Vast antimatter regions and SUSY-condensate baryogenesis

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Abstract

The possibility of natural and abundant creation of antimatter in the Universe in a SUSY-baryogenesis model with a scalar field condensate is described. In this scenario the vast quantities of antimatter, corresponding to galaxy, cluster and supercluster scales today, can be naturally separated. Theoretical and observational constraints on such antimatter regions are discussed.

Why discuss antimatter in the Universe

Is our Universe globally baryonic or the observed in our vicinity baryon asymmetry is just a local characteristic? We do not know the answer, yet.

In case we asume a *global* character of the baryon asymmetry, one must think out a mechanism for generating the asymmetry between matter and antimatter, predicting the correct sign and value of the asymmetry observed.

The unaesthetic assumption that the asymmetry is simply an initial condition while baryon number is conserved, shortens by an order of magnitude the inflationary stage, making impossible the successful evolution of the Universe to its present state (Dolgov, 1988). So, baryon violating (BV) processes must have proceeded during inflation or after it, inorder to generate the observed baryon asymmetry today. The observed value of the asymmetry is: $\beta = (N_B - N_{\bar{B}})/N_\gamma \sim 10^{-9} - 10^{-10}$ where N_B and $N_{\bar{B}}$ are the baryon and antibarion number densities and N_γ is the photon density. This observational data are the only known "experimental" indication for BV.

Accepting the *local* character of the asymmetry, the problem of baryon asymmetry reduces to finding a natural baryogenesis mechanism able to produce baryons and antibaryons at different space regions. There exist different baryogenesis models, which predict matter and antimatter regions (Dolgov A., Phys.Rep. 222, 309, 1992). Some of them are in accordance with the numerous observational constraints. Theory can suggest the presence of antimatter domains in the Universe.

The observational data, available till now, points to a strong predominance of matter over antimatter in our vicinity. Cosmic ray and gamma ray data exclude the possibility of noticeable amounts of antimatter in our Galaxy: Experimental search for antinuclei and antiprotons in cosmic rays were conducted on high-altitude balloons and on spacecraft. Antiprotons detected in primary cosmic radiation over energies $0.1-19$ GeV were found with negligible numbers, their ratio to protons consists few 10^{-5} for energies lower than 2 GeV and a few 10^{-4} for higher energies. They can be totally due to interactions of the primary CR particles with the interstellar medium.

No antinuclei were observed. The upper limit on the ratio of antihelium-to helium flux from BESS flights is $1.7.10^{-6}$ (Saeki et al.,PLB, 422,319, 1998). The upper limit from Alpha Magnetic Spectrometer is $1.1.10^{-6}$ (95% C.L.) in the rigidity range $1-140$ GeV (assumed that the $\bar{H}e$ spectrum is with the same shape as the He one) (Steuer M., Nuovo Cimento, 24, 661, 2001).

Thus, cosmic ray results indicate that there is no antimatter objects within a radius 1 Mpc.

The data are not so definite for larger scales: Although the measured flux of antiprotons and its spectrum is in agreement with the predicted ones for secondary particles, the data do not exclude a primary component (BESS97,98, 99, 00, CAPRICE98, MASS, etc.). The antiproton flux and spectrum measured in the energy region 3-49 GeV by CAPRICE98 experiment gave strong indications for that: Two antiproton events with the highest energy antiproton were measured at a kinetic energy 43 GeV, between 29 and 49 GeV, compared with an expected number from secondaries only 0.2 to 0.4 events (Boezio M. et al., astro-ph/0103513, 2002). And these data are free of uncertainties due to solar modulation effects, besides in this energy range all calculations of secondary $\bar{p}$ are consistent with each other.

An interesting study of the antiproton spectrum through years with solar minimum (1995, 1997) and maximum (1998) , showed that for the low energy region of the spectrum the agreement during solar minimum is less consistent than for the maximum solar activity. As far as antiprotons from primary sources are suppressed as solar activity increases, while secondary $\bar{p}$ spectrum is affected modestly. The results were interpreted in favour of a primary $\bar{p}$ (Maeno T. et al., astro-ph/0010381, 2000). Slightly excessive $\bar{p}$ fluxes, relative to the theoretical calculations were found during solar minimum also in the analyses of Orito et al. (PRL 84,1078,2000) and Matsunaga H. et al. (PRL 81,4052 ,1998) for the very low energies below 0.5 GeV. So, a fraction of the antiprotons observed may well be cosmic rays from distant antigalaxies. (Our preliminary analysis results including 1999 and 2000 BESS published data do not find such trend, however (D.K., M Panayotova, T.Valchanov, in preparation).

In conclusion, the statistical sample of antiprotons presently available is very limited, so that a primary component cannot be ruled out with high significance, even in case the propagation parameters were known. Besides, cosmic rays at the rigidities accessible to current antimatter experiments should be strongly suppressed by galactic, cluster and intergalactic magnetic fields (Ormes et al.,Ap.JL 482,L187,1997).

There exist observational constraints, on the basis of the gamma rays data, interpreted as a result from annihilation, on the antimatter fraction of the nearest galaxy clusters pointing that the antimatter regions, if present, should be separated from the matter ones. The scale of the necessary separation is of the order of the galaxy cluster scales ~ 20 Mpc (Steigman G.,Ann. Rev. Astr. Astrop.14, 339,1976).

Recent analysis discussed the contribution of the relic gamma rays from early annihilation to the cosmic diffuse gamma spectrum and presented a lower limit of 1000 Mpc in case of matter-antimatter symmetric Universe and for certain baryogenesis models (Cohen A. et al.,Ap.J. 495,539,1998). However, the conclusions are not applicable to isocurvature baryogenesis models, like the one discussed below. Besides, the assumption for the matter-antimatter asymmetry in the visible Universe is not obligatory! Antimatter regions may be less than the matter ones, then gamma observations put only constraints to the antimatter-matter ratio at different scales. It was shown in recent years that even a small fraction ($< 10^{-6}$) of antimatter stars in our Galaxy (Khlopov M., Gravitation and Cosmology 4, 69,1998) and antimatter globular clusters (Belotsky K.,Yad.Fiz. 63,290,2000) is allowed!. And as we will discuss later, within the framework of the presented here baryogenesis model, antigalaxies and anticlusters may be present. CR and γ-ray data do not rule out antimatter domains in the Universe.

So it is interesting to explore how considerable regions of antimatter were produced in the Universe.

The baryogenesis model

Assuming that point of view we discuss here the SUSY-baryogenesis model, predicting large separated regions of matter and antimatter. (It is discussed in detail in (D.K.& M.Chizhov, MNRAS 314, 256 ,2000; AATr 10, 69, 1996) It arises naturally in the *low temperature baryogenesis scenarios with baryon charge condensate* (Dolgov A.& D.K.,J.M.Phys. Soc.1,217,1991; D.K.& M. Chizhov 1996).

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 $\phi \rightarrow q\bar{q}l\gamma$ an antisymmetric plasma appears. In the model there in 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. Due to the exponential expansion during the inflationary epoch these microscopic regions become of astronomically considerable size.

The model has some very attractive features, namely: It is compatible with the inflationary models, it does not suffer from the problem of insufficient re-

heating after inflation, it evades the problem of the washing out of the baryon excess at the electroweak phase transition, due to the account for particle creation processes (Dolgov & D.K. Sov.J.Nucl.Phys.51,172,1990), it provides naturally a generation of a small baryon asymmetry for a natural initial conditions (i.e. it evades fine tuning). The analysis of the evolution of the baryon charge space distribution (D.K. & Chizhov 1996,2000) provided in the framework of that baryogenesis model showed that it proposes an elegant solution to the problem of the very large scale (~ 120 Mpc) in the distribution of the visible matter (Broadhurst et al. Nature,343,726.1990; Einasto et al.1994-00).

Attractive features from the view point of antimatter cosmology are: It does not suffer from the basic problems of antimatter cosmology models, i.e. the causality problem, the annihilation catastrophe problem, the domain walls problem, discussed in detail in Steigman 1976; Kolb&Turner1983. It can provide a natural separation mechanism of considerable quantities of matter from such ones of antimatter. The characteristic scale of antimatter regions and their distance from matter ones may be in accordance with the observational constraints for natural choice of parameters. Although the CMB anisotropy constraints on isocurvature models may apply to it, there are ways to evade even the stringest CMB constraints for different concrete realizations of the model.

So, the model proposes the possibility that only our vicinity is baryonic, while globally the Universe may contain considerable quantities of antibaryons and in the extreme case may be symmetric.

Generation of matter and antimatter regions sufficiently separated

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 is 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: The natural assumption of a monotonic distribution of the baryon density within a domain with a certain sign of the baryon number was made.

* Unharmonic potential of the field carrying the baryon charge: The unharmonicity of the potential is essential. Due to it different amplitudes corresponding to different space points result into different periods , as far as the period depends on the amplitude in the unharmonic case. Therefore, the initial smooth dependence soon transfers into quasiperiodic one and the region which initially was characterized with its baryon excess splits into regions with baryon excess and such of baryon underdensities (Dolgov A& Chizhov 1992).

* 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, the causality problem is naturally solved.

Two cases are possible: 1.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 to baryonic and antibaryonic regions and divided by nearly baryonically empty space. 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. The exact quantitative calculations of CMB anisotropy for the specific case are not provided. Anyway, a certain possibility remains (though not very elegant) namely, that the antibaryonic supercluster size regions are beyond the observable part of the Universe. So, in principle a symmetric matter-antimatter Universe is possible.

2.In case of an explicit CP-violation, 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 mean number. Then the domain with a given sign of explicit CP-violation may consist predominantly of baryonic regions plus small quantity (for the concrete model it is $\sim 10^{-4}$) of antibaryonic ones.

The baryogenesis model. Main characteristics.

Generation of the baryon condensate.

The essential ingredient of the model is a squark condensate ϕ with a nonzero baryon charge. It naturally appears in supersymmetric theories and is a scalar superpartner of quarks. The condensate $< \phi > \neq 0$ is formed during the inflationary period as a result of the enhancement of quantum fluctuations of the ϕ field (Vilenkin & Ford 1982, Linde 1982, Bunch & Davies 1978, Starobinsky 1982): $< \phi^2 >= H^3 t/4\pi^2$. 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, a condensate of a baryon charge (stored in $< \phi >$) is developed during inflation with 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.

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 $H = \dot{a}/a$.

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

We study the 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 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. 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 $\phi_o^{max} \sim H_I \lambda^{-1/4}$ and $\dot{\phi}_o = 0$.

After inflation ϕ 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. (Figs.1 and 2.

Fast oscillations of ϕ after inflation result in particle creation due to the coupling of the scalar field to fermions $g\phi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. 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 & D.K. 1996). 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.

For a constant Γ along the flat directions of the potential this reduction is exponential and for a natural range of the model's parameters, the baryon asymmetry is waved away till baryogenesis epoch. Here remains a possibility that the scalar field is the inflaton itself, then the baryon asymmetry will not be waved away due to the extremely small coupling constant in this case. However, as will be discussed later, this case is forbidden by the CMB anisotropy data. In the other case the production rate is a decreasing function of time, so that the damping process may be slow enough for a considerable range of acceptable model parameters 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.(Dolgov A., D.K., 1991) Then ϕ decays to quarks with non-zero average baryon charge. This charge, diluted further by some entropy generating processes, dictates the observed baryon asymmetry.

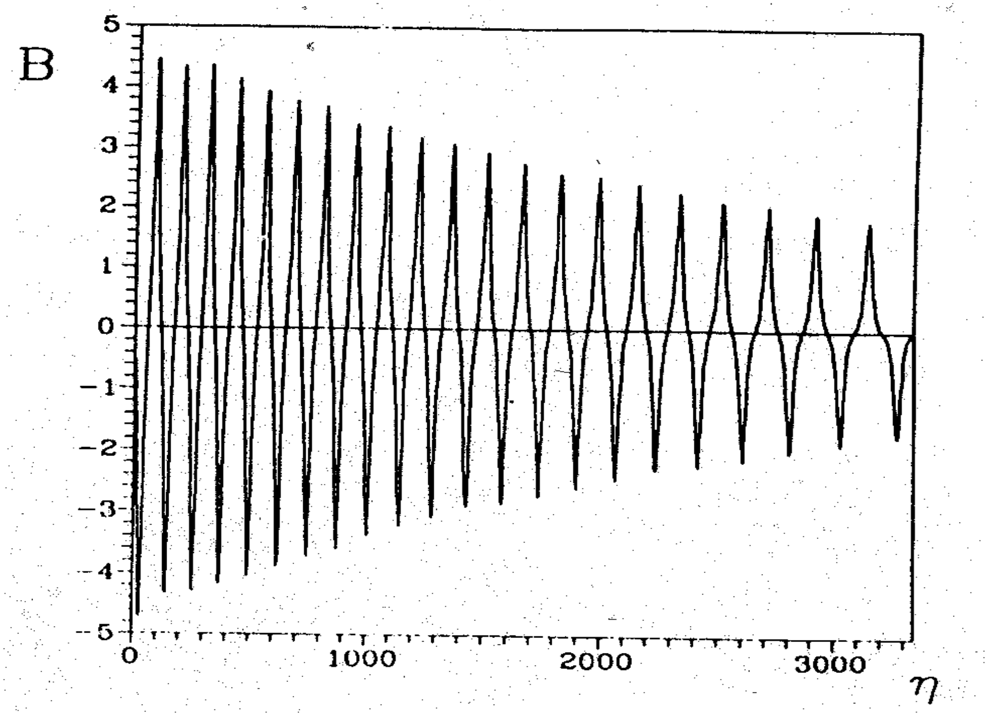

Figure 1: The evolution of the baryon charge $B(\eta)$ contained in the condensate $<\phi>$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$, $\phi_o = H_I \lambda^{-1/4}$, and $\dot{\phi}_o = 0$.

Evolution of the baryon density distribution - numerical modelling

We have made the natural assumption that initially ϕ is a slowly varying function of the space coordinates $\phi(r,t)$. For each set of studied parameter values of the model λ_i, α, m/H_i, we have numerically calculated the baryon charge evolution $B(t)$ for different initial values of the field ϕ_o, corresponding to the accepted initial distribution of the field (Figs.1 and 2.). 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 it was expected, in case of nonharmonic field's 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 on its turn is a function of r. As a result in different points different periods are observed and space behaviour of ϕ becomes

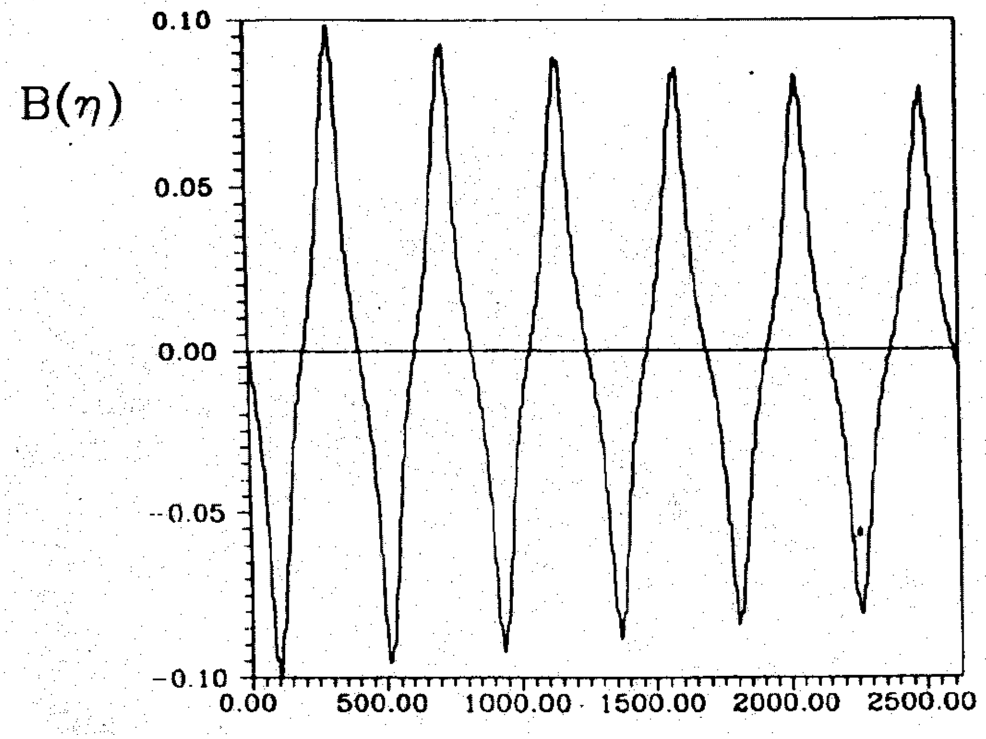

Figure 2: The evolution of the baryon charge $B(\eta)$ contained in the condensate $< \phi >$ for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$, $\phi_o = \frac{1}{50} H_I \lambda^{-1/4}$, and $\dot{\phi}_o = 0$.

quasiperiodic. 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 (Fig. 3).

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, that at present the visible part of the Universe consists of baryonic and antibaryonic regions. Note that due to the smoothly decreasing baryon density towards the borders between the matter and antimatter regions, the resulting annihilation must not be considerable at the early epoch when the condensate decays into ordinary particles and antiparticles. After its decay the baryon and antibaryon regions should further contract towards their centers, where density is higher. Hence, matter and antimatter domains will become separated by large empty from baryons voids, perhabs filled with dark matter. So, as far as there is no direct contact between them $p\bar{p}$ annihilation is not observed and thus the stringent limits on antimatter domains from (Cohen et al., Ap.J. 495, 539, 1998) do not hold.

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_o. The provided 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. for a natural

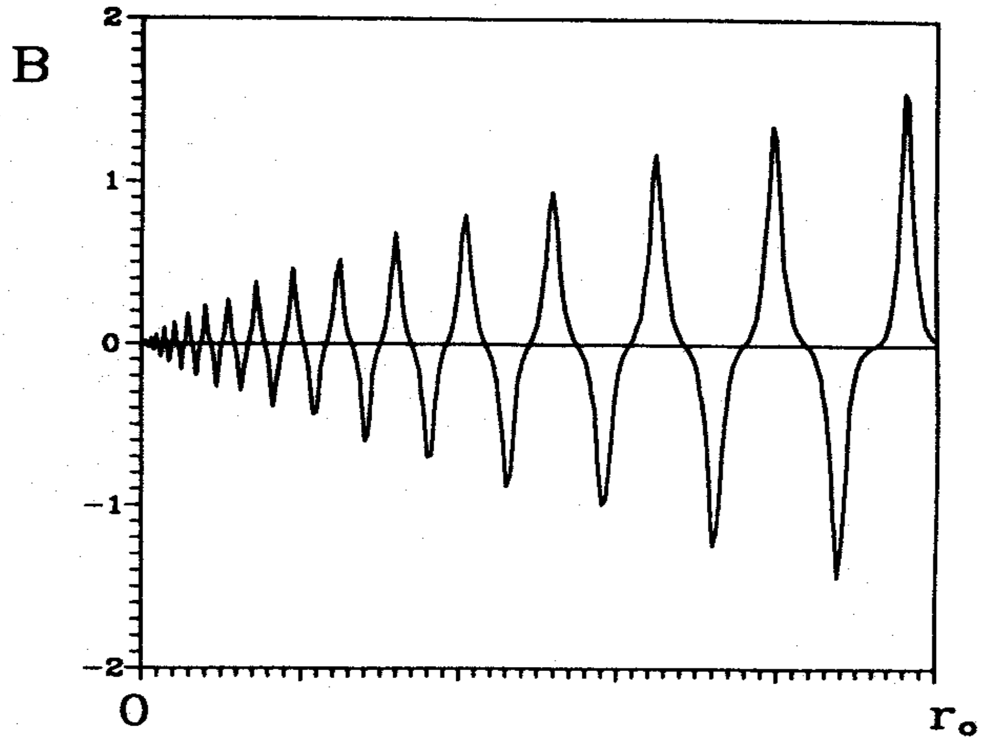

Figure 3: The space distribution of baryon charge at the moment of baryogenesis for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$.

choice of the values of these parameters the separation scale may be in the Mpc - 100 Mpc range.

Different antimatter scenarios and observational constraints

There are known several constraints on inhomogeneous baryogenesis models: from gamma rays and cosmic ray data, from Big Bang Nucleosyynthesis and from the anisotropy measurements of CMB. We will use them to choose among different realisations of the discussed mechanism suggesting vast antimatter domains.

Recent CMB measurements ruled out pure isocurvature models, so, accordingly, the case when the baryon charge carrying field is the inflaton itself, is excluded. Other possibilities, when besides the inflaton there exists a second scalar field during inflation with the features discussed in our model remains viable. According to the recent mixed isocurvature plus adiabatic models, although the isocurvature contribution is not suggested it has neither been ruled out.

The first most simple case we considered (D.K&M.C. 2000) assumes that the overdensity regions correspond to superclusters of galaxies with big voids between with a characteristic size ~ 120 Mpc. In that case the antimatter domains are roughtly of the same scale and the similar density as the matter ones. Hence, they fullfill the constraints from CR and gamma-ray data. Large variation of the primordially produced elements, should be observable at the corresponding scales (we do not have data for the rest light elements at large distances, however the observed D towards high Z quasars shows some deviations from the expected primordial plateau. However, in that case the induced anisotropies in CMB radiation may be greater than allowed. (Note that calculation of the resulting angular variations of the temperature of CMB in the specific case are not done.) Even if the stringent constraint applies, there remains possible the trivial case, that we leave in one large scale fluctuation of the baryon number , scaling almost to the visible horizon of our Universe, while regions consisting of antimatter only are situated safely beyond the horizon. But this is not an exciting possibility both from observational and theoretical point of view.

Smaller scales (≤ 20 Mpc) of the structures of matter and antimatter are constrained from CR and gamma-ray radiation.

The case when the generated baryon density fluctuations are superimposed on an almost constant baryon background is more promising. Though not so esthetic, because in that case there should be besides the stochastic CP breaking discussed, another mechanism of CP violation producing the mean baryon density.

The possibilities are the following:

1. There exist vast matter superclusters at a $L \sim 120$ Mpc separation, while the antimatter objects are of characteristic scales $l \leq 10^{-4}L$. Hence, depending on the folowing evolution these antimatter regions may collapse to form small galaxies, star clusters or vast dense hydrogen clouds. They are at a safe distance from the matter superclusters at about 60 Mpc. All the observational constraints are satisfied.

2. In case we do not insist on explaining the very large supercluster scale by this baryogenesis model, the scales of the matter domains may be taken

smaller, corresponding to the characteristic scale of galaxy clusters or galaxies themselves. In such a case many different possibilities for antimatter domains may be realized, namely between galaxy clusters an antimatter galaxy may wonder, in the space between galaxies a lonely antistar may be found. The CMB constraint weakens with decreasing the considered scale. However, CR and gamma-ray data restricts the number of such smaller antimatter objects, not excluding however the possibility for their existence.

In conclusion: The discussed baryogenesis model depending on the parameters may predict different antimatter structures: superclusters, antigalaxies situated between clusters of galaxies, antistars. While the anti superclusters should not be possible to observe, the other cases are more exciting.

Conclusions.

A mechanism of separation of matter and antimatter regions at an earlier epoch is discussed from the viewpoint of existing observational and theoretical constraints on antimatter in the Universe.

There exists the interesting possibility that in the framework of this SUSY-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 presence of vast antimatter regions.

The discussed baryogenesis model, depending on the values of its parameters, may predict different antimatter structures: superclusters, antigalaxies between clusters of galaxies, antistars. Future positive indication for antimatter may help fix the parameters of the SUSY baryogenesis model, or rule it out.

The discussed mechanism for generation of baryon antibaryon regions separated at great distances in the observed today Universe could be realized in a variety of models, depending on the type of the baryogenesis model (Chizhov & Dolgov 1990; D.K.& M.Chizhov, 1994), depending on the field potential, depending on the type of the CP-violation, on the initial space distribution of the baryon density at the inflationary stage, etc.

Thus, it looks probable that the results of future experiments on long balloon flights and spacecraft, planning to measure antiproton and positron spectra at wide range of energies (0.1- 150GeV) (as by PAMELA magnetic spectrometer) and reach a sensitivity for antinuclei at $\sim 10^{-7}$ (AMS magnetic spectrometer), will reveal the secrets of nearby (well.. up to 150 Mpc) antiworlds. It is exciting that we may know soon the answer. Future positive indications for antimatter may help also to choose among the existing variety of ”anti” baryogenesis models, and for the case discussed here, it may reveal SUSY parameters, as well.