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Inflationary universe and the vacuumlike state of physical medium

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Abstract. **This paper reviews two cosmologies which assume that the observable universe was initially vacuumlike (i.e., the cosmological medium was Lorentz invariant). In the earlier nonsingular Friedmann cosmology, the Friedmann universe comes into being during the phase transition of an initial vacuumlike state to the state of 'ordinary' matter. In the course of this transition, the emerging matter is accelerated, which causes the universe to expand and attain the Friedmann expansion regime. In the inflationary cosmology, the transition to the Friedmann universe is preceded by an epoch of inflation in which the universe grows spontaneously by many tens of orders of magnitude without or almost without changes in its composition and density. The idea of inflation gives rise to a variety of scenarios involving a cosmological singularity, or the birth of one universe within another, or the world-as-a-whole as an infinite set of universes, etc. The present paper provides arguments against the inflation idea. On dismissing it, both cosmologies are essentially identical from the viewpoint of their application to the observable universe.**

From the Editor

É B Gliner's paper "Inflationary universe and the vacuumlike state of physical medium," which we offer to our readers' attention, does not in fact meet either the form or style standards of *Physics Uspekhi*. Concerned with the cosmology of the early universe, the paper touches on rather controversial aspects of the field. Although peer-reviewed and approved by a professional cosmologist, some of whose comments were accepted by É B Gliner, the paper would be more suitable for a specialized journal rather than *Uspekhi* — were it not for some circumstances that intervene.

On the one hand, É B Gliner has authored a number of pioneering works in the field of cosmology (see items 1, 2, and 10 in the list of references, the first dating back to 1965). On the other hand — as was too often the case in his time — Gliner's life and career were far from easy. In 1945, three times wounded in WWII battles, and a possessor of two military orders, he was imprisoned on charges of 'anti-Soviet agitation'. He was lucky enough to spend part of his ten-year term as a physicist and engineer in specialized prisons, so-called 'sharashkas'. Many years later three author certificates were given to him for the inventions of that period. In 1956 he was declared innocent 'for lack of body of offense.' From 1955 to 1963 he worked in a murky design office, and from 1964 to September 1979, at the A F Ioffe Physical Technical Institute in St. Petersburg.

Unfortunately, in 1980 Gliner had to emigrate because of the challenges his children met on their way to higher education — a situation only too well known to many at the time. In the United States Gliner was quite successful in solar physics and general relativity studies at a number of universities — until a seminar in 1987 at a world-famous university. His ideas, close to those in the paper below, apparently turned out to be objectionable to some prosperous cosmology authorities in the US. Alas, this cost É B Gliner his job, and his pension too, because his dismissal left him one year short of the necessary period of service.

Now in his 78th year, a World War II disabled soldier Érast Gliner is still fully active in his research. As things stand, however, he has no affiliations, cannot attend scientific conferences, and is denied access to the University On-Line Services. Besides, publishing a paper in a major journal costs money.

My feeling is that we owe a great debt to É B Gliner, and should therefore take this opportunity to publish his paper — the more so that, in my judgement at least, the paper is quite deep in its content. It is perhaps noteworthy that É B Gliner's pioneering work has been highly appreciated in *Physics Uspekhi* (see, e.g., *Usp. Fiz. Nauk* **169** 419 (1999) [*Phys. Usp.* **42** 353 (1999)] and in a recent paper by A D Chernin in *Usp. Fiz. Nauk* **171** 1153 (2001) [*Phys. Usp.* **44** 1099 (2001)]), as well as by I D Novikov in his RAS Presidium talk (see *Vestnik Ross. Akad. Nauk* **71** (10) 886 (2001)]) — thus adding more weight to our decision to make this publication.

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1. Introduction

One of the predictions, which is made by the general theory of relativity (GR) and is crucial in the Grand Unification theory, is that the physical medium may exist in a vacuumlike (Lorentz invariant) state [1]. If the cosmological medium were in this state once, the information about the universe's previous evolution would have been lost due to the specific properties of this state. Therefore, in this case one can speak of the vacuumlike state as the initial state of the *observable* universe.

The assumption of the vacuumlike initial state of the *observable* universe underlies the scenario of the '*nonsingular Friedmann cosmology*' [2] (see Appendix). But the most popular cosmology adopting the same initial state of the observable universe is currently the *inflationary cosmology*, in which the above scenario appears as the *final phase* of a number of suggested scenarios. This final phase is assumed to be preceded by the *inflation* process in which the universe increases in its extent by many tens or even hundreds of orders of magnitude without changes in its density until a phase transition to the Friedmann universe finally occurs.

Inflationary cosmology contains two methodologically distinct branches: the study of phase transition in media of highest density, based on the Grand Unification theory, and cosmological scenarios themselves. In this symbiosis of elementary particle physics and GR, the latter — the author thinks — is not sufficiently represented, which leads to inconsistency in the inflationary cosmology itself. This was the incentive to the present work.

This view determines the style of the present work. While the general relativity aspects of the subject are treated in close detail, the problems of particle physics, if touched at all, are only discussed in terms of their general relativistic implications.

A reader is assumed to be acquainted with the basics of the inflationary cosmology. The exposition is not exhaustive from some other points, as well. The author offers his sincere apologies to those whose related works are not referenced here.

2. Inflation as part of inflationary cosmology

The prevailing cosmological models assume that spacetime is isotropic. Its metric can thus be represented in the Robertson – Walker form

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\right]. \quad (1)$$

The constant k is the curvature of space. The scale factor $a(t)$ describes the change, as time t goes on, of the distances between points with *fixed spatial coordinates* r, θ, φ. The scale factor is determined by the Friedmann equations

$$\dot{a}^2 = \frac{G}{3}\mu a^2 - k, \qquad \ddot{a} = -\frac{G}{6}(\mu + 3p)a \quad (2)$$

and by the equation of state of the physical medium

$$p = p(\mu). \quad (3)$$

Here the dot denotes differentiation with respect to time t, G is the gravitational constant, μ is the density of cosmological medium, and p is the pressure in it.

In the standard cosmology, which usually considers the only universe, the unit of length is habitually chosen so that the curvature k takes one of the three values, 1, 0, or -1, corresponding to three possible types of homogeneous universes. Throughout this paper it is more convenient to use the same unit of length. Then the curvature constant k may have any real value; and the metric (1) describes a continuum of universes differing by the value of k.

The Grand Unification theory assumes that in the cosmological medium of early universe prevails a vacuumlike (Lorentz invariant) phase with density exceeding that of matter (ordinary, not Lorentz invariant phase). The density, μ, of the vacuumlike phase, and the pressure p in it, are related by the equation of state [1]

$$p = -\mu. \quad (4)$$

From the Friedmann equations (2), in a universe filled with the vacuumlike medium, the density of the latter is conserved, i.e. $\mu = \text{const}$, but the scale factor $a(t)$ grows exponentially. In view of continuity, one can argue that a small addition of ordinary matter does not essentially affect the way the scale factor grows, and that the density of the medium remains almost unchanged. This growth, which, by the analogy with Friedmann models, is interpreted as the expansion of the universe — but almost without a change of its density! — was called inflation[1]. The idea of inflation forms the basis of the inflationary scenarios.

Until recently, inflationary scenarios have assumed that the initial density of the cosmological medium is not restricted from above, in other words, that there exists cosmological singularity. Grand Unification allows for a theoretical description up to a Planck density of 10^{19} GeV, at which spin-1/2 fields, quarks and leptons, are supposed to be massless; massive fields are the Higgs bosons, which form a vacuumlike medium.

Inflationary scenarios assume that in this highest symmetry state [SU(5) or higher] the universe is expanding, and the temperature of the cosmological matter decreases. When it falls to $\sim 10^{15}$ GeV (at $t \sim 10^{-35}$ s after the expansion began), the highest symmetry state becomes energy-unfavorable, and — through a series of spontaneous symmetry breakings — the massless fields acquire mass and appear as a 'condensate.' (This 'Higgs scheme' extends the Ginzburg – Landau superconductivity theory, in which a condensate of paired electrons appears as the temperature decreases.)

This elegant scheme leads, however, to certain difficulties. For example, near the Planck density 'heretical' particles — say, magnetic monopoles — must appear, and their contribution to the mass of the *observable* universe is many orders of magnitude greater than from the particles actually observed! As a way out, Guth [12] put forward the following conjecture, which was to become the basis for inflationary cosmology. Namely, he suggested that after the spontaneous breaking of GUT symmetry follows a phase transition of the first kind. As a result, after the critical temperature is reached, the phase transition in the medium does not occur all at once, but instead the universe remains in the supercooled metastable high-symmetry state for some time. During this period (apparently $\sim 10^{-31}$ s), the energy gain, obtained in the transition, acts (speaking broadly) as a contribution to the

[1] Sometimes (see, e.g., Ref. [3]), the term inflation is understood very broadly and includes Friedmann expansion — something which is not meant in this work.

density of the vacuumlike phase. The metric of the universe remaining in the supercooled state is very close to the de Sitter metric, and the scale factor grows exponentially. By choosing the transition parameters, one can achieve a tremendous increase of the scale factor such as, for instance, by a factor of 10^{100}. This frequently cited number means a growth more than 70 orders of magnitude larger than that under a second order phase transition that leads rapidly to a gravitationally decelerated Friedmann expansion.

Interpreting the scale factor growth as that of the size of the universe implies that the whole universe may appear due to the inflation of some microscopic region. It is in terms of the small size of the latter that the inflationary cosmology explains the absence of observable monopoles and resolves some other cosmological problems, not discussed in the present context. This small size has also prompted the idea of universes arising due to the inflation of microscopic fluctuations. This possibility is embodied in the scenarios of the permanent production of universes.

Technically, inflationary scenarios are based on *ad hoc* assumptions and require fitting of the numerous free parameters involved. In the emerging new field of research, where Grand Unification ideas are combined with relativistic cosmology, the *ad hoc* approach can hardly cause any objections. What is questionable is the relativistic basis of the scenarios — the idea of inflation. We will show that in the presence of a vacuumlike medium the interpretation of the scale factor growth similar to that in case of Friedmann models is incorrect and does not imply the corresponding expansion of the universe [4].

3. Vacuumlike medium

The idea of a vacuumlike medium was first proposed within the GR framework [1]. Traditionally, the right-hand side of the Einstein equations had been treated semi-empirically (see, e.g., Ref. [5]), as input data from a certain outside source. The successful elaboration of elementary particle physics has made, however, generally acceptable that the algebraic structure of the quantities a physical theory deals with is the integral part of the theory. It follows then that in GR the algebraic classification of symmetric second-rank tensors determines the possible types of physical media (cf. Ref. [6]). As the result, the theory acquires some degree of integrity, by determining not only the mechanics, but also the media whose motion it describes. In this sense, GR predicts [1] the existence of a medium that in its homogeneous and isotropic state is described by the 'simplest' possible energy-momentum tensor

$$T_k^i = \mu \delta_k^i \,, \tag{5}$$

where the scalar μ is the energy density of the medium. Then, in view of Eqn (5), the pressure in the medium is determined by Eqn (4).

What makes this consideration productive is the fact that tensor (5) describes the unique physical medium that, being of non-zero mass density, is nevertheless Lorentz invariant. Such a medium had escaped being noticed in GR. In the limit $\mu \to 0$ this medium is the ordinary vacuum.

Formally, Eqn (5) has the same algebraic structure as the cosmological term that Einstein earlier introduced into his GR equations *ad hoc*. Later he discarded this term, because it described a perennial world-wide force that acted but could not been influenced in any way. In contrast, *describing the state of the medium*, the tensor (5) does not alter the equations of the theory. It also behaves as a standard dynamic variable both under phase transitions and in non-homogeneous states.

The vacuumlike medium plays a leading part in the problem of singularities in GR. As Wheeler put it boldly in Ref. [7], the gravitational collapse was 'the greatest crises in physics of all time.' The reason for this emotional statement will become clearer if one notes that the problem with spacetime singularities is not so much that they cannot be described internally (the feature they share with elementary particles, for example) as the fact that they also cannot be consistently described externally [8]. As soon as the notions of geometry lose their meaning near singularity, the singularity remains outside of physics.

The idea of a vacuumlike state, together with the suggestion that any physical medium makes a transition to this state as the density increases, is thus far the only conceivable alternative to the unavoidable appearance of singularity under gravitational collapse. Roughly, this alternative can be comprehended from Eqn (4). Even in the Newtonian physics, the increase in the internal pressure in the collapsing body cannot stop gravitational compression because of the long-range nature of gravity — a fact which was already noted by Laplace. In terms of the post-Newtonian approximation, the source of gravity in GR is the trace of the energy-momentum tensor equal to $3p + \mu$. On approaching the condition (4), gravity becomes repulsive, i.e., there arise the divergence of geodesics. As soon as the collapsing body approaches the vacuumlike state, the gravitational repulsion prevents the appearance of singularity for the same reason that gravitational attraction would promote an unlimited compression process.

The transition of cosmological medium into a vacuumlike state rules out the concept of an *unavoidable* cosmological singularity, which has aroused when the fact of expansion of the universe became accepted. The time-reversed course of cosmological expansion reproduces the picture of a gravitational collapse. Hence, if with increasing density the medium does not pass to a vacuumlike state, then there exists in its past a cosmological singularity; otherwise, somewhere in the past the universe was in the vacuumlike state. This latter state may naturally be thought of as the initial state of the *observable* universe. This is not, however, the absolute origin of time because timelike lines can in principle be continued even further to the past.

A qualitative analysis of the relativistic equations of motion of a non-uniform medium compressing under negative pressure shows that the non-uniformity decreases as the compression process goes on [1]. Thus, it is likely that as a result of this homogenization the final state of a medium, which was compressed by negative pressure, does not critically depend on its initial non-uniformity.

4. Cosmology of a vacuumlike medium

The metric satisfying the vacuumlike phase condition (4) was found by de Sitter [9] in the form

$$\mathrm{d}s^2 = A\,\mathrm{d}\tilde{t}^{\,2} - A^{-1}\,\mathrm{d}\tilde{r}^{\,2} - \tilde{r}^{\,2}(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\varphi^2)\,,$$

$$A \equiv 1 - \frac{G}{3}\,\mu\tilde{r}^{\,2}\,. \tag{6}$$

This metric is static. The metric of isotropic spacetime, however, can always be presented in the form (1). If the medium is not vacuumlike, then the scale factor $a(t)$ is defined by the Friedmann equations (2) uniquely, and there exists no transformation that puts the metric (1) in a static form (6). The vacuumlike medium produces a special case; to see this, just note that the metric (6) is static. In view of Eqn (4), the Friedmann system of equations (2) degenerates: the second of Eqns (2) follows from the first. The first equation can be solved directly by determining the family of vacuumlike solutions $a = a(t|\,k)$, $-\infty < k < \infty$, differing in the choice of the constant k. It is easily shown [10] that each of these metrics can be obtained from the de Sitter metric (6) by the regular coordinate transformation

$$\tilde{t} = \tilde{t}(t, r|\,k)\,, \qquad \tilde{r} = \tilde{r}(t, r|\,k)\,. \tag{7}$$

Thus, the de Sitter metric (6) corresponds to a continuum of scale factors $a = a(t|\,k)$ and metrics (1). Consequently, one cannot ascribe any definite time evolution to a vacuumlike spacetime, i.e., to the de Sitter universe [4]. The time dependence of the transformed metric is a coordinate effect, in this sense.

The absence of a preferred state of motion expresses the principle of relativity for a vacuumlike medium: such a medium — unlike ordinary media, but like ordinary vacuum — cannot carry a reference frame. This principle forbids the direct transition of a vacuumlike medium to ordinary matter, because of the uncertainty in the momentum of the emerging matter. The presence of ordinary matter may initiate a transition, however. The ban is lifted as applied to the universe as a whole because one cannot ascribe to a universe a definite momentum.

The difference between the universes dominated by vacuumlike medium and those of Friedmann models lies in the difference between the algebraic structure of the energy-momentum tensors of the prevailing components of the cosmological medium. In the Friedmann medium the non-diagonal elements of the energy-momentum tensor — i.e., energy and momentum flows — depend on the choice of a reference frame, and there is one and only one frame where they are absent. This comoving frame describes the physical motion of the Friedmann medium. As regards the non-diagonal components of the energy-momentum tensor of the vacuumlike medium, they vanish in all reference frames. For this reason the very concept of this medium's proper motion cannot be formulated. Thus, the properties of the ordinary vacuum are extended to the Lorentz invariant media with nonzero energy density. The classical 'physical emptiness' is replaced by an essentially relativistic Lorentz invariant medium, for which the very idea of internal motion is incompatible with its Lorentz invariance.

Because of the principle of relativity, the vacuumlike medium exchanges energy and momentum with matter by either influencing the geometry of spacetime or in the mutual phase transitions. In the absence of the latter, matter in a vacuumlike medium falls freely. Therefore reference frames comoving with the falling ordinary matter do not reflect the behavior of the vacuumlike medium [4]; and as long as only a small amount of matter is present, the universe is close to the static de Sitter universe.

This would appear to be inconsistent with the exponential growth of the factor $a(t)$ for metrics close to the de Sitter one. Nevertheless, it is only illusion created by some habitual aspects of Friedmann models that the scale factor is always in one-to-one correspondence with the expansion of the universe.

Consider, for instance, a gas of test particles in the de Sitter universe. Between collisions particles fall freely along the geodesics of the de Sitter metric. Because, just like the metric, geodesics do not vary in time, the gas of test particles can neither expand nor contract as a whole. Due to the collisions, this gas is hot and, predictably, its temperature has to be of the Gibbons – Hawking value [11]. Thus, even though the scale factor is growing, the universe is not.

One can directly extend this picture to universes in which, along with the prevailing vacuumlike phase, some amount of ordinary matter is present (cf. Ref. [4]). When falling along geodesics, which are determined primarily by the prevailing phase, this matter does not follow the growth of the scale factor, nor does the entire 'almost vacuumlike' universe. Therefore the very idea of inflation appears to be erroneous.

5. Attempts at justifying inflation

Although the inflation of both the vacuumlike universe and a vacuumlike medium of finite extent have been viewed as real effects since the Guth's first scenario [12], only a few attempts have been made to directly justify the inflation reality. It is worthwhile discussing at least some of them in detail here.

It is sometimes said that, given the equation of state (4), the possibility of inflation is a consequence of classical thermodynamics. It is argued, namely, that if a given volume V of the vacuumlike medium increases by $\mathrm{d}V$, then the energy density of the medium decreases by $\mathrm{d}\mu = -\mu\,\mathrm{d}V$, but in view of Eqn (4), the work $-p\,\mathrm{d}V = \mu\,\mathrm{d}V$ done by negative pressure forces exactly compensates this loss. Thus the expansion of the vacuumlike medium with its energy density being conserved does not violate the energy conservation law. Let us go further, however. Let us convert a certain mass to a vacuumlike state and let it expand freely. If we now make a reverse transition, we obtain a gain in mass. Operating on this principle, one could make a *perpetuum mobile* creating energy from nothing. What then does thermodynamics give us? Well, nothing really. The paradox has arisen from the fact that the concepts we used were devoid of physical meaning. We can specify a certain space volume mentally — but we cannot associate with it a material element of the Lorentz invariant medium because there is no such thing as a notion 'to be comoving' in vacuumlike medium. When applied to a vacuumlike medium, the standard equations of thermodynamics degenerate, just as do Friedmann's equations.

Heuristically, the internal state of a vacuumlike medium is a balance between the forces of compression (negative pressure) and the gravitationally induced divergence of geodesics (gravitational repulsion). This implies that the factors causing a change in gravitational field change also the balance of forces in the vacuumlike medium and thereby alter its energy-momentum tensor as well, so that the latter does not generally have the isotropic form (4), but corresponds to another equilibrium state (see, e.g., Refs [13 – 15]). In the general case, it is only when a physical system is in a uniform state that its energy-momentum tensor uniquely corresponds to its inherent properties. For gravitating matter with a spherically symmetric distribution, the energy-momentum tensor cannot be uniform because the forces of gravity depend on the radius. The vacuumlike medium is naturally expected to have the same properties. Therefore the only characteristic feature it has is that under isotropic internal conditions, its energy-momentum tensor has the form (4), being unachievable for ordinary matter. The assumption that it always has the form (4) would in fact mean going back to the idea of the cosmological term[2] instead of using the idea of a dynamic variable.

Note, by the way, that inhomogeneities in a vacuumlike medium seem to lift the absolute taboo on phase transitions between it and the ordinary matter. In this sense, a non-uniform vacuumlike medium contains a virtual addition of matter, similar to that in a non-uniform gravitational field in the ordinary vacuum.

Analyzing models of the spontaneous inflation of a vacuumlike medium into the ordinary vacuum, some authors [17–21] incline to the opinion that inflation is real.

Let us turn to Ref. [21], a kind of a summarizing paper, which examines the inflation of a vacuumlike sphere into vacuum. The energy-momentum tensor is taken to be of the form (4) everywhere within the sphere. Under the inflation assumption, this is logical, because the suggested inflation process conserves the density by definition, and therefore does not change it within the sphere; the sphere must be uniform all the way to the boundary. For the inflation process to occur under this condition, however, a spherically symmetric solution to the Einstein equations must exist, in which a class C^1 transition from the de Sitter to the Schwarzschild metric takes place at a certain spherical boundary moving towards the vacuum. It is easy to see that such a solution does not exist — not even in class C^0. So, the authors of Ref. [21] note in the Introduction section, that one more dynamic object, a transition layer, must exist. The energy-momentum tensor there cannot be of the form (4), but is determined by the solution of the Einstein equations complemented by the equations of state governing the behavior of the medium. But since the gravitational field within the sphere cannot be homogeneous, this 'layer' (described by the δ-function in the paper) has no lower boundary and should extend to the center of the sphere. Hence, to postulate the de Sitter metric for a finite expending region is altogether impossible.

Now let us look at the vacuumlike sphere from a different point of view. In the empty space which surrounds it, the gravitating sphere induces the Schwarzschild metric

$$ds^2 = -A\,dt^2 + A^{-1}\,dr^2 + r^2(d\theta^2 + \sin^2\theta\,d\varphi^2)\,,$$

$$A = 1 - \frac{2GM}{r}\,. \tag{8}$$

The Schwarzschild mass of the sphere,

$$M = 4\pi\int_0^{r_0} \mu(r) r^2\,dr\,, \tag{9}$$

is conserved, by the Jebsen–Birkhoff theorem, for any time-variations allowed for the energy density $\mu(r)$ and the radius of the sphere r_0 (physically, this means that no gravitational monopole radiation is present). The conservation of the integral (9) implies that the expansion of the sphere cannot occur without density redistribution, which means that inflation is not possible (cf. [4]).

Taking the point of view that inflation is real, the authors of Ref. [21] argue that this kind of 'naïve' argumentation leads to paradoxes. Two close observers, for instance, one inside and the other outside the sphere, would come to different conclusions, in such a case. Whereas the former will observe inflation, the latter will not. This paradox, however, presupposes inflation — otherwise both observers would observe the same. The paradoxes, the authors say, are resolved by considering the non-Euclidean nature of spacetime, in particular, the fact that the standard Schwarzschild coordinates do not cover it completely. The authors therefore turn to the fully extended Schwarzschild metric as a way out.

This analytical extension, however, implies a strictly spherical symmetry — otherwise it does not exist as a mathematical fact. The physical phenomenon that corresponds to it should therefore be unstable (cf. Ref. [22]). Further, the spacetime with an extended Schwarzschild metric by no means must exist any time a Schwarzschild metric region exists. Moreover, the extended metric includes a pair of similar *singularities* (!). That there are some real processes causing them to appear is difficult to conceive. One can therefore think of no way enabling any particular inflation process to extend the standard Schwarzschild metric it is immersed in (cf. Ref. [25]).

6. Vacuumlike medium and cosmological expansion

The fact that the inflation of an infinite or a finite medium with the de Sitter or near the de Sitter metric cannot be part of cosmological models does not discredit the idea, dating back to de Sitter, Eddington, and Lemaitre, namely that the de Sitter metric have been of crucial importance in the early universe. In the recent scenarios [2, 24–26], the homogeneity of the emerging universe, the existence of an impetus to its expansion, and the absence of a cosmological singularity are ensured by the assumption of this metric.

Removing inflation epochs from inflationary cosmology takes, in fact, its general relativistic scenario back to the nonsingular Friedmann cosmology ([2], see Appendix). This latter consistently relates the vacuumlike stage to the observable universe (density, entropy, the Hubble constant) and is likely to become the basis for further developments. Refs [27–29] should be noted, in this regard.

Nonsingular cosmology [2] implies that the initial state of the observable universe was vacuumlike but unstable with respect to the phase transition to the ordinary (not Lorentz invariant) medium. This should, for example, occurs if the fluctuationally-induced decrease in the density μ invalidates the vacuumlike degeneracy condition, $p = -\mu$ (or, equivalently, $3p + \mu = -2\mu < 0$), replacing it by the inequality

$$-2\mu < 3p + \mu < 0\,. \tag{10}$$

According to the Friedmann equations, this inequality corresponds to the accelerated expansion of the cosmological medium and an associated decrease in its density. The latter makes the process irreversible [4]. In this scenario the vacuumlike medium gives an impetus for expansion not to itself (inflation), but to the emerging Friedmann medium. In Grand Unification terms, the above scheme seems to imply that the highest symmetry state is unstable, and hence is the

[2] Recent observations [16] of the accelerated expansion in some parts of the universe most likely suggest the discovery of the vacuumlike medium rather than of the cosmological term. The anticipated presence in the universe of low-density vacuumlike medium is discussed in Ref [14]. There are listed (Sec. 5) five consequences of such presence (including its influence on the cosmological expansion) that are in principle amenable to observation. See also Refs [13, 15].

highest-density state as well. This, in particular, would eliminate the problem of the cosmological singularity, as well as that of whether a fauna of 'heretic' particles exist.

Recently it has been suggested [30] that the matter satisfying the inequality (10) can be thought of as a special (sixth?) phase of matter, '*quintessence*'. However, inequality (10) in itself is insufficient to define a new phase of matter, because the blend of ordinary and vacuumlike phases satisfies this inequality as well. If, however, one admits that the two phases involved are in a *transient equilibrium*, the quintessence can really be comprehended as a specific '*transient matter*' having no stationary state.

7. Comparison of the two scenarios

For the sake of brevity, in what follows the nonsingular and inflationary scenarios are denoted by the letters N and I, respectively.

(1) In both scenarios the initial state of the *observable* universe is a homogeneous and isotropic vacuumlike state. Hence, both scenarios solve the same problems of the Friedmann cosmology.

(2) Contrary to the widely held view, neither scenario — as indeed no other cosmological theory — explains why the observed universe is close to Friedmann's flat model. Because the metric of the earliest universe should be close to that of vacuumlike matter, and because the latter may be put into a form corresponding to any Friedmann model [10], no formal arguments in favor of a particular model are yet available (cf. Ref. [31]).

(3) Both scenarios assume that a Friedmann universe could arise from a finite domain of a vacuumlike medium; in I — through (actually unrestricted) inflation, in N — by way of expansion, which is controlled by the phase transition process.

(4) In N the dogma of cosmological singularity is replaced by the hypothesis that the universe expands from a homogeneous and isotropic vacuumlike state. This is justified by the inner logic of GR, as well as by the impossibility to present a singularity in physical terms. The high initial symmetry [3] of the initial state in N may perhaps be of evolutionary origin: the qualitative analysis of the relativistic equations of motion for a medium contracting under the influence of negative pressure indicates the tendency toward the equalization of the density distribution [1].

N does not involve the epoch, present in I, which lasts from the Big Bang, or from the infinitely high density epoch, to the epoch in which spontaneous symmetry breakings occur and massless particles 'materialize'. At the first sight this deprives vacuumlike phase in N of its past. The initial state in N is not, however, the 'onset of time': timelike lines may be continued through it to the past, toward some pre-existing cosmos (cf. Ref. [26]).

(5) The fact that no 'heretic' particles — for example, magnetic monopoles — are observed at present is explained in I in terms of inflation diluting these particles to almost zero concentration. In N, the density of the initial state is a free parameter. Provisionally, its choice is dictated by the lack of heretical particles. The density should be about ten orders of magnitude below the Planck one. (Note in this connection that really there is no motivation for the gap of many tens orders of magnitude between the densities of elementary particles and the Planck density).

(6) In I, it is assumed that during inflation the vacuumlike medium *cools*, while the extent of the quantum fluctuations of the underlying scalar field increases to become larger than the Hubble length. Just these proceedings define when the decay of vacuumlike medium begin and in the course of the subsequent heating a Friedmann universe emerges. However, the temperature measured by a thermometer falling freely in vacuumlike medium depends only on the density of the latter [11]. Hence this temperature cannot change during inflation. Calculations [27] also show that it is precisely this Gibbons – Hawking temperature, which turns out to be the temperature of the matter emerging in the decay . Further, the fluctuations involved can be formally considered as quasiparticles in the vacuumlike medium. It would appear reasonable that they fall freely in the medium (otherwise, what physical meaning can be given at all to the concept of vacuumlike medium?). Then, why do they 'stretch'? Moreover, these fluctuations occur in a Gibbons – Hawking thermal bath at a temperature apparently in excess of 10^{11} GeV. And are they still essential, against background?

Thus, the processes, which should stop the inflation, scarcely work as expected and scarcely they not only cannot ensure the simultaneity of the decay of the inflating medium, but also bring the inflation to a stop. Scenario N does not involve the inflation stage and the associated ambiguity in the temperature definition.

There remains, however, the problem of simultaneous cosmological start common to the most contemporary cosmologies. For causality reasons, in Ref. [2] it has been assumed that the transition to the Friedmann universe occurs only in some causally-connected region. This, strictly speaking, only ensures spherical symmetry, rather than homogeneity. Today, however, it can be thought that the global transition to expansion should not violate causality [32], so that the restriction of the start to a causally-connected region is scarcely correct.

Thus, the main difference between the two scenarios is associated with the idea of inflation — almost unlimited spontaneous expansion of cosmological medium without a significant change in its density. This seemingly erroneous idea being dismissed, the both scenarios can be all but dissimilar as applied to the observable universe.

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[3] The concept of the vacuumlike state does not imply its high global symmetry (see, e.g., Refs [14, 15]).

[4] Reproduced in the Appendix to this paper.

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Appendix

Nonsingular Friedmann cosmology [5]

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A cosmological model is developed based on the suggestion that as density increases the physical medium enters a state of negative pressure. The model contains neither a past nor a future singularity. The solution of the Friedmann equations yields a closed universe whose mass increases by tens of orders of magnitude from the start of expansion.

In Friedmann cosmology there is a certain arbitrariness in the choice of the initial state. In the framework of general relativity theory one can construct a Friedmann cosmology without a singularity in the past or in the future by assuming that at some ultrahigh density ρ_0 the pressure in the cosmological medium $p = -\varepsilon_0$, where $\varepsilon_0 = \rho_0 c^2$. The equation $p = -\varepsilon$, where ε is the energy density, corresponds to one of the possible equilibrium states of medium of ultrahigh density. Matter in this state has properties similar to those of vacuum (Gliner, 1965; Zel'dovich, 1968). Under certain fairly general assumptions about the dependence of p on ε, the passage of matter through such a vacuumlike state corresponds to a change from compression to expansion. Therefore, the vacuumlike state of a medium can be taken as the initial cosmological state of the expanding universe.

Let us write the Friedmann equation in the form

$$\ddot{a} = -\frac{1}{6}\varkappa a(\varepsilon + 3p)\,, \qquad \dot{a}^2 = \frac{1}{3}\varkappa a^2\varepsilon - kc^2\,, \tag{1}$$

which corresponds to the homogeneous universe metric

$$ds^2 = c^2\,dt^2 - a^2(t)\left[(1-kr^2)^{-1}\,dr^2 + r^2(d\theta^2 + \sin^2\theta\,d\varphi^2)\right], \tag{2}$$

where $k = \pm 1$ or 0. On a cosmological scale, the vacuumlike state should be unstable with respect to a transition to matter with positive pressure. To see this, note that in the reference frame comoving with the matter formed through fluctuations, from Eqn (1) we find that if $p \sim -\varepsilon_0$, then $\ddot{a} > 0$, i.e., the matter arising in this way is in the state of expansion, its density decreases, and the fluctuation process becomes irreversible. Hence, in the model considered the onset of expansion relates to the properties of the initial state.

The value $\dot{a} = \dot{a}_0$ at the moment when expansion started is the correlated component of the velocity of the fluctuation-produced matter. It expresses a general tendency towards expansion ($\dot{a} > 0$) or contraction. But, due to the initial state is vacuumlike, there is no correlation among the velocities of matter emerging at different places. Therefore $\dot{a}_0 = 0$ and, in view of the second of Eqns (1), parameter $k > 0$, which corresponds to a closed universe with $a_0^2 = 3c^2\varkappa^{-1}\varepsilon_0^{-1}$. For $p = -\varepsilon$, the metric (2) corresponds to the de Sitter spacetime with event horizon radius a_0. Hence, the expanding Friedmann universe emerges from that part of a vacuumlike medium that is confined inside the event horizon. But being a removable singularity, event horizon in de Sitter spacetime poses no restrictions on the extent of medium with $p = -\varepsilon$. This suggests the possibility of a multiple creation of universes from a common initial state.

Near the state with $p = -\varepsilon_0$, the leading term in the expansion of the sum $p + \varepsilon$ in the power series in $(\varepsilon_0 - \varepsilon)$ can be written in the form $p + \varepsilon = \gamma\varepsilon_1(\varepsilon_0 - \varepsilon)^{\alpha}(\varepsilon_0 - \varepsilon_1)^{-\alpha}$, where α is a constant and ε_1 is the density for which the pressure $p = (\gamma - 1)\varepsilon_1$. Let us assume that this term in the equation of state remains leading up to the value $\varepsilon = \varepsilon_1$ at which the vacuumlike component of the medium becomes insignificant. The value $\gamma = 1$ corresponds to the 'cold' model, and $\gamma = 4/3$ to the 'hot' one. It is easily shown that the present state of the universe limits the values of α and ε_1 by the condition

$$\frac{\varepsilon_1^{1/2}}{\varepsilon_0}\exp\frac{2(\varepsilon_0 - \varepsilon_1)}{3\gamma\varepsilon_1(1-\alpha)} \approx \frac{\varepsilon_{\gamma c}^{1/2}}{\varepsilon_c}\left(1 - \frac{3H_c^2}{\varkappa\varepsilon_c}\right)^{-1}, \tag{3}$$

where ε_c and $\varepsilon_{\gamma c}$ are the current densities of the components of matter formed by massive and massless particles, respectively; H_c is the present value of the Hubble parameter. If the relation (3) is satisfied, the entropy of the universe in our model agrees with that in the observed universe.

It can be shown that all values of α in the range (0, 1) are attainable, including $\alpha \to 1$ and $\alpha \to 0$. In the latter case $\varepsilon_1 \to \varepsilon_0$, i.e., the change from the state with $p = -\varepsilon_0$ to that

[5] This work maintains two basic points: (1) the suggestion of the vacuumlike onset of the universe not only eliminates the necessity to admit the existence of the cosmological singularity, but also explains the cause of the expansion of the universe; (2) the acceleration of the cosmological medium occurs *during its phase transition to ordinary matter*.

After a quarter of century has elapsed, the authors certainly do not accept the responsibility for all aspects of this work. It would be written today differently. (*Author's note to English translation.*)

with $p > 0$ is close to a phase transition at a constant density ε_0.

For numerical estimates, let us adopt the present values: the average density of the universe, $\sim 10^{-29}$ g cm^{-3}; the background radiation temperature, 2.7 K (hence $\gamma = 4/3$); the Hubble parameter, 54 km (s Mpc)$^{-1}$. There are two characteristic ultrahigh densities: the Planck density of $\sim 10^{93}$ g cm^{-3} and the density of $\sim 10^{27}$ g cm^{-3} determined by the weak coupling constant. Calculations have been performed for the two initial vacuumlike states corresponding to these characteristic values of the density ρ_0.

The table below presents the following quantities: t_1, the time from the start of expansion to the $p = \varepsilon/3$-epoch; a_0 and a_1, the radii of the universe at the start of expansion and at time $t = t_1$; ρ_1, the density of the medium at $t = t_1$; M_0, the mass of the universe at the start of expansion; M_1, the mass of the universe at $t = t_1$. If two values are given in the table, the first applies to $\alpha \to 1$, and the second to $\alpha \to 0$.

Table

Parameters	$\rho_0 = 0.4 \times 10^{27}$ g cm^{-3}	$\rho_0 = 5 \times 10^{93}$ g cm^{-3}
t_1, s	$(2-4) \times 10^{-9}$	$(1-2) \times 10^{-42}$
a_0, cm	2	0.5×10^{-33}
a_1, cm	$(1.2-4.2) \times 10^{11}$	$(6.4-27) \times 10^{-4}$
ρ_1, g cm^{-3}	$0.4 \times 10^{27} - 3.1 \times 10^{24}$	$5 \times 10^{93} - 2 \times 10^{91}$
M_0, g	6.3×10^{28}	1.7×10^{-5}
M_1, g	$(15-4.5) \times 10^{60}$	$(2.7-0.7) \times 10^{85}$

We see from the table that the model under consideration involves a huge (40 to 90 orders) growth in mass for the universe during the epoch of negative pressure. The growth is due to the gravitational repulsion action at negative pressure in the ultrahigh density medium. During the epoch of *positive* pressure, the mass drops to the current value of $\sim 5 \times 10^{57}$ g. This is due to the predominance of the positive pressure of pairs and radiation at the beginning of the positive pressure epoch.

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