Possible state of matter just before the collapse stage

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The formation of black holes is analyzed as a particular example of a process which results in the following situation: In the stage *just preceding* the collapse of the universe, the various forms of matter may, while unifying, retain only the properties of a gravitating hydrodynamic matter. Even these properties, however, are lost in the final stage of the collapse, in which the matter arises in the form of a Λ-term devoid of a gravitational constant and of displacement properties.

It was hypothesized some time ago that there might be a limiting density for any form of matter in the universe (in the comoving coordinate system). A specific expression was proposed for this limiting density[1,2]: $\rho_0 = c^5/\hbar\kappa_0^2 \sim 10^{94}$ g/cm^3, where κ_0 is the gravitational constant.

The present letter poses the hypothesis that when the limiting density is reached, all differences in the forms of matter (or fields) become unified, and at the limiting density the matter should be characterized by only hydrodynamic properties. The physical meaning of this hypothesis is that at some densities in the course of the contraction of the matter the particles which make up the matter must lose their specific characteristics. Expressed in a different way, the meaning is that at the corresponding densities (which may differ for different classes of particles) there will be violations of the conservation laws which will involve the violation, in particular, of the invariance of Abelian and non-Abelian symmetries. In connection with the hypothesis of a limiting density of matter, our attention is drawn by the circumstance that the right side of Einstein's equation has no quantities of any sort characterizing the gravitational field. The right side of this equation contains only the density tensor of various forms of matter. In other words, the hypothesis of the existence of a final density of solely these types of matter does not rule out the appearance of a singularity in the course of the collapse of the universe. This singularity might be associated with,

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for example, gravitational background radiation. The energy density of this radiation is presently estimated to be $\rho_{grav} \sim 10^{-35}$ g/cm^3. It is thus about two orders of magnitude lower than the density of the background photon radiation.[3] If we take the size of the universe to be $R_{max} \sim 10^{28}$ cm, then we find that the density of the gravitational energy of the background gravitons alone would reach the Planck density $\rho_0 \sim 10^{94}$ g/cm^3 when the universe is at a radius—we wish to stress this point—$R \sim 10^{-5}$ cm in the course of its collapse. The energy density of the gravitational field is described in general not by a tensor but by a pseudotensor, and in many cases this quantity may disappear under certain coordinate transformations. For the case of the *total* energy and momentum of an isolated system, however, the corresponding pseudotensor acquires the properties of a tensor.[4] Furthermore, realistic possibilities for the conversion of the energy of gravitons into other forms of matter were taken up in quantum mechanics a long time ago.[5] In other words, the gravitational energy must also be limited to a certain density. In general the classic studies[6,7] of the perturbations of the metric of a gravitational field indicate that the difficulties stem from the singularities that arise: these difficulties have yet to be overcome in the existing models of universes.

Returning to the discussion of the hypothesis of a unification of all forms of matter at extreme densities, we should recall in connnection with the appearance of such entities as black holes in the theory that "black holes have no hair," as Wheeler would say. A black hole as a whole can have only a mass, an electric charge, and an angular momentum. We know that a closed universe cannot have a nonzero total mass, a nonzero charge, and, as follow; from Ref. 8, a nonzero angular momentum. As a result of these arguments, it seems logical to suggest that when a closed universe, in the course of its collapse, reaches a density of matter at the Planck level, all the matter of the universe will unify into a collection of elementary black holes—"maximons"[9] in our terminology—which may have neither an electric charge nor a spin. Furthermore, in this stage of the collapse the matter consisting of maximons could apparently also be absolutely cold. A heating of this matter consisting of a "close" packing of maximons having a mass of limiting density might disrupt the hypothesis of a limiting density. There is the suggestion that elementary black holes might either form directly from a gravitational field or undergo a prior transformation into other forms of matter. We are talking here about both transverse perturbations (gravitons) and longitudinal perturbations (sound). In any case, this hypothesis seems natural in the linear approximation. We do not rule out the possibility that a description of the nonlinear region of events in classical terms will reduce to a formalism of the Born-Infeld type, i.e., a finiteness of the curvature.[1]

So far we have been talking about stable elementary black holes in a "close packing" in a "continuous" maximon medium. An analysis of the physical properties of such matter requires a systematic quantum theory and a theory of the gravitational field. In principle, the example of a neutron which is stable in a bound state might be instructive. There are astrophysical considerations which argue against the stability of a final state of a free black hole, just as there are such considerations which argue against the existence of a large number of magnetic monopoles. There are also several arguments in favor of their stability[1)] (Refs. 10–12).

In a series of papers we have analyzed a hydrodynamic model in an oscillating universe, in particular, one filled with dusty matter. In the preceding papers we showed that a model of this sort, in which the role of the dust is played by an ensemble of elementary black holes, may prove capable of describing the state of the universe at times close to the final stage of collapse. On the other hand, we see that a specific version of the model of this collapse, which we set forth in several papers[13,14]—specifically, the model of an "oscillating Friedmann–de Sitter universe with a Λ term which depends on the state of the matter"—has much in common in the initial stage of the expansion of the universe with models of so-called inflationary universes.[2)]

We recall Einstein's equation, which we adapt to the case of an oscillating Friedmann dusty universe:

$$(\dot{a}/ca)^2 + \frac{1}{a^2} = \frac{8\pi\kappa_0}{3c^2}[\rho F(\rho^2/\rho_0^2) + \Lambda'\theta(\rho^2/\rho_0^2)], \qquad (1)$$

where a is the "radius" of the universe, ρ is the density of matter, and Λ' is a constant with the dimensionality of a mass density. The functions F and θ are chosen in such a way that we have $F\to 0$ as $\rho\to\rho_0$, $\theta\to 1$ as $\rho\to\rho_0$, $F\to 1$ as $\rho\ll\rho_0$, and $\theta\to 0$ as $\rho\ll\rho_0$. Here

$$\Lambda'\frac{8\pi\kappa_0}{3c^2} = \Lambda_0$$

is a constant (the Λ_0 term). We wish to stress that the second term in (1) does not contain the gravitational constant κ_0: It is a $\sim\Lambda'\kappa_0$-term, which depends on only the density of matter. At low densities ($F\to 1;\kappa_0\Lambda'\theta\to 0$), Eq. (1) thus describes a closed Friedmann universe: The Λ-term essentially disappears. In the limit $\rho\to\rho_0$, on the contrary, a Λ-term arises. In the limiting case it also is equal to a constant, $\kappa_0\Lambda'$, while the density of the gravitating energy tends toward zero ($\rho F\to 0$), and the universe becomes a purely de Sitter universe. The pumping of the density of the observable gravitating energy ρF into the Λ-term is described by the "conservation equation"

$$\frac{1}{\sqrt{-g}}\frac{\partial}{\partial t}(\rho F\sqrt{-g}) + \Lambda'\frac{\partial}{\partial t}\theta = 0, \qquad (2)$$

which follows automatically from the vanishing of the covariant divergence of the left side of Einstein's equation. The functions F and θ are chosen on the basis of an additional condition: In this case, it is required that the collapse of the universe stop at densities $\rho = \rho_{\max} \lesssim \rho_0$ and at a radius of the universe $a_{\min} \sim l_{Pl} \approx \sqrt{h\kappa_0/c^3} \sim 10^{-33}$ cm. These conditions are satisfied by the simple functions

$$F = [1-(\rho^2/\rho_0^2)]; \quad \theta = \rho^2/\rho_0^2 \quad \text{and} \quad \Lambda'/\rho_0 = 2, \qquad (3)$$

The duration of the de Sitter phase, i.e., the phase of the new expansion of the universe after the collapse has stopped, depends on the choice of the functions F and θ and on the values of $\rho_{\max}$ and[2)] Λ'. The duration of this phase varies dramatically with the particular values of the constants ρ_0 and Λ' and with the particular functions F and θ. An integration of Eq. (2) gives us a relationship among ρ, ρ_0, Λ', a, and the integration constant M_0, which represents the total mass of all the dust particles forming the closed universe:

$$\left[(\rho_0^2 - \rho^2) \times \rho \frac{(\rho_0 + \rho)}{|\rho_0 - \rho|} \right]^{\Lambda'/\rho_0} = \frac{M_0 \rho_0^2}{2\pi a^3}. \tag{4}$$

In the limit $\rho \to \rho_{\max}$, in which Eq. (1) becomes

$$(\dot{a}/ca)^2 + \frac{1}{a^2} \approx \Lambda_0, \tag{5}$$

we have

$$a \sim a_{min}\, e^{\pm c \sqrt{\Lambda_0}\, t} \tag{6}$$

in the de Sitter phase. In inflationary models the role of the Λ-term is usually played by the potential energy of a scalar field φ. It is assumed that $\dot{\varphi}$ is small. In an early stage of an inflationary universe, the physical distinction between our model of the universe and inflationary models is that the latter have no true Λ_0 term and no true constant of the de Sitter metric, which characterizes a peculiar *nongravitating* form of matter.[3)] Accordingly, upon the collapse of an inflationary universe it does not revert to the state of an initial de Sitter universe, and $\dot{\varphi}$ does not automatically vanish in the course of the collapse. Furthermore, the universes which arise from "nothing," which have become quite fashionable, must by definition be closed.

A Λ_0-term was introduced by Einstein on the left side of an equation which does not contain the gravitational constant κ; $R_{\mu\nu} - 1/2 g_{\mu\nu} R + g_{\mu\nu}\Lambda_0 = \kappa_0 T_{\mu\nu}$. In inflationary models, the role of a Λ-term is usually played *formally* by a scalar field φ, i.e., by gravitating matter. In results generated under these assumptions ($\dot{\varphi} = 0$), it is possible to obtain a solution of the de Sitter type at the initial time, but, strictly speaking, we would be dealing with a quasi–de Sitter initial phase of the universe.

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[1)]At black-hole masses close to the Planck mass, the Hawking radiation spectrum would apparently be deformed, since there is reason to believe that the levels of a quantized black hole do not overlap greatly.

[2)]The formation of galaxies requires an analysis of various perturbations in the "rebound" phase in the given model.

[3)]It follows from the discussion above that a unification of matter in the form of a medium of elementary black holes would be a step in the subsequent conversion of the matter into a physical reality describable by a Λ-term, which is essentially the primordial matter in the Anaxagoras sense[14] (which would not consist of parts capable of being moved with respect to each other).

[1]M. A. Markov, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 214 (1982) [JETP Lett. **36**, 265 (1982)].

[2]N. Rosen, Astrophys. J. **297**, 347 (1985).

[3]Ya. B. Zel'dovich and I. D. Novikov, Stroenie i évolyutsiya Vselennoĭ (Structure and Evolution of the Universe), 1975, p. 391.

[4]R. Isaacson, Phys. Rev. **166**, 1263, 1272 (1968).

[5]D. D. Ivanenko, Kvantovaya teoriya (Quantum Theory), 1952, p. 675.

[6]E. M. Lifshitz, Zh. Eksp. Teor. Fiz. **16**, 587 (1946).

[7]E. M. Lifshitz and I. M. Khalatnikov, Usp. Fiz. Nauk **80**, 391 (1963) [Sov. Phys. Usp. **6**, 495 (1964)].

[8]V. A. Berezik, Trudy FIAN **152**, 31 (1983).

[9]M. A. Markov, Progr. Theo. Phys. Supplement. Commemoration Issue for the 30th Anniversary of the Meson Theory by Dr. H. Yukawa.

[10]V. K. Maltsev and M. A. Markov, Preprint P-0160, Institute for Nuclear Research, Moscow, 1980.

[11]V. F. Mikhanov, Preprint No. 163. "Evaporation and entropy of quantized black hole," P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow, 1986.
[12]Y. Aharonov, A. Casher, and S. N. Nussinov, Phys. Lett. **B191**, 51 (1987).
[13]M. A. Markov, Ann. Phys. **155**, 33 (1984).
[14]M. A. Markov, Group Theoretical Methods in Physics, Yurmala, USSR. 22–24 May, 1985.

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