Antimatter regions in the baryon-dominated Universe

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Abstract

Quantum fluctuations of a complex, baryonic charged scalar field caused by inflation can generate large domains, which convert later into antimatter regions. As a result the Universe can become globally matter-dominated, with minor contribution of antimatter regions. The distribution and evolution of such antimatter regions could cause every galaxy to be a harbour of an anti-star globular cluster. At the same time, the scenario does not lead to large-scale isocuvature perturbations, which would disturb observable CMB anisotropy. The existence of one of such antistar globular cluster in our Galaxy does not contradict the observed γ-ray background, but the expected fluxes of $\overline{^{4}\mathrm{He}}$ and $\overline{^{3}\mathrm{He}}$ from such an antimatter object are definitely accessible to the sensitivity of the coming AMS–02 experiment.

1 Introduction

The whole set of astrophysical observations[1] prefers that our Universe be globally matter/antimatter asymmetrical. This statement comes mostly from the fact that equal amounts of matter and antimatter domains, coexisting with each other, would annihilate on their borders, consequently disturbing the observed diffused γ-ray background [1,2]. A closed contact of coexisting matter and antimatter at the early epochs is almost unavoidable [3]. The γ-ray flux at 100 MeV range caused by this kind of annihilation would be below the observable one only in the case when the characteristic size of domains exceeds 10^3 Mpc [2]. This fact requires baryon domination over the whole volume of the Universe.

However, the above mentioned arguments cannot exclude the Universe composed almost entirely of matter, with relatively small insertions of antimatter regions. The fate of such antimatter regions depends on their size. If the physical size of some of them is larger than the critical surviving size $L_c = 8h^2$ kpc [4], they survive annihilation with surrounding matter. It is very likely that the dense fraction of the antimatter domains out of the preserved population evolve into condensed antimatter astrophysical objects [5].

In this report we consider the model of inhomogeneous baryogenesis [6] based on the inflationary evolution of the baryon charged scalar field. This scenario makes it reasonable to discuss the existence of an antistar globular cluster (GC) in our Galaxy, preventing at the same time large-scale isocurvature fluctuations, which could be imprinted into CMB anisotropy. The main experimental signature of the discussed scenario is indicated in the expected fluxes of $\overline{^{4}\mathrm{He}}$ and $\overline{^{3}\mathrm{He}}$, which are accessible for the sensitivity of AMS–02 detector [7].

2 Scenario of inhomogeneous baryogenesis with antimatter generation

Our approach [6] is based on the spontaneous baryogenesis mechanism [8], which implies the existence of a complex scalar field $\chi = (f/\sqrt{2})\exp(\theta)$ carrying the baryonic charge. The $U(1)$ symmetry, which corresponds to the baryon charge, is broken spontaneously and explicitly. The explicit breakdown of $U(1)$ symmetry is caused by the phase-dependent term

$$V(\theta) = \Lambda^4(1 - \cos\theta), \tag{1}$$

which results in the pseudo Nambu–Goldstone (PNG) potential of Fig. 1. The possible lepton-number violating interaction of the field χ with matter fields can have the following structure [9,6]

$$\mathcal{L} = g\chi\bar{Q}L + \text{h.c.}, \tag{2}$$

where fields Q and L represent a heavy quark and lepton, coupled to the ordinary matter fields. In the early Universe, at a time when the friction term, induced by the Hubble constant, becomes comparable with the angular mass $m_\theta = \frac{\Lambda^2}{f}$, the phase θ starts to oscillate around the minima of the PNG potential and decays into matter fields according to (2). The coupling (2) gives rise to the following [9,6]: as the phase starts to roll down in the clockwise direction during the first oscillation (Fig. 1), it preferentially creates baryons over antibaryons, while the opposite is true as it starts to roll down in the opposite direction. The baryon/antibaryon number, created in these oscillations, is given by [6]

$$N_{B(\bar{B})} \approx \frac{g^2 f^2 m_\theta}{8\pi^2}\mathcal{W}_{\theta_i}\theta_i^2 \int\limits_{\mp\theta_i/2}^{\infty} d\omega \frac{\sin^2\omega}{\omega^2}, \tag{3}$$

where $\mathcal{W}_{\theta_i}$ is the volume, in which the phase has the value θ_i. Thus, the distribution of the resulting baryon charge reflects the primordial distribution of the phase θ in the early Universe.

We suppose [6] that the radial mass m_χ of the field χ is larger than the Hubble constant H_{infl} during inflation, while for the angular mass of χ just the opposite condition, $m_\theta \ll H_{infl}$, is satisfied in that period. Thus $U(1)$ symmetry is already broken spontaneously on the energy scale f at the beginning of inflation, whereas the phase θ behaves like a massless scalar field. This means that the quantum fluctuations of θ at the de Sitter background [10] will define the primordial phase distribution in the early Universe. Thus to have a globally baryon-dominated Universe one must have the phase sited in the range $[\pi, 0]$ (Fig. 1), just at the beginning of inflation [a] (when the size of the modern Universe crosses the horizon). Then quantum fluctuations in some regions move the phase to the values $\bar{\theta}_i$ in the range $[0, \pi]$ (Fig. 1, right panel) where a successive antibaryon excess gets produced. If a domain with $\bar{\theta}_i$ leaves the horizon H_{infl}^{-1} before the 45th e-fold [6], it becomes biger than the critical survival size L_c and survives annihilation.

Since baryon/antibaryon numbers are produced by the out-of-equilibrium decay of non-inflaton field χ, the isocurvature perturbations [11] will be imprinted in baryons, giving rise to the effect on the CMB angular power spectrum. The size of the effect is defined dispersion by the $\delta\theta = H_{infl}/(2\pi f)$ and diminished by a factor Ω_B/Ω_{tot}. At the large scales corresponding to the first 6 e-folds of inflation, the measured CMB anisotropy does not allow to be the dispersion larger, than $\delta\theta \le 10^{-3}$, while at the N_c e-fold corresponding to L_c one needs to get the phase already to the antibaryon production region of vacuum manifold, which requires quite a large magnitude of dispersion $\delta\theta \simeq 10^{-2}$ [6]. An outcome of this disagreement could be found by making the dispersion $\delta\theta$ dynamically changing with respective to the current e-fold. One assumes a vacuum that dynamics makes the energy scale of $U(1)$ symmetry breaking f variable during

[a] We put the duration of the inflation period to 60 e-folds.

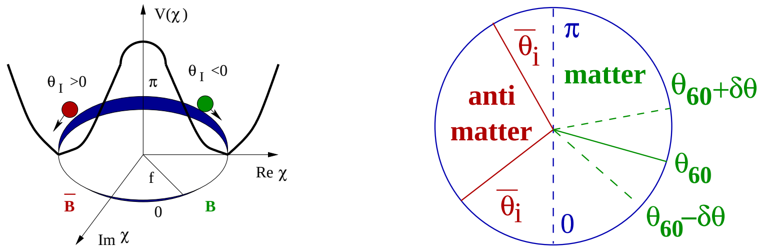

Figure 1: **Left panel:** PNG potential in the spontaneous baryogenesis mechanism. The sign of produced baryon asymmetry depends on the starting point of oscillations. **Right panel:** The inflational evolution of the phase. The phase θ_{60} sits in the range $[\pi, 0]$ at the beginning of inflation and makes Brownian step $\delta\theta_{eff} = H_{infl}/(2\pi f_{eff})$ at each e–fold. The typical wavelength of the fluctuation $\delta\theta$ is equal to H_{infl}^{-1}. The whole domain H_{infl}^{-1}, containing phase θ_N gets divided, after one e–fold, into e^3 causally disconnected domains of radius H_{infl}^{-1}. Each new domain contains almost homogeneous phase value $\theta_{N-1} = \theta_N \pm \delta\theta_{eff}$. Every successive e-fold this process repeats in every domain.

inflation. Phenomenologicaly the requirement dynamics can be obeyed by the potential with the following couplings [b] of inflaton ϕ to χ

$$V(\phi, \chi) = \frac{1}{2} m_\phi \phi^2 + \lambda \left(\chi\chi^* - \frac{f^2}{2} \right)^2 - g_{\phi\chi} \chi\chi^* (\phi - cM_{Pl})^2. \tag{4}$$

The radius of phase vacuum manifold becomes e-fold dependent, making the effective dispersion $\delta\theta_{eff}$ small at the beginning of inflation, thereby suppressing the magnitude of large-scale isocurvature fluctuations

$$f_{eff}(N) = f \sqrt{1 + \frac{g_{\phi\chi} M_{Pl}}{12\pi\lambda} (N_c - N)}; \ \delta\theta_{eff} = \frac{H_{inf}}{2\pi f_{eff}}. \tag{5}$$

The dispersion grows up to its maximun value, when inflantion reachs the N_cth e-fold. Then it decreases again to a negligible value. Such dynamics allows to generate an above-critical size progenitor of antimatter region in every volume box corresponding to each galaxy, preserving at the same time the general barion asymmetry of the Universe as a whole (see Fig. 2). Fig.2. The evolution of created baryon number density is straightforward [6]. The other advantage of mechanism (4), (5) is to make the antimatter domain size distribution almost independent of the initial position of the phase at the beginning of inflation, requiring only that it be located somewhere in the baryon-production region of the vacuum manifold.

3 Evolution and observational signature of antimatter domains

The antibaryon number (3) in progenitors shows a strongly rising dependence on the initial value of the phase $\bar{\theta}_i$, which makes sense to discuss the possibility of having high density antimatter region in every galaxy. Let us consider the evolution of such a high density antimatter region in the surrounding matter.

It is well known [12] that a cloud of mass $10^5 M_\odot$–$10^6 M_\odot$, which has temperature near 10^4 K and a density several tens of times that of the surrounding hot gas, is gravitationally unstable. This object is identified as a proto-object of GC and reflects the Jeans mass at the recombination epoch. Thus if the phase $\bar{\theta}_i$ inside an antimatter region progenitor was in a position to generate an antimatter density higher than the surrounding matter density by one order of magnitude, it is very likely that the region evolves into an antimatter GC [5]. GCs are the oldest galactic star systems to form in the Universe, and contain stars of the first population. Thereby a GC at large

[b] The coupling in (4) can be generated by SUSY/SUGRA potentials (see for details [11])

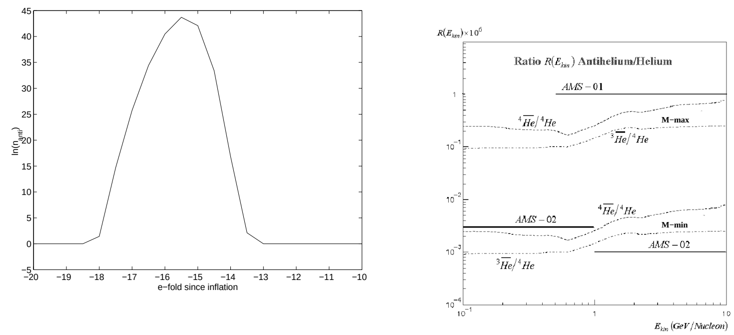

Figure 2: **Left panel**: The size (e-fold) distribution of antimatter domain progenitors calculated with respective to the variable dispersion mechanism. The calculations have been done under the assumptions $H_{infl} = 10^{13}$GeV, $\frac{g_{\phi\chi} M_{Pl}}{12\pi\lambda} \simeq 10^3$. About 10^{11} of critical size antimatter domains appear, while the number of larger domain as well as much smaller domains is highly suppressed. The volume occupated by antimatter is less then 10^{-4} of the total volume of the Universe. **Right panel**: The expected fluxes of $^4\overline{He}$ and $^3\overline{He}$ from anti–star GC in the mass range $10^3 M_\odot$–$10^5 M_\odot$, (M-min–M-max), in the comparison with the AMS02 sensitivity.

galactocentric distance is the ideal astrophysical object that could be made out of antimatter. The $\bar{p}$ releasing from such an antistar GC by the stellar wind and anti-supernova explosions will be collected in our Galaxy and annihilate with p giving a contribution into GeV range diffused γ-ray background [13]. This contribution, being compared with the γ– ray background measured by EGRET sets the upper limit on the mass of antistar GC in our galaxy to $10^5 M_\odot$ [13], while L_c defines the lower mass limit $10^3 M_\odot$ on a possible antistar GC.

The most important experimental signature of the existence of an antistar GC in our Galaxy, would be the observation of antinuclei in the cosmic rays near the Earth's orbit [14]. The expected fluxes of $\overline{^4\mathrm{He}}$ and $\overline{^3\mathrm{He}}$ (Fig. 2) from such an antimatter object [14] are only a factor of 2 below the limit of the AMS–01 (STS–91) experiment [15] and definitely accessible for the sensitivity of the coming AMS–02 experiment [7].

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