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# BARYOGENESIS MODEL SUGGESTING ANTIGALAXIES

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## Abstract

A non-GUT baryogenesis model, according to which our Universe may contain clusters of antigalaxies is discussed. A mechanism of separation of vast quantities of matter from such of antimatter is described. The provided analysis showed that for a natural range of model parameters a sufficient separation between matter and antimatter regions, required from observational data, can be obtained.

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# 1 Introduction

*Is our Universe globally baryonic or the observed in our vicinity baryon asymmetry is just a local characteristic?* In case we assume a global character of the baryon asymmetry, one must find out a mechanism for generating the total asymmetry between matter and antimatter, predicting the correct sign and value of the asymmetry observed. The value of the baryon asymmetry observed is usually given by the ratio of the difference between the densities of baryons $N_B$ and the antibaryons $N_{\bar{B}}$ to the photon density $N_\gamma$: $\beta = (N_B - N_{\bar{B}})/N_\gamma \sim few \times 10^{-10}$. In case the asymmetry is of local character, one must find a mechanism of separating vast quantities of matter from such ones of antimatter. A recent review of the problem of matter-antimatter symmetric Universe can be found in (Dolgov 1993, Dolgov 1996) and (De Rujula 1996, Cohen et al. 1997), where symmetric cosmological models and observational data concerning antimatter in the Universe are reviewed.

*The observational data*, available till now, namely from searches for antiprotons, antinuclei in cosmic rays, as well as positrons and energetic gamma quanta, points to a strong predominance of matter over antimatter in our vicinity (Steigman 1976, Stecker 1985).

We have direct evidence that the planets of the Solar System are matter ones. The cosmic rays from the Sun show that our nearest star is a matter one, otherwise solar wind would produce gamma rays when entering the atmosphere. Experimental searches for antiprotons in galactic cosmic rays entering the Earth atmosphere give an upper bound of $2 \times 10^{-5}$ for the antiproton/proton ratio (Salamon 1990, Mitchell 1996). These results are consistent with cosmic ray antiprotons being dominated by secondaries due to primary cosmic ray radiation interactions with the interstellar medium. The same holds for the positron flux observed (Barbiellini 1996). Cosmic ray and gamma ray data exclude the possibility of noticeable amounts of antimatter in our Galaxy. The most stringent constraints on the possible antimatter is obtained from the absence of gamma excess from hydrogen in or between clouds in our Galaxy - the antimatter-matter ratio obtained for the hydrogen media is less than $10^{-15}$.

*The data beyond our Galaxy* is not so definite. We may think that the galaxies in a cluster must be all made either of matter or of antimatter. Otherwise, we should have observed a strong annihilation radiation from the borders of the matter and antimatter regions. The lack of gamma ray excess points to a uniform matter (or antimatter) composition of clusters at a level $10^{-6}$. I.e. there exist observational constraints on the antimatter fraction of the nearest galaxy clusters pointing that the antimatter regions, if present, should be separated from the matter ones at distances greater than or equal to the characteristic scale for galaxy clusters. These observational data are usually interpreted as an evidence for the global baryon asymmetry of the Universe. However, as we have pointed already, there is not even a definite evidence for the fact that the nearest galaxy clusters are matter ones. The observations put only a lower limit on the distance to the antimatter-rich region. They neither reject nor confirm the existence of antimatter regions in the Universe enough separated from us. So, now there exists the other possibility, namely that in the Universe regions of antimatter exist, safely separated from these of matter, so that annihilation is not observed. The scale of the necessary separation estimated on the basis of the gamma rays data, interpreted as a result from annihilation, is of the order of the galaxy cluster scales - $10^{12}M_o$ - $10^{14}M_o$, where $M_o$ is the solar mass (Steigman 1976). The flux of cosmic antiprotons also points to a distance larger than 10 Mpc. An interesting indication for matter-antimatter Universe may be the observed cosmic gamma-ray background, which nature could be understood assuming it to be the result of proton-antiproton annihillation (Stecker, 1989). Therefore, we think that models of baryon- antibaryon symmetric Universe should be considered seriously.

Assuming the possibility for great quantities of antimatter in the Universe, we discuss here a mechanism of matter-antimatter separation. It arises naturally in the *low temperature baryogenesis scenario with baryon charge condensate* (Dolgov & Kirilova 1991; Kirilova & Chizhov 1996, 1995). The model has some very attractive features, namely:

* It is compatible with the inflationary models: it does not suffer from the problem of insufficient reheating after inflation as far as baryogenesis proceeds at low energies.

* It evades the problem of the washing out of the previously produced baryon asymmetry at the electroweak phase transition, because the baryon excess is generated afterwards.

* It accounts for particle creation processes, reducing the baryon charge (Dolgov & Kirilova 1990).

An analysis of the evolution of the baryon charge space distribution (Chizhov & Kirilova 1995; Kirilova & Chizhov 1996), provided in the framework of that baryogenesis model, showed that

* It may solve elegantly the problem of large scale periodicity of the visible matter, detected in the deep pencil beam survey of Broadhurst et al. (1990), and confirmed in further studies of supercluster structures (Bahcall 1991, Guzzo 1992, Tully 1992), and by the analysis of three-dimensional distribution of high density regions defined by very rich Abell and APM clusters of galaxies ( Landy et al. 1996, Einasto et al. 1994, 1997, Retzlaff et al. 1997, Tadros et al. 1997) For a recent review of the problem of the regularity of the Universe in large scales see Einasto (1997).

The baryon excess according to that model is generated at the inflationary stage, as a result of quantum fluctuations and it is contained in a condensate of a complex scalar field $\phi$, which is present in the early Universe together with the inflaton, and in some cases may coincide with it. At high energies the baryon charge is not conserved. Later on, at low energies the nonconservation becomes negligible. At the baryon charge conserving stage the baryon charge contained in the field is transferred to that of the quarks during the decay of the field $\phi$. So as a result of the decays $\phi \to q\bar{q}l\gamma$ an antisymmetric plasma appears. In the model there is no explicit breaking of the $CP$-symmetry. $CP$ is broken only stochastically at the inflationary stage. I.e. as a result of the quantum fluctuations of the field a baryon charge is generated at micro distances. The baryon charge in different domains may have different values. As a whole, on macro distances there may be no global violation of the baryon charge, i.e. at macro scales the baryon density fluctuations are unobservable. Then due to the exponential expansion during the inflationary epoch these microscopic regions grow to astronomically considerable size.

Here we want to discuss other attractive features of that model, namely:

* It can provide a natural separation mechanism of great quantities of matter from such ones of antimatter. The characteristic scale of separation between matter and antimatter regions, predicted by the model is in accordance with the observational constraints.

* It naturally appears in the standard cosmology model and does not suffer from the basic problems of symmetric cosmology models, i.e. the causality problem, the annihilation catastrophe problem, the domain wall problem and the microwave background distorsion problem. (For a discussion on these problems see (Steigman 1976; Kolb & Turner 1983).)

So, it allows the possibility that the baryon asymmetry observed may be of local type, while globally the Universe may be symmetric.

## 2 Generation of matter and antimatter regions sufficiently separated

### 2.1 The mechanism of separation

The necessary conditions for the generation of sufficiently separated vast regions of matter and antimatter for the discussed baryogenesis model are the following:
*Baryon charge violation at micro distances at the inflationary stage:* The concrete realization of the B-violation we used in our model was the rise of quantum fluctuations during the inflationary stage, due to which a condensate of the baryon charge carrying scalar field was formed.

*Initial space distribution of the baryon density at the inflationary stage*: We made the natural assumption that a monotonically changing distribution of the baryon density within a domain with a certain sign of the B-violation existed initially.(In fact, the initial type of space distribution is not essential, the important point is that there should be some space distribution.)

*Unharmonic potential of the field carrying the baryon charge:* The unharmonicity of the potential is essential. Without this characteristic the field would have preserved the type of its initial distribution during its evolution in the postinflationary stage. However, due to the nonharmonicity, different amplitudes corresponding to different space points will result into different periods , as far as the period depends on the amplitude in the unharmonic case (Chizhov & Dolgov 1990, Dolgov 1993). Therefore, the initial smooth dependence soon transfers into a quasiperiodic one and the region which initially was characterized with its baryon excess splits into regions with baryon excess and such of baryon underdensities. There may be two interesting cases:

A) First, when the variations appear around the zero baryon charge, which corresponds to the case of a *stochastic CP-violation.* In that case the underdense regions are in fact antibaryonic ones. The initially baryonic domain is broken to baryonic and antibaryonic shells and divided by nearly baryonically empty regions. This case is very attractive as far as it allows the realization of symmetric Universe without domain walls. However, in that case the resulting fluctuations of the baryon density may be considerable and may lead to unacceptably large angular variations of the microwave background radiation. One possible way of solving that problem was proposed in the island Universe model (Dolgov & Kardashev 1986, Dolgov et al. 1987). There is another more natural for our baryogenesis model decision. In case the baryon fluctuations are small compared to the smoothly distributed density of the inflaton field, the ratio of the baryon density fluctuations to the total energy density may be safely small.

B) The other case is that of an *explicit CP-violation*, when the field's equilibrium value is non zero, and the fluctuations of the field around it result into fluctuations of the baryon density around some nonzero number. Then the domain with a given sign of the CP-violation may consist totally either of baryonic regions or of antibaryonic ones. Again we may think of a universe consisting of matter and antimatter regions but the boundary separating the matter regions from the antimatter ones should be at a great enough distance from our Galaxy so that it will not contradict the existing constraints for domain walls in the Universe.

*The inflationary expansion of the initially microscopic baryon distribution:* In our model the regions with different baryon density (overdensity, underdensity or density of antibaryons) become macroscopically large due to inflation. In this way the causality problem [2] is naturally solved. In the presence of inflation, the regions of the order of the clusters of galaxies, though not causally connected at $40MeV$ were well within the horizon during the inflationary period. So, a physical mechanism at that early period (like the discussed one) is allowed to be the cause for their separation.

## 2.2 The baryogenesis model. Main characteristics.

Here we describe the main characteristics of the model, which are essential for our analysis.

*Generation of the baryon condensate:* The essential ingredient of the model is a complex scalar field $\phi$, which according to our model of low temperature baryogenesis, based on the Affleck and Dine scenario, is a scalar superpartner of quarks (Affleck & Dine 1985). The condensate $< \phi >\neq 0$ is formed during the inflationary period if $B$ and $L$ were not conserved, as a result of the enhancement of quantum fluctuations of the $\phi$ field: $< \phi^2 >= H^3 t/4\pi^2$. 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

[2] Namely that baryon regions corresponding to the mass scales of galaxy clusters should be separated from those of antibaryons at very early epoch $T < 40MeV$, when the baryon density was big enough $N_b/N_\gamma > 10^{-10}$, but on the other side then they appear to be beyond the horizon so that it is not possible for physical processes to separate them because they are not causally connected.

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.

*Generation of the baryon asymmetry:* After inflation $\phi$ 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 (Dolgov & Kirilova 1990, 1991). Fast oscillations of $\phi$ after inflation result in particle creation due to the coupling of the scalar field to fermions $g\phi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. In the expanding Universe $\phi$ satisfies the equation

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

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

The potential $U(\phi)$ is of the form

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

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 $\lambda_i$ are of the order of the gauge coupling constant $\alpha$. A natural value of $m$ is $10^2 \div 10^4$ Gev. In case when at the end of inflation the Universe is dominated by a coherent oscillations of the inflaton field $\psi = m_{PL}(3\pi)^{-1/2}\sin(m_\psi t)$, the Hubble parameter was $H = 2/(3t)$. The initial values for the field variables can be derived from the natural assumption that the energy density of $\phi$ at the inflationary stage is of the order $H_I^4$, then $\phi_o^{max} \sim H_I\lambda^{-1/4}$ and $\dot{\phi}_o = 0$.

The term $\Gamma\dot{\phi}$ in the equations of motion explicitly accounts for the eventual damping of $\phi$ as a result of particle creation processes (Chizhov & Kirilova 1995). We have used for our calculations the production rate $\Gamma$ as obtained in (Dolgov & Kirilova 1990). The analysis of the problem by the explicit account of the particle creation, provided in (Chizhov & Kirilova 1995, Kirilova & Chizhov 1996) showed that, the bigger the initial amplitudes of the field were, the greater the damping effect due to the particle creation would be. The amplitude of $\phi$ is damped as $\phi \to \phi\exp(-\Gamma t/4)$ and the baryon charge, contained in the $\phi$ condensate, is exponentially reduced due to particle production. So, the role of particle creation processes is important for baryogenesis models (Dolgov & Kirilova 1991), large scale structure periodicity (Chizhov & Kirilova 1995, Kirilova & Chizhov 1996) formation and the investigation of symmetric Universe models. Fortunately, the damping process may be slow enough for a considerable range of values of $m$, $H$, $\alpha$, and $\lambda$, so that the baryon charge contained in $\phi$ may survive until the advent of the $B$-conservation epoch $t_b$. Then $\phi$ decays to quarks with non-zero average baryon charge. This charge, diluted further by some entropy generating processes, dictates the observed baryon asymmetry.

### 2.3 Evolution of the baryon density distribution - numerical modelling

We have made the natural asumption that initally $\phi$ is a slowly varying function of the space coordinates $\phi(r,t)$. For each set of parameter values of the model $\lambda_i$, $\alpha$, $m/H_i$ $\phi(r,t_o)$ we have numerically calculated the baryon charge evolution $B(t)$ for different initial values of the field $\phi_o$, corresponding to the accepted inital distribution of the field. The space distribution of the baryon charge was found for the moment of baryogenesis $t_B$. It was obtained from the evolution analysis $B(t)$ for different initial values of the field, corresponding to its initial space distribution $\phi(t_i, r)$. As it was expected, in the case of nonharmonic field's potential, the initially monotonic space behavior is quickly replaced by space oscillations of $\phi$, because of the dependence of the period on the amplitude, which on its turn is a function of $r$. As a result in different points different periods are observed and the space behavior of $\phi$ becomes quasiperiodic (Chizhov & Dolgov 1992; Chizhov & Kirilova 1994, 1995). Correspondingly, the space distribution of the baryon charge contained in $\phi$ becomes quasiperiodic as well. Therefore, the space distribution of baryons at the moment of baryogenesis is found to be quasiperiodic. Accordingly, the observed space distribution of the visible matter today is defined by the space distribution of the baryon charge of the field $\phi$ at the moment of baryogenesis $t_B$, $B(t_B, r)$. So that, at present, the visible part of the Universe consists of baryonic and antibaryonic regions.

*The characteristic scale between matter and antimatter regions* according to this concrete baryogenesis model is a function of the following parameters: the coupling constants of the potential $\lambda_i$, the initial amplitudes of the field $\phi(r, t_i)$, the period of baryogenesis $t_B$ and the characteristic scale of the baryon space variation at the inflationary stage $r_o$. Our numerical analysis showed that it is within the natural values of model's parameters to predict safely separated regions of antimatter and matter in the Universe, i.e. the separation scale may be greater than the galaxy cluster mean distances.

The discussed mechanism for the generation of baryon antibaryon regions separated at great distances in the observed today Universe could be realized in a great variety of models, depending on the type of baryogenesis scenario (namely, it can be realized both in low and high temperature baryogenesis ones, see for example (Chizhov & Dolgov 1992, Dolgov 1993)), depending on the concrete form of the field potential and the coupling constant values, depending on the type of the CP-violation, on the initial space distribution of the baryon density at the inflationary stage, etc.

From the provided analysis of this concrete realization of a baryogenesis model we can conclude that there exists the interesting possibility that in the framework of a low temperature non-GUT baryogenesis one can find simultaneously the explanation of several cosmological puzzles, namely the explanation of the observed local baryon asymmetry, the observed periodicity of the visible matter in the very large scale texture of the Universe, as well as the natural realization of a globally symmetric Universe, containing matter and antimatter regions separated from each other at distances greater or of the order of the galaxy cluster ones.

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