PHASE TRANSITIONS OF COSMOLOGICAL VACUUM AND PRIMORDIAL BLACK HOLES

N.S. Kardaskhev, I.D. Novikov
Space Research Institute, USSR Academy of Sciences

We propose to discuss here the possibility of the origin and existence of primordial black holes and their expected parameters in the scenarios of the early Universe in which vacuum phase transitions play a decisive role.

The possibility of the origin of primordial black holes was advanced in a paper by Zeldovich and Novikov (1966) and later in a paper by Hawking (1971) and was successfully developed subsequently by others.

The earlier work dealt with the investigation of the physical meaning of the cosmological constant as a manifestation of vacuum properties and was initiated by Zeldovich (1967) and Sakharov (1967). Papers by Kirzhnitz (1972), Kirzhnitz and Linde (1972), Linde (1974) and Weinberg (1974) initiated the development of the theory of phase transitions with spontaneously broken symmetry, which according to the Grand Unified Theories should have occurred at early stages of the universal expansion. This trend then had a brilliant development. The essential stage was the scenario of the universal evolution with a term caused by quantum effects advanced by Starobinsky (1980), and the scenario of the universal evolution with a Λ-term in the Grand Unified Theories advanced by Guth (1981) and Linde (1981). We now believe that we are close to the solution of many important problems: the problem of the beginning of the cosmological expansion (origin of the universe in the context of supersymmetry theories), the isotropy and homogeneity of the Universe at large scales due to the causal connection between the parts in the earlier period of exponential expansion, the nearness of the present density to the critical one (flat three-dimensional space), and the appearance of inhomogeneities essential for forming stars and galaxies. One of the most complicated problems of the developing theory is the concrete definition of the phase transition process. Although much remains to be worked out, a qualitative picture of the universal expansion at the earlier stages seems to be as follows (Figure 1): In the process of expansion, the universe vacuum was initially in the state of so-called false vacuum with high energy density. Now we can single out three states.

<u>The first state</u> corresponds to the unified gravitational, strong, weak and electromagnetic interactions (the temperature was close to the Planck mass: $T_1 = \sqrt{\hbar c/G} = 2.2 \times 10^{-5}$ g $= 1.2 \times 10^{19}$ GeV $= 1.4 \times 10^{32}$ K).

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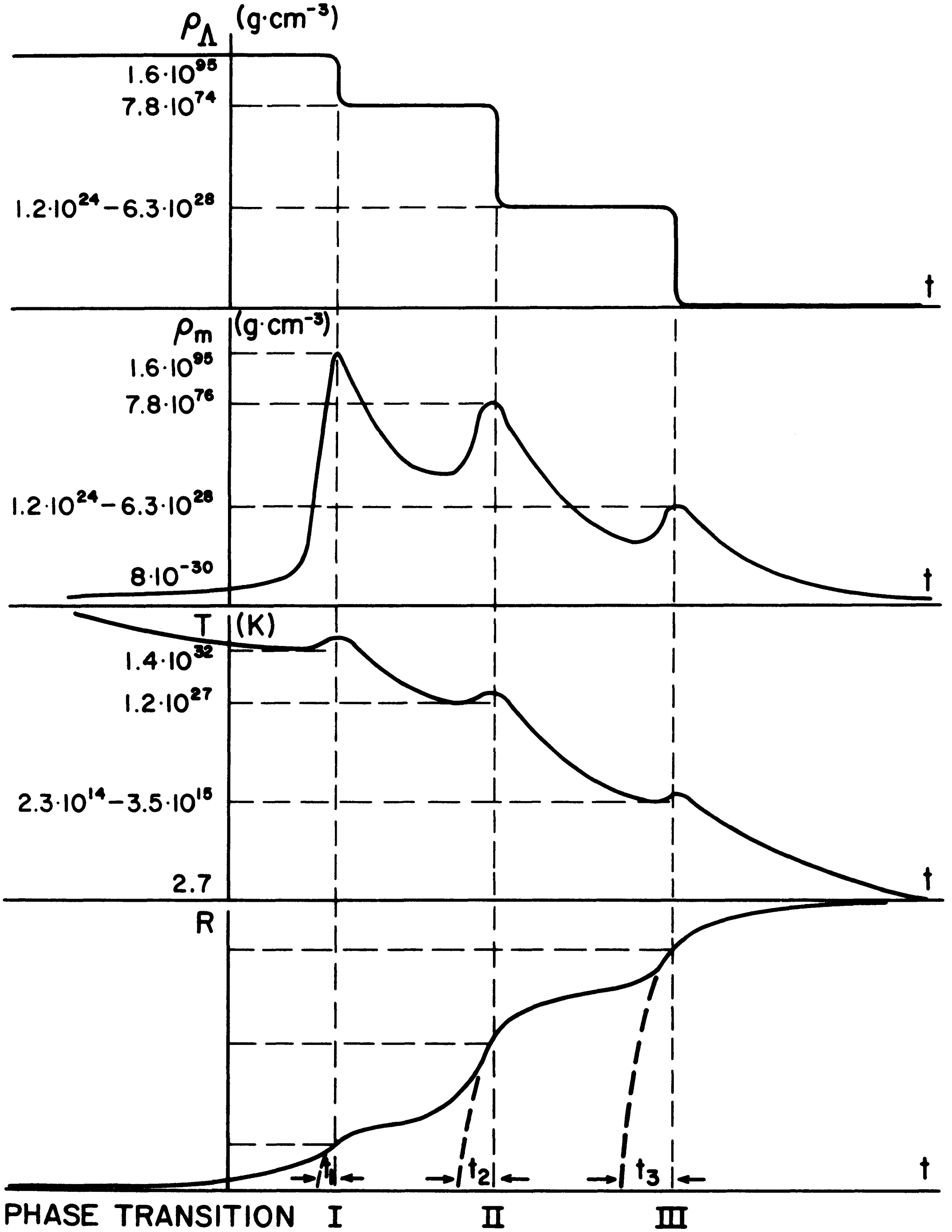

Figure 1. Expected evolution in the early big bang with three phase transitions. ρ_Λ is the vacuum energy density, ρ_m is the matter density, T is the particle temperature, and R is the scaling factor.

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The vacuum energy density at this temperature and possibly at higher temperatures $\rho_1 = \pi^2 N(kT)^{-4}/30\hbar^3 c^5 \simeq 1.6 \times 10^{95}$ g/cm^3, where N is the number of various types of elementary particle. We adopt N = 100 for all calculations. This state corresponds to a cosmological constant $\lambda_1 = 8\pi G\rho_1 = 2.7 \times 10^{89}$ s^{-2}, $\Lambda_1 = \lambda_1/c^2 = 3.0 \times 10^{68}$ cm^{-2}. After the transition to the new vacuum state we can assume that the expansion obeys the law of the common cosmological model of a flat world, where the main density of vacuum energy is transformed to that of relativistic matter, heated to approximately the same temperature, and a small part of vacuum energy corresponds to the next metastable state. It can be assumed that during the transition from one vacuum state to another some small part of the matter could transform to the black hole state (see, for example, Sato 1981).

From the relation for Friedmann models at relativistic stages, $\rho_1 = 3/32\pi Gt^2$, we determine $t_1 = 1.7 \times 10^{-45}$ s, which characterizes a time interval of density variation, and provides an estimate of a possible characteristic mass of appearing primordial black holes at this stage: $M_1 = 4/3\ \pi(ct_1)^3\rho_1 \simeq 8.4 \times 10^{-8}$ g. Such holes should rapidly evaporate, or even fail to form in general because of quantum effects. In the process of further expansion, the matter density and temperature fall according to a power law, and at some time the Λ-term of the next metastable vacuum state becomes decisive for another expansion.

The second state is the unified strong, weak and electromagnetic interactions; $T_2 = 10^{14}$ GeV $= 1.2 \times 10^{27}$ K, $\rho_2 = 7.8 \times 10^{74}$ g/cm^3, $\lambda_2 = 1.3 \times 10^{69}$ s^{-2}, $\Lambda_2 = 1.4 \times 10^{48}$ cm^{-2}; $t_2 = 2.4 \times 10^{-35}$ s, and $M_2 = 1.2 \times 10^3$ g are determined, respectively. The lifetime of such black holes due to the Hawking process is: $t_H = 8.8 \times 10^{-27} M_2^3 = 1.5 \times 10^{-17}$ s.

After this phase transition, the vacuum energy density once again transforms to hot matter, it expands, and the Λ-term of the new metastable state again becomes decisive.

The third state is the unified weak and electromagnetic states. $T_3 \approx g^{-1/2} \simeq 300$ GeV $\approx 3.5 \times 10^{15}$ K (g is the weak interaction constant), $\rho_3 = 6.3 \times 10^{28}$ g/cm^3, $\lambda_3 = 1.1 \times 10^{23}$ s^{-2}, $\Lambda_3 = 120$ cm^{-2} $t_3 = 2.7 \times 10^{-12}$ s, $M_3 = 1.4 \times 10^{26}$ g, $Z_3 = 9.2 \times 10^{15}$.[1] According to a paper by Guth and Weinberg (1980), the transition to the spontaneous phase variation occurs for $T_3^* = K(\alpha)(2-\alpha)^{1/4}\sigma$, $K(\alpha)$ smoothly varies from 0.081 to 0.087 as α varies from 2 to 0. We take $\alpha \simeq 1$. The value $\sigma = (\sqrt{2}g)^{-1/2} = 246$ GeV is experimentally determined, from which $T_3^* = 20$ GeV $= 2.3 \times 10^{14}$ K. Then $\rho_3^* = 1.2 \times 10^{24}$ g/cm^2, $\lambda_3^* = 2.0 \times 10^{18}$ s^{-2}, $\Lambda_3^* = 2.2 \times 10^{-3}$ cm^{-2}, $t_3^* = 6.1 \times 10^{-10}$ s, $M_3^* = 3.1 \times 10^{28}$ g, and $Z_3^* = 6.0 \times 10^{14}$. The masses obtained for black holes (of the order of the mass of the Moon and terrestrial planets) have very weak Hawking glow and should have been preserved up to the present. Apparently, after the third phase transition (although maybe it is not so), the true vacuum forms (its energy density and the Λ-term are equal to zero), and the expansion is close to the Einstein-de Sitter flat model, with all main properties of the existing theory of the large explosion. The kinetics and even the duration of

[1] $Z_3 = R_0/R_3 = (0.5\ N)^{1/2}\ T_3/T_0 = 9.2 \times 10^{15}$ is the compression measure of the Universe (redshift), $T_0 = 2.7$ K is the modern temperature of the cosmological background.

each phase of the vacuum "boiling" have not quite been cleared up yet. It is possible that the number of transitions is much more than three, but it is also possible that they all merge together forming a common region stretched over temperatures. Probably, however, the conclusion is valid that only in the latter case (Z_3) do primordial black holes form that are capable of existing up to the present. One possibility is that these black holes represent a hidden mass giving the Universe a density close to the critical one. During the subsequent evolution, the accretion process scarcely changes their mass (Novikov and Polnarev 1980). Under our assumption of the age of the Einstein-de Sitter model, $t_0 = 10^{10}$ years, $H_0 = 2/3t_0 = 65$ km/s, the density, $\rho_0 = 3H_0^2/8\pi G = 8 \times 10^{-30}$ g/cm^3, is completely determined by primordial black holes. Then, for the moment t_3 their contribution to the density is $\rho_{BH} = \rho_0 Z_3^3 = 6.2 \times 10^{18}$ g/cm^3, and $\rho_{BH}/\rho_3 = 10^{-10}$; i.e., primordial holes can constitute an insignificant part of density at this moment. The important peculiarity of primordial black holes is the fact that all these objects cannot have relativistic velocities even during the initial epoch (though the opposite possibility should be investigated). The theory of nonlinear perturbations in the gas from stars or black holes can be used, resulting in the formation of black hole clusters (Doroshkevich, Zeldovich 1974; Peebles 1974). The cluster mass is $M_c = M_3 Z^{6/7}$, where Z is the beginning of the nonlinear stage.

With a uniform distribution of primordial black holes in space, their density will be $n_0 \simeq 2.5 \times 10^{-58}$ to 5.6×10^{-56} cm^{-3}, the distance to the nearest hole is $n_0^{-1/3} = 1$ to 15 pc. If it is assumed that the hidden mass in the Galaxy near the sun is $\rho_0 \simeq 0.05\ M_\odot/pc^3$ (Faber and Gallagher 1979), the black hole density is $n_0 \simeq 1.1 \times 10^{-52}$ to 2.4×10^{-50} cm^{-3} and the distance to the nearest hole is $n_0^{-1/3} = 2.3 \times 10^3$ to 1.4×10^4 a.u.

In conclusion, it should be mentioned that the presence of a large number of black holes with masses in the interval considered does not contradict observations. Figure 2, taken from Carr (1979), shows that just in this interval of masses the contribution of black holes providing the critical density of the Universe is possible.

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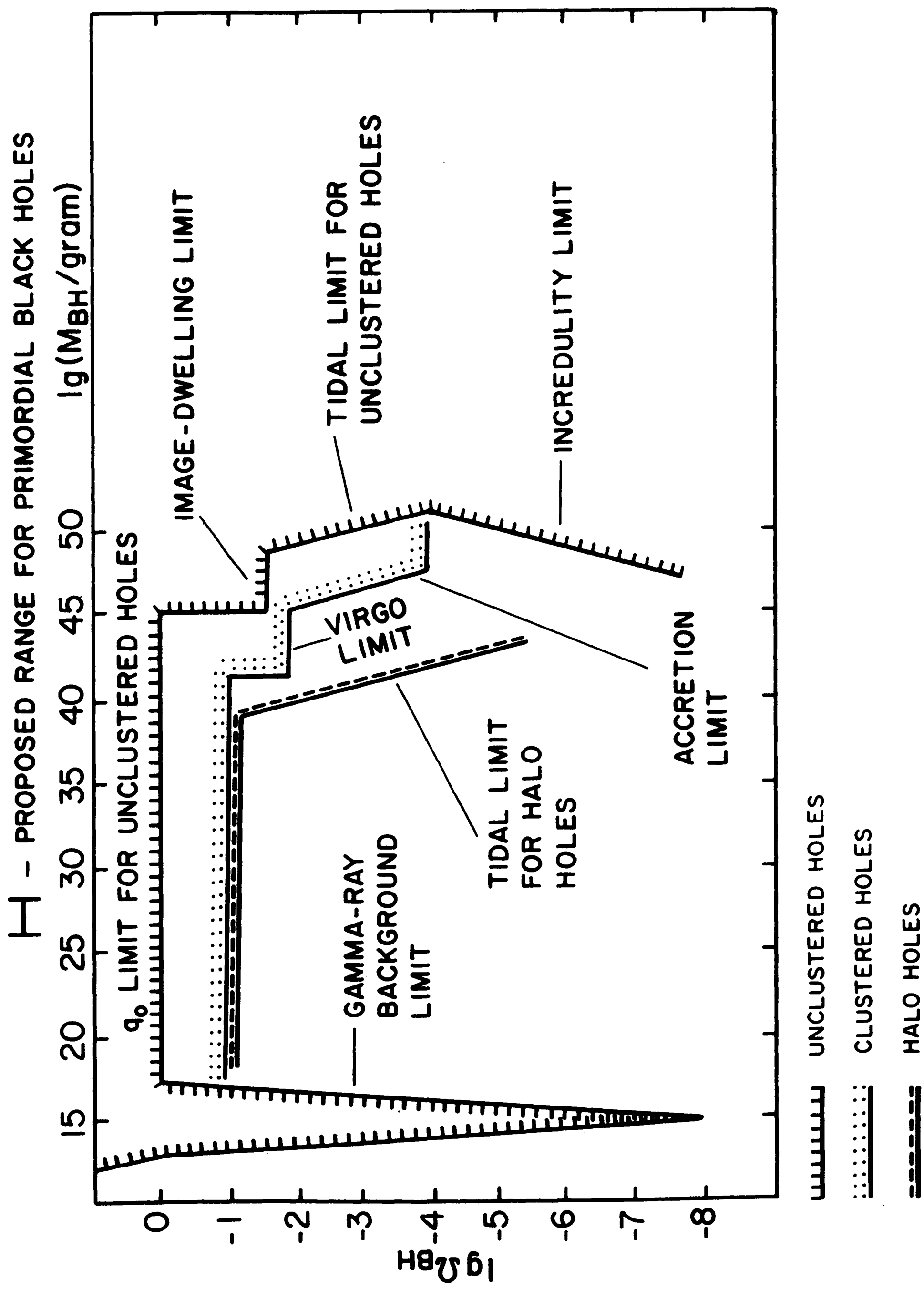

Figure 2. Limits on the cosmological density of the primordial black holes (Carr 1978).

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Discussion

Rees: You have, I think, assumed that the black holes start to cluster immediately after they form. However, for reasons discussed in papers by (among others) Guyot and Zeldovich, and Meszaros, this clustering will not start until the end of the radiation-dominated phase (i.e., $T \simeq 10^5\ \Omega °K$). Taking this into account, it will be hard to evolve a cluster of even a stellar mass.

Kardashav: We agree.

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