Macroscopically large antimatter regions
in the baryon asymmetric universe

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Abstract. The existence of macroscopic regions with antibaryon excess in the matter – dominated Universe is a possible consequence of the evolution of baryon charged, pseudo – Nambu – Goldstone field with lepton number violating couplings. Such regions can survive the annihilation with surrounding matter only in the case if their sizes exceeds the critical surviving size. The evolution of survived antimatter – regions with high original antibaryon density inside results in the formation of globular clusters, which is made out from antimatter stars. The origin of antimatter regions in the chosen scenario is accompanied the formation of closed domain walls, which can collapse into massive black holes deposed inside the high density antimatter regions. This fact can give us an additional hint, that an anti – stars globular cluster could be one of the collapsed – core star clusters, which populate our galaxy.

INTRODUCTION

Since a long time the generally accepted motivation for baryon asymmetric Universe were the direct observations, which claim to exclude the macroscopic amount of antimatter within the distance up to 20Mpc from the solar system [1]. Moreover, if larger than 20Mpc regions of matter and antimatter coexist, then it would be impossible to keep them out of the close contact during an early time, because the uniformity of CMBR excludes the existence of any significant voids. The annihilation, which would take place at the border between matter and antimatter region, during the period \(1100 > z > 20\), would disturb the diffuse \(\gamma\) – ray background [2], if the size of matter or antimatter regions does not exceed \(10^3\)Mpc. Thus the baryon symmetric Universe is practically excluded. However, such arguments cannot exclude the case when the Universe is composed almost entirely of matter with relatively small insertions of primordial antimatter. Thus we could expect the existence of macroscopically
large antimatter regions in the baryon asymmetric universe as a whole. We call such a region the local antimatter area (LAA).

Any primordial LAA having initial size up to $\simeq 1 \text{pc}$ or more at the end of radiation dominated (RD) stage is survived the boundary annihilation with surrounding matter until the contemporary epoch [3] and in the case of successive homogeneous expansion has the critical surviving size $l_c \simeq 1 \text{kpc}$ or more. The smaller LAA’s will be eaten up by the annihilation. This fact makes problematically to apply any model with usual thermal phase transition to modulate primordial matter antimatter distribution over the size exceeding $l_c$ [4,5]. We could think about a possible inflational blow upping of the correlation length of a usual phase transition [6], but one should also take care about some unwanted topological defects, which could accompany phase transitions and significantly contribute to the energy density of the universe. Mostly, to get rid from unwanted topological defects some mechanisms of symmetry restoration should be invoked [6]. Here we present the issue for inhomogeneous baryogenesis [5], which is free from the difficulties connected with usual phase transition approach and able to generate a considerable number of above – critical LAAs, what makes reasonable to discuss the existence of primordial LAA in our galactic volume.

**FORMATION AND EVOLUTION OF LAA’S**

*The Formation scenario.* Our antimatter generation scenario [5] is based on the spontaneous baryogenesis mechanism [7], which implies the existence of complex scalar field $\chi = \left(\frac{f}{\sqrt{2}}\right) \exp(\theta)$ carrying baryonic charge with explicitly broken $U(1)$ symmetry. The explicit breakdown of $U(1)$ symmetry is coming from the phase depended term, which tilts the bottom of the Nambu – Goldstone (NG) potential. We suppose [5] that the radial mass $m_\chi$ of field $\chi$ is larger then the Hubble constant $H$ during inflation, while for the angular mass of $\chi$ just the opposite condition $m_\theta \ll H$ is satisfied at that period. It makes sure that $U(1)$ symmetry is already broken spontaneously at the beginning of inflation, but the background vacuum energy is still so high, that the tilt of the potential is vanished. This implies that the phase $\theta$ behaves as ordinary massless NG boson and the radius of NG potential is firmly established by the scale $f$ of spontaneous $U(1)$ symmetry breaking. Owing to quantum fluctuations of effectively massless angular component $\theta$ at the de Sitter background [9] the phase $\theta$ is varied in different regions of the Universe. Actually, such fluctuations can be interpreted as the one – dimensional Brownian motion [9] along the circle valley corresponding to the bottom of the NG potential. When the vacuum energy decreases the tilt of potential becomes topical, and pseudo NG (PNG) field starts oscillate. Let us assume that the phase value $\theta = 0$ corresponds to South Pole of NG field circle valley, and $\theta = \pi$ corresponds to the opposite pole. The positive gradient of phase in this
picture is routed as counterclockwise direction, and the dish of PNG potential would locate at the South Pole of circle. The possible interaction of field $\chi$ that violates the lepton number can have such a structure $[5,8]$, that as the $\theta$ rolls down in clockwise direction during the first oscillation, it preferentially creates baryons over antibaryons, while the opposite is true as it rolls down in the opposite direction during the first oscillation. Thus to have the globally baryon dominated Universe one must have the phase sited in the range $[\pi, 0]$, just at the beginning of inflation (when the size of the modern Universe crosses the horizon). Then subsequent quantum fluctuations move the phase to some points $\theta_i$ at the range $[0, \pi]$ causing the antibaryon excess production. If it takes place not later then after 15 e–folds from the beginning of inflation $[5]$, the size of LAA’s will exceed the critical surviving size $l_c$. Let set the phase at the point $\theta_{60}$ in the range $[\pi, 0]$, where for simplicity we suggest that the total number of inflational e–folds is 60. The phase makes Brownian step $\delta \theta = H/(2\pi f)$ at each e–fold. Because the typical wavelength of the fluctuation $\delta \theta$ generated during such timescale is equal to $H^{-1}$, the whole domain $H^{-1}$, containing $\theta_{60}$, after one e–fold effectively becomes divided into $e^3$ separate, causal disconnected domains of radius $H^{-1}$. Each domain contains almost homogeneous phase value $\theta_{60-1} = \theta_{60} \pm \delta \theta$. In half of these domains the phase evolves towards $\pi$ (the North Pole) and in the other domains it moves towards zero (the South Pole). To have LAA’s with appropriate sizes to avoid full annihilation one should require that the phase value crosses $\pi$ or zero not later then after 15 steps. The numerical calculations $[5]$ of the domain size distribution filled with appropriate phase values $\theta_i$ show that a volume box corresponding to each galaxy can contains $1–10$ above – critical regions with appropriate phase $\theta_i$ at the condition that the fraction of the universe containing $\theta_i$ is many orders of magnitude less then 1 $[5]$. The last conclusion makes sure that the universe will become baryon asymmetric as a whole. At the some moment after the end of inflation deeply at the Friedman epoch the condition $m_\theta \ll H$ is violated and the oscillations of $\theta$ around the minima of PNG potential are started. Then the stored energy density $\rho_\theta \simeq \theta^2 m^2_\theta f^2$ will convert into baryons and antibaryons. All domains where the phase starts to oscillate from the values $\theta_i$ will contain antimatter. The density of antimatter depends on the initial value $\theta_i$ and can be different in the different domains $[5]$. The average number density of surrounding matter should be normalised on the observable one $n_B/s \simeq 3 \cdot 10^{-10}$. This normalisation sets the condition $f/m_\theta \geq 10^{10}$ for the PNG potential $[5]$.

Anti – star globular cluster formation. At the condition $f \geq H \simeq 10^{13}$GeV $[5]$ we can have a considerable number of high density above – critical LAA’s that makes sense to discuss the possible evolution of such a LAA in our galaxy. It is well known $[10]$ that clouds, which have temperature near $10^4$K and densities several ten times that of the surrounding hot gas, are gravitationally unstable if their masses are of the order of $10^5M_\odot - 10^6M_\odot$. These objects are identified as the progenitor of globular cluster (GC) and
reflect the Jeans mass at the recombination epoch. From the other side the typical size of that mass is close to the $l_c$ at the end of RD epoch. Thus if the primordial antibaryon density inside a LAA was one order of magnitude higher than surrounding matter density, that LAA can evolve into antimatter GC [11]. Moreover, to imprint a characteristic Jeans mass the proto – GC must cool slowly [10] after the recombination, so the heating of dense antimatter might be supported by annihilation with surrounding matter. Thereby GC at the large galactocentric distance is the ideal astrophysical objects which could be made out of antimatter, because GC’s are the oldest galactic system to form in the universe, and contain stars of the first population. The existence of one of such anti – star GC with the mass $10^3 M_\odot - 10^5 M_\odot$ will not disturb observable $\gamma$ – ray background [11], but the expected fluxes of $^4\text{He}$ and $^3\text{He}$ from such an antimatter object [12] are only factor two below the limit of AMS–01 (STS–91) experiment [13] and definitely accessible for the sensitivity of coming up AMS–02 experiment.

Topological defects and black holes (BH). The angular term of $\chi^2 f^2(1 - \cos \theta)$, which breaks $U(1)$ symmetry explicitly has a number of discrete degenerate minima [14]. The equation of motion with such a potential admits a kink – like, domain wall (DW) solution, which interpolates between two adjacent vacua, for example between $\theta = 0$ and $\theta = 2\pi$. From the other side our scenario [5] deals with the situation when at the beginning of inflation the universe contains the uniform $\theta$ in the interval $[\pi, 0]$ and hence the final vacuum state of baryon asymmetric part is $\theta = 2\pi$. On the contrary, there will be the island with $\theta$ in the range $[0, \pi]$ where the phase came trough the North Pole due to the fluctuations. The phase inside that islands will produce preferentially antimatter and come to the vacuum state $\theta = 0$. Thus both states $\theta = 2\pi$ and $\theta = 0$ are separated by closed DW’s. The collapse of such a DW is unavoidable [14], and DW’s which are generated before 20 inflation $e$ – folds will form BH’s. The density profile, concentration and observable central cusp in the stars velocity dispersion of the collapsed – core clusters GC NGC 7078 (M15) consist with the hypothesis of the massive $\approx 10^5 M_\odot$ central BH existence [10]. This mass corresponds to the 33 inflation $e$ – folds. It means that the DW was originally already encompassed the size $l_c$ giving rise the central BH formation, which could induce the collapsed – core properties of M15.

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