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LARGE SCALE PERIODICITY OF THE UNIVERSE AND BARYOGENESIS

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1 Introduction

The pencil beam surveys [1], performed into the directions towards the galactic poles up to $1000h^{-1}Mpc$ in both directions, found an intriguing periodicity in the very large scale distribution of the luminous matter in the Universe with a characteristic scale of periodicity of about $128h^{-1}Mpc$. The analysis of the observational data on the basis of the models of clustering of galaxies [2] shows that the probability to obtain such a periodicity in the framework of the standard models for galaxies clustering is extremely small, less than 1%. This $128h^{-1}Mpc$ periodicity is inconsistent with the local ($\leq 100h^{-1}Mpc$) observations, and is rather to be regarded as a new feature appearing only when very large scales ($> 100h^{-1}Mpc$) are probed. In this connection we propose a mechanism for generating baryon density perturbations 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.

A similar mechanism was already discussed in [3] and the basic idea was formulated in [4]. It was proved that in the models of spontaneous or stochastic CP violation the CP-odd amplitudes are naturally space dependent and in case when the CP-odd complex classical field did not reach the equilibrium till the baryogenesis moment t_b it may produce the observed periodic fluctuations of the baryonic number density. Following these basic considerations here we will discuss the generation and the evolution of the baryon density perturbations in the scenario of the scalar field condensate baryogenesis [5]. The model of baryogenesis [5], based on the original Affleck and Dine scenario [6], has several very attractive features. It can solve both the problems connected with the low postinflation temperature [7] and those due to a possible destruction of the previously created baryon excess during the electroweak phase transition [8]. An especially attractive feature of the model, concerning the Universe structure formation, is that neither explicit nor spontaneous charge symmetry violation is needed. The charge symmetry is stochastically broken by quantum fluctuations. Therefore, matter and antimatter domains with a given baryon charge can be formed without domain walls. It appears very interesting that in the framework of this scenario an attractive possibility can be realized, namely the scalar field relevant for the Universe baryogenesis could be also the creator of the observed large scale periodicity of the visible matter.

2 Qualitative description of the model

The essential ingredient of the model is a complex scalar field ϕ which is a scalar superpartner of a colourless and electrically neutral combination of quark and lepton fields [5,6]. It could have achieved a nonzero expectation value $<\phi>\neq 0$ during the inflationary period if B and L were not conserved, as a result of the enhancement of quantum fluctuations [9] of the ϕ field $<\phi^2>= H^3t/4\pi^2$ till they reach the limiting value $<\phi^2>\sim H^2/\sqrt{\lambda}$ in case that $\lambda\phi^4$ dominates in the potential energy of ϕ. 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.

First we want to make a brief description of the model of baryon generation [5]. During the inflationary stage ϕ slowly moves to the equilibrium point because of the Hubble friction. 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 [10,5] [3]. Therefore, the field amplitude must be exponentially damped. As far as the particle creation proceeds at the stage of fast sign changing oscillations of ϕ, the created fermion states have zero average baryon charge. Indeed, if C and CP are conserved ϕ decays with equal probability to particles and antiparticles. Because of this decay, the amplitude of ϕ is damped as $\phi \to \phi \exp(-\Gamma_p t/2)$ and the baryon charge, contained in the ϕ condensate, is exponentially reduced by the term $\exp(-\Gamma_p/(2m))$. This may lead to a practically complete destruction of the baryon charge of the condensate (as for example in the case with flat directions of the potential in ref.[5]). However, in the case without flat directions in the field's potential, the damping process may be slow enough and the mass term in the potential becomes important earlier than the baryon charge is washed out by the damping of ϕ amplitude. Consequently, for a considerable range of values of m, H, and λ the baryon charge contained in ϕ survives until the advent of the B-conservation epoch, when ϕ decays to quarks with non-zero average baryon charge. This charge, diluted further by some entropy generating processes, dictates the observed baryon asymmetry.

Now let us explore the spatial distribution behavior of the scalar field condensate. It is natural to accept that ϕ is a function of the space coordinates $\phi(r,t)$. In case when the potential of ϕ is not strictly harmonic, a monotonic initial behavior in r will result into spatial oscillations of ϕ, because the oscillation period depends on the amplitude and it on its turn depends on r. So there will be different time periods at different space points. Therefore, the space behavior of ϕ will become nonmonotonic [3]. Just for an illustration of this let us consider the simple toy model potential

$$V(\phi) = \frac{\lambda}{n}\left(\frac{\phi^2}{4} + \frac{|\phi|^2}{2} + \frac{\phi^{*2}}{4}\right)^n \tag{1}$$

We have neglected the space derivative term as far as inflation makes it negligible in comparison with the time derivative. The equations of motion for $\phi = x + iy$ read

$$\begin{aligned} \ddot{x} + 3H\dot{x} + \lambda x^{2n-1} &= 0 \\ \ddot{y} + 3H\dot{y} &= 0 \end{aligned} \tag{2}$$

where $H = \alpha/(3t)$ is the Hubble parameter, with $\alpha > 1$ for RD and MD Universe. The second equation has a solution $y(t) = y_o + y_o'/t^{\alpha-1}$, and at $t \to \infty$ $y \to y_o$ and y does not depend on the initial value y_o'. We assume that initially at $t = t_i$, $\dot{x}_o = 0$ and $x_o(r)$ is the initial value of x. By the substitution $x = \psi(r,t)z(\tau)$, where $\psi(r,t) = (t_i/t)^{\alpha/(n+1)}x_o(r)$ and $\tau = \sqrt{\lambda}(1-\alpha(n-1)/(n+1))^{-1}\psi(r,t)^{n-1}t$ the first equation is reduced to

$$z'' + \gamma z/\tau^2 + z^{2n-1} = 0, \tag{3}$$

where $z''(\tau) = d^2z(\tau)/d\tau^2$ and

$$\gamma = \frac{\alpha}{n+1}\left(1 - \frac{\alpha n}{n+1}\right)\left(1 - \alpha\frac{n-1}{n+1}\right)^{-2}.$$

This equation can be reduced to Emden's equation, which is thoroughly investigated. When the relation $n \leq 1/(\alpha-1)+1$ is fulfilled, eq.(3) has only oscillatory solutions. At $t \to \infty$ there exists a relation $\delta\tau = \tau_{k+1} - \tau_k = n^{-1/2}\Gamma(1/2)\Gamma(\frac{1}{2n})\Gamma(\frac{n+1}{2n})$ between the roots of the equation $z(\tau_k) = 0$ for the oscillatory function $z(\tau)$. So, if $x_o(r)$ is a linear function of r $x_o(r) = x_{oo}(1 + \vec{r}\vec{n}/r_o)$ the function $x(r,t)$ is an oscillatory function of r such that

$$\frac{\Delta r}{r_o} = \delta\tau\left(\frac{(n-1)\sqrt{\lambda}t}{1-\alpha(n-1)/(n+1)}[x_{oo}(t_i/t)^{\alpha/(n+1)}]^{n-1}\right)^{-1}. \tag{4}$$

Thus when the potential of ϕ is initially not strictly harmonic, the space behavior of ϕ after some time interval will become quasiperiodic. During Universe expansion the characteristic scale of its variation r_o 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 $\phi(r,t)$ (if the characteristic time scale of baryogenesis is small in comparison with $\phi/\dot{\phi}$). So, the present 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 t_B.

3 The model — characteristics, calculations and results

In the expanding Universe ϕ satisfies the equation

$$\ddot{\phi} - a^{-2}\partial_i^2\phi + 3H\dot{\phi} + U'_\phi = 0, \tag{5}$$

where $a(t)$ is the scale factor and $H = \dot{a}/a$. The potential $U(\phi)$ is generically of the form (at least near equilibrium)

$$U(\phi) = m^2|\phi|^2 + \frac{\lambda_1}{2}|\phi|^4 + m_1^2(\phi^2 + \phi^{*2}) + \frac{\lambda_2}{4}(\phi^4 + \phi^{*4}) + \frac{\lambda_3}{4}|\phi|^2(\phi^2 + \phi^{*2}) \tag{6}$$

The mass parameters of the potential must be small in comparison to the Hubble constant during inflation $m \ll H_I$. Otherwise the oscillations of ϕ will be exponentially damped in several Hubble times. In supersymmetric theories the constants λ_i are of

[3] Fast oscillations of ϕ after inflation result in particle creation due to the coupling of the scalar field to fermions $g\phi f_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. The production rate Γ_p was calculated in [10]. For $g < \lambda^{1/2}$ it considerably exceeds the rate of the ordinary decay of the field $\Gamma = (g^2/4\pi)m$ at the stage of B-non-conservation.

the order of the gauge coupling constant α, and m is the mass of the ϕ field after symmetry breaking. In a large class of a supersymmetric models, a natural value of m is $10^2 \div 10^4 Gev$. Anyway, we assume $m \ll H_I$. The following 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: $x_o \sim y_o \sim H_I \lambda^{-1/4}$ and $\dot{x}_o \sim \dot{y}_o \sim H_I^2$.

As has been noted before the space derivative term is suppressed by exponentially rising scale factor $a(t) \sim \exp(H_I t)$ and can be safely neglected. Then the field equations are of the form

$$\begin{aligned} \ddot{x} + 3H\dot{x} + (\lambda + \lambda_3)x^3 + \lambda' x y^2 = 0 \\ \ddot{y} + 3H\dot{y} + (\lambda - \lambda_3)y^3 + \lambda' y x^2 = 0 \end{aligned} \qquad (7)$$

where $\lambda = \lambda_1 + \lambda_2$, $\lambda' = \lambda_1 - 3\lambda_2$. An analytical form for the $B-$oscillation period can be obtained for $\lambda_1 = 3\lambda_2$ and $\lambda_3 = \pm 4\lambda_2$.

We assume that at the end of inflation the Universe is dominated by a coherent oscillations of the inflaton field $\psi = m_{PL}(3\pi)^{-1/2}\sin(m_\psi t)$, so that 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 $\eta = 3(t/t_i)^{1/3}$. The functions $u(\eta)$ and $v(\eta)$ satisfy the equations

$$\begin{aligned} u'' + u[(\lambda + \lambda_3)u^2 + \lambda' v^2 - 2\eta^{-2}] = 0 \\ v'' + v[(\lambda - \lambda_3)v^2 + \lambda' u^2 - 2\eta^{-2}] = 0. \end{aligned} \qquad (8)$$

The baryon charge in the comoving volume $V = V_i(t/t_i)^2$ is $B = 2H_I^2 V_i/t_i(u'v - v'u)$. As far as the term proportional to η^{-2} quickly diminishes in comparison with λu^2 (λv^2) we neglect it at big η and the eq.(8) reduce to a system of coupled unharmonic oscillators with constant coefficients:

$$\begin{aligned} u'' + (\lambda + \lambda_3)u^3 + \lambda' u v^2 = 0 \\ v'' + (\lambda - \lambda_3)v^3 + \lambda' v u^2 = 0. \end{aligned} \qquad (9)$$

We want to note here that the eqs.(9) are invariant according to the scale transformations $\tilde{\eta} = k\eta$, $\tilde{\lambda} = k^{-2}\lambda$ or $\tilde{u} = ku$, $\tilde{v} = kv$, $\tilde{\lambda} = k^{-2}\lambda$. This can be used for the analysis of the solution of eq.(9). The numerical calculations were performed for the initial conditions $u_o^{max} = v_o^{max} = \lambda^{-1/4}$; $u_o'^{max} = v_o'^{max} = 2/3(1 + \lambda^{-1/4})$.

We considered the case: $\lambda > \lambda' \sim \lambda_3$. Then the unharmonic oscillators u and v are weakly coupled. The oscillations of the baryon charge $B(\eta)$ proceed around zero (see fig.1.) That must be expected as far as the equilibrium value of ϕ is zero and ϕ oscillates around zero.Therefore the baryonic layers in that model are alternated by antibaryonic ones. The number of roots N within the interval $u_o \in [0, \lambda^{-1/4}]$ depends smoothly on $\Delta\lambda = \lambda - \lambda'$. (The dependences $N_{\lambda'}(\Delta\lambda)$ are plotted on fig.2.) Thanks to the invariances (10) one can easily obtain the number of roots at any moment of time using the obtained dependences. It is defined by the parameters λ, λ', u_0 and v_0. For the accepted initial distribution $u_0(r)$ and $v_0(r)$, the result strongly depends on the maximal initial values of $u_0(r)$ and $v_0(r)$. The dependence on λ is weaker, it is proportional to $\lambda^{1/2}$. The spatial distribution of the visible matter at the present moment t_0 will be defined by the spatial distribution of the baryon charge of the ϕ

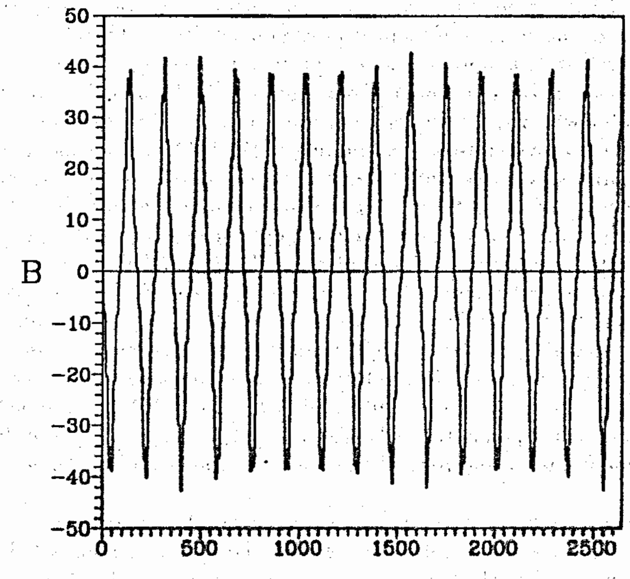

Fig.1

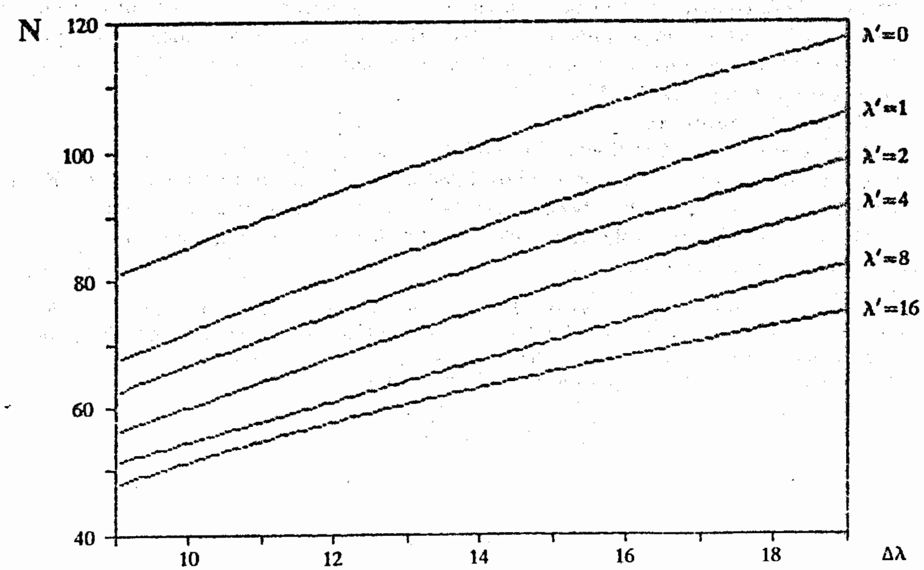

Fig.2

field at the moment of baryogenesis t_b. The baryon density distribution on its turn can be expressed through the number of roots at that moment $N(t_b)$. Then the void's size at the present moment t_0 is obtained according to $\Delta r = r_0/N(t_b)$, where t_b is the moment of baryogenesis. For our model of baryogenesis [5], t_b coincides with the moment t_s from [5] after which the mass terms in the equations of motion for the ϕ field cannot be neglected, provided that the damping of the field's amplitude due to the particle creation processes is accounted for. [4] Actually t_b marks the beginning of the B-conserving decays of the ϕ field. Thus estimated time t_b essentially differs from the time of B-conserving decays t_b', obtained without the account of the particle creation processes by the oscillating scalar field $t_b < t_b'$. For the lower bound of the Universe size at the present moment t_0 we accepted the size of the present day horizon of the Universe $R_0(t) = 10^{28} cm$. Hence, for the value of the characteristic scale r_0 we have accepted $r_0 \geq R_0$. For a wide range of parameters the observed average distance between matter shells in the Universe can be obtained. For example for $x_0/H_i \sim \lambda_1^{-1/4}$, $\lambda_1 \sim 10^{-2}$, $\lambda_2 \sim \lambda_3 \sim 10^{-3}$ and $H_i t_b \sim 6.8 \cdot 10^8$ the number of roots is $N = 30$, which corresponds to voids' size $\bar{r} \sim 128 h^{-1} Mpc$. So, according to our model, at present the visible part of the Universe consists of baryonic and antibaryonic islands.

An extremely attractive to us seams the following fact: 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, according to the model of scalar field condensate baryogenesis. In conclusion we want to note that if the data of ref.[1] is true, i.e. there exists a periodic distribution of the visible matter in the Universe with the period of about $128 Mpc$, the mechanism for generating baryon density perturbations proposed here constrains from beneath the time of baryogenesis. For example from the constraint $r(t_0) \geq R_0$ at present, it follows $r(t_0) = N(t_b) \times 128 h^{-1} Mpc \geq R_0$. So, the time of baryogenesis must be bigger than or equal to t_b^*, where t_b^* is the root of the equation $N(t_b) \times 128 h^{-1} Mpc = R_0$.

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[4]The particle creation by the oscillating scalar field was not accounted for implicitly in the equations of motion of ϕ. It was considered however in the estimation of the beginning of the epoch of B-conserving decays t_s. The effect of the processes of particle creation on the space distribution of the scalar field ϕ will be calculated more precisely elsewhere.

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