Non-GUT baryogenesis and large-scale structure of the Universe

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ABSTRACT

We discuss a mechanism for producing baryon density perturbations during the inflationary stage, 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 large-scale structure formation in the Universe and, in particular, may be essential for understanding the existence of a characteristic scale of $130\,h^{-1}\,\mathrm{Mpc}$ (comoving size) in the distribution of the visible matter.

A detailed analysis shows 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, the visible part of the Universe at present may consist of baryonic and antibaryonic regions, sufficiently separated, so that annihilation radiation is not observed.

Key words: cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION

The large-scale texture of the Universe shows a great complexity and variety of observed structures: it displays a strange pattern of filaments, voids and sheets. Moreover, owing to the increasing quantity of different types of observational data and theoretical analysis in recent years, it has been realized that there exists a characteristic very large scale of about $130\,h^{-1}\,\mathrm{Mpc}$ in the large-scale texture of the Universe. Specifically, galaxy deep pencil-beam surveys (Broadhurst, Ellis & Shanks 1988; Broadhurst et al. 1990) found an intriguing periodicity in the very large-scale distribution of the luminous matter. The data consisted of several hundred redshifts of galaxies, coming from four distinct surveys, in two narrow cylindrical volumes in the directions of the North and the South Galactic Poles of our Galaxy, up to redshifts of more than $z \sim 0.3$, combined to produce a well-sampled distribution of galaxies by redshift on a linear scale extending to $2000\,h^{-1}\,\mathrm{Mpc}$. A plot of the number of galaxies as a function of redshift displays a remarkably regular redshift distribution, with most galaxies lying in discrete peaks, with a periodicity over a scale of about $130\,h^{-1}\,\mathrm{Mpc}$ comoving size.

It has been realized also that the density peaks in the regular spatial distribution of galaxies in the redshift survey of Broadhurst et al. (1990) correspond to the locations of superclusters, as defined by rich clusters of galaxies in the given direction (Bahcall 1991). A survey of samples in other directions, located near the

South Galactic Pole, also indicated a regular distribution on slightly different scales near $100\,h^{-1}\,\mathrm{Mpc}$ (Ettori, Guzzo & Tarenghi 1995; see also Tully et al. 1992; Guzzo et al. 1992; Willmer et al. 1994). This discovery of a large-scale pattern at the Galactic poles was confirmed in a wider angle survey of 21 new pencil beams distributed over a $10°$ field at both Galactic caps (Broadhurst et al. 1995), and also by new pencil-beam galaxy redshift data around the South Galactic Pole region (Ettori, Guzzo & Tarenghi 1997).

Analysis of other types of observations confirms the existence of this periodicity. Specifically, such structure is consistent with the reported periodicity in the distribution of quasars and radio galaxies (Foltz et al. 1989; Komberg, Kravtsov & Lukash 1996; Quashnock et al. 1996; Petitjeau 1996; Cristiani 1998) and the Lyman α forest (Chu & Zhu 1989); studies of the spatial distribution of galaxies (both optical and *IRAS*) and clusters of galaxies (Kopylov et al. 1984; de Lapparent, Gellar & Huchra 1986; Geller & Huchra 1989; Huchra et al. 1990; Bertschinger, Deckel & Faber 1990; Rowan-Robinson et al. 1990; Bahcall 1992; Fetisova et al. 1993a; Einasto et al. 1994; Buryak, Doroshkevich & Fong 1994; Bellanger & de Lapparent 1995; Cohen et al. 1996), as well as peculiar velocity information (Lynden-Bell et al. 1988; Lauer & Postman 1994; Hudson et al. 1999), suggest the existence of a large-scale superclusters–voids network with a characteristic scale around $130\,h^{-1}\,\mathrm{Mpc}$.

An indication of the presence of this characteristic scale in the distribution of clusters has also been found from studies of the correlation functions and power spectrum of clusters of galaxies

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(Kopylov et al. 1988; Bahcall 1991; Mo et al. 1992; Peacock & West 1992; Deckel et al. 1992; Einasto et al. 1993; Einasto & Gramann 1993; Fetisova et al. 1993b; Frisch et al. 1995; Saar et al. 1995; Einasto et al. 1997b; Tadros, Efstathiou & Dalton 1997; Retzlaff et al. 1998). The galaxy correlation function of the Las Campanas redshift survey also showed the presence of a secondary maximum at the same scale, and a strong peak in the two-dimensional power spectrum corresponding to excess power at about 100 Mpc (Landy et al. 1995, 1996; Shectman et al. 1996; Doroshkevich et al. 1996; Geller at al. 1997; Tucker, Lin & Shectman 1999). The supercluster distribution was shown also to be not random but rather described by some weakly correlated network of superclusters and voids with a typical mean separation of $100–150\,h^{-1}$ Mpc. Many known superclusters were identified with the vertices of an octahedron superstructure network (Battaner 1998). The network was proven to resemble a cubical lattice, with a periodic distribution of the rich clusters along the main axis (coinciding with the supergalactic Y-axis) of the network, with a step of $\sim 130\,h^{-1}$ Mpc (Toomet et al. 1999). These results are consistent with statistical analysis of the pencil-beam surveys data (Kurki-Suonio, Mathews & Fuller 1990; Amendola 1994), which advocates a regular structure.

A recently performed study of the whole-sky distribution of high-density regions defined by very rich Abell and APM clusters of galaxies (Baugh 1996; Einasto et al. 1994, 1996, 1997a; Landy et al. 1996; Tadros et al. 1997; Gaztanaga & Baugh 1998; Retzlaff et al. 1998; Kerscher 1998) confirmed from three-dimensional data the presence of the characteristic scale of about $130\,h^{-1}$ Mpc of the spatial inhomogeneity of the Universe, found by Broadhurst et al. (1988, 1990) from the one dimensional study. The combined evidence from cluster and cosmic microwave background data (Scott et al. 1996; Baker et al. 1999) also favours the presence of a peak at $130\,h^{-1}$ Mpc and a subsequent break in the initial power spectrum (Atrio-Barandela et al. 1997; Broadhurst & Jaffe 1999). For a recent review of the regularity of the Universe on large scales, see Einasto (1997).

Considering all these rather convenient data, pointing out that different objects trace the same structure at large scales, we are forced to believe in the reality of the $130\,h^{-1}$ Mpc scale as a typical scale for the matter distribution in the Universe (see also Einasto 1998). However, this periodicity points to the existence of a significantly larger scale in the structure of the Universe observed today than predicted by standard models of structure formation by gravitational instability (Davis 1990; Szalay et al. 1991; Davis et al. 1992; Luo & Vishniac 1993; Bahcall 1994; Atrio-Barandela et al. 1997; Eisenstein & Hu 1998; Retzlaff et al. 1998; Lesgourgues, Polarski & Starobinsky 1998; Eisenstein et al. 1998; Eisenstein & Hu 1999; Meiksin, White & Peacock 1999), and is rather to be regarded as a new feature appearing only when very large scales ($>100\,h^{-1}$ Mpc) are probed.

The problem of the generation of the spatial periodicity in the density distribution of luminous matter at large scales was discussed in numerous publications (e.g. Hill, Fry & Schramm 1989; Lumsden, Heavens & Peacock 1989; Ostriker & Strassler 1989; Davis 1990; Coles 1990; Kurki-Suonio et al. 1990; Trimble 1990; Kofman, Pogosyan & Shandarin 1990; Ikeuchi & Turner 1991; van de Weygaert 1991; Buchert & Mo 1991; SubbaRao & Szalay 1992; Coleman & Pietronero 1992; Tully et al. 1992; Chincarini 1992; Weis & Buchert 1993; Atrio-Barandela et al. 1997; Lesgourgues et al. 1998; Meiksin et al. 1998; Eisenstein et al. 1998; Eisenstein & Hu 1999). It was shown that a random structure could not explain the observed distribution. Statistical

analysis of the deviations from periodicity showed that, even for a perfectly regular structure, a favoured direction and/or location within the structure may be required. The presence of the observed periodicity up to great distances and in different directions seems amazing. Bearing in mind these results and the difficulties that perturbative models encounter in explaining very large-scale structure formation (namely the existence of the very large characteristic scale and the periodicity of the visible matter distribution), we have chosen another way of exploration: namely, we assume that these results represent a typical new feature that appears only for very large scales ($>100\,h^{-1}$ Mpc). In other words, we consider the possibility that the density fluctuations required to explain the present cosmological largest scale structures of the universal texture may have arisen in a way that is different from the standard one: they may result from a completely different mechanism, not necessarily with a gravitational origin.

Such a successful mechanism has already been proposed (Chizhov & Dolgov 1992) and analysed in the framework of high-temperature baryogenesis scenarios.[1] According to the mechanism under discussion, an additional complex scalar field (besides inflaton) is assumed to be present at the inflationary epoch, and it yields the extra power at the very large scale discussed. Primordial baryonic fluctuations are produced during the inflationary period, owing to the specific evolution of the spatial distribution of the complex scalar field carrying the baryon charge.

In the present work we study the possibility of generating the periodic spatial distribution of primordial baryon density fluctuations at the end of the inflationary stage, applying this mechanism for the case of low-temperature baryogenesis with the baryon charge condensate of Dolgov & Kirilova (1991). The preliminary analysis of this problem, provided by Chizhov & Kirilova (1994), proved its usefulness in that case. Here we provide a detailed analysis of the evolution of the baryon density perturbations from the inflationary epoch until the baryogenesis epoch, and describe the evolution of the spatial distribution of the baryon density. The production of matter–antimatter asymmetry in this scenario proceeds generally at low energies ($\leqslant 10^9$ GeV). This is of particular importance, bearing in mind that the low-temperature baryogenesis scenarios are the preferred ones, insofar as for their realization at the post-inflationary stage it is not necessary to provide the considerable reheating temperature typical for GUT high-temperature baryogenesis scenarios. Hence the model under discussion (Dolgov & Kirilova 1991) has several attractive features.

(i) It is compatible with the inflationary models insofar as it does not suffer from the problem of insufficient reheating.

(ii) Generally, the scenario evades the problem of 'washing out' of the previously produced baryon asymmetry at the electroweak transition.

(iii) As will be proved in the following, it may solve the problem of large-scale periodicity of the visible matter.

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[1] By high-temperature baryogenesis scenarios, we mean those scenarios that proceed at very high energies of the order of the grand unification scale, and especially the grand unification theory (GUT) baryogenesis scenarios. In contrast, low-temperature baryogenesis scenarios, like the Affleck & Dine scenario and electroweak baryogenesis, proceed at energies several orders of magnitude lower.

As has already been discussed by Dolgov (1992) and Chizhov & Dolgov (1992), a baryonic density distribution that is periodic in space can be obtained, provided that the following assumptions are realized:

(i) there exists a complex scalar field ϕ with a mass that is small in comparison with the Hubble parameter during inflation;

(ii) its potential contains non-harmonic terms; and

(iii) a condensate of ϕ forms during the inflationary stage and is a slowly varying function of the spatial points.

All of these requirements can be naturally fulfilled in our scenario of the scalar field condensate baryogenesis (Dolgov & Kirilova 1991), and in low-temperature baryogenesis scenarios based on the Affleck & Dine mechanism (Affleck & Dine 1985).

In the case where the potential of ϕ is not strictly harmonic, the oscillation period depends on the amplitude $P[\phi_0(r)]$, and it in turn depends on r. Therefore a monotonic initial spatial distribution will soon result in spatial oscillations of ϕ (Chizhov & Dolgov 1992). Correspondingly, the baryon charge, contained in ϕ: $N_B = i\phi^* \overset{\leftrightarrow}{\partial_0} \phi$, will have quasi-periodic behaviour. During the expansion of the Universe, 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 baryogenesis epoch t_B, the baryogenesis will make a snapshot of the spatial distribution of $\phi(r, t_B)$ and $N_B(r, t_B)$, and thus the present periodic distribution of the visible matter may date from the spatial distribution of the baryon charge contained in the ϕ-field at the advent of the B-conservation epoch.

Density fluctuations with a comoving size today of $130\,h^{-1}$ Mpc re-entered the horizon at late times at a redshift of about 10 000 and a mass of $10^{18}\,M_\odot$. After recombination the Jeans mass becomes less than the horizon one and the fluctuations of this large mass begin to grow. We propose that these baryonic fluctuations, periodically spaced, lead to an enhanced formation of galaxy superclusters at the peaks of baryon overdensity. The concentration of baryons into periodic shells may also have catalysed the clustering of matter coming from the inflaton decays on to these 'baryonic nuclei'. After baryogenesis proceeded, superclusters may have formed at the high peaks of the background field (the baryon charge carrying scalar field we discuss). [See the results of statistical analysis (Plionis 1995), confirming the idea that clusters formed at the high peaks of the background field, which is analogous to our assumption.] We imply that afterwards the self-gravity mechanisms might have optimized the arrangement of this structure into the thin regularly spaced dense baryonic shells and voids in between, with the characteristic size of $130\,h^{-1}$ Mpc observed today.

The analysis 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 being due to the evolution of a complex scalar field.

Moreover, for a certain range of parameters, the model predicts that the Universe may consist of sufficiently separated baryonic and antibaryonic shells. This possibility has been discussed in more detail elsewhere (Kirilova 1998). It is an interesting possibility insofar as observational data on antiparticles in cosmic rays and gamma-ray data do not rule out the possible existence of superclusters of galaxies of antimatter in the Universe (Steigman 1976; Ahlen et al. 1982, 1988; Stecker 1985, 1989; Gao et al. 1990). The observations exclude the possibility of noticeable amounts of antimatter in our Galaxy, however they are not sensitive enough to test the existence of antimatter extragalactic

regions. For example, current experiments (e.g. Salamon et al. 1990; Ahlen et al. 1994; Golden et al. 1994, 1996; Yoshimura et al. 1995; Mitchell et al. 1996; Barbiellini & Zalateu 1997; Moiseev et al. 1997; Boesio et al. 1997; Orito et al. 1999) put only a lower limit on the distance to the nearest antimatter-rich region, namely $\sim$20 Mpc. Future searches for antimatter among cosmic rays are expected to increase this lower bound by an order of magnitude. For example, the reach of the AntiMatter Spectrometer is claimed to exceed 150 Mpc (Ahlen et al. 1982) and its sensitivity is three orders of magnitudes better than that of previous experiments (Battiston 1997; Plyaskin et al. 1998). For a more detailed discussion on the problem of the existence of noticeable amounts of antimatter at considerable distances, see Dolgov (1993), Cohen, DeRujula & Glashow (1998) and Kinney, Kolb & Turner (1997).

The following section describes the baryogenesis model, and the final section deals with the generation of the periodicity of the baryon density, and discusses our results.

2 DESCRIPTION OF THE MODEL: MAIN CHARACTERISTICS

Our analysis was performed in the framework of the low-temperature non-GUT baryogenesis model described by Dolgov & Kirilova (1991), based on the Affleck & Dine supersymmetry GUT-motivated mechanism for generation of the baryon asymmetry (Affleck & Dine 1985). In this section we describe the main characteristics of the baryogenesis model, which are essential for investigation of the periodicity in the next section. For more details, please see the original paper.

2.1 Generation of the baryon condensate

The essential ingredient of the model is a squark condensate ϕ with a non-zero baryon charge. It naturally appears in super-symmetric theories and is a scalar superpartner of quarks. The condensate $\langle \phi \rangle \neq 0$ is formed during the inflationary period as a result of the enhancement of quantum fluctuations of the ϕ-field (Bunch & Davies 1978; Vilenkin & Ford 1982; Linde 1982; Starobinsky 1982): $\langle \phi^2 \rangle = H^3 t / 4\pi^2$. The baryon charge of the field is not conserved at large values of the field amplitude, owing to the presence of the B non-conserving self-interaction terms in the field potential. As a result, a condensate of a baryon charge (stored in $\langle \phi \rangle$) is developed during inflation with 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 expansion of the Universe and to particle production by the oscillating scalar field (Dolgov & Kirilova 1990, 1991). Here we discuss the simple case of particle production when ϕ decays into fermions and there is no parametric resonance. We expect that the case of decays into bosons owing to parametric resonance (Kofman, Linde & Starobinsky 1994, 1996; Shtanov, Traschen & Brandenberger 1995; Boyanovski et al. 1995; Yoshimura 1995; Kaiser 1996), especially in the broad resonance case, will lead to an explosive decay of the condensate, and hence an insufficient baryon

asymmetry. Therefore we explore the more promising case of ϕ decaying into fermions.

In the expanding universe, ϕ satisfies the equation

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

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

The potential $U(\phi)$ is chosen in the form

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

The mass parameters of the potential are assumed to be small in comparison with 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 10^2–10^4 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 of H_I^4: then $\phi_0^{\max} \sim H_I\lambda^{-1/4}$ and $\dot{\phi}_0 = 0$.

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. Explicitly accounting for the effect of particle creation processes in the equations of motion was first done by Chizhov & Kirilova (1994) and Kirilova & Chizhov (1996). The production rate Γ was calculated by Dolgov & Kirilova (1990). 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.[2] For $g < \lambda^{3/4}$, Γ considerably exceeds the rate of ordinary decay of the field $\Gamma_m = \alpha m$. Fast oscillations of ϕ after inflation result in particle creation owing to the coupling of the scalar field to fermions $g\phi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{\text{SUSY}}$. 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 considerably reduced. Dolgov & Kirilova (1991) discussed in detail that for a constant Γ this reduction is exponential and generally, for a natural range of model parameters, the baryon asymmetry is washed out until the baryogenesis epoch as a result of the particle creation processes. Fortunately, in the case without flat directions[3] of the potential, the production rate is a decreasing function of time, so that the damping process may be slow enough for a considerable range of acceptable model parameter 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. Generally, in cases of more effective particle creation, like in the case with flat directions in the potential, or in the case when ϕ decays spontaneously into bosons as a result of parametric resonance, the mechanism of baryon asymmetry generation under discussion cannot be successful. Hence it also cannot be useful for the generation of the matter periodicity.

2.3 Baryogenesis epoch t_B

When inflation is over and ϕ relaxes to its equilibrium state, its coherent oscillations produce an excess of quarks over antiquarks or vice versa, depending on the initial sign of the baryon charge condensate. This charge, diluted further by some entropy-generating processes, dictates the observed baryon asymmetry. This epoch, when ϕ decays to quarks with non-zero average baryon charge and thus induces baryon asymmetry, we call the

baryogenesis epoch. The baryogenesis epoch t_B for our model coincides with the advent of the baryon-conservation epoch, i.e. the time after which the mass terms in the equations of motion cannot be neglected. In the original baryogenesis scenario (Affleck & Dine 1985), this epoch corresponds to energies of 10^2–10^4 GeV. However, as has already been explained, the amplitude of ϕ may be reduced much more quickly owing to the particle creation processes and, as a result, depending on the model parameters, the advent of this epoch may be considerably earlier. For the correct estimation of t_B and the value of the generated baryon asymmetry, it is essential to account for the eventual damping of the field amplitude owing 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 GENERATION OF THE BARYON DENSITY PERIODICITY

In order to explore the spatial distribution behaviour of the scalar field and its evolution during the expansion of the Universe, it is necessary to analyse equation (1). We have made the natural assumption that initially ϕ is a slowly varying function of the spatial coordinates $\phi(r, t)$. The spatial derivative term can be safely neglected because of the exponential increase of the scalefactor $a(t) \sim \exp(H_I t)$. Then the equations of motion for $\phi = x + iy$ read

$$\ddot{x} + 3H\dot{x} + \tfrac{1}{4}\Gamma_x\dot{x} + (\lambda + \lambda_3)x^3 + \lambda'xy^2 = 0,$$

$$\ddot{y} + 3H\dot{y} + \tfrac{1}{4}\Gamma_y\dot{y} + (\lambda - \lambda_3)y^3 + \lambda'yx^2 = 0, \tag{3}$$

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

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

$$u'' + 0.75\,\alpha\Omega_u(u' - 2u\eta^{-1}) + u[(\lambda + \lambda_3)u^2 + \lambda'v^2 - 2\eta^{-2}] = 0,$$

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

The baryon charge in the comoving volume $V = V_i(t/t_i)^2$ is $B = N_B V = 2(u'v - v'u)$. The numerical calculations were performed for $u_0, v_0 \in [0, \lambda^{-1/4}]$, $u'_0, v'_0 \in [0, 2/3\lambda^{-1/4}]$. For simplicity we considered the case $\lambda_1 > \lambda_2 \sim \lambda_3$, when the non-harmonic 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 spatial distribution of the field (see Figs 1 and 2).

The numerical analysis confirms the important role of the particle creation processes for baryogenesis models and large-scale structure periodicity (Chizhov & Kirilova 1994, 1996) that was obtained from an approximate analytical solution. In the present work we have accounted for particle creation processes explicitly.[4]

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[2] For the toy model that we discuss here, we consider this approximation to be instructive enough.

[3] Flat direction – along which the potential $V(\phi)$ remains constant when ϕ grows.

[4] It has been shown that the damping effect due to particle creation is proportional to the initial amplitudes of the field. Insofar as the particle creation rate is proportional to the field frequency, it can be concluded that the frequency depends on the initial amplitudes. This result confirms our analytical estimate provided in earlier papers (Chizhov & Kirilova 1994, 1996).
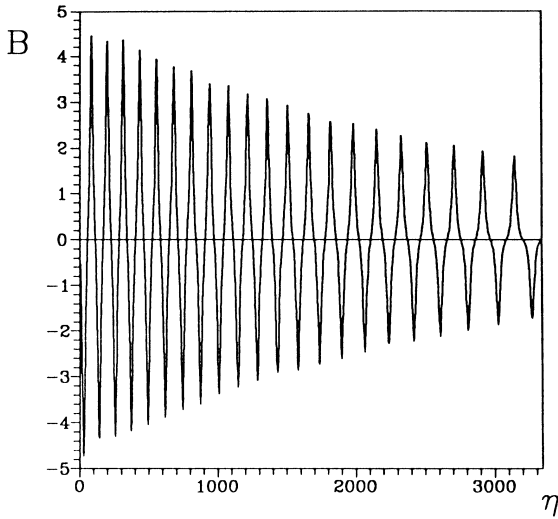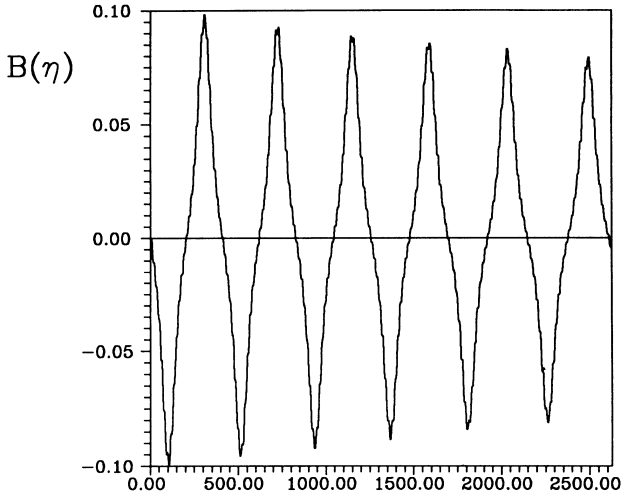
Figure 1. The evolution of the baryon charge $B(\eta)$ contained in the condensate $\langle\phi\rangle$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}, H_I/m = 10^7$, $\phi_0 = H_I\lambda^{-1/4}$ and $\dot{\phi}_0 = 0$.

Figure 2. The evolution of the baryon charge $B(\eta)$ contained in the condensate $\langle\phi\rangle$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$, $\phi_0 = \frac{1}{50}H_I\lambda^{-1/4}$ and $\dot{\phi}_0 = 0$.

The spatial distribution of the baryon charge is calculated for the moment t_B. It is obtained from the evolution $B(\eta)$ for different initial values of the field, corresponding to its initial spatial distribution $\phi(t_i, r)$ (Fig. 3). As expected, in the case of a non-harmonic field potential, the initially monotonic spatial behaviour is quickly replaced by spatial oscillations of ϕ, because of the dependence of the period on the amplitude, which in turn is a function of r. As a result, different periods are observed at different points, and the spatial behaviour of ϕ becomes quasi-periodic. Correspondingly, the spatial distribution of the baryon charge contained in ϕ becomes quasi-periodic as well. Therefore the spatial distribution of baryons at the moment of baryogenesis is found to be periodic.

The observed spatial distribution of the visible matter today is defined by the spatial distribution of the baryon charge of the field ϕ at the moment of baryogenesis t_B, $B(t_B, r)$. At present, therefore, the visible part of the Universe consists of baryonic shells, divided by vast underdense regions. *For a wide range of parameter values*
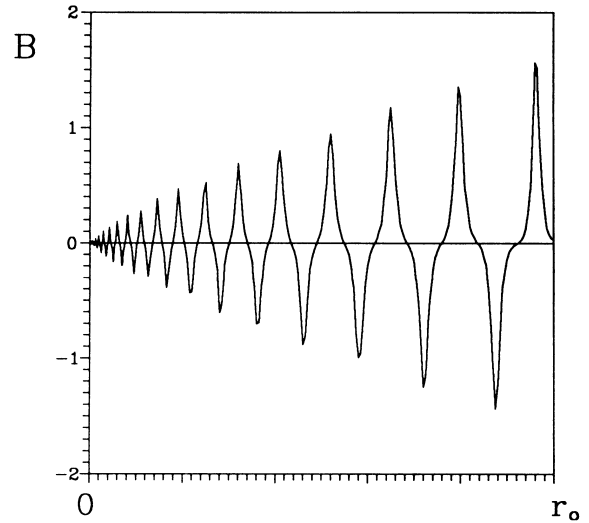

Figure 3. The spatial distribution of baryon charge at the moment of baryogenesis for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$ and $H_I/m = 10^7$.

the observed average distance of $130\,h^{-1}$ Mpc between matter shells in the Universe can be obtained. The parameters of the model that fix the observable size of the regions between the matter domains lie in 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 attractive feature of the 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.

Moreover, for some model variations the presence of vast antibaryonic regions in the Universe is predicted. This is an interesting possibility insofar as the observational data do not rule out the possibility of antimatter superclusters in the Universe. The model proposes an elegant mechanism to achieve 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.

It would be interesting, bearing in mind the positive results of this investigation, to provide a more precise study of the subject for different possibilities of particle creation, and to consider their relevance for the scenario under discussion of baryogenesis and periodicity generation. In the case of narrow-band resonance decay, the final state interactions regulate the decay rate; parametric amplification is effectively suppressed (Allahverdi & Campbell 1997) and does not drastically enhance the decay rate. Therefore we expect that this case will be interesting to explore. Another interesting case may be that of strong dissipative processes of the products of the parametric resonance. Insofar as the dissipation reduces the resonant decay rate (Kolb, Linde & Riotto 1996; Kasuya & Kawasaki 1996) it may be worthwhile to consider such a model as well.

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