The very late universe

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(Submitted 3 July 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **56**, No. 4, 185–188 (25 August 1992)

If a limiting curvature exists, the state of a very late closed universe should be the initial state of a very early universe. In contrast with the original early universe, however, it must decay into a multitude of universes.

Various models of the very early universe have been discussed theoretically. The basic thrust of this work has been a systematic study of that stage of the history of the universe which is characterized by an inflationary process.[1] If we are talking about a closed universe, then the expansion of the universe should ultimately give way to a contraction, which would lead to a collapse. None of the existing models of the early universe automatically lead to a process which would cause an inflation to give way to an anti-inflation during a contraction of the universe. An "anti-inflation" is understood here as a process which repeats the various phases of the inflation process in the opposite chronological order.

In the course of a collapse, various perturbations arise and cause radical changes in the metric. Physically, the models of the very early universe correspond to the decay of some primordial matter in a phase of a de Sitter-like metric into all the numerous subsequent particles (fields), say, a Friedmann universe.

If, in some stage of the very late universe not far from the classical singularity, the universe should take the form of the original universe, then all forms of matter in the Friedmann universe should again convert into some sort of primordial matter, in which all distinctions among forms of matter would disappear. A process in which black holes form at high densities of the very late universe would then seem natural here. Upon the formation of black holes, all distinctions between particles and fields of the Friedmann phase of the universe would disappear. These ideas suggest that again in the course of the inflation the primordial matter might be a scalar field whose quantum is an elementary black hole (a maximon) or simply a gas of black holes.

As we will see, in discussing the very late universe it is useful to work with a classical model—one might say a "toy model"—which describes the cases of inflation and anti-inflation symmetrically.[2,3] Such a model turns out to be useful for clarifying problems of the very late universe. We have in mind an *ad hoc* modification of the right side of the Einstein equation. For the hydrodynamic case of an isotropic metric we have

$$(\dot{a}/c)^2 + 1 = \frac{8\pi a^2 k_0}{3c^2}[\rho(1 - \rho^2/\rho_0^2) + \Lambda'(\rho^2/\rho_0^2)], \tag{1}$$

where a is a scale factor, k_0 is the gravitational constant, ρ is the density of matter (dust), the constant ρ_0 places an upper limit on the density of matter, and Λ' is the constant

$$\Lambda' = \Lambda^0 \frac{3c^2}{8\pi k_0}.$$

Here Λ^0 is the "lambda term" in the Einstein equation.

This equation describes an oscillating toy classical universe which is oscillating continuously between $a_{\min}$ and $a_{\max}$. The evolution of this universe obeys the law

$$\frac{\rho(\rho+\rho_0)^3}{|\rho_0-\rho|} = \frac{M_0\rho_0^2}{2\pi^2 a^3},$$

where M_0 is the bare mass of the closed universe.

Let us plug in some numbers. We assume a toy classical universe with a critical (maximum) density $\rho_0 = 10^{22}$ g/cm^3, and we adopt $\Lambda'/\rho_0 = 2$, $M_0 = 10^{55}$ g, and $\Lambda_0 = 10^{-6}$ cm^2. A calculation then leads to

$$a_{min} \sim 10^3 \text{ cm},$$

or, more precisely,

$$a_{min} = 10^3(1 + m_0/M_0) \text{ cm, where } m_0 \sim \rho_0 a_{min}^3,$$

i.e.,

$$a_{min} = 10^3(1 + 10^{-31}) \text{ cm}.$$

If we are bold enough to take ρ_0 for classical equation (1) as being made up of the universal constants $\hbar$, c, and k_0, i.e., if we assume

$$\rho_0 = c^5/\hbar k^2 \sim 10^{94} \text{ g},$$

$$\Lambda^0 \sim 1/l_{pl}^2 ,$$

$$l_{pl} = \sqrt{\hbar k_0/c^3} ,$$

$$M_0 = 10^{55} \text{ g},$$

then we find, in this case,

$$a'_{min} = l_{pl}(1 + m_{pl}/M_0) \sim 10^{-33}(1 + 10^{-60}) \text{ cm}.$$

The discussion of this toy model has revealed two instructive points: There is no singularity in such a universe, and at $a_{\min}$, at the rebound point, a new inflationary phase of the toy universe begins.

1. At the rebound of the very late universe, the bare mass of the closed universe, M_0, is conserved. Since the entropy (temperature) of a real universe increases in the course of the expansion and contraction, i.e., since M_0 must increase from one oscillation to the next, we must reject this homogeneous and isotropic model of the very late universe.

Something must occur during the collapse of the very late universe to resolve the problem of the increase in entropy in the subsequent evolution of the universe. It turns out that there are some significant and natural guidelines here. Specifically, we have selected the idealized case of a homogeneous and isotropic universe. In such a universe there would unavoidably be perturbations of the density of matter. The critical density might thus be reached earlier in some regions of the very late universe than elsewhere. When this critical density is reached, the collapse would have to stop, and the state of the early universe would have to arise. Does this not mean that the perturbations would cause the universe to decay into a large number of universes, each with its own M_0? In principle, it is possible to solve the problem of the increase in entropy by this line of reasoning.

2. A very instructive property of this model is that the point of the rebound ($a_{\min}$) turns out to be essentially *the same for all universes with* $M_0 \gg m_{pl}$.

We recall that in the case of Planckian size, $M_0 > 10^{55}$, we would have

$$a'_{min} = l_{pl}(1 + m_{pl}/M_0) = 10^{-33}(1 + 10^{-60})\ \text{cm}. \qquad (2)$$

On the one hand, $a_{\min}$ represents the final size of the very late universe, while on the other, it represents values characterizing the initial data of the new universe after the rebound. In other words, all memory of the prior universe is embodied in the term m_{pl}/M_0. The retention of a memory of the prior universe is meaningful if lengths very close to the Planckian length are *physically distinguishable,* i.e., if

$$l = 10^{-33}\ \text{cm} \quad \text{and} \quad l = 10^{-33}(1 + 10^{-60})\ \text{cm}.$$

Let us imagine an experiment in which we use a Heisenberg microscope to measure lengths. Measuring distances smaller than Planckian distances requires quanta of corresponding wavelengths, $\lambda \ll l_{pl}$. Photons of this wavelength, however, would evidently be elementary black holes of Planckian radius. A further decrease in the wavelength would lead to an increase in the black hole's mass and dimensions, which would span the Planckian dimensions of the object to be measured. One might make the *a priori* assumption that lengths smaller than or on the order of Planckian lengths "simply do not exist."[1)] In casting doubt on the possibility of distinguishing these lengths, we are therefore casting doubt on a deterministic description of the very late universe. The conservation of M_0 in the classical model is linked with such a description. The meaning would be that a new universe regenerated after the collapse would have unpredictable properties, in accordance with Wheeler's ideas ("Beyond the End of Time").[4]

3. Among the various perturbations of the very late universe, the most dangerous ones would be associated with a realization of Kazner solutions and, in general, solutions with a free gravitational field. Here there is the possibility of avoiding singularities if these perturbations reduce to the production of new matter, which would only increase the inhomogeneity of the density of matter in this model.

Going back to our toy model, we should stress that one of its main features is the idea of asymptotic freedom of gravitational interactions. As we know, there is the hope that the singularity problem can be resolved by tinkering with the left side of the Einstein equation. For example, Mal'tsev[5] wrote the Lagrangian in the form

$$L = \int L'(/G\pi k)(R + \beta R^2 + \dots)\sqrt{-g}dx^4$$

and transformed the left side into its standard form in the corresponding equations. On the right side of the equation, we then find T_0^0 in the form

$$T_0^0 = \epsilon(1 - \epsilon/\epsilon_0 + \dots) = \epsilon k_0 f(\epsilon/\epsilon_0),$$

where $k_0 f(\epsilon/\epsilon_0)$ is now playing the role of a gravitational constant which tends toward zero with increasing energy density ϵ. In Ref. 3 we used the following example for f:

$$f = (1 + \epsilon/\epsilon_0)^{-2} \simeq (1 - \epsilon/\epsilon_0 + \dots).$$

We do not rule out the possibility that our toy model contains some important real features of a future cosmology. We have in mind the existence of a limiting density of matter and the idea of asymptotic freedom.

[1)]The physical meaning of this possibility is discussed in Ref. 6.

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[5]V. Mal'tsev, Report to Anglo-Soviet Seminar, 14 May 1990.
[6]M. A. Markov, "Possible complete violation of determinism in the behavior of gravitational collapse near a singularity" [in Russian]; *Proceedings of the First A.D. Sakharov Int. Conf. on Physics* (1991) (to be published).

Translated by D. Parsons