Lonsdale S, Moss I *Phys. Lett. B* **189** 12 (1987)
27. Rosenta'l I L *Elementarnye Chastitsy i Struktura Vselennoiÿ* (Elementary Particles and Structure of Universe) (Moscow: Nauka, 1984) [Translated into English *Big Bang Big Bounce* (Heidelberg: Springer, 1988)]
28. Barrow J D, Tipler F J *The Anthropic Cosmological Principle* (Oxford: Oxford Univ. Press, 1986)
29. Hoyle F *Galaxies, Nuclei, Quasars* (New York: Harper Row Publ., 1965) [Translated into Russian (Moscow: Mir, 1968)]
30. Okun' L B *Usp. Fiz. Nauk* **161** 177 (1991) [*Phys. Usp.* **34** 77 (1991)]
31. Dirac P A M *Nature* (London) **139** 323 (1937)
32. Chechev V, Kramarovskiĭ Ya *Radioaktivnost' i Evoluytsiya Vselennoiÿ* (Radioactivity and Evolution of Universe) (Moscow: Nauka, 1978)
33. Varshalovich D A, Levshakov S A , Potekhin A Yu *Usp. Fiz. Nauk* **163** 111 (1993) [*Phys. Usp.* **36** 11 (1995)]
34. Cowie L L, Songaila A *Astrophys. J.* **453** 596 (1995)
35. Gildener E, Weinberg S *Phys. Rev. D* **13** 3333 (1976)
36. Witten E *Nucl. Phys. B* **188** 513 (1981)
37. Veinstein A I, Zakharov V I, Shifman M A *Usp. Fiz. Nauk* **146** 583 (1985) [*Sov. Phys. Usp.* **28** 483 (1985)]
38. Matinyan S G *Usp. Fiz. Nauk* **136** 200 (1980) [*Sov. Phys. Usp.* **23** 99 (1980)]
39. Rosental' I L *Geometriya, Dinamika, Vselennaya* (Geometry, Dynamics, Universe) (Moscow: Nauka, 1990)
40. Gurevich L, Mostepanenko V *Phys. Lett. A* **35** 201 (1971)
41. Rozental I *Science Spectra* **2** 64 (1995)
42. Ginzburg V L *On Physics and Astrophysics* (Moscow: Kvantum, 1995) p. 86
43. Feynman R *The Character of Physical Law* (London: 1965) [Translated into Russian (Moscow: Mir, 1968) p. 228]
44. Done J P, Preprint Fermilab. Conf. 95/372 (October 1996)
45. Barbashov B M , Nesterenko V V *Usp. Fiz. Nauk* **150** 489 (1986) [*Sov. Phys. Usp.* **29** 389 (1986)]
46. Aref'eva I Ya, Volovich I V *Usp. Fiz. Nauk* **146** 655 (1985) [*Sov. Phys. Usp.* **28** 555 (1985)]

47. Green M, Schwartz J, Witten E *Superstring Theory* Vol. 2 (Cambridge: Cambridge. Univ. Press, 1987) [Translated into Russian (Moscow: Mir, 1990)]
48. Polyakov A M *Gauge Fields and Strings* (New York: Harwood Acad. Publ., 1987)
49. Amaldi U, de Boer W, Fuestenau H *Phys. Lett. B* **260** 447 (1991)