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INHOMOGENEOUS BARYOGENESIS MODEL AND ANTIMATTER IN THE UNIVERSE

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Abstract. Cosmic ray and gamma-ray data at present do not rule out antimatter domains in the Universe, separated at distances bigger than 20 Mpc from us. Hence, it is interesting to explore the possible generation of vast antimatter structures during the early Universe evolution. We discuss an inhomogeneous baryogenesis model, based on a SUSY baryogenesis scenario. We have accounted for the particle creation processes that play an essential role for the correct determination of the final value of the baryon asymmetry, generated in these baryogenesis scenarios. We have explored the dependence of the produced baryon asymmetry on the parameters of the model. It is shown that for a natural range of the parameters' values this model is able to explain the value of the locally observed matter-antimatter asymmetry and also to predict antimatter domains, separated from the matter ones by baryonically empty voids.

1. INTRODUCTION: THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE

One of the amazing and still unresolved mysteries of our Universe is the strong predominance of matter over antimatter in our surroundings. The baryon asymmetry (BA) in our neighborhood (within radius of 20 Mpc) is indicated by cosmic and gamma rays observations. It is usually defined by β:

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \tag{1}$$

and locally is measured to be $\beta \sim \frac{n_B}{n_\gamma} = \eta$, i.e. considerable quantity of antimatter is not observed in our vicinity.

The baryon density η is measured in several different ways, namely: The consistency between theoretically obtained and observationally measured abundances of light elements produced in BBN at $z \sim 10^9$ (Nakamura (PDG) 2010) requires

$$5.1 \times 10^{-10} \leq \eta_{BBN} \leq 6.5 \times 10^{-10} \quad at \quad 95\% \quad CL; \tag{2}$$

Information for η from measurements of Deuterium towards low metallicity quasars combined with BBN data points to (Pettini 2008)

$$\eta_D = 6 \pm 0.3 \times 10^{-10} \quad at \quad 95\% \quad CL; \tag{3}$$

A precise determination of η, provided by measurements of the CMB anisotropy ($z \sim 1000$) by WMAP7 (Larson, et. al. 2011):

$$\eta_{WMAP} = 6.16 \pm 0.16 \times 10^{-10} \quad at \quad 68\% \quad CL. \tag{4}$$

Today we do not yet know the exact baryogenesis mechanism, i.e. different baryogenesis possibilities are studied. We discuss an inhomogeneous baryogenesis model, which has been shown in previous publications to predict a successful coexistence of matter and antimatter domains. Here we explore the possibility for a natural range of model's parameters to explain the value of the locally observed matter-antimatter asymmetry.

2. THE BARYOGENESIS MODEL

We study a scalar condensate baryogenesis model, based on the scalar baryogenesis scenario (SCB) (Dolgov, Kirilova 1991). The model has the following important ingredients:

* *Baryon charge violation at micro distances at the inflationary stage:* The baryon excess is generated at the inflationary stage and contained in a condensate of a complex scalar field φ (squark), which naturally appears in supersymmetric theories. The condensate $< \varphi > \neq 0$ is formed during the inflationary period as a result of the rise of quantum fluctuations of φ (Vilenkin, Ford 1982, Linde 1982, Bunch, Davies 1978, Starobinsky 1982). Thus, during inflation a condensate of a baryon charge (stored in $< \varphi >$) is developed with a baryon charge density $\sim H_I^3$, where H_I is the Hubble parameter at the inflationary stage.

While B is not conserved at large field amplitude due to the presence of the B nonconserving (BV) self-interaction terms in its potential, at low φ B-violation becomes negligible. At the B conserving stage during the decay of φ, $\varphi \to q\bar{q}l\gamma$, the baryon charge contained in the field is transferred to quarks and antiquarks. This charge, eventually diluted by some entropy generating processes, gives the observed locally BA.

* *Decrease of field's amplitude due to particle creation*: After inflation φ starts to oscillate around its equilibrium point with a decreasing amplitude due to the Universe expansion and to the particle production by the oscillating scalar field (Dolgov, Kirilova 1990).

* *Unharmonic potential of the field carrying the baryon charge*: The unharmonicity of the potential provides that different amplitudes corresponding to different space points result into different periods. Hence, the initially smooth space dependence transfers into quasiperiodic one (Dolgov, Kirilova 1991).

* *Inflationary expansion of the initially microscopic baryon distribution.* Due to inflationary growth of scales the initially microscopic domains of given baryon sign evolve into astronomically important regions of matter or antimatter.

3. THE EVOLUTION OF THE BARYON CHARGE AFTER INFLATION

In the expanding Universe φ satisfies the equation

$$\ddot{\varphi} - a^{-2}\partial_i^2\varphi + 3H\dot{\varphi} + \frac{1}{4}\Gamma\dot{\varphi} + U'_\varphi = 0, \tag{5}$$

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

In this concrete model the potential was chosen of the form:

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

The mass is assumed 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. We have studied the natural range of m: $10^2 \div 10^4$ GeV. The initial values for the field variables were taken to be $\varphi_o^{max} \sim H_I\lambda^{-1/4}$ and $\dot{\varphi}_o = (H_I)^2$.

We have assumed a predominance of the inflanton density: $\rho_\psi >> \rho_\varphi$, i.e. the Hubble parameter was $H = 2/(3t)$.

Fast oscillations of φ after inflation result in particle creation due to the coupling of the scalar field to fermions $g\varphi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. The term $\Gamma\dot{\varphi}$ in the equations of motion explicitly accounts for the damping of φ as a result of particle creation processes (Chizhov, Kirilova 1996). The amplitude of φ is damped as $\varphi \rightarrow \varphi\exp(-\Gamma t/4)$ and the baryon charge, contained in the φ, is exponentially reduced during BV stage, i.e. while φ is large.

It is known that if the production rate is a decreasing function of time the damping process may be slow enough for the baryon charge contained in φ to survive until the B-conservation epoch t_b (Dolgov, Kirilova 1991). Then the baryon charge of φ due to its decays is transferred to quarks and antiquarks and thus the observed excess of matter is produced.

4. RESULTS OF THE NUMERICAL ANALYSIS

For different sets of studied parameter values of the model λ_i, α, m and H_I, we have provided a numerical analysis of the scalar field φ evolution and the evolution of the baryon excess $B(t)$ for the period after the inflationary stage until the BC epoch when φ decays, in the energy range $10^{12} \div 100 \quad GeV$. We have used Runge-Kutta 4th order method with step 10^{-6} to solve the system of ordinary differential equations representing the equation of motion for the real and the imaginary part of $\varphi(t)$. The ranges of model's parameters studied are: $\lambda = 10^{-2} \div 5\times10^{-2}, \alpha = 10^{-3} \div 5\times10^{-2}, H = 10^7 \div 10^{12} \quad GeV, m = 100 \div 1000 \quad GeV$.

In our analysis the particle creation processes were accounted in two different ways - semi-analytically, using $\Gamma = \alpha\Omega$, where $\Omega \sim \lambda^{1/2}\varphi$ and $\alpha = g^2/4\pi$ and numerically, calculating Ω at each step as $\Omega = 2\pi/T$, where T is the period of the field oscillations. As it was found in previous publications (Dolgov, Kirilova 1991, Kirilova, Panayotova 2006), the account of particle creation processes strongly reduces the baryon charge contained in the condensate. The precise numerical account of the particle creation in this analysis points to stronger and earlier reduction of the generated baryon excess (see Fig. 1) in comparisson with the case of analytical account. We have found that the values of the final B, obtained with numerical and semi-analytical account of particle creation, may differ by up to two orders of magnitude.

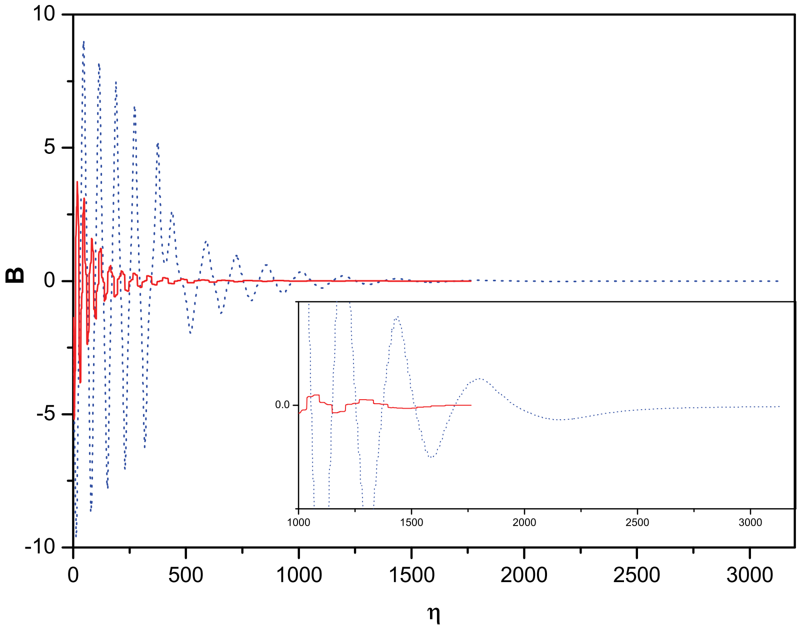

Figure 1: The evolution of the baryon charge $B(\eta)$ for $\lambda_1 = 5\times10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $\alpha = 10^{-2}$, $H = 10^{10}GeV$, $m = 350GeV$, $\varphi_o = H_I\lambda^{-1/4}$ and $\dot{\varphi}_o = {H_I}^2$. The case of particle creation processes accounted for analytically is presented by the dotted curve and the case of numerical account for the particle creation is given by the solid curve.

We have studied the dependence of the generated baryon excess on different parameters of the model. Due to the oscillatory character of B, the generated BA is very sensitive both to small shifts of the model's parameters and to numerical methods used. This observation is in accordance with the results of other surveys of similar models (Kirilova, Valchanov 2005). Nevertheless, it is possible to determine the main trend of the behavior of the final BA on the parameters values.

The next figure (Fig. 2) presents the dependence of the baryon charge, at the BC conserving epoch, on the mass of the condensate. The numerical study confirms the expected dependence, namely, the produced baryon charge decreases with m increase. This can be easily understood having in mind that the longer φ decays till BC epoch the smaller the charge, that remains stored in it. The time of its decay is proportional to $\sim m^{-1}$.

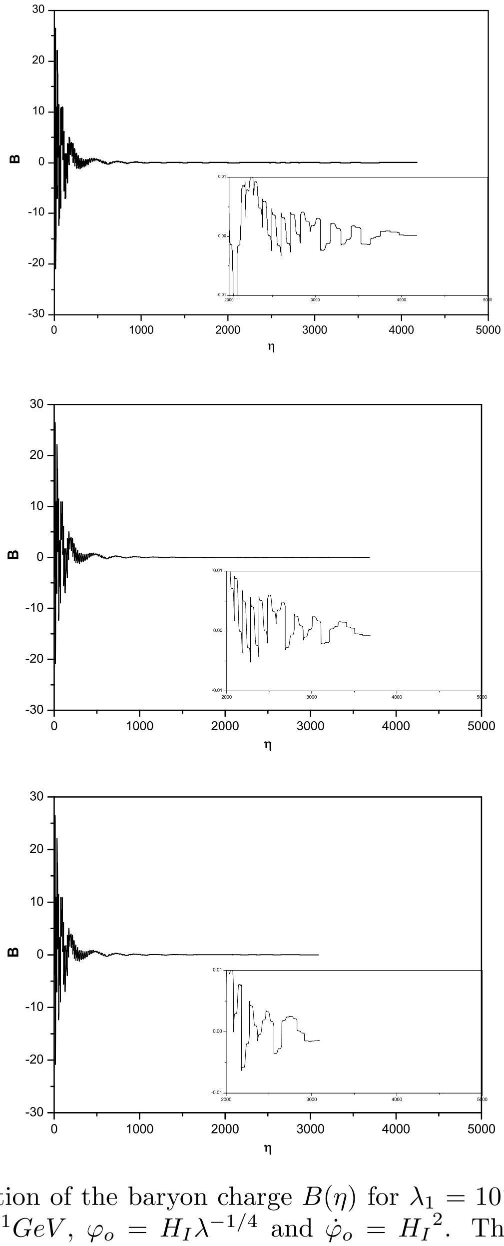

Figure 2: The evolution of the baryon charge $B(\eta)$ for $\lambda_1 = 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $\alpha = 10^{-2}$, $H = 10^{11} GeV$, $\varphi_o = H_I \lambda^{-1/4}$ and $\dot{\varphi}_o = {H_I}^2$. The upper curve is for $m = 350 GeV$, the middle is for $m = 500 GeV$ and the lower - for $m = 800 GeV$. The particle creation processes are accounted for numerically.

The last figure (Fig. 3) presents the dependence of the generated baryon charge on the value of H_I. The numerical study shows that the produced baryon charge decreases when increasing H_I. Qualitatively, this dependence is an expected result because the initial value of φ is proportional to H_I and on the other hand particle creation is proportional to φ, $\Gamma \sim \Omega \sim \varphi$.

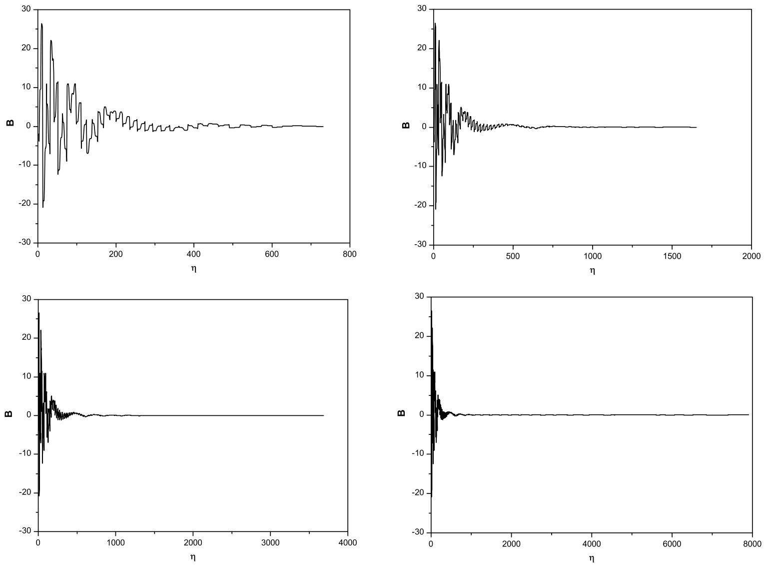

Figure 3: The evolution of the baryon charge $B(\eta)$ for $\lambda_1 = 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $\alpha = 10^{-2}$, $m = 500GeV$, $\varphi_o = H_I \lambda^{-1/4}$ and $\dot{\varphi}_o = {H_I}^2$. The upper left curve corresponds to $H = 10^9 GeV$, the upper right curve to $H = 10^{10} GeV$, the lower left curve to $H = 10^{11} GeV$ and the lower right curve to $H = 10^{12} GeV$. The particle creation processes are accounted for numerically.

This baryogenesis model is interesting also because it naturally predicts safely separated domains of matter and antimatter, discussed shortly in the next section.

5. THE PREDICTED ANTIMATTER DOMAINS

The preliminary results of our analysis of the evolution of the spacial distribution of the field shows that the initial natural monotonic distribution of the field due to the unharmonicity of its potential transfers into quasiperiodic distribution. Thus, an initially baryon excess region results into regions with baryon excess and such of baryon underdensities. This result is in accordance with similar previous surveys (Kirilova, Chizhov 1996, 2000). For a natural range of the model's parameters this model is able to predict astronomically interesting vast antimatter domains, separated from the matter ones by baryonically empty voids, as discussed in (Kirilova, Panayotova, Valchanov 2002, Kirilova 2003).

6. CONCLUSIONS

Within a scalar condensate baryogenesis model we have investigated the dependence of the baryon charge evolution and its final value on the model's parameters. Provided that correct account for particle creation processes is made, this model is able to provide the generation of the observed baryon asymmetry for a natural initial conditions. Besides, the model is capable to provide a natural separation between matter and antimatter regions, eventually present in the Universe.

The results of this analysis may be useful for construction of realistic baryogenesis models. Moreover, from the observed value of the baryon asymmetry it is possible to put cosmological constraints on the SUSY parameters within a concrete inflationary scenario, or/ and point to the preferable inflationary model.

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References

Affleck, I., Dine, M.: 1985, *Nucl. Phys.*, **B249**, 361.
Bunch, T., Davies, P.: 1978, *Proc. Roy. Soc.*, **A360**, 117.
Dolgov , A., Kirilova , D.: 1991, *J. Moscow Phys. Soc.*, **1**, 217.
Dolgov , A., Kirilova , D.: 1990, *Sov.J.Nucl.Phys.*, **51**, 172.
Kirilova, D., Chizhov, M.: 1996, *AATr*, **10**, 69.
Kirilova, D., Chizhov, M.: 2000, *MNRAS*, **314**, 256.
Kirilova, D., Panayotova, M., Valchanov, T.: 2002, *Proc. XIVth Rencontres de Blois "Matter-Antimatter Asymmetry"*, 439.
Kirilova, D.: 2003, *Nucl. Phys. Proc. Suppl.*, **v.122**, 404.
Kirilova, D., Panayotova, M.: 2007, *Bulg. J. Phys.*, **34**, 330.
Larson, D.: 2011, *ApJS*, **192**, 16.
Kirilova, D., Valchanov, T.: 2005, *Publications of the Astronomical Society "Rudjer Boskovic"*, **5**, 209.
Linde, A.: 1982, *Phys. Lett.* , **B116**, 335.
Nakamura, K., et. al. (Particle Data Group): 2010, *J. Phys.*, **G37**, 075021 and 2011 partial update for the 2012 edition.
Pettini , M., et al.: 2008, *MNRAS*, **391** , 1499.
Starobinsky, A.: 1982, *Phys. Lett.*, **B117**, 175.
Vilenkin, A., Ford, L.: 1982, *Phys. Rev.*, **D26**, 1231.