CERN-TH/2002-218

VAST ANTIMATTER REGIONS AND SCALAR CONDENSATE BARYOGENESIS

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The possibility of natural and abundant creation of antimatter in the Universe in a SUSY-baryogenesis model with a scalar field condensate is described. This scenario predicts vast quantities of antimatter, corresponding to galaxy and galaxy cluster scales today, separated from the matter ones by baryonically empty voids. Theoretical and observational constraints on such antimatter regions are discussed.

1 Antimatter in the Universe – Observational Status

Is our Universe globally baryonic or the observed baryon asymmetry is just a local characteristic? We do not know the answer, yet. The observed value of the baryon asymmetry in our local vicinity 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 antibaryon number densities and N_γ is the photon density.

The available cosmic ray (CR) and gamma ray data points to a *strong predominance of matter over antimatter in our Galaxy:*

Experimental search for antinuclei and $\bar{p}$ in CR were conducted on high-altitude balloons and on spacecraft. $\bar{p}$ detected in primary cosmic radiation over energies $0.1 - 19$ GeV are 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 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 [1] is 1.7×10^{-6}; at energies $0.1 - 8.6$ GeV/nucl. obtained in balloon experiments [2] is 8×10^{-6}; from BESS magnetic rigidity spectrometer in rigidity region 1 to 16 GV 3.1×10^{-6},

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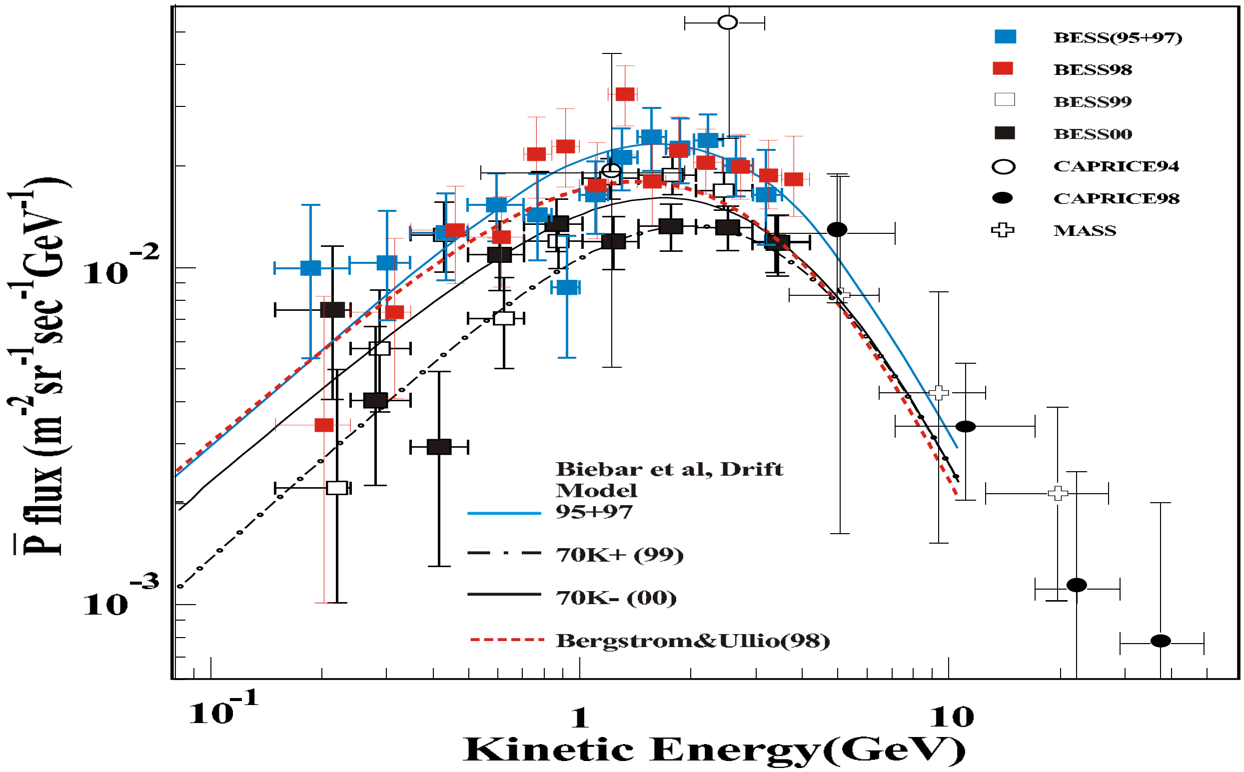

Figure 1: BESS 1995-2000 antiproton spectrum at the top of the atmosphere and CAPRICE and MASS data. The curves represent the theoretical calculations for secondary $\bar{p}$ for the corresponding solar activity level.

i.e. the model-independent upper limit on the antihelium flux, is 6×10^{-4} m^{-2}sr^{-1}s^{-1}, and for nuclei with $Z > 3$ within energy range $1 - 15$ Gev/nucl is 8×10^{-5}. 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 $\bar{He}$ spectrum is with the same shape as the He one)[3,4]. The search will continue in future AMS and PAMELA missions as far as an antinucleus detection would be a certain signature for antimatter BBN or antistars, because the secondary flux for antinuclei is expected to be extremely low[5].

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

However, *the data are not definite for larger scales.* In Fig.1 we present all the published BESS data[6], namely the antiproton spectrum for 1995, 1997-2000. As far as the measurements of $\bar{p}$ spectrum at energies above a few GeV are free of uncertainties due to secondary $\bar{p}$ production and solar modulation effects, we present also CAPRICE[7] and MASS[8] $\bar{p}$ high energy measurements. The curves present the theoretical predictions for the secondary $\bar{p}$ by Bieber et al.[9], and Bergstrom (from ref.[7]), calculated within contemporary two-zone diffusion models for the corresponding level of solar activity. The uncertainties due to propagation range between 10% and 20% depending on the part of the spectrum[11].

Although the measured $\bar{p}$-flux and its spectrum is in agreement with the predicted ones for secondary particles, the data do not exclude a primary component. There are even some hints for $\bar{p}$ excess:

(a) 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. As far as $\bar{p}$ from primary sources are suppressed as solar activity increases, while secondary $\bar{p}$ spectrum is affected modestly, the results were interpreted in favor of a primary $\bar{p}$[8].

(b) Slightly excessive $\bar{p}$ fluxes, relative to the theoretical calculations were found during solar minimum in the analysis by Orito and by Matsunaga [6] for the energies below 0.5 GeV.

It is interesting to provide similar analysis including the available new BESS data for 1999 and 2000 years of maximum of solar activity and try to limit the possible extragalactic component of $\bar{p}$ and, hence, the primary $\bar{p}$. Our preliminary analysis of all the available BESS data do not find such trend, however [12]. In case an excess of low energy antiprotons will be disfavored by the data, still high energy spectrum may be studied, having in mind also that this part of the spectrum is free of uncertainties due to solar modulation effects, and in this energy range all calculations of secondary $\bar{p}$ are consistent with each other.

(c) 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 [13].

So, a fraction of the observed $\bar{p}$ may well be CR from distant antigalaxies.

In conclusion, *the statistical sample of $\bar{p}$ 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, CR at the rigidities accessible to current antimatter experiments should be strongly suppressed by galactic, cluster and intergalactic magnetic fields [2].

Gamma rays data, interpreted as a result from annihilation provides observational constraints on the antimatter fraction of different structures [14,15,16]. No evidence for annihilation features due to contacting matter and antimatter in the period $z < 100$ was found in the cosmic gamma ray background. The measurements of the gamma ray flux in the MeV region exclude significant amounts of antimatter up to the distance of galaxy cluster scales $\sim 10 - 20$ Mpc [17]. Hence, it is interesting to explore baryogenesis models predicting large antimatter structures.

The analysis of the relic gamma rays contribution from early annihilation to the cosmic diffuse gamma spectrum gave the limit 1 Gpc in case of the following assumptions: matter-antimatter symmetric Universe, continuous close contact between domains of matter and antimatter and adiabatic perturbations [18]. This constraint is not applicable to isocurvature baryogenesis models [19], like the one discussed below, according to which there was not a close contact between matter and antimatter regions, and afterwards the separation increased. Besides, the assumption for the asymmetry is not obligatory! Antimatter regions may be less than the matter ones, then gamma observations constrain the antimatter-matter ratio at different scales.

The analysis of annihilation features within concrete baryogenesis model [20] and the EGRET gamma-ray background data showed that even a small fraction ($< 10^{-6}$) of antimatter stars in our Galaxy is allowed! The allowed mass range $10^4 - 10^5 M_{Sun}$ corresponds to antistar globular cluster [21,22]. An interesting possibility of primordial antiblackholes, antiquasars and antistars was revealed also in ref.[23].

And as we will discuss below, within the framework of the presented here baryogenesis model, antigalaxies and anticlusters may be a possibility, too.

CR and γ-ray data do not rule out antimatter domains in the Universe.

Other observational signatures of antimatter are the distortion of the energy spectrum of the Cosmic Microwave Background Radiation and spatial variations of the primordial light elements abundances. The isotropy of CMB rules out large voids between matter and antimatter regions during earlier time. Successful BBN restricts the amount of annihilation at early epoch and, hence, puts stringent limits on the fraction of antimatter [24,25].

So it is interesting to explore how large regions of antimatter may be produced in the Universe and what are the observational signatures and constraints for them.

2 The baryogenesis model

There exist different inhomogeneous baryogenesis models, which predict matter and antimatter regions[26]. We discuss here the SUSY-baryogenesis model, predicting vast regions of antimatter, safely separated from the matter ones, so that the CR and gamma-ray constraints are satisfied. It is discussed in detail in [28,29]. It arises naturally in the *low temperature baryogenesis scenarios with baryon charge condensate*[27,29].

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 ref.[15]. 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. 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.

The essential ingredient of the model is a baryon charged complex scalar field ϕ, present together with the inflaton. A condensate with a nonzero baryon charge is formed during the inflationary period due to enhancement of quantum fluctuations of ϕ [31]:

$$< \phi^2 >= H^3 t/4\pi^2.$$

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 $H = \dot{a}/a$. The baryon charge of the field is not conserved at large values of ϕ due to B-violating self-interaction terms in the field's potential:

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

We have studied the evolution of the condensate after inflation for the case when at the end of inflation the Universe is dominated by a coherent oscillations of the inflaton field:

$\psi = m_{PL}(3\pi)^{-1/2}\sin(m_\psi t)$, $H = 2/(3t)$, $m \ll H_I$, $\lambda_i \sim \alpha_{GUT}$, $\phi_o^{max} \sim H_I \lambda^{-1/4}$ and $\dot{\phi}_o = 0$.

After inflation ϕ oscillates around its equilibrium point with a decreasing amplitude, as a result of the Universe expansion and to the particle production by the oscillating scalar field[32], due to the coupling to fermions $g\phi\bar{f}_1 f_2$, where $g^2/4\pi = \alpha_{SUSY}$. 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 also. If $\Gamma = const$ the baryon asymmetry is waved away till baryogenesis epoch unless the scalar field is the inflaton itself. However, this case is forbidden by the CMB anisotropy data. If Γ is a decreasing function of time, the baryon charge contained in ϕ may survive until B-conservation epoch t_b [27]. At t_b the baryon charge is transfered to that of the quarks during the decay of the field $\phi \to q\bar{q}l\gamma$ and an antisymmetric plasma appears. Its charge, eventually diluted further by some entropy generating processes, dictates the observed baryon asymmetry.

3 Evolution of the baryon density distribution

The necessary conditions for generation of vast separated regions of matter and antimatter in the model are: initial space distribution $\phi(r, t_0)$, unharmonic potential and inflationary expansion. We studied the evolution of the baryonic space distribution, assuming a monotonic initial distribution of the baryon density within a domain with a certain sign of the baryon number $\phi(r, t_0)$. For different sets of parameter values of the model λ_i, α, m/H_i, we have numerically followed the evolution $B(t, r)$ for all initial values of the field $\phi_o^i = \phi(r_i, t_0)$ till t_B.

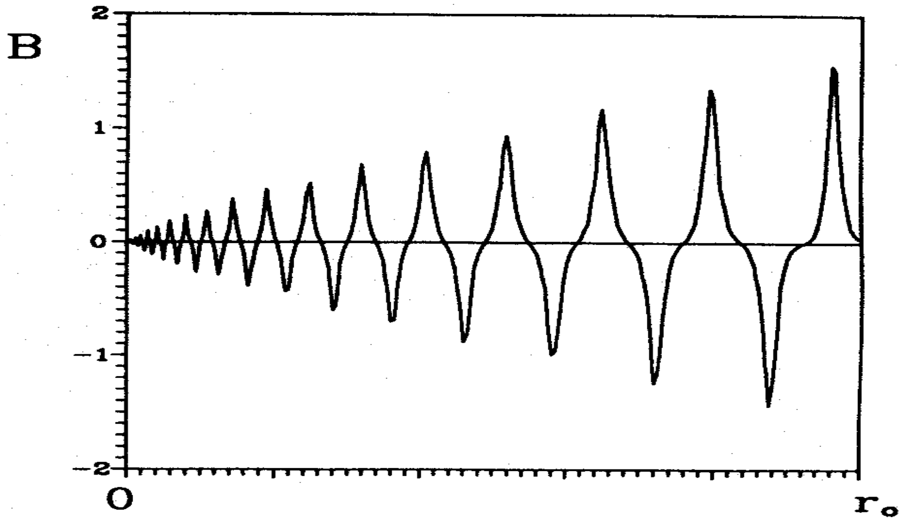

Figure 2: The space distribution of baryon charge at t_B for $\lambda_1 = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = \alpha = 10^{-3}$, $H_I/m = 10^7$.

In case of nonharmonic field's potential, the initially monotonic space behavior is quickly replaced by space oscillations of ϕ, because of the dependence of the period on the amplitude[30]. In our model the dependence is $\omega \sim \lambda^{1/2}\phi_i(r)$. As a result in different points different periods are observed and spatial behavior of ϕ becomes quasiperiodic. Correspondingly, the spatial distribution of baryons $B(t_B, r)$ at the moment of baryogenesis is found to be quasiperiodic (Fig. 2).

The region r_0 which initially was characterized with its baryon excess splits into regions with baryon excess and such of baryon underdensities[29]. Due to the smoothly decreasing baryon density towards the borders between the baryonic and antibaryonic regions, predicted by the model, annihilation is not considerable at t_B. After that, the baryon and antibaryon regions further contract towards their centers, where density is higher. Hence, matter and antimatter domains become separated by large empty from baryons voids, perhaps filled with dark matter. Thus the stringent limit[18] on antimatter domains is evaded.

Two cases are possible:

A. *Stochastic CP-violation*: The variations appear around zero baryon charge. The initially baryonic domain is broken to baryonic and antibaryonic regions and divided by nearly baryonically empty space. The case is attractive as far as it allows the realization of symmetric Universe without domain walls. However, the resulting fluctuations of the baryon density may be considerable and lead to unacceptably large angular variations of the microwave background radiation.

B. *Stochastic+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 at t_B the domain with a given sign of explicit CPV may consist predominantly of baryonic regions plus small quantity (for $l \sim 100$ Mpc it is $\sim 10^{-4}$) of antibaryonic ones. Though not so aesthetic, because in that case there should be besides the stochastic CPV discussed, another mechanism of CPV producing the mean baryon density, this case is more promising.

Due to inflation the regions with different baryon density (overdensity, underdensity or density of antibaryons) become macroscopically large $d \to d\exp(Ht)$. *The characteristic scale between matter and antimatter regions* is a function of the models 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 for a natural choice of the values of these parameters the separation scale may be in the Mpc - 100 Mpc range.

4 Predicted antimatter structures and observational constraints

Using the constraints from gamma rays and CR data, BBN and CMB anisotropy measurements, we discuss different realizations of the model.

Recent CMB measurements ruled out pure isocurvature perturbations 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 remain viable [33]. According to the recent mixed isocurvature plus adiabatic models, although the isocurvature contribution is not suggested it has neither been ruled out.

A. *Stochastic CP-violation*

A.1 The first most simple case we considered in [28] aiming to explain the observed 120 Mpc periodicity in the visible matter distribution, assumed that the overdensity regions correspond to galaxy or antigalaxy superclusters with big voids between with a characteristic size ~ 120 Mpc. In that case the antimatter domains are roughly of the same scale and the similar density as the matter ones. CR and gamma-ray data constraints are fulfilled. Large variation of the primordially produced elements, should be observable at the corresponding scales. There are no 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. Alas, in that case the magnitude of the isocurvature perturbations is high and may induce CMB anisotropies not compatible with the data [33]. [b]

A.2 Smaller structures of antimatter $< 10 - 20$ Mpc are possible. The CMB constraint weakens when decreasing the scale. However, CR and gamma-ray data restricts the number of such smaller antimatter objects, not excluding, however, the possibility for their existence. Spatial variations of the light elements are expected also.

B. *Stochastic+explicit CP-violation*:

B.1. There exist vast matter superclusters with typical scale D at a $L \sim 120$ Mpc separation (as observed), while the antimatter objects are of characteristic scales $d \leq 10^{-4}D$. Hence, depending on the following evolution these antimatter regions may collapse to form small antigalaxies, antistar clusters or vast dense antihydrogen clouds. They are at a safe distance from the matter superclusters at about $l_b \sim 60$ Mpc. All the observational constraints may be satisfied.

B.2 The scales of the antimatter domains are of galaxy cluster or galaxy scales. Different possibilities for antimatter domains may be realized, namely between galaxy clusters an antimatter galaxy may wonder, in the space between groups of galaxies a globular star anticluster may be found.

In conclusion:

A baryogenesis model predicting vast antimatter regions safely separated from the matter ones is discussed from the viewpoint of existing observational and theoretical constraints on antimatter in the Universe. The analysis shows that different antimatter structures are possible: antigalactic clusters, antigalaxies situated between clusters of galaxies, antistar globular clusters.

The discussed mechanism of separation of matter from antimatter domains could be realized in a variety of models, depending on the type of the baryogenesis model, on the field potential, on the type of the CP-violation, on the initial space distribution of the baryon density at the inflationary stage, etc.

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 $(0.1 - 150$ GeV) (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

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[b] Calculation of the resulting angular variations of the temperature of CMB in the specific case are not done.

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.

Acknowledgments

D.K. thanks the organizing committee of the conference for the hospitality and financial support for her participation. D.K. appreciates useful discussions and suggestions by A. Dolgov and A. Sakharov, and acknowledges CERN TH visiting position and Abdus Salam ICTP regular associateship.

References

1. T. Saeki *et al*, *Phys. Lett.* B **422**, 319 (1998).
2. J. Ormes *et al*, *Ap.J.* **482**, L187 (1997).
3. M. Steuer, *Nuovo Cimento* **24**, 661 (2001).
4. B. Alpat, *Nucl. Phys.* B **S85**, 15 (2000).
5. P. Chardonnet, J. Orloff, P. Salati, *Phys. Lett.* B **409**, 313 (1997).
6. S. Orito *et al*, BESS Collaboration, *Phys. Rev. Lett.* **84**, 1078 (2000); Y. Asaoka *et al*, BESS Collaboration, *Phys. Rev. Lett.* **88**, 051101 (2002); Matsunaga H. *et al*, PRL **81**, 4052 (1998).
7. WiZard/CAPRICE Collaboration, *Ap. J.* **561**, 787 (2001).
8. T. Maeno *et al.*, BESS Collaboration, *Astropart.Phys.* **16**, 121 (2001).
9. J. Bieber, *Phys. Rev. Lett.* **83**, 674 (1999).
10. L. Bergstrom, J. Edsjo, P. Ullio, astro-ph/9902012.
11. F. Donato *et al.*, *Ap.J.* **563**, 172 (2001).
12. D. Kirilova, T. Valchanov, M.Panayotova, in preparation.
13. M. Boezio *et al*, astro-ph/0103513, 2002. ormes97
14. F. Stecker, these proceedings, hep-ph/0207323.
15. G. Steigman, *Ann. Rev. Astr. Astrop.* **14**, 339 (1976).
16. A. Dudarevich, A. Wolfendale, *MNRAS***268**, 609 (1994).
17. F. Stecker, *et al*, *Phys. Rev. Lett.* **27**, 1469 (1971); *Nucl. Phys.* B **252**, 25 (1985).
18. Cohen A. *et al*, *Ap.J.* **495**, 539 (1998).
19. A. Dolgov, *Nucl. Phys.* B **S95**, 42 (2001), hep-ph/0012107.
20. M. Khlopov, S. Rubin, A. Sakharov, *Phys. Rev.* D **62**, 083505 (2000).
21. A. Sakharov, M. Khlopov, S. Rubin in *Budapest 2001, High energy physics*, hep2001/212, Budapest, 2001, astro-ph/0111524.
22. K. Belotsky *et al*, *Yad.Fiz.* **63**, 290 (2000).
23. A. Dolgov, J. Silk, *Phys. Rev.* D **47**, 4244 (1993).
24. J. Rehm and K. Jedamzik, *Phys. Rev. Lett.* **81**, 3307 (1998); H. Kurki-Suonio and E. Sihvola, *Phys. Rev. Lett.* **84**, 3756 (2000).
25. V. Chechetkin *et al*, *Phys. Lett.* B **118**, 329 (1982).
26. A. Dolgov, these proceedings; Z. Berezhiani, these proceedings; A. Dolgov, *Phys.Rep.***222**, 309 (1992).
27. A. Dolgov and D. Kirilova, *J.M.Phys. Soc.* **1**, 217 (1991).
28. D. Kirilova and M. Chizhov, *MNRAS* **314**, 256 (2000).
29. D. Kirilova and M. Chizhov, *Astr. Astrop. Tr.* **10**, 69 (1996).
30. M. Chizhov and A. Dolgov, *Nucl. Phys.* B **372**, 521 (1992).
31. Bunch T. and Davies P., *Proc. Roy.Soc.* **A360**, 117 (1978); A. Vilenkin and L. Ford, *Phys. Rev.* D **26**, 1231 (1982); A. Linde 1982, *Phys. Lett.* B **116**, 335 (1982).
32. A. Dolgov and D.Kirilova, *Yad. Fiz.* **51**, 273 (1990).
33. K. Enqvist, H. Kurki-Suonio, J. Valiviita, *Phys. Rev.* D **26**, 103003 (2000); M. Bucher, K. Moodley, N. Turok, astro-ph/00212141.