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BARYOGENESIS MODEL SUGGESTING ANTIGALAXIES

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

KEY WORDS **Cosmology, baryogenesis, antimatter galaxies: separation mechanism**

1 INTRODUCTION

Is our Universe the global baryon asymmetry or the one observed in our vicinity is just a local characteristic? In case we assume a global character of the baryon asymmetry, one must think out a mechanism for generating the total asymmetry between matter and antimatter, predicting a correct sign and value of the asymmetry observed. Otherwise, if we accept a local character of the asymmetry, the problem of baryon asymmetry reduces to finding a mechanism of separating vast quantities of matter from those of antimatter.

The observational data available till now point to a strong predominance of matter over antimatter in our vicinity. We have a direct evidence that the planets of the Solar System consist of matter. The cosmis rays from the Sun show that our nearest star consists of matter too. In the Galactic cosmic rays the ratio of antiprotons to protons is negligible – 10^{-4}. Cosmic ray and gamma ray data exclude the possibility of noticeable amounts of antimatter in our Galaxy. *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_γ : $\beta = (N_B - N_{\bar{B}})/N_\gamma = 10^{-9}$–$10^{-10}$.

The data on larger scales is not so definite. We may just 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, which is not detected. So there exist observational constraints on the antimatter fraction of the nearest galaxy clusters indicating that the antimatter regions, if present, should be separated from the matter ones at distances greater or equal to the characteristic scale for galaxy clusters. These observational data are frequently interpreted as an evidence for the global baryon asymmetry of the Universe. However, as we have already pointed out, there is not even a definite evidence for the fact that the observable part of our Universe is made of matter. There exists another possibility – 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 of annihilation, is of the order of the galaxy cluster scales – $10^{12}M_0$–$10^{14}M_0$, where M_0 is the solar mass (Steigman, 1976). Besides, there is some direct evidence for the presence of primary antimatter. The positron-to-electron-plus-positron ratio $e^+/(e^+ + e^-)$ observed does not fall with the decrease of energy as theoretically expected, it is stabilized at around 5 GeV. Both the expected total flux of antiprotons and its spectrum differs from the predicted one for secondary particles. Primary antiprotons have a power-law spectrum similar to the observed one. So the antiprotons observed may well be cosmic rays from distant galaxies.

Asuming that point of view, we discuss here a mechanism of matter-antimatter separation. It arises naturally in the *low temperature baryogenesis scenario with baryon charge condensate* (Dolgov and Kirilova, 1991; Kirilova and Chizhov, 1995, 1996). The model has some very attractive features, namely:

(1) 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.

(2) It evades the problem of the washing out of the previously produced baryon asymmetry in the electroweak phase transition, because the baryon excess is generated afterwards.

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

Recently, an analysis of the evolution of the baryon charge space distribution (Chizhov and Kirilova, 1995; Kirilova and Chizhov, 1996) provided in the framework of that baryogenesis model showed that:

- It proposes an elegant decision of the problem of large scale periodicity of the visible matter, detected in the deep pencil beam survey of Broadhurst *et al.* (1990).

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 ϕ, 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 transfered to that of the quarks during the decay of the field ϕ. So, as a result of the decays $\phi \longrightarrow q\bar{q}l\gamma$, 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. Thus, as a result of the quantum fluctuations of the field, a baryon charge is generated at microdistances. The baryon charge in different domains may have different values. As a whole at macrodistances there may be no global violation of the baryon charge, i.e. at macroscales the baryon density fluctuations are unobservable. Due to the exponential expansion during the inflationary epoch these microscopic regions become of astronomically considerable size.

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

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

(2) 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 walls problem and the microwave background distorsion problem. (For a discussion on these problems see Steigman, 1976; Kolb and Turner, 1983.)

So, it proposes the possibility that the baryon asymmetry observed may be of local type, while globally the Universe may be symmetric. Therefore, we think that models of baryon-antibaryon symmetric Universe should be considered seriously.

2 GENERATION OF MATTER AND ANTIMATTER REGIONS IS 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 microdistances at the inflationary stage: The concrete realization of the B-violation we used in the numerical calculations was the rise of quantum fluctuations during the inflationary stage, due to which a condensate of the baryon carrying scalar field was formed.

Initial space distribution of the baryon density at the inflationary stage: We made the natural assumption that a monotonic 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, an important point is that there should be some space distribution.)

Nonharmonic potential of the field carrying the baryon charge: The nonharmonicity 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 in different periods, as far as the period depends on the amplitude in the nonharmonic case. Therefore, the initial smooth dependence will soon transfer into quasiperiodic one and the region which initially was characterized with its baryon excess will split into regions with baryon excess and those of baryon underdensities. There may be two interesting cases. Namely, when the variations appear around the zero baryon charge, which corresponds to the case of *stochastic CP-violation*. In that case the underdense regions are in fact antibaryonic ones. The initially baryonic domain is broken into baryonic and antibaryonic shells and divided by nearly baryonically empty regions. This case is very attractive as far as it allows the realization of a symmetric Universe without domain walls. However, in that case the resulting fluctuations of the baryon density may be considerable and may lead to unacceptable large angular variations of the microwave background radiation. One possible decision of that problem was proposed in the island Universe model (Dolgov and Kardashev, 1986; Dolgov *et al.*, 1987). There is another decision more natural for our baryogenesis model. 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. The other case is that of an *explicit CP-violation*, when the field's equilibrium value is nonzero, and the fluctuations of the field around it result in 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 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 sufficient distance from our Galaxy so that the annihilation radiation or the domain wall should be unobservable.

The inflationary expansion of the initially microscopic baryon distribution: Due to inflation the regions with different baryon density (overdensity, underdensity or density of antibaryons) become macroscopically large. So, there is a natural decision of the causality problem. Namely, the baryon regions corresponding to the mass scales of galaxy clusters should be separated from those of antibaryons at very early epoch $T < 40$ MeV, when the baryon density was high enough $N_b/N_\gamma > 10^{-10}$, but then they appear to be beyond the horizon so that it is impossible for physical processes to separate them because of causalesity problem.

In the presence of inflation, the regions of the order of the clusters of galaxies, though not causally connected at 40 MeV, were well within the horizon during the inflationary period. So, it is allowed for a physical mechanism at that early period (like the discussed one) to be the cause of their separation. For example, at the inflationary period even the nowadays supercluster scale was within the horizon.

2.2 The Baryogenesis Model. Main Characteristics

Here we describe the main characteristics of the model essential for our discussion.

Generation of the baryon condensate: The essential ingredient of the model is a complex scalar field ϕ, which according to our model of low temperature baryogenesis, based on the Affleck and Dine scenario, is a scalar superpartner of quarks (Affleck and Dine, 1985). The condensate $\langle\phi\rangle \neq 0$ is formed during the inflationary period if B and L were not conserved, as a result of the enhancement of quantum fluctuations of the ϕ field: $\langle\phi^2\rangle = H^3t/4\pi^2$. The baryon charge of the field is not conserved at large values of the field amplitude due to the presence of the B non-conserving self-interaction terms in the field's potential. As a result, the quantum 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 ϕ starts to oscillate around its equilibrium point with a decreasing amplitude. This decrease is due to the Universe expansion and the particle production by the oscillating scalar field (Dolgov and Kirilova, 1990, 1991). Fast oscillations of ϕ after inflation result in particle creation due to the coupling of the scalar field to fermions $g\phi\bar{f}_1f_2$, where $g^2/4\pi = \alpha_{SUSY}$. In the expanding Universe ϕ satisfies the equation

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

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

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

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

The mass parameters of the potential are assumed small in comparison to 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 $10^2 \div 10^4$ GeV. In case 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 ϕ at the inflationary stage is of the order 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 (Chizhov and Kirilova, 1995). The production rate Γ was calculated in (Dolgov and Kirilova, 1990). The analysis of the problem by the explicit account of the particle creation, provided in Chizhov and Kirilova, 1995, 1996 showed that, the higher the initial amplitudes of the field were, the greater the damping effect due to the particle creation would be. The amplitude of ϕ is damped as $\phi \to \phi\exp(-\Gamma t/4)$ and the baryon charge, contained in the ϕ condensate, is exponentially reduced due to particle production. So, the role of particle creation processes is important for baryogenesis models (Dolgov and Kirilova, 1991), large scale structure periodicity (Chizhov and Kirilova, 1995, 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, α, and λ, so that the baryon charge contained in ϕ may survive until the advent of the B-conservation epoch t_b. Then ϕ decays into 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 ϕ is a slowly varying function of the space coordinates $\phi(r,t)$. For each set of parameter values of the model λ_i, α, m/H_i, $\phi(r,t_0)$ we have numerically calculated the baryon charge evolution $B(t)$ for different initial values of the field ϕ_0, corresponding to the accepted initial distribution of the field. The space distribution of the baryon charge was found for the moment 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 was expected, in case of a nonharmonic field potential, the initially monotonic space behaviour is quickly replaced by space oscillations of ϕ, because of the dependence of the period on the amplitude, which in turn is a function of r. As a result, at different points different periods are observed, and the space behaviour of ϕ becomes quasiperiodic (Chizhov and Dolgov, 1992; Chizhov and Kirilova, 1994, 1995). Correspondingly, the space distribution of the baryon charge contained in ϕ 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 ϕ at the moment of baryogenesis t_B, $B(t_B,r)$. So, 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 λ_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_0. The provided analysis showed that it is for the natural values of model's parameters to predict safely separated regions of antimatter and matter in the Universe, i.e. for a natural choice of the values of these parameters, the separation scale may be greater than the galaxy cluster mean distances, required by the observational data on gamma rays.

The discussed mechanism for generation of baryon antibaryon regions separated at great distances in the Universe observed today 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 e.g. Chizhov and Dolgov, 1990; Dolgov, 1992), 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 an 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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