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NON–GUT BARYOGENESIS AND LARGE SCALE STRUCTURE OF THE UNIVERSE

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ABSTRACT

We discuss a mechanism for generating baryon density perturbations and study the evolution of the baryon charge density distribution in the framework of the low temperature baryogenesis scenario. This mechanism may be important for the large scale structure formation of the Universe and particularly, may be essential for understanding the existence of a characteristic scale of $130h^{-1}$ Mpc in the distribution of the visible matter.

The detailed analysis showed that both the observed very large scale of the visible matter distribution in the Universe and the observed baryon asymmetry value could naturally appear as a result of the evolution of a complex scalar field condensate, formed at the inflationary stage.

Moreover, according to our model, at present the visible part of the Universe may consist of baryonic and antibaryonic shells, sufficiently separated, so that annihilation radiation is not observed. This is an interesting possibility as far as the observational data of antiparticles in cosmic rays do not rule out the possibility of antimatter superclusters in the Universe.

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1 Introduction

The structure of the Universe at large scales is very complicated, it shows a strange pattern of filaments, voids and sheets. Recently, due to the increasing amount of different types of observational data and theoretical analysis, it is realized, that there exists a characteristic scale of about $130h^{-1}$ Mpc in the large scale texture of the Universe.

The galaxy redshift surveys [1] found an intriguing periodicity in the very large scale distribution of the luminous matter in the Universe. The characteristic scale of periodicity is about $130h^{-1}$ Mpc. This periodicity points to the existence of a significantly larger scale in the observed today Universe structure than predicted by standard models of structure formation by gravitational instability [2] and is rather to be regarded as a new feature appearing only when very large scales ($> 100h^{-1}$ Mpc) are probed.

The analysis of different types of observations, namely on spatial distribution of galaxies, clusters of galaxies and quasars [11] as well as peculiar velocity information [13] suggests the existence of a large scale superclusters-voids network with a characteristic scale around $130h^{-1}$ Mpc. So, the large scale structure traced by both galaxies and clusters is consistent with each other. An indication of the presence of this characteristic scale in the distribution of clusters has been found also from the studies of the correlation functions and power spectrum of clusters of galaxies [15].

There are some indications that the supercluster distribution is not random and rather can be described as some weakly correlated network of superclusters and voids with typical mean separation of $100-150h^{-1}$ Mpc. This is consistent with the statistical analyses of the pencil beam surveys data [14]. Large-scale superclusters have been traced very successfully also by clusters of galaxies [12]. At last the study of the whole-sky distribution of rich clusters of galaxies (based on the Abell-ACO catalogue of 4072 rich clusters) up to the distance z=0.2 confirmed from 3-dimensional data the presence of the characteristic scale of about $130h^{-1}$ Mpc of the spatial inhomogeneity of the Universe, found by Broadhurst et al. [1] from the one dimensional study. The density maxima on the distribution of galaxies in the redshift survey [1] correspond to the location of superclusters of rich clusters in the given direction.

Concerning all this rather convenient data we are forced to believe in the real existence of the scale of $130h^{-1}$ Mpc in the large scale structure of the Universe. The existence of discrete scales in the large-scale structure means that there must be some characteristic scales in the initial density spectrum. Standard Cold Dark Matter perturbation model finds it difficult to accommodate recent observations of the large scale supergalactic structure [16, 1]. It is difficult for later nonlinear gravitational interaction to produce such a large scale also.

Given the difficulties that perturbative models encounter in explaining the large scale structure formation, namely the existence of the very large characteristic scale and the periodicity of the visible matter distribution, one possible way of exploration is to regard these as a typical new feature appearing only when very large scales ($> 100h^{-1}$ Mpc) are probed. In fact density fluctuations required to explain the present cosmological structure may have arisen in different ways. The largest scale features of the universal texture may be a result from a completely different mechanism not necessarily with gravitational origin.

In this connection we study a mechanism for generating baryon density perturbations and the evolution of the baryon charge density distribution in the framework of the low temperature baryogenesis scenario [3], which may be essential for the Universe large-scale structure formation and particularly, may be relevant for the observed periodic distribution of the visible matter in the Universe.

As it was already discussed in [4, 5], a periodic in space baryonic density distribution can be obtained provided that the following assumptions are realized:

(a) There exists a complex scalar field ϕ with a mass small in comparison with the Hubble parameter during inflation.

(b) Its potential contains nonharmonic terms.

(c) A condensate of ϕ forms during the inflationary stage and it is a slowly varying function of space points.

All these requirements can be naturally fulfilled in our scenario of the scalar field condensate baryogenesis [3] and in the low temperature baryogenesis scenarios based on the Affleck and Dine mechanism [6].

In case when the potential of ϕ is not strictly harmonic, a monotonic initial behavior in r will result into spatial oscillations of ϕ [7], because the oscillation period depends on the amplitude $P(\phi_0(r))$, and it on its turn depends on r. Correspondingly, the baryon charge, contained in ϕ: $N_B = i\phi^* \overleftrightarrow{\partial_0} \phi$, will have quasi-periodic behavior. During Universe expansion the characteristic scale of the variation of N_B will be inflated up to a cosmologically interesting size. Then if ϕ has not reached the equilibrium point at the moment of the baryogenesis t_B, the baryogenesis would make a snapshot of the space distribution of $\phi(r, t_B)$ and $N_B(r, t_B)$. So, according to that model, the present periodic distribution of the visible matter dates from the spatial distribution of the baryon charge contained in the ϕ field at the advent of the B-conservation epoch.

The detailed analysis, provided in this work, shows that in the framework of our scenario both the generation of the baryon asymmetry and the periodic distribution of the baryon density can be explained simultaneously as due to the evolution of a complex scalar field. In conclusion we want to underline, that the revealed here scenario allows the generation of the quasiperiodic structure in the framework of the low-temperature baryogenesis (in contrast to the proposed in [7] scenario, concerning the high temperature baryogenesis scenarios). This is of special importance having in mind that the low-temperature baryogenesis is the preferred one as far as for its realization in the post inflationary stage it is not necessary to provide considerable reheating temperatures typical for GUT high temperature baryogenesis scenarios. Moreover, according to this model the Universe may consist of sufficiently separated baryonic and antibaryonic shells.

2 Description of the model. Main characteristics.

2.1 Generation of the baryon condensate.

The essential ingredient of the model is a complex scalar field ϕ, which according to the Affleck and Dine version of low temperature baryogenesis, is a scalar superpartner of quarks [3, 6]. The condensate $< \phi > \neq 0$ is formed during the inflationary period if B and L were not conserved, as a result of the enhancement of quantum fluctuations of the ϕ field [8]: $< \phi^2 >= H^3 t / 4\pi^2$. The baryon charge of the field is not conserved at large values of the field amplitude due to the presence of the B nonconserving self-interaction terms in the field's potential. As a result, the quantum fluctuations of the field during

the inflation create a baryon charge density of the order of H_I^3, where H_I is the Hubble parameter at the inflationary stage.

2.2 Generation of the baryon asymmetry.

After inflation ϕ starts to oscillate around its equilibrium point with a decreasing amplitude. This decrease is due to the Universe expansion and to the particle production by the oscillating scalar field [9, 3]. Fast oscillations of ϕ after inflation result in particle creation due to the coupling of the scalar field to fermions $g\phi \bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. Therefore, the amplitude of ϕ is damped as $\phi \to \phi \exp(-\Gamma t/4)$ and the baryon charge, contained in the ϕ condensate, is exponentially reduced. Fortunately, this damping process may be slow enough for a considerable range of values of m, H, α, and λ, so that the baryon charge contained in ϕ may survive until the advent of the B-conservation epoch. Then ϕ decays to quarks with non-zero average baryon charge. This charge, diluted further by some entropy generating processes, dictates the observed baryon asymmetry. For the correct estimation of the value of the generated baryon asymmetry, it is essential to account for the eventual damping of the field's amplitude due to particle production processes by an external time-dependent scalar field, which could lead to a strong reduction of the baryon charge contained in the condensate [3].

2.3 Baryogenesis epoch t_b.

In our model of baryogenesis t_b coincides with the moment after which the mass terms in the equations of motion cannot be neglected. For the correct estimation of this moment it is essential to account for the effects of particle production by the time-dependent scalar field. The moment t_B, defined when particle production is accounted for, may considerably differ from the moment, defined without accounting for these processes, because of the fast exponential damping of the field's amplitude. Consequently, thus estimated value of the baryon charge conservation epoch t_b is considerably smaller than in the case without particle creation.

3 Generation of the baryon density periodicity.

Now let us explore the spatial distribution behavior of the scalar field and its evolution during Universe expansion. We have made the natural assumption that initially ϕ is a function of the space coordinates $\phi(r, t)$. In the expanding Universe ϕ satisfies the equation

$$\ddot{\phi} - a^{-2}\partial_i^2\phi + 3H\dot{\phi} + \frac{1}{4}\Gamma\dot{\phi} + U'_\phi = 0, \quad (1)$$

where $a(t)$ is the scale factor and $H = \dot{a}/a$.

The potential $U(\phi)$ is of the form

$$U(\phi) = \frac{\lambda_1}{2}|\phi|^4 + \frac{\lambda_2}{4}(\phi^4 + \phi^{*4}) + \frac{\lambda_3}{4}|\phi|^2(\phi^2 + \phi^{*2}) \quad (2)$$

The mass parameters of the potential are assumed small in comparison to the Hubble constant during inflation $m \ll H_I$. In supersymmetric theories the constants λ_i are of the order of the gauge coupling constant α. A natural value of m is $10^2 \div 10^4$ Gev. The initial values for the field variables can be derived from the natural assumption that the energy density of ϕ at the inflationary stage is of the order H_I^4, then $\phi_o^{max} \sim H_I \lambda^{-1/4}$ and $\dot{\phi}_o = 0$.

The term $\Gamma\dot{\phi}$ in the equations of motion explicitly accounts for the eventual damping of ϕ as a result of particle creation processes. The production rate Γ was calculated in [9]. For simplicity here we have used the perturbation theory approximation for the production rate $\Gamma = \alpha\Omega$, where Ω is the frequency of the scalar field. For $g < \lambda^{3/4}$, Γ considerably exceeds the rate of the ordinary decay of the field $\Gamma_m = \alpha m$.

The space derivative term can be safely neglected because of the exponential rising of the scale factor $a(t) \sim \exp(H_I t)$. Then the equations of motion for $\phi = x + iy$ read

$$\begin{aligned} \ddot{x} + 3H\dot{x} + \tfrac{1}{4}\Gamma_x \dot{x} + (\lambda + \lambda_3)x^3 + \lambda' x y^2 = 0 \\ \ddot{y} + 3H\dot{y} + \tfrac{1}{4}\Gamma_y \dot{y} + (\lambda - \lambda_3)y^3 + \lambda' y x^2 = 0 \end{aligned} \quad (3)$$

where $\lambda = \lambda_1 + \lambda_2$, $\lambda' = \lambda_1 - 3\lambda_2$.

In case when at the end of inflation the Universe is dominated by a coherent oscillations of the inflation field $\psi = m_{PL}(3\pi)^{-1/2}\sin(m_\psi t)$, the Hubble parameter was $H = 2/(3t)$. In this case it is convenient to make the substitutions $x = H_I(t_i/t)^{2/3}u(\eta)$, $y = H_I(t_i/t)^{2/3}v(\eta)$ where $\eta = 2(t/t_i)^{1/3}$. The functions $u(\eta)$ and $v(\eta)$ satisfy the equations

$$\begin{aligned} u'' + 0.75\,\alpha\Omega_u(u' - 2u\eta^{-1}) + u[(\lambda + \lambda_3)u^2 + \lambda' v^2 - 2\eta^{-2}] = 0 \\ v'' + 0.75\,\alpha\Omega_v(v' - 2v\eta^{-1}) + v[(\lambda - \lambda_3)v^2 + \lambda' u^2 - 2\eta^{-2}] = 0. \end{aligned} \quad (4)$$

The baryon charge in the comoving volume $V = V_i(t/t_i)^2$ is $B = N_B \cdot V = 2(u'v - v'u)$. The numerical calculations were performed for a wide range of the models parameters $u_o, v_o \in [0, \lambda^{-1/4}]$, $u'_o, v'_o \in [0, 2/3\lambda^{-1/4}]$.

We considered the case: $\lambda_1 > \lambda_2 \sim \lambda_3$, when the unharmonic oscillators u and v are weakly coupled. For each set of parameter values of the model λ_i we have numerically calculated the baryon charge evolution $B(\eta)$ for different initial conditions of the field corresponding to the accepted initial monotonic space distribution of the field (see Figs. 1,2). From the analysis it has been obtained that, the bigger the initial amplitudes of the field were, the greater the damping effect due to the particle creation would be. As far as the particle creation rate is proportional to the field's frequency, it can be concluded that the frequency depends on the initial amplitudes. In our work we have accounted for particle creation processes explicitly in the equations (1). The results of the more general numerical analysis prove the earlier conclusions conserving the important role of particle creation processes for baryogenesis models and large scale structure periodicity [3, 9, 10], which were obtained from an approximate analytical solution.

The space distribution of the baryon charge is found for the moment t_B on the basis of the results from the evolution analysis $B(\eta)$ for different initial values of the field, corresponding to its initial space distribution $\phi(t_i, r)$ (Fig. 3). As was expected, in case of nonharmonic field's potential, the initially monotonic space behavior is fastly replaced by space oscillations of ϕ, because of the dependence of the period on the amplitude, which on its turn is a function of r. As a result in different points different periods are observed and space behavior of ϕ becomes quasiperiodic [7, 10]. Correspondingly, the space distribution of the baryon charge contained in ϕ becomes quasiperiodic as well. Therefore, the space distribution of baryons at the moment of baryogenesis is found to

be periodic. Corresponding to this model, the observed space distribution of the visible matter today is defined by the space distribution of the baryon charge of the field ϕ at the moment of baryogenesis t_B, $B(t_B, r)$. So, according to our model, at present the visible part of the Universe consists of baryonic and antibaryonic shells.

This is an interesting possibility as far as the observational data of antiparticles in cosmic rays do not rule out the possibility of antimatter superclusters in the Universe. Moreover, there exists some indication of observational excess of antiprotons in comparison with the theoretical expectations for secondarily produced antiprotons.

Other attractive feature of this model is that it proposes an elegant mechanism for achieving a sufficient separation between regions occupied by baryons and those occupied by antibaryons, necessary in order to inhibit the contact of matter and antimatter regions with considerable density. Otherwise annihilation radiation must be observed from the contact areas, and actually this is not the case.

The determination of the characteristic scale of separation between the matter antimatter regions can be provided in a following way. The number of baryonic-antibaryonic shells in the Universe corresponds to the number of roots N of $B(t_B, r)$ which is defined by the parameters λ_i and the initial values of the field. To estimate the characteristic scale of the space periodicity, we have accepted for the lower bound of the Universe size at the present moment t_0 the size of the present day horizon of the Universe $R_0(t) = 10^{28}$ cm.

For a wide range of parameters values the observed average distance of $130h^{-1}$ Mpc between matter shells in the Universe can be obtained. This value ensures also the sufficient separation between matter and antimatter regions, as far as it is safely larger than the distance between matter antimatter regions required in order not to contradict the observational data on annihilation gamma rays.

The parameters of the model ensuring the necessary observable size between the matter domains belong to the range of parameters for which the generation of the observed value of the baryon asymmetry may be possible in the model of scalar field condensate baryogenesis. This is an exclusively attractive feature of this model because both the baryogenesis and the large scale structure periodicity of the Universe can be explained simply through the evolution of a single scalar field.

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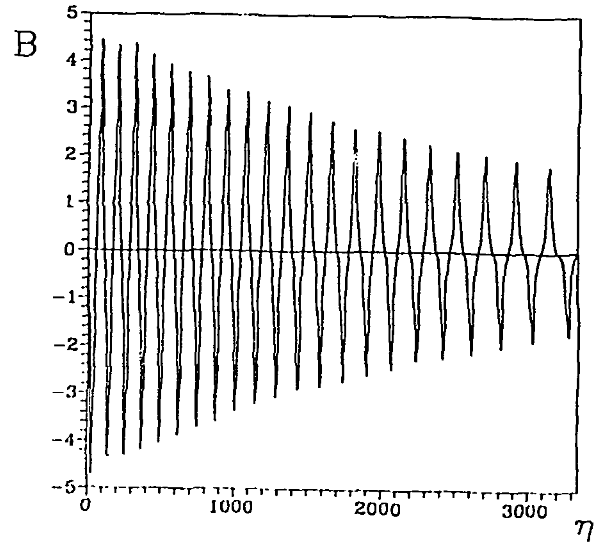

Figure 1: The evolution of the baryon charge $B(\eta)$ contained in the condensate $<\phi>$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$, $\phi_o = H_I \lambda^{-1/4}$, and $\dot{\phi}_o = 0$.

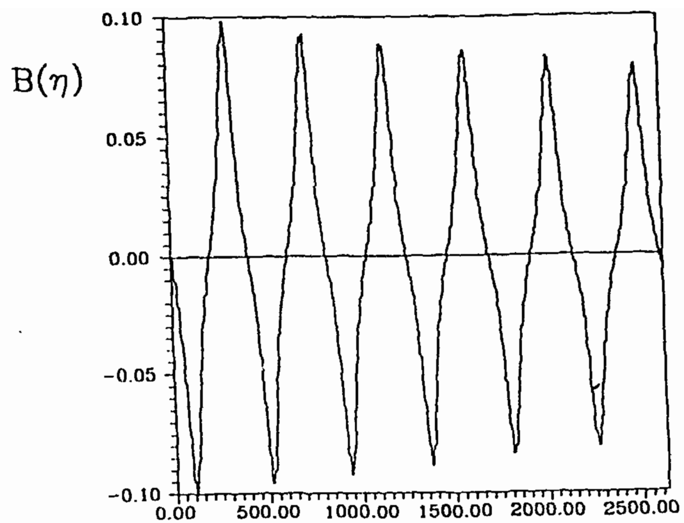

Figure 2: The evolution of the baryon charge $B(\eta)$ contained in the condensate $< \phi >$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$, $\phi_o = \frac{1}{50} H_I \lambda^{-1/4}$, and $\dot{\phi}_o = 0$.

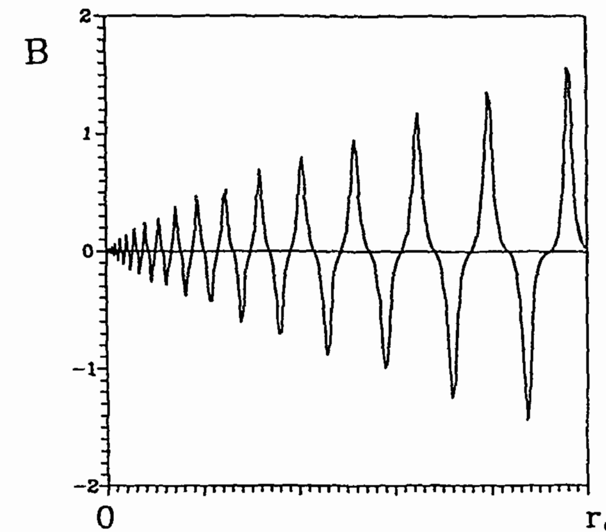

Figure 3: The space distribution of baryon charge at the moment of baryogenesis for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$.