

## Research Article

# Parameterizing the SFC Baryogenesis Model

**Daniela Kirilova<sup>1,2</sup> and Mariana Panayotova<sup>1</sup>**

<sup>1</sup>*Institute of Astronomy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria*

<sup>2</sup>*Joint Institute for Nuclear Research, 141980 Dubna, Russia*

Correspondence should be addressed to Daniela Kirilova; [dani@astro.bas.bg](mailto:dani@astro.bas.bg)

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We have numerically explored the scalar field condensate baryogenesis model for numerous sets of model's parameters, within their natural range of values. We have investigated the evolution of the baryon charge carrying field, the evolution of the baryon charge contained in the scalar field condensate, and the final value of the generated baryon charge on the model's parameters: the gauge coupling constant  $\alpha$ , the Hubble constant at the inflationary stage  $H_I$ , the mass  $m$ , and the self-coupling constants  $\lambda_i$ .

## 1. Introduction

There exists baryon asymmetry  $\beta \neq 0$  in the neighborhood of our Galaxy, within 20 Mpc.  $\beta$  is usually parameterized as  $\beta = (n_b - n_{\bar{b}})/n_\gamma$ , where  $n_b$  is the number density of baryons,  $n_{\bar{b}}$  is the number density of antibaryons, and  $n_\gamma$  is the number density of photons. Contemporary observational knowledge on the baryon density of the Universe is based mainly on the following sets of precise observational data: data based on Big Bang Nucleosynthesis (BBN), that is, the determination of the baryon density from the requirement of consistency between theoretically predicted abundance and observationally measured abundance of the primordial produced light elements [1]; measurements of Deuterium towards low metallicity distant quasars compared with BBN predicted  $D$  [2]; and CMB anisotropy measurements (see WMAP [3] and Planck [4]), allowing precise determination of the main Universe characteristics, including the baryon density.

Namely, the consistency between theoretically obtained abundance and observationally measured abundance of the light elements produced in BBN [1] requires that the baryon-to-photon density is in the range:

$$5.1 \times 10^{-10} \leq \left( \frac{n_b}{n_\gamma} \right)_{\text{BBN}} \leq 6.5 \times 10^{-10} \quad \text{at 95\% CL.} \quad (1)$$

The information from measurements of Deuterium towards low metallicity quasars combined with BBN data [2] points to

$$\left( \frac{n_b}{n_\gamma} \right)_D = 6 \pm 0.3 \times 10^{-10} \quad \text{at 95\% CL.} \quad (2)$$

The most precise determination is provided by the measurements of the CMB anisotropy ( $z \sim 1000$ ). Recent results by WMAP9 [3] point to

$$\left( \frac{n_b}{n_\gamma} \right)_{\text{WMAP}} = 6.19 \pm 0.14 \times 10^{-10} \quad \text{at 68\% CL.} \quad (3)$$

The up-to-date data from Planck project [4] point to

$$\left( \frac{n_b}{n_\gamma} \right)_{\text{Planck}} = 6.108 \pm 0.038 \times 10^{-10} \quad \text{at 68\% CL.} \quad (4)$$

Observational constraints exist on the presence of the antimatter in our local vicinity (within tens of Mpc), mainly based on Cosmic Ray data [5–9] and Gamma Ray data [10–14]. No antimatter in astronomically considerable amounts has been observed/detected (still, domains of antimatter are not absolutely ruled out [15–17]). Hence, the baryon asymmetry in our neighborhood is  $\beta \sim n_b/n_\gamma$ . Observational evidence for matter-antimatter asymmetry in the Universe has been recently reviewed in [17, 18].

In case this locally observed asymmetry is a *global* characteristic of the Universe, that is, baryon asymmetry of the Universe (BAU), it may be due to the generation of a baryon excess at some early stage of the Universe. This excess eventually diluted during the Universe further evolution determined the BAU observed today.

Sakharov [19] defined the conditions for the generation of predominance of matter over antimatter from initially symmetric state of the early Universe. Namely, these are nonconservation of baryons, C and CP-violation, and deviation from thermal equilibrium. None of these conditions is obligatory. Different baryogenesis scenarios, where some of the Sakharov's requirements are not fulfilled, have been discussed in [20].

The exact (nature chosen) baryogenesis mechanism is not known yet. It is known that baryon asymmetry may not be postulated as an initial condition, in case of inflationary early stage of the Universe evolution, and it should have been generated in the period after inflation and before BBN epoch [21].

Numerous baryogenesis scenarios exist today, whose aim is to explain the observed baryon asymmetry, its sign, and its value. For a review see [22–25]. In [24] different mechanisms for generation both of the baryon asymmetry and the dark matter of the Universe and their dependence on the reheating temperature have been discussed. The most studied among the baryogenesis scenarios are Grand Unified Theories (GUT) baryogenesis [19], electroweak (EW) baryogenesis [26–30], baryogenesis-through-leptogenesis (often called leptogenesis) [31–33], Affleck-Dine (AD) baryogenesis [34], and so forth.

*GUT baryogenesis* is the earliest baryogenesis scenario, proceeding at GUT unification scale  $M_{\text{GUT}}$ . However, most inflationary models predict reheating temperature below this scale. Besides, successful unification requires supersymmetry. SUSY implies the existence of gravitinos, which are too numerous produced unless the reheating temperature is well below  $M_{\text{GUT}}$  [35, 36].

*EW baryogenesis* is theoretically attractive because it relies only upon weak scale physics and is experimentally testable scenario. For a review see [28, 37–39]. However, the simplest and most appealing version of this scenario cannot generate within the Standard Model the observed value of the baryon asymmetry, because of the insufficient CP-violation [40–42] induced by CKM phase and the requirement of first-order electroweak transition, possible only for Higgs boson mass considerably smaller than the detected one by ATLAS and CMS collaborations.

EW baryogenesis in Minimal Supersymmetric Standard Model was considered [43]. Now MSSM window for EW baryogenesis is substantially narrowed by the experimental data from the Large Hadron Collider (LHC) [44–46] and recent electron dipole measurements. Constraints on EW baryogenesis in case of a minimal extension of the Standard Model from current data from LHC have been discussed as well [47]. The viable parameter space is considerably reduced. Baryogenesis in next-to-minimal SM is being discussed now [48].

*Baryogenesis-through-leptogenesis* is a plausible possibility. Baryon asymmetry in this scenario is created before the electroweak phase transition, which then gets converted to the baryon asymmetry in the presence of  $(B + L)$  violating anomalous processes. For a review see [23, 49–51]. It has become especially attractive after the discovery of nonzero neutrino masses in neutrino oscillations experiments. Baryogenesis through leptogenesis mechanisms in different extensions of the SM is studied.

Possibilities for falsifying concrete realizations of high scale leptogenesis from recent LHC data have been proposed [52, 53].

*Neutrino Minimal Standard Model* (NMSM) can potentially account simultaneously for baryon and dark matter generation and neutrino oscillations [54]. NMSM is testable at colliders and in astrophysical observations. For a recent review and constraints from collider experiments, astrophysics, and cosmology see [55].

*AD baryogenesis* scenario [22, 34] is one of the most promising today baryogenesis scenarios, compatible with inflation. Nice reviews of AD baryogenesis contemporary status can be found in [22, 56]. AD baryogenesis has numerous attractive features. A short list of these is as follows: (i) it is extremely efficient: it can produce equal or much bigger baryon asymmetry than the observed one; (ii) it can be realized at lower energy, that is, relatively late in the Universe evolution. That is, it is consistent with the low energy scales after inflation; (iii) AD condensate can be generated generically in different cosmological models; (iv) it can explain simultaneously the generation of the baryon and the dark matter in the Universe and explain their surprisingly close values; (v) AD model, due to its high efficiency, can be successful even in case of significant production of entropy at late times, predicted by some particle physics models.

AD scenario is based on SUSY. In supersymmetric models scalar superpartner of baryons and leptons  $\varphi$  exists. The potential  $U(\varphi)$  of such scalar field may have flat directions, along which the field can have a nonzero vacuum expectation value due to quantum fluctuations during inflation. After inflation  $\varphi$  evolves down to the equilibrium point  $\varphi = 0$  and if the potential  $U(\varphi)$  is not symmetric with respect to the phase rotation it acquires nonvanishing and typically large baryon charge. Subsequent  $B$ -conserving decay of  $\varphi$  into quarks and leptons transforms baryon asymmetry into the quarks sector. In contrast to other scenarios of baryogenesis, in which the generated asymmetry usually is insufficient, the original Affleck-Dine scenario leads to higher value of  $\beta$  and additional mechanisms are needed to dilute it down to the observed value.

AD mechanism was reexamined in [57]. It was realized that finite energy density of the early Universe breaks SUSY and induces soft parameters in the soft potential along flat directions, which are of the order of the Hubble parameter. Then, contrary to the original AD mechanism the observed value of the baryon asymmetry may be generated, without the requirement of subsequent entropy release. Different issues on AD baryogenesis were presented in [58–60]. AD baryogenesis mechanism was used in numerous SM extensions

and different inflationary scenario. A short list of several of the more recent studies includes: AD in effective supergravity [61], AD in anomaly mediated SUSY breaking models [62], AD in SUSY with R-parity violation [63], AD in  $D$ -term inflation [64], and so forth. Most of AD baryogenesis models can naturally explain the origin of the dark matter in the Universe. Constraints on the subclass of AD models were obtained from current CMB data, based on the backreaction of the flat direction on the inflationary potential [65].

Here we discuss the scalar field condensate baryogenesis model (SFC baryogenesis), which is among the preferred today baryogenesis scenarios, compatible with inflation. It is based on the Affleck-Dine scenario.

SFC baryogenesis model was first discussed and studied analytically in [66, 67]. There it was shown that the account of particle creation by the time varying scalar field during postinflationary period will lead to strong reduction of the produced baryon excess in the Affleck-Dine scenario. Namely, it was proven that fast oscillations of  $\varphi$  result in particle creation due to the coupling of the scalar field to fermions  $g\varphi f_1 f_2$ , where  $g^2/4\pi = \alpha$ . For  $\lambda_i^{3/4} > g$  the rate of particle creation  $\Gamma$  exceeds the ordinary decay rate of  $\varphi$  at the stage of baryon nonconservation and, therefore, its amplitude is damped. Hence, the baryon charge, contained in the condensate, is reduced due to particle creation at this stage with considerable baryon violation (when  $\Gamma = \text{constant}$ , the baryon charge of the condensate is reduced exponentially and does not survive till  $\varphi$  decays to quarks and leptons. However, when  $\Gamma$  is a decreasing function of time, the damping process may be slow enough for the baryon charge in the condensate to survive until its decay; i.e., this case is more promising).

The importance of a precise numerical account for the particle creation processes was explored further in [68, 69]. Different possibilities of SFC baryogenesis models were discussed. The possibility to generate simultaneously, within inhomogeneous SCF baryogenesis model, the observed baryon asymmetry and the observed large scale structure quasiperiodicity of the baryonic matter was studied in [68, 70, 71]. On the basis of inhomogeneous SCF baryogenesis elegant mechanisms were proposed for achieving sufficient separation between domains of matter and antimatter (to inhibit the contact and evade annihilation of matter and antimatter regions with big density) that allow the production of considerable antimatter domains with different size in the Universe and their observational signatures were analyzed [15, 17, 71–74].

In series of papers [69, 75, 76], we explored numerically SFC baryogenesis model. Here we present the results of our extended numerical analysis of the evolution of the baryon excess in SFC baryogenesis model and its dependence on the model parameters.

In the next section we briefly describe the SCF baryogenesis model and the numerical approach we have used. The last section presents the results; that is, we present the value of the produced baryon density for numerous sets of model's parameters.

## 2. SFC Baryogenesis Model

*2.1. Description.* The essential ingredient of the model is a baryon charged complex scalar field  $\varphi$ , present together with the inflaton. A condensate  $\langle \varphi \rangle \neq 0$  with a nonzero baryon charge is formed during the inflationary period as a result of the rise of quantum fluctuations of the  $\varphi$  field [77–80]:  $\langle \varphi^2 \rangle = H^3 t / 4\pi^2$  until the limiting value  $\langle \varphi^2 \rangle \sim H^2 / \sqrt{\lambda}$  in case that  $\lambda\varphi^4$  terms dominate in the potential energy of  $\varphi$ .

The baryon charge of the field is not conserved at large field amplitude due to the presence of the  $B$  nonconserving self-interaction terms in its potential.

We choose the form of the potential as follows:

$$U(\varphi) = m^2 \varphi^2 + \frac{\lambda_1}{2} |\varphi|^4 + \frac{\lambda_2}{4} (\varphi^4 + \varphi^{*4}) + \frac{\lambda_3}{4} |\varphi|^2 (\varphi^2 + \varphi^{*2}). \quad (5)$$

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 self-coupling constants  $\lambda_i$  are of the order of the gauge coupling constant  $\alpha$ . A natural range of  $m$  is  $10^2 - 10^4$  GeV.

We examine the case when after inflation there exist two scalar fields, the inflaton  $\psi$  and the scalar field  $\varphi$ , and the inflaton density dominates prior to the decay of  $\varphi$ :  $\rho_\psi > \rho_\varphi$ . Hence, at the end of inflation the Hubble parameter is  $H = 2/(3t)$ .

In the expanding Universe, spatially homogeneous field  $\varphi$  satisfies the equation of motion:

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{1}{4}\Gamma\dot{\varphi} + U'_\varphi = 0, \quad (6)$$

where  $a(t)$  is the scale factor and  $H = \dot{a}/a$ ,  $\Gamma$  accounts for the particle creation processes.

The initial values for the field variables are derived from the natural assumption that the energy density of  $\varphi$  at the inflationary stage is of the order  $H_I^4$ ; then

$$\varphi_o^{\max} \sim H_I \lambda^{-1/4}, \quad (7)$$

$$\dot{\varphi}_o = (H_I)^2.$$

After inflation  $\varphi$  oscillates around its equilibrium point and its amplitude decreases due to the Universe expansion and the particle creation by the oscillating scalar field. In case  $\Gamma$  is a decreasing function of time the damping process may be slow enough for the baryon charge contained in  $\varphi$  to survive until the  $B$ -conservation epoch [67].

At low  $\varphi$  baryon violation (BV) becomes negligible. At the  $B$  conserving stage the baryon charge contained in the field is transferred to that of quarks during the decay of the field  $\varphi \rightarrow q\bar{q}l\gamma$  at  $t_b$ . As a result, in case  $\varphi$  has not reached the equilibrium point at  $t_b$ , the baryogenesis makes a snapshot of  $\varphi(t_b)$  and a baryon asymmetric plasma appears. This asymmetry, eventually further diluted during the following evolution of the Universe, gives the present observed baryon asymmetry of the Universe.

2.2. *Evolution of the Baryon Charge Carrying Field.* We have solved the system of ordinary differential equations, corresponding to the equation of motion for the real and imaginary components of  $\varphi = x + iy$ :

$$\begin{aligned}\ddot{x} + 3H\dot{x} + \frac{1}{4}\Gamma_x\dot{x} + (\lambda + \lambda_3)x^3 + \lambda'xy^2 &= 0, \\ \ddot{y} + 3H\dot{y} + \frac{1}{4}\Gamma_y\dot{y} + (\lambda - \lambda_3)y^3 + \lambda'yx^2 &= 0,\end{aligned}\quad (8)$$

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

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  $\eta = 2(t/t_i)^{1/3}$ . Then the functions  $u(\eta)$  and  $v(\eta)$  satisfy the equations:

$$\begin{aligned}u'' + 0.75\alpha\Omega_u(u' - 2u\eta^{-1}) \\ + u \left[ (\lambda + \lambda_3)u^2 + \lambda'v^2 - 2\eta^{-2} + \frac{m^2}{H}\eta^4 \right] &= 0, \\ v'' + 0.75\alpha\Omega_v(v' - 2v\eta^{-1}) \\ + v \left[ (\lambda - \lambda_3)v^2 + \lambda'u^2 - 2\eta^{-2} + \frac{m^2}{H}\eta^4 \right] &= 0.\end{aligned}\quad (9)$$

The baryon charge in the comoving volume  $V = V_i(t/t_i)^2$  is given by

$$B = N_B \cdot V = 2(u'v - v'u). \quad (10)$$

We have solved numerically the system of ordinary differential equations (9), corresponding to the equation of motion for the real and imaginary part of  $\varphi$  and  $B$  contained in it, using Runge-Kutta fourth-order method and Fortran 77. The Runge-Kutta fourth-order routine from [81] is used.

We studied numerically the evolution of  $\varphi(\eta)$  and  $B(\eta)$  in the period after inflation until the BC epoch. The typical range of energies discussed was  $10^{15}$ – $100$  GeV. Therefore, serious computational resources were used. A single calculation took between several hours and three weeks, depending on the concrete parameters.

We analyzed  $\varphi$  and  $B$  evolution for natural ranges of values of the model's parameters:  $\lambda = 10^{-2}$ – $5 \times 10^{-2}$ ,  $\alpha = 10^{-3}$ – $5 \times 10^{-2}$ ,  $H_I = 10^7$ – $10^{16}$  GeV, and  $m = 100$ – $1000$  GeV. The numerical analysis was provided for around seventy sets of parameters.

We have accounted numerically for the particle creation processes by varying  $\varphi$ , which allowed us to describe more precisely the evolution of  $B$  and determine its final value which was transferred to quarks (antiquarks) at  $t_b$  epoch and defined the baryon asymmetry. In this work we calculated  $\Gamma$  numerically in contrast to our previous papers, where for the rate of particle creation  $\Gamma$  the analytical estimation was used  $\Gamma = \alpha\Omega$ , where  $\Omega \sim \lambda_1^{1/4}\varphi$ . In the program  $\Omega_u$  and  $\Omega_v$  were calculated at each step in separate routine procedures.

The results of our numerical study are presented in the next section.

### 3. The Generated Baryon Charge for Different Parameters Values: Numerical Results

We have calculated  $B$  for different sets of values of model's parameters: gauge coupling constant  $\alpha$ , Hubble constant during inflation  $H_i$ , mass of the condensate  $m$ , and self-coupling constants  $\lambda_i$ . We have not made calculations for all the possible values of the parameters, because each single point requires days or weeks of CP time. Our main aim was to find the dependence of the final  $B$  on the parameters and choose the more promising ranges of the parameters for successful baryogenesis, rather than providing full systematic numerical study. Therefore, some entries in Tables 1, and 3 are missing.

3.1. *Dependence on Hubble Constant during Inflation  $H_I$ .* We have followed the evolution  $B(\eta)$  varying  $H_I$  for fixed values of the other parameters. The results of our preliminary analysis of this dependence have been first discussed in [69, 75].

In this work we have performed an extended analysis of this dependence, studying wider range of models parameters.

In the rows in Tables 1, 2, and 3 we present the results of the generated baryon charge in the SFC baryogenesis model for different values of the Hubble constant  $H_I$  and for different fixed values of the other parameters of the model. The first table presents  $B(H_I)$  for  $\lambda_1 = 10^{-2}$ ,  $\alpha = 10^{-2}$ , and  $\lambda_2 = \lambda_3 = 10^{-3}$ , the second one presents it for  $\lambda_1 = 5 \times 10^{-2}$ ,  $\alpha = 10^{-2}$ , and  $\lambda_2 = \lambda_3 = 10^{-3}$ , and the third one presents it for  $\lambda_1 = 5 \times 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ ,  $m = 350$  GeV, and two different values of  $\alpha$ , namely,  $10^{-2}$  and  $5 \cdot 10^{-2}$ .

Figure 1 presents the dependence of the evolution of the baryon charge on  $H_I$  at fixed values of the other parameters.

Our detailed analysis for numerous different parameters of the SCF model shows that  $B$  evolution becomes longer and the final  $B$  value decreases with the increase of  $H_I$ . This result is in agreement with previous numerical and analytical studies. It is an expected result because particle creation, which reduces  $\beta$ , is proportional to  $\varphi$ ,  $\Gamma \sim \Omega \sim \varphi$ , and the initial value of  $\varphi$  is proportional to  $H_I$ . Thus, the bigger  $H_I$  is, the more efficient is the decrease of  $\beta$  due to particle creation.

3.2. *Dependence on Gauge Coupling Constant  $\alpha$ .* Using the numerical account for  $\Gamma$  we have calculated  $B(\eta)$  for  $\alpha$  varying in the range  $10^{-3}$ – $10^{-2}$  and fixed other parameters; see also [69]. The dependence of  $B$  on  $\alpha$  is very strong, as can be expected, knowing that particle creation processes play essential role for the evolution of the field and the baryon charge, contained in it, and keeping in mind that the analytical estimation is  $\Gamma = \alpha\Omega$ .

With increasing  $\alpha$ ,  $B$  evolution becomes shorter and the final  $B$  decreases. An illustration of this dependence  $B(\alpha)$  is given in Figure 2.

In the columns of Table 3 we present the results for the baryon charge contained in the SFC at the time of its decay for different values of  $\alpha$  and for  $\lambda_1 = 5 \times 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ , and  $m = 350$  GeV.

TABLE 1: The baryon charge  $B$  contained in the SFC at the time of its decay for different  $H_I$  and  $m$  and fixed set of  $\lambda_1 = 10^{-2}$ ,  $\alpha = 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ ,  $\varphi_o = H_I \lambda^{-1/4}$ , and  $\dot{\varphi}_o = H_I^2$ . The particle creation processes are accounted for numerically.

$m, \text{ GeV}$	$H, \text{ GeV}$						
	$1.00E + 14$	$1.00E + 12$	$1.00E + 11$	$1.00E + 10$	$1.00E + 09$	$1.00E + 08$	$1.00E + 07$
350	$-2.75E - 07$	$2.10E - 06$	$1.18E - 04$	$1.61E - 03$	$2.89E - 02$	$-4.08E - 01$	$-2.31E - 01$
500		$7.44E - 05$	$-7.72E - 04$	$-6.72E - 04$	$-1.00E - 02$	$2.69E - 01$	$1.58E - 01$
800		$-1.07E - 04$	$-1.40E - 03$	$2.27E - 03$	$2.86E - 02$	$1.11E - 01$	$9.04E - 01$

TABLE 2: The baryon charge  $B$  contained in the SFC at the time of its decay for different  $H_I$  and  $m$  and fixed set of  $\lambda_1 = 5 \times 10^{-2}$ ,  $\alpha = 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ ,  $\varphi_o = H_I \lambda^{-1/4}$ , and  $\dot{\varphi}_o = H_I^2$ .

$m, \text{ GeV}$	$H, \text{ GeV}$					
	$1.00E + 12$	$1.00E + 11$	$1.00E + 10$	$1.00E + 09$	$1.00E + 08$	$1.00E + 07$
350	$1.00E - 05$	$1.00E - 04$	$-5.00E - 05$	$-1.00E - 04$	$7.00E - 03$	$-4.00E - 03$
500	$2.57E - 06$	$1.00E - 06$	$-2.00E - 04$	$-1.34E - 02$	$7.87E - 02$	$5.00E - 01$

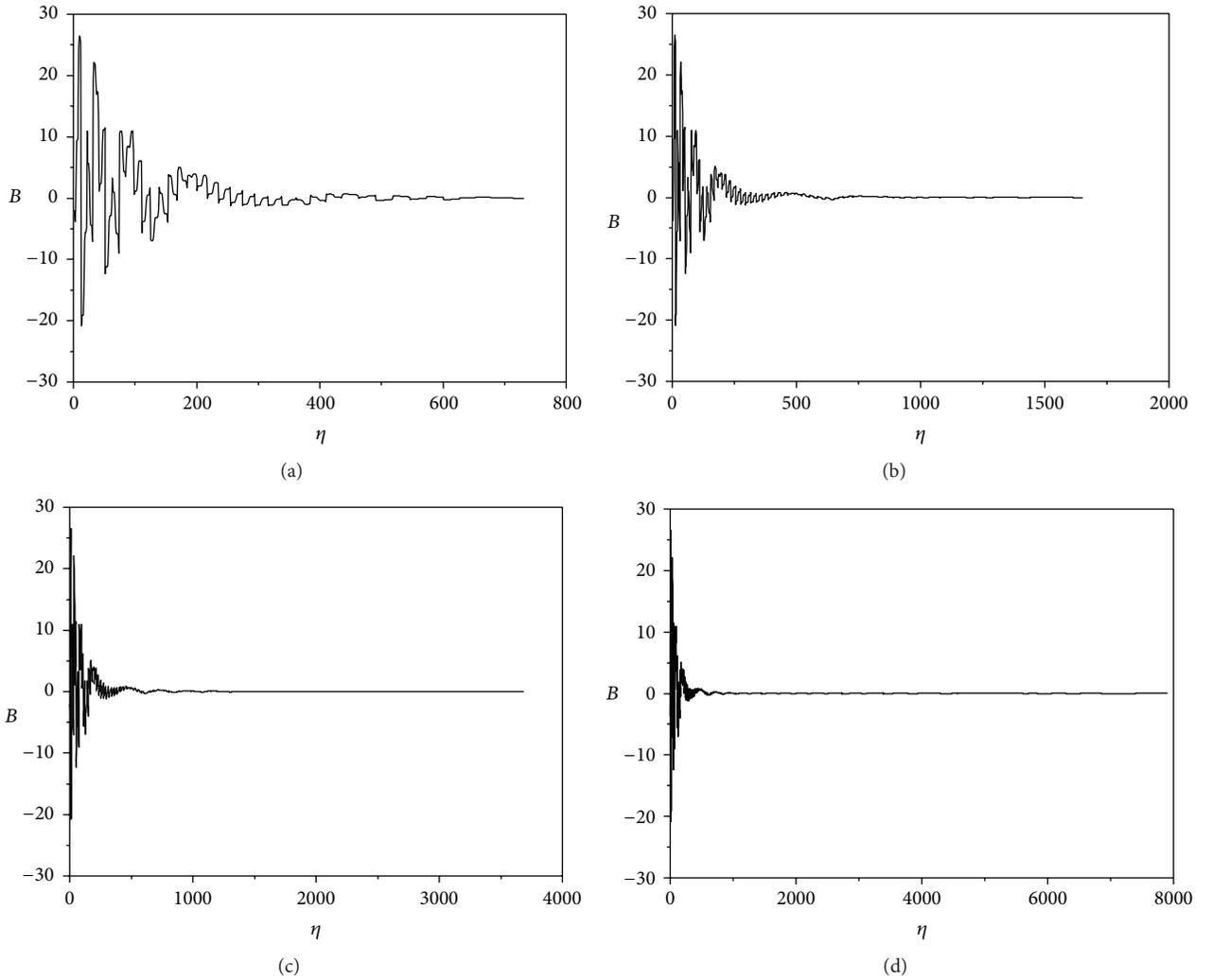


FIGURE 1: The evolution of the baryon charge  $B(\eta)$  for  $\lambda_1 = 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ ,  $\alpha = 10^{-2}$ ,  $m = 500 \text{ GeV}$ ,  $\varphi_o = H_I \lambda^{-1/4}$ , and  $\dot{\varphi}_o = H_I^2$ . (a) For  $H_I = 10^9 \text{ GeV}$ , (b) for  $H_I = 10^{10} \text{ GeV}$ , (c) for  $H_I = 10^{11} \text{ GeV}$ , and (d) for  $H_I = 10^{12} \text{ GeV}$ .

TABLE 3: The baryon charge  $B$  contained in the SFC at the time of its decay for different  $\alpha$  and  $H_I$  and  $\lambda_1 = 5 \times 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ ,  $m = 350$  GeV,  $\varphi_o = H_I \lambda^{-1/4}$ , and  $\dot{\varphi}_o = H_I^2$ .

$\alpha$	$H, \text{ GeV}$					
	$1.00E + 12$	$1.00E + 11$	$1.00E + 10$	$1.00E + 09$	$1.00E + 08$	$1.00E + 07$
$1.00E - 02$	$1.00E - 05$	$1.00E - 04$	$-5.00E - 05$	$-1.00E - 04$	$7.00E - 03$	$-4.00E - 03$
$5.00E - 02$	$8.01E - 07$		$5.50E - 05$	$2.40E - 03$	$8.10E - 03$	$6.90E - 02$

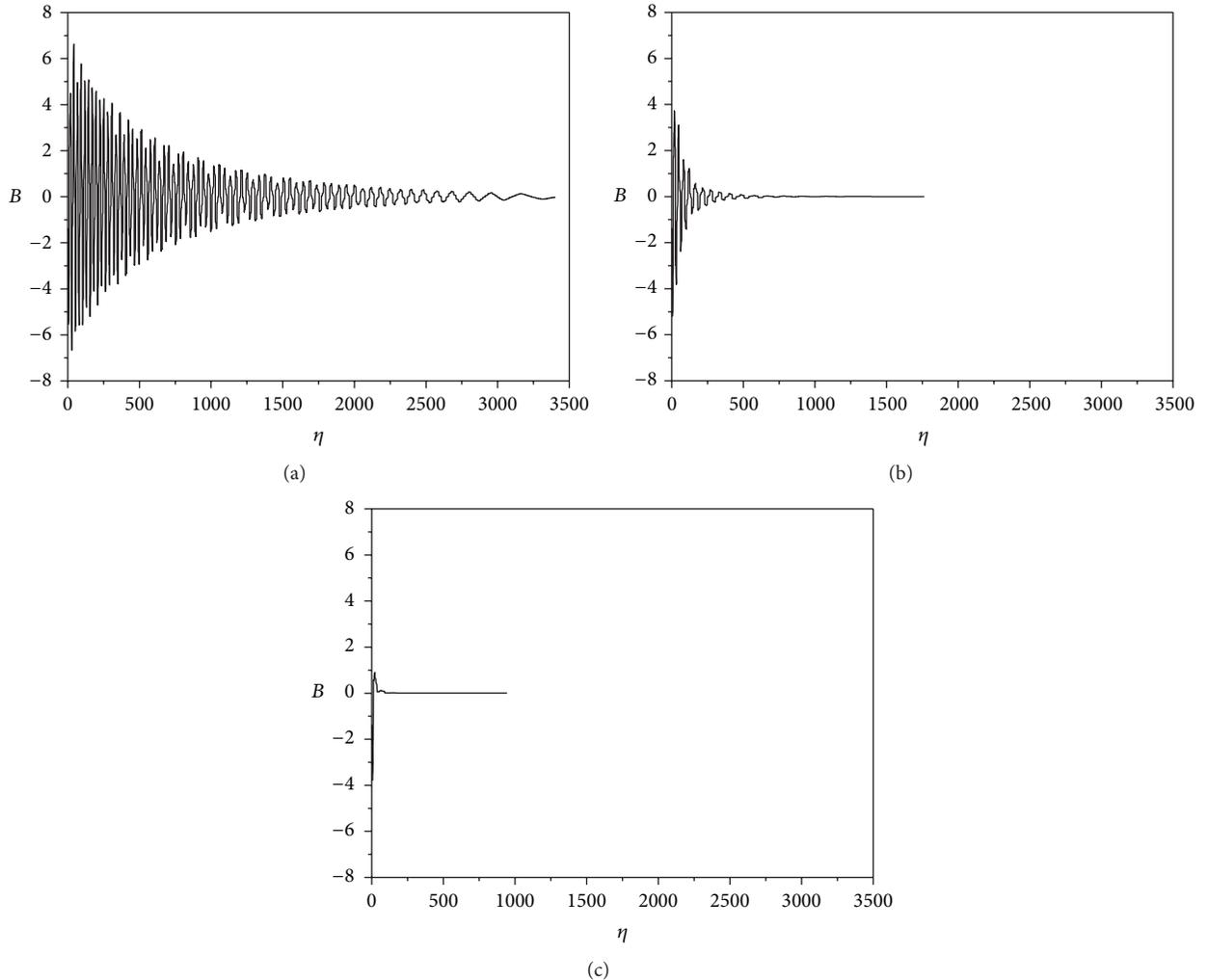


FIGURE 2: The evolution of the baryon charge  $B(\eta)$  for  $\lambda_1 = 5 \times 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-3}$ ,  $H = 10^{10}$  GeV,  $m = 350$  GeV,  $\varphi_o = H_I \lambda^{-1/4}$ , and  $\dot{\varphi}_o = H_I^2$ . (a) For  $\alpha = 10^{-3}$ , (b) for  $\alpha = 10^{-2}$ , and (c) for  $\alpha = 5 \times 10^{-2}$ .

**3.3. Dependence on the Mass  $m$  of the Condensate.** The dependence of the final baryon charge on  $m$  for fixed  $\lambda_1, \lambda_2, \lambda_3, \alpha$ , and  $H_I$  has been first discussed in [69, 75]. Here we present the results of a more detailed study. In Table 2 the dependence of generated baryon asymmetry values on the mass of the field is given for different fixed sets of the other parameters of the model.

It has been found that in general  $B$  decreases with the increase of the value of  $m$ . This behavior is more clearly and more strongly expressed for big values of  $H_I$  and then corresponds to the expected one from analytical estimations

(namely, as far as  $m$  defines the onset of BC epoch:  $t_s \sim 1/\alpha m$ , and hence for lower values of  $m$ ,  $B$  evolution is longer and the final  $B$  value is smaller). The dependence is illustrated in Figure 3.

For smaller values of  $H_I$  the dependence is weaker and not so straightforward and clear. In Table 2 we present the generated baryon asymmetry values for different mass of the field and fixed values of the other parameters of the model.

In the columns of Tables 1 and 2 we present the results for the baryon charge contained in the SFC at the time of its

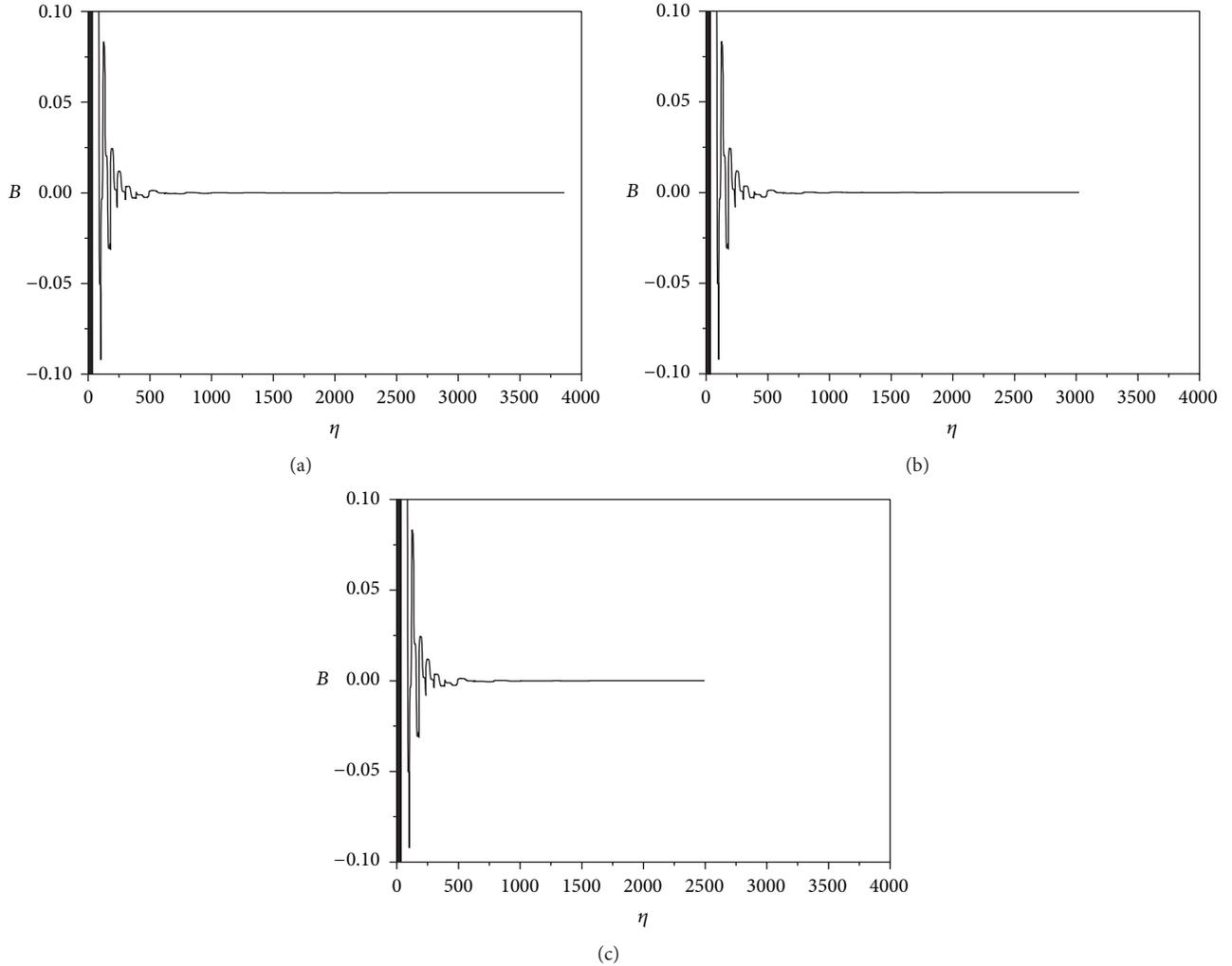


FIGURE 3: The evolution of the baryon charge  $B(\eta)$  for  $\lambda_1 = 5 \times 10^{-2}$ ,  $\lambda_2 = \lambda_3 = 10^{-2}$ ,  $\alpha = 5 \times 10^{-2}$ ,  $H = 10^{11}$  GeV,  $\varphi_o = H_I \lambda^{-1/4}$ , and  $\dot{\varphi}_o = H_I^2$ . (a) Curve is for  $m = 100$  GeV, (b) for  $m = 200$  GeV, and (c) for  $m = 350$  GeV.

decay for different values of the mass of the field  $m$  and for different fixed values of the other parameters of the model.

**3.4. Dependence on the Self-Coupling Constants.** The dependence of the baryon charge, at the  $B$ -conservation epoch, on the value of the coupling constants  $\lambda_i$  was first discussed in [76]. Our extended analysis confirms that the final  $B$  value decreases when increasing  $\lambda_1$  and  $B$  evolution becomes shorter. The effect provides a difference in the final  $B$  value of an order of magnitude.

The results of the extended analysis showed that the final value of  $B$  may be much sensitive to  $\lambda_2$  and  $\lambda_3$  compared to that previously estimated. Namely, we have found that the final values of  $B$  may differ up to 3 orders of magnitude even for small changes of these parameters. For example, for  $m = 350$  GeV,  $H_I = 10^{10}$ ,  $\alpha = 10^{-3}$ , and  $\lambda_1 = 5 \times 10^{-2}$  the final  $B$  value for  $\lambda_2 = \lambda_3 = 5 \times 10^{-4}$  is  $B = 3.88 \times 10^{-5}$ , while for  $\lambda_2 = \lambda_3 = 10^{-3}$  it is  $B = 2.36 \times 10^{-2}$ .

Thus, we have found that the dependence of baryon generation on the self-coupling constants is important for

determination of the parameters range for the successful baryogenesis model.

## 4. Estimation of the Generated Baryon Asymmetry

In order to estimate the baryon asymmetry on the basis of the obtained results for the produced baryon density it is necessary to know the temperature of the relativistic plasma after the decay of  $\varphi$  and the decay of the inflaton.

In case the inflaton energy density dominates until the decay of  $\varphi$ , that is, prior to reheating,  $\rho_\psi > \rho_\varphi$ , the entropy is mainly defined by the relativistic particles from inflaton decay. Thus, the temperature after the decay of  $\psi$  at  $t_\psi$  will be approximately

$$T_R \sim (\rho_\psi)^{1/4} = (\rho_\psi^0)^{1/4} \left( \frac{\eta_0}{\eta_\psi} \right)^{3/2}. \quad (11)$$

Then the baryon asymmetry will be given by

$$\beta \sim \frac{N_B}{T_R^3} \sim \frac{BT_R}{H_I}, \quad (12)$$

where  $T_R$  is the reheating temperature after the decay of the inflaton.

Hence, from these estimations it is seen that the lower the reheating temperature after inflaton decay is the lower the produced baryon asymmetry will be. Also, the later the inflaton decays the smaller the produced  $\beta$  will be. Knowing that the reheating temperature should be sufficiently low to avoid gravitino problem, that is, in our model it should be several orders or more lower than the value of  $H_I$ , and having the results for  $B$ , it is easy to obtain the value of the observed baryon asymmetry for different sets of parameters in this model.

Of course  $H_I$ , the decay time of  $\psi$ , and the value of the reheating temperature may be different in different inflationary scenarios. We would like only to note here that the results of the numerical analysis of the SCF baryogenesis model are encouraging. The analysis points that this model provides an opportunity to produce baryon asymmetry  $\beta$ , consistent with its observed value for natural values of the model's parameters. Therefore, this model deserves further considerations.

## 5. Conclusions

It was found that the analytical estimations of the baryon charge evolution and its final value in SFC baryogenesis model may considerably differ from the exact numerically calculated ones. Therefore, in this work we have numerically explored the SFC baryogenesis model for numerous sets of model's parameters.

We have investigated the dependence of the evolution of the field and the evolution of the baryon charge contained in it, as well as the final value of the baryon charge contained in it on the model's parameters: the gauge coupling constant  $\alpha$ , the Hubble parameter at the inflationary stage  $H_I$ , the mass  $m$ , and the self-coupling constants  $\lambda_i$ . Qualitative dependence of the final  $B$  on these parameters has been found. Namely, it was shown that the produced baryon excess is a strongly decreasing function of  $\alpha$ , and it also is a decreasing function of  $H_I$ . The dependence on  $m$  is not so straightforward. For small  $m$  values  $B$  decreases with  $m$  increase; however, for larger  $m$  the dependence is more complicated.

The analysis may be used to indicate the values of the model's parameters for which baryon asymmetry  $\beta$ , consistent with its observed value, may be produced in a given inflationary scenario.

The results of this analysis may be used for constructing realistic SCF baryogenesis models. Moreover, assuming SCM baryogenesis and assuming a concrete inflationary scenario, from the observed value of the baryon asymmetry it is possible to put cosmological constraints on the model's parameters, provided by physics theories, that is, constrain physics beyond Standard Model.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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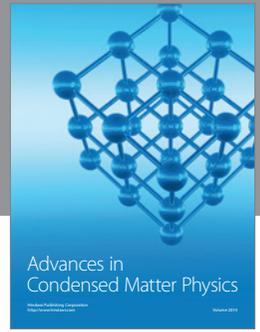
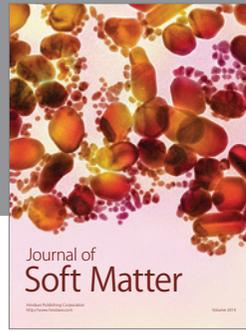
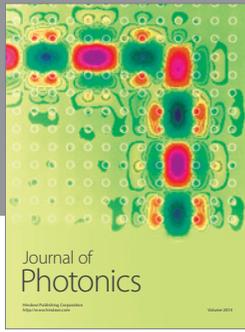
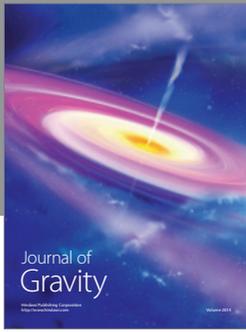
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