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Baryogenesis with Scalar Field Condensate and Baryon Assymmetry of the Universe*

M. Panayotova, **D. Kirilova**
Institute of Astronomy and NAO Rozhen, Bulgarian Academy of Sciences, Sofia 1784, Bulgaria

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Abstract. A short review of the recent results of the numerical studies of the Scalar Field Condensate baryogenesis model is presented. The dependence of the evolution of the generated baryon charge on the model's parameters: the gauge coupling contstant α, the Hubble constant at the inflationary stage H_I, the mass m, the self-coupling constants λ_i is discussed.

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1 Introduction

In the neighborhood of our Galaxy (within 20 Mpc) there exists matter-antimatter asymmetry

$$\beta = (n_b - n_{\bar{b}})/n_\gamma \sim n_b/n_\gamma \sim 6.1 \times 10^{-10},$$

where n_b is the number density of baryons, $n_{\bar{b}}$ of antibaryons and n_γ is the number density of photons.

The most precise determination of the baryon density of the Universe n_b/n_γ is provided by the measurements of the CMB anisotropy [1] and measurements of Deuterium towards low metallicity quasars and BBN data [2]. The observational evidence for matter-antimatter asymmetry in the Universe [3, 4] is mainly based on Cosmic Ray data [5–9] and Gamma Ray data [10–14].

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

The conditions for the generation of predominance of matter over antimatter from initially symmetric state of the early Universe [15] are: non-conservation

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of baryons, C and CP-violation and deviation from thermal equilibrium. The Nature chosen baryogenesis mechanism is not known yet.

Numerous baryogenesis scenarios exist today [16–19]. The most studied among them being Grand Unified Theories (GUT) baryogenesis [15], Electroweak (EW) baryogenesis [20–24], Baryogenesis-through-leptogenesis (often called leptogenesis) [25–27], Affleck-Dine (AD) baryogenesis [28], etc.

AD baryogenesis [16,28] is extremely efficient, compatible with inflation, consistent with the low energy scales after inflation, realized in different cosmological models and SM extensions.

Here we discuss the scalar field condensate baryogenesis model (SFC baryogenesis), based on the Affleck-Dine scenario.

SFC baryogenesis model was first studied in refs. [29, 30]. It was shown that the account of particle creation by the time varying scalar field during post-inflationary period leads to strong reduction of the produced baryon excess in the Affleck-Dine scenario because fast oscillations of φ result in particle creation due to the coupling of the scalar field to fermions, when the rate of particle creation Γ exceeds the ordinary decay rate of φ at the stage of baryon non-conservation and φ amplitude is damped. Hence, the baryon charge, contained in the condensate, is reduced and SFC model perdicts baryon excess of the order of the observed one.

A precise numerical account for the particle creation processes was provided in refs. [31,32]. Different possibilities of SFC baryogenesis models were discussed [31–40]. Here we present a summary of our results [32,39–41] of the numerical analysis of the evolution of the baryon excess generated in SFC baryogenesis model and its dependence on the model parameters.

The next section briefly describes the SCF baryogenesis model and the numerical approach we use. The last section presents the results, i.e. we present the value of the produced baryon density for numerous sets of model's parameters.

2 SFC Baryogenesis Model

The main ingredient of the model is a baryon charged complex scalar field φ, present together with the inflaton. During the inflationary period a condensate $< \varphi > \neq 0$ with a nonzero baryon charge is formed due to growth of quantum fluctuations of φ [42–45].

B nonconserving self-interaction terms in φ potential exist, due to which the baryon charge of the field is not conserved at large field amplitude.

We study the potential

$$U(\varphi) = m^2\varphi^2 + \frac{\lambda_1}{2}|\varphi|^4 + \frac{\lambda_2}{4}(\varphi^4 + \varphi^{*4}) + \frac{\lambda_3}{4}|\varphi|^2(\varphi^2 + \varphi^{*2}) \qquad (1)$$

The mass parameters of the potential are small $m \ll H_I$, the self coupling constants λ_i are of the order of the gauge coupling constant α.

After inflation there exist two scalar fields: the inflaton ψ; and the scalar field φ and $\rho_\psi > \rho_\varphi$. Hence, at the end of inflation the Hubble parameter is $H = 2/(3t)$.

The equation of motion of φ is

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{1}{4}\Gamma\dot{\varphi} + U'_\varphi = 0, \tag{2}$$

where $a(t)$ is the scale factor, $H = \dot{a}/a$, Γ accounts for the particle creation processes by the oscillating scalar field.

The initial values for the field variables are chosen so the energy density of φ at the inflationary stage is of the order H_I^4: $\varphi_0^{\max} \sim H_I \lambda^{-1/4}$ and $\dot{\varphi}_0 = (H_I)^2$.

After inflation φ oscillates around its equilibrium value and its amplitude decreases due to the Universe expansion and the particle creation. In case Γ is a decreasing function of time the damping process is slow and baryon charge contained in φ survives until the B-conservation epoch [30].

The baryon charge contained in the field is transferred to that of quarks during the decay of the field $\varphi \to q\bar{q}l\gamma$ at t_b and a baryon asymmetric plasma appears.

3 Analysis of the Evolution of the Baryon Charge

We solve numerically the system of ordinary differential equations, that describe the evolution of the real and imaginary components of $\varphi = x + iy$.

$$\begin{aligned} u'' &+ 0.75\alpha\Omega_u(u' - 2u\eta^{-1}) \\ &\quad + u[(\lambda + \lambda_3)u^2 + \lambda' v^2 - 2\eta^{-2} + \frac{m}{H}^2\eta^4] = 0 \\ v'' &+ 0.75\,\alpha\Omega_v(v' - 2v\eta^{-1}) \\ &\quad + v[(\lambda - \lambda_3)v^2 + \lambda' u^2 - 2\eta^{-2} + \frac{m}{H}^2\eta^4] = 0. \end{aligned} \tag{3}$$

where

$$\lambda = \lambda_1 + \lambda_2, \quad \lambda' = \lambda_1 - 3\lambda_2.$$
$$x = H_I(t_i/t)^{2/3}u(\eta), \quad y = H_I(t_i/t)^{2/3}v(\eta), \quad \eta = 2(t/t_i)^{1/3}.$$

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

$$B = N_B \cdot V = 2(u'v - v'u). \tag{4}$$

We studied numerically the evolution of $\varphi(\eta)$ and $B(\eta)$ in the period after inflation until the BC epoch. We have used Runge-Kutta 4th order method and fortran 77.The studied range of energies was $10^{16} - 100$ GeV, the 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, $m = 100 - 1000$ GeV. The numerical analysis was provided for around seventy sets of parameters.

In [41] we calculated Γ numerically in contrast to previous papers, where the analytical estimation $\Omega \sim \lambda_1^{1/4}\varphi$, $\Gamma = \alpha\Omega$ was used.

4 Results and Conclusions

We have numerically calculated $B(t)$ for different sets of model's parameters values - gauge coupling constant α, Hubble constant during inflation H_i, mass of the condensate m and self coupling constants λ_i.

Dependence on Hubble constant during inflation H_I

In several works [32,39,41] the dependence of the evolution of $B(\eta)$ on H_I for fixed values of the other parameters was studied.

Our detail analysis for different parameters of the SCF model shows that *B evolution becomes longer and the final B value decreases with the increase of* H_I. It is an expected result because particle creation, which reduces β is proportional to φ, $\Gamma \sim \Omega \sim \varphi$, and the initial value of φ is proportional to H_I. Thus, the bigger H_I - more efficient is the decrease of β due to particle creation.

Dependence on gauge coupling constant α

$B(\alpha)$ for α varying in the range $10^{-3} - 10^{-2}$ and fixed other parameters was studied [32, 41]. The dependence of B on α is expected to be very strong, having in mind the analytical estimation $\Gamma = \alpha\Omega$.

The numerical study showed that *with increasing* α*,* B *evolution becomes shorter and the final* B *decreases* (see Figure 1).

Dependence on the mass m ***of the condensate***

The dependence of the final baryon charge on m for fixed λ_1, λ_2, λ_3, α and H_I has been analyzed in refs. [32,39,41]. We studied a range of m $10^2 - 10^3$ GeV.

It has been found that B decreases with the increase of m. This behavior is more clearly and more strongly expressed for big values of H_I and corresponds to analytical estimations. For smaller values of H_I the dependence is weaker and not so straightforward.

Dependence on the self-coupling constants

The dependence of the baryon charge, at the B-conservation epoch, on the value of the coupling constants λ_i was discussed in refs. [40, 41]. The final B value

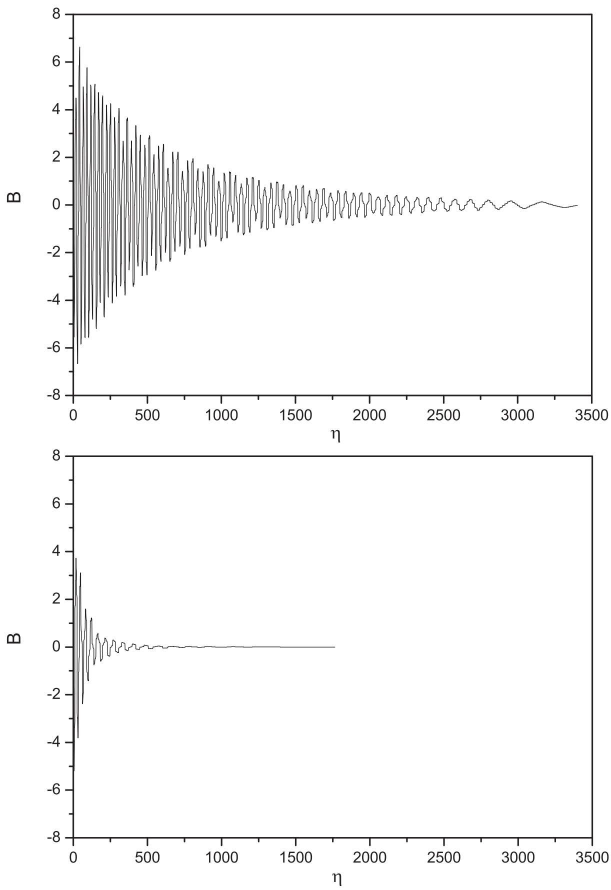

Figure 1. The evolution of the baryon charge $B(\eta)$ for $\lambda_1 = 5\times10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $H = 10^{10}$ GeV, $m = 350$ GeV, $\varphi_o = H_I\lambda^{-1/4}$ and $\dot\varphi_o = {H_I}^2$. The upper plot is for $\alpha = 10^{-3}$, the lower plot is for $\alpha = 10^{-2}$.

decreases when increasing λ_1 and B evolution becomes shorter. The final B value may differ by an order of magnitude.

However, the final values of B may differ up to 3 orders of magnitude even for small changes of λ_2 and λ_3.

5 Estimation of the Generated Baryon Asymmetry

To estimate the baryon asymmetry corresponding to the produced baryon excess in SFC model it is necessary to know the temperature of the relativistic plasma after the decay of φ and the decay of the inflaton. In case the inflaton energy density dominates until the reheating, $\rho_\psi > \rho_\varphi$, the entropy is mainly defined by the inflaton decay. The temperature after the decay of ψ at t_ψ is

$$T_R \sim (\rho_\psi)^{1/4} = (\rho_\psi^0)^{1/4}(\eta_0/\eta_\psi)^{3/2}. \tag{5}$$

The baryon asymmetry is:

$$\beta \sim N_B/T_R^3 \sim BT_R/H_I \tag{6}$$

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

Hence, the lower the reheating temperature after inflaton decay the smaller the produced baryon asymmetry. H_I, the decay time of ψ and the value of the reheating temperature may be different in different inflationary scenarios.

6 Conclusions

We have numerically explored the SFC baryogenesis model for numerous sets of model's parameters.

We studied the dependence of the evolution of the baryon charge contained in φ and its final value on the model's parameters: the gauge coupling constant α, the Hubble parameter at the inflationary stage H_I, the mass m and the self-coupling constants λ_i. The dependence of the final B on these parameters have been found. It was shown that the produced baryon excess is a strongly decreasing function of α and a decreasing function of H_I. For small m values B decreases with m increase for larger m, the dependence is more complicated.

Knowing the reheating temperature and having the results for B, it is easy to obtain the value of the observed baryon asymmetry for different sets of parameters in our model.

The analysis points that this model provides an opportunity to produce baryon asymmetry β, consistent with its observed value for natural values of the model's parameters.

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