Supergravitation and the inflationary universe

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The realization of a new scenario for an inflationary universe within the framework of $N = 1$ supergravitation is proposed. It is shown that it is possible to determine the density inhomogeneities, $\delta\rho/\rho \sim 10^{-4}$, necessary for the formation of galaxies and to solve the problem of primordial monopoles at the same time.

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As is well known, the new scenario of an inflationary universe[1] (see also Ref. 2) opens up the fundamental possibility of solving a series of cosmological problems such as the problem of the horizon, flatness, homogeniety, and isotropy of the universe, as well as the problem of primordial monopoles, domain walls, and the gravitino. It turned out, however, that this scenario cannot be used fully in the simplest grand unification theories, since a sufficiently strong inflation of the universe in this case is not obtained[3,4] and, in addition, after inflation, in these theories, density inhomogeneities $\delta\rho/\rho$ form with a "flat" spectrum, necessary for subsequent formation of galaxies,[5] but with an amplitude that greatly exceeds the required amplitude $\delta\rho/\rho \sim 10^{-4}$.[4,6] To overcome this difficulty, it was proposed in Refs. 7 and 8 that supersymmetrical theories be used with a scale of symmetry breaking of the order of the Planck mass $M_P \sim 10^{19}$ GeV. It turned out that it is possible, in principle, to obtain both strong inflation of the universe and density inhomogeneities of the desired amplitude in these theories.[9] However, as asserted in Refs. 7 and 8, within the framework of the approach used therein, it is not possible to solve the problem of primordial monopoles, since monopoles in this scenario are already formed after inflation stops. In addition, a more detailed investigation of the simplest models, used in Refs. 7 and 8, has shown that the scenario proposed therein itself needs to be modified.[10] For this reason, there arises the question as to whether it is possible to realize the new inflation scenario within the framework of supersymmetrical theories and to solve at the same time the problem of primordial monopoles.

To study this question, we shall examine, adopting the method used in Ref. 11, $N = 1$ supergravitation, which interacts with a chiral superfield Φ. The effective potential relative to the first (scalar) component of this field z has the following form[11]:

$$V(z, z^*) = e^{\frac{1}{2}zz^*}\left(2\left|\frac{dg}{dz} + \frac{1}{2}z^* g\right|^2 - 3|g^2|\right), \tag{1}$$

where $g(z) = \mu^3 f(z)$, μ is a parameter with the dimensionality of the mass, and $f(z)$ is an arbitrary function. For simplicity, all dimensional quantities are expressed in units of $M_P/\sqrt{8\pi}$. We shall examine the phase transition with symmetry breaking in theory (1) due to the appearance of a real part φ of the field z. Because of the freedom in choosing $f(z)$, the effective potential $V(\varphi)$ in (1) can have an arbitrary form on condition that

$V(\varphi) = 0$, where φ_0 corresponds to the minimum in $V(\varphi)$. This condition is necessary for the cosmological term to vanish in the present epoch. The simplest potential of this type has the following form:

$$V(\varphi) = 3\mu^6\left(1 - \alpha^2\varphi^2 + \frac{\alpha^4}{4}\varphi^4\right); \tag{2}$$

hence, $\varphi_0 = \sqrt{2}/\alpha$.

At the earliest stages of the evolution of the universe, the temperature was high, symmetry was set up, and the field φ was equal to zero.[12] As the universe expanded, the temperature dropped rapidly and the effective potential assumed the form (2), but with small α and μ, the symmetry breaking proceeded very slowly. As shown in Refs. 2 and 3, the amplitude of the field φ arising in this case increases as follows:

$$\varphi^2 \approx \frac{\mu^6}{16\pi^2\alpha^2}\left(e^{4\mu^3\alpha^2(t-t_0)} - 1\right), \tag{3}$$

where t_0 is the time at which the symmetry breaking process appears. The field φ reaches its eqilibrium value $\varphi_0 = \sqrt{2}/\alpha$ within a time

$$\Delta t_1 \sim 6\mu^{-3}\alpha^{-2}. \tag{4}$$

For most of this time, the quantity $V(\varphi)$ in (2) remained essentially the same as its initial value at $\varphi = 0$, and the universe expanded (inflated) exponentially according to the law

$$a(t) = a_0 \exp[\mu^3(t - t_0)], \tag{5}$$

where $a(t)$ is the scale factor of the universe.[1] Quantum fluctuations of the field φ during the symmetry breaking process increased and led to the appearance of density inhomogeneities $\delta\rho$. Using the equations in Refs. 3 and 5, where this process was investigated, it is easy to obtain an expression for the relative amplitude of these fluctuations $\delta\rho(l)/\rho$, which corresponds to inhomogeneities $\delta\rho$ on a scale l at the time when inflation stopped:

$$\frac{\delta\rho(l)}{\rho} \sim \frac{\mu^3}{4\pi^{3/2}\alpha}(\mu^3 l)^{2\alpha^2}. \tag{6}$$

For density inhomogeneities on a galactic scale $l \sim e^{50}\mu^{-3}$,[3,5] so that

$$\frac{\delta\rho}{\rho} \sim \frac{\mu^3\exp(10^2\alpha^2)}{20\alpha}. \tag{7}$$

It is evident that the required term $\delta\rho/\rho \sim 10^{-4}$ arises, for example, with $\alpha \sim \mu \sim 10^{-1}$ (more exactly, with $\mu^3 \sim 10^{-4}$. In addition, in accordance with Zel'do-vich's prediction,[4] the spectrum of $\delta\rho(l)/\rho$ is essentially independent of l (6). For the indicated values of α and μ, the universe, according to (4) and (5), inflates by approximately a factor e^{600} during the period of exponential expansion (5). This is entirely sufficient for realization of the new scenario of the inflationary universe.[1]

We shall now examine the problem of the creation of primordial monopoles in this scenario. According to (4), for $\alpha \sim \mu \sim 10^{-1}$, the duration of the explosive period of the universe is $\Delta t_1 \sim (10^{11}\ \mathrm{GeV})^{-1}$, and in addition, during most of this period the temperature of the universe is nearly zero.[1] For this reason, the process of symmetry breaking in the grand-unification theories, which occurs over a scale time $\Delta t_2 \sim M_x^{-1} \sim (10^{15}\ \mathrm{GeV})^{-1}$, begins almost simultaneously with the onset of inflation. Thus the phase transition in the grand-unification theories does not occur after inflation, as proposed in Refs. 6 and 7, but long after inflation stops ($\Delta t_2 \ll \Delta t_1$). The density of the monopoles formed during this phase transition, as a result of the subsequent inflation of the universe, decreases nearly to zero.

In general, after inflating, the universe again could heat up to a temperature exceeding the critical temperature for restoring symmetry in grand-unification theories, $T_c \sim 10^{15}$ GeV, after which the phase transition will occur once again with the formation of monopoles. However, analysis of the process by which the universe is heated in the scenario being examined shows that the temperature of the universe T_p after inflation turns out to be many orders of magnitude lower than $T_c (T_p \sim 10^{11})$ GeV[10], so that after inflation monopoles are no longer formed.

Thus the new scenario of an inflationary universe can be completely realized in the simple model examined here. In addition, it is possible to obtain the spectrum of inhomogeneities required for the formation of galaxies and to solve in a straightforward manner the problem of primordial monopoles.

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