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The Formalism of Milky-Way Antimatter-Domains Evolution

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Abstract: If baryosynthesis is strongly nonhomogeneous, macroscopic regions with antibaryon excess can be created in the same process from which the baryonic matter is originated. This exotic possibility can become real, if the hints to the existence of antihelium component in cosmic rays are confirmed in the AMS02 experiment, indicating the existence of primordial antimatter objects in our Galaxy. Possible forms of such objects depend on the parameters of models of baryosynthesis and evolution of antimatter domains. We elaborate the formalism of analysis of evolution of antibaryon domain with the account for baryon-antibaryon annihilation at the domain borders and possible "Swiss cheese" structure of the domain structure. We pay special attention to evolution of various forms of high, very high and ultrahigh density antibaryon domains and deduce equations of their evolution in the expanding Universe. The proposed formalism will provide the creation of evolutionary scenarios, linking the possible forms and properties of antimatter bodies in our Galaxy to the mechanisms of nonhomogeneous baryosynthesis.

Keywords: General Relativity; Classical General Relativity and exact solutions; antibaryons; antibaryon annihilation

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1. Introduction

The presence of antihelium component of cosmic rays at the level accessible to AMS02 experiment cannot be explained by natural astrophysical sources [1] and, if confirmed, can constitute evidence for the existence of primordial macroscopic antimatter objects in the Milky Way galaxy. The appearance of such objects in the baryon asymmetrical Universe would reflect strong nonhomogeneity of baryosynthesis and would shed light on the origin of baryonic matter in the Universe (see [2–7] for review and references).

The aim of the present paper is specifying the possible mechanisms of creation of antimatter objects in our Galaxy and studying the evolution of antimatter domains. Low-density antimatter domains cannot take part and evolve in the Galaxy formation, so that they cannot be present in our Galaxy.

In Section 2, the diffusion equation of dense antimatter domains is spelled out. All the terms that characterize the diffusion equation of dense antimatter domains are therefore provided with a well-posed Physical interpretation.

In Section 3, dense antimatter domains are classified. In particular, ultra-high-density antimatter domains, very-high-density ones, and high-density ones are introduced and distinguished.

The perfect-fluid Relativistic FRW equations of dense antimatter domains are identified in the three cases, according to the density properties of the delineation of the antimatter domains.

Baryon subdomains are studied. The matter domains are depicted as of a size exceeding the survival size, located inside an antimatter domain, according to the baryosynthesis process.

Further structures are indicated, which result according to the baryosynthesis process. In more detail, an antimatter domain containing a matter domain is depicted; an antimatter domain containing several antimatter domains is described such as a 'Swiss-cheese' structure; and an antimatter domain containing a matter domain, containing an antimatter domain is illustrated such as a 'Chinese-boxes' structure.

The non-relativistic perfect-fluid equation for the antimatter domains is written.

In Section 4, Relativistic FRW solutions of dense antimatter domains are given, for the three cases of the antimatter-domains densities.

The conditions and evolution of different types of strong primordial inhomegeneities in non-homogeneous baryosynthesis processes are provided.

The analytical expressions of the Relativistic density of surviving antimatter domains at the time of Galaxy formation are written.

In Section 5, the experimental verifications proposed for the presence of antimatter domains are reviewed.

Comparison with other types of celestial bodies is denoted.

In Section 6, outlooks and perspectives are envisaged.

In Section 7, brief concluding remarks are presented.

2. Dense Antimatter Domains

In the first approximation, we can consider domain with surviving size with internal density in it as homogeneous, after annihilation of smaller matter domains within it.

Diffusion Equation of Dense Antimatter Domains

This assumption should be proved by analysis of relaxation of plasma after local annihilation inside the domain and on its borders. It is evident that there will be transitional zone at the outer border of the domain, where internal antibaryon density is changed by the outer baryon density, but we can neglect this detail in the first approximation. However, we should take into account the dynamical back-reaction of annihilation at the border (here the analysis [8] may be useful)

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} + Q(\vec{r}, p, t) - \frac{n_{\bar{b}}}{t_d} + \sum_i F_i(p, \dot{p}; \ldots) - f(\rho_E, \vec{p}; R_d, l_d; \vec{v}_T, v_f; \tilde{i}) - \mu \nabla^2 n_{\bar{b}}. \quad (1)$$

In Equation (1), $n_{\bar{b}}$ is the the antibaryon number density, n_b the baryon number density, $< \sigma v >_{ext}$ the cross section with external matter, $Q(\vec{r}, p, t)$ is a source term (which can be neglected as any further antimatter production is not at this stage considered), $F_i(p, \dot{p}; \ldots)$ are further terms depending on the momentum, which can be neglected, f is further plasma characterization functions in terms of the viscosity properties and of the turbulent velocity (which can be neglected for dense domains), $\frac{n_{\bar{b}}}{t_d} \simeq < \tilde{\sigma} \tilde{v} >_{int} n_{\bar{b}} n_b$ is decay rate inside the interior of the domain [9], t_d is time scale for annihilation the annihilation cross-section $< \tilde{\sigma} \tilde{v} >_{int}$ as from Equation (6.29) in [10], $\beta n_{\bar{b}}$ is a relativistic addend that takes into account the expansion of an FRW universe [11]. From Equation (1), it is only effect of annihilation of free baryons at the borders of domains and inside them, and no effects of pressure (because of different densities of baryon and antibaryon neighbouring/contact areas and/or of annihilation radiation), diffusion in matter, CMB, and other effects are analytically described.

After introducing the quantityx t_s, which is defined as proportional to the inverse of the mean free path of antibaryons in the external spherical-shell interaction region, and t_d, which is defined as proportional to the inverse of the mean free path of antibaryons in the internal region of the domain, the following description is found

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} - < \tilde{\sigma} \tilde{v} >_{int} n_b n_{\bar{b}} - \mu \nabla^2 n_{\bar{b}} \equiv -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - < \tilde{\sigma} \tilde{v} >_{int} n_b n_{\bar{b}} - \frac{n_{\bar{b}}}{t_s} - \beta n_{\bar{b}} - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} \quad (2)$$

as a function of t_s the time scale of the annihilation at the boundary and $< \tilde{\sigma} \tilde{v} >_{int}$ the cross section of the interaction inside the domain.

Equation (2) rewrites

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - < \tilde{\sigma}\tilde{v} >_{int} n_b n_{\bar{b}} - \beta n_{\bar{b}} - \frac{n_{\bar{b}}}{t_d} \equiv -\frac{3d}{R}\frac{n_{\bar{b}}}{t_s} - < \tilde{\sigma}\tilde{v} >_{int} n_b n_{\bar{b}} - \beta n_{\bar{b}} - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} \quad (3)$$

After imposing the physical implementation of the diffusion equation specified for the kinds of antimatter domains, Equation (2) rewrites

$$\frac{d\bar{r}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} r n_\gamma \bar{r} - \beta \bar{r} - < \sigma v >_{int} r n_\gamma \bar{r} - \frac{\mu}{n_\gamma} \nabla^2 n_{\bar{b}}. \quad (4)$$

The hypothesis

$$< \sigma v > r n_\gamma \Delta t \sim 1, \quad (5)$$

in which the dependence of the cross section is hypothesised as depending on the time interval Δt only, does not hold for dense antimatter domains. According to the further purposes of the analysis, one notes that the diffusion term is described as

$$\nabla^2 n_{\bar{b}} \simeq const$$

i.e., such that one imposes the characterization

$$-\frac{\beta}{n_\gamma} n_{\bar{b}} \equiv \tilde{\beta} \quad (6)$$

with

$$\tilde{\beta} << 1. \quad (7)$$

Equation (4) is solved as

$$ln[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0) + < \tilde{\sigma}\tilde{v} >_{int} r n_\gamma (t_\tau - t_0)] = -\frac{1}{3}(\frac{4\pi}{3})^{1/3} < \sigma v >_{ext} r n_\gamma \int_{t_i}^{t_\tau} \frac{\delta(t)}{a(t)} dt \quad (8)$$

with $a(t) = 4\pi R(t)/3$ and $d = \delta(t)$, from which

$$\frac{d}{dt_\tau}(ln[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0) + < \tilde{\sigma}\tilde{v} >_{int} r n_\gamma (t_\tau - t_0)]) = -\frac{1}{3}(\frac{4\pi}{3})^{1/3} < \sigma v >_{ext} r n_\gamma \frac{\delta(t_\tau)}{a(t_\tau)} \quad (9)$$

3. Classification of Dense Antimatter Domains

By construction both antibaryon and baryon densities are much higher than average baryon density in all the Universe and we should consider several cases as follows.

(i) Ultra-high-density antimatter domains: the antibaryon and baryon excess starts to exceed the contribution of thermal quark-antiquark pairs before QCD phase transition. The baryon density is much greater than the DM density, while, locally, ρ_B starts to dominate pairs (which are in thermal equilibrium) before the QCD-phase transition.

The baryon density in this case exceeds the density of Relativistic species s, i.e.,

$$\rho_{\bar{B}} > \rho_s. \quad (10)$$

Before the QCD phase transition, it exceeds the quark-antiquark $q\bar{q}$ density, i.e.,

$$\rho_{\bar{B}} > \rho_{q\bar{q}}. \quad (11)$$

This means that locally, a region of cold Universe can be considered, in which there is a strong degeneracy of (anti-)baryonic matter. It requires rigorous analysis of the specifics of electroweak and QCD phase transitions at high (anti-)baryonic densities. Qualitative evolution of such ultra-high-density domains should lead to their separation from expansion. Indeed, before the QCD phase transition, but after the electroweak phase transition, the masses of quarks and leptons have already been created. Nevertheless, during the QCD phase transition, the density is not concentrated only in the $\bar{u}$ $\bar{d}$ states, but there is also an excess of $\bar{s}$ quarks; in principle, there are very non-trivial models in which there is the possibility of constituent masses of quarks, but there are at least bare masses of quarks. Because of the s masses, until the QCD phase transition there is no relevant phenomena due to the $q\bar{q}$ presence, and the plasma is Relativistic due to its chemical potential and not due to the high temperature, as it is the case in the Big Bang Universe. The antibaryon density exceeds the Relativistic energy density after the QCD phase transition, and the plasma is semi-Relativistic. Within this regime, the non-Relativistic matter is dominant, a huge excess of antibaryons is present; and a separation from the General-Relativistic expansion is caused. One should note that the antibaryon chemical potential may be so high that antibaryons in this region may experience relativistic degeneracy, but this specifics of the internal property of domain does not influence the principal conclusion of its early separation and formation of ultra-high density antibaryonic object.

(ii) Very-high-density antimatter domains: the antibaryon density and the baryon one exceed the contribution of plasma and radiation after the QCD phase transition.Antibaryons start dominating on the Relativistic species; in this regime, at the QCD phase transition the separation happens immediately; the contribution of the antibaryon excess starts dominating immediately the Relativistic species, at temperatures below the QCD temperature phase transition.

(iii) High-density antimatter domains: the antibaryon density and baryon one exceed the DM density.

3.1. Perfect-Fluid FRW Equations of Dense Antimatter Domains

Perfect-fluid FRW equations of dense antimatter domains are found; the physical characterization of the diffusion equation is accomplished according to the density of the antimatter domains, for which the dominant terms are outlined.

Locally, the antibaryon density is larger than the DM density; the separation of matter and antimatter takes place much later than the QCD phase transition. At temperatures which are larger than that of the radiation-dominated epoch, the antibaryon excess starts to dominate.

(i) In the case of ultra-high-density antimatter domains, the following specification holds

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} - \mu \nabla^2 n_{\bar{b}} \equiv -\frac{n_{\bar{b}}}{t_s} - \beta n_{\bar{b}} + \tilde{\beta} + \tilde{\mu} \tag{12}$$

(ii) In the case of very-high density antimatter domains, the following designation holds

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} \equiv -\frac{n_{\bar{b}}}{t_s} - \beta n_{\bar{b}} - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} \tag{13}$$

(iii) In the case of high-density antimatter domains, the following identification holds

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} \equiv -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \frac{n_{\bar{b}}}{t_s} - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} \tag{14}$$

3.2. Baryon-Subdomains and Their Characterization

It is within reach to represent baryon subdomains contained into the dense antimatter domains.

The presence of antibaryons inside the baryon domain is dependent on the second phase transition. For axion-like particles, it is dependent on the QCD phase transition, according to the type of phase transition, which is determined after the value of the parameter (function) Λ.

(I) In the case of $\Lambda < \Lambda_{QCD}$ Baryons density n_b in a baryon subdomain exceeding the survival size of volume $V_j = 4\pi R_j^3/3$ filled with (grazing) antibaryons there holds the plasma characterization

$$\frac{dn_b}{dt} = - < \tilde{\sigma} \tilde{v} >_{j \ ext} n_b n_{\bar{b}} - < \hat{\sigma} \hat{v} >_{j \ int} n_b n_{\bar{b}} - \nu \nabla^2 n_b \tag{15}$$

ν being the specific chemical potential, for which the following perfect-fluid relativistic FRW solution is found

$$-\frac{1}{3}(\frac{4\pi}{3})^(1/3)\bar{r}_{ext}n_\gamma < \tilde{\sigma}\tilde{v} >_{j\ \ ext} \frac{\tilde{\delta}(t_\tau)}{\tilde{a}(t_\tau)} = \frac{d}{dt_\tau} ln[r_{int}\bar{r}_{int}n_{\gamma\ \ int} < \hat{\sigma}\hat{v} >_{j\ \ int} - \tilde{v}(t_\tau - t_0)] \tag{16}$$

(II) In the case of $\Lambda > \Lambda_{QCD}$, it is practicable to analyze the number density of baryons n_b in a baryon subdomain exceeding the survival size of volume $V_j = 4\pi R_j^3/3$ without free antibaryons inside, whose number-density can be considered as negligible as

$$\frac{dn_b}{dt} = - < \tilde{\sigma}\tilde{v} >_{j\ \ ext}\ n_b n_{\bar{b}} - \nu\nabla^2 n_b \tag{17}$$

for which the following perfect-fluid relativistic FRW solution is found

$$-\frac{1}{3}(\frac{4\pi}{3})^{1/3}\bar{r}_{ext}n_\gamma < \tilde{\sigma}\tilde{v} >_{j\ \ ext} \frac{\delta(\tilde{t_\tau})}{\tilde{a}(t_\tau)} = \frac{d}{dt_\tau} ln[-\tilde{v}(t_\tau - t_0)] \tag{18}$$

3.3. Further Structures

It is viable to analyze further structures comprehended in the antimatter-domains description.

3.4. Antibaryon Domain Containing One Baryon Subdomain

In the simplest case, it is attainable to consider a baryon domain of baryon density n_{bi}, whose size is large enough not to undergo complete annihilation, contained in the antimatter domain.

One of the modification terms of the differential equation of the antibaryon to photon ration depends on the cross-section $< \sigma_i v_i >$ of the antibaryon to baryon annihilation process which takes place in the spherical shell containing the baryon domain of width d_i and volume $V_i = 4\pi R_i^2 d_i$, being R_i the radius of the small baryon domain; Equation (1) modifies as

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \tilde{\sigma}\tilde{v} >_{ext}\ n_{\bar{b}}n_b - \beta n_{\bar{b}} + Q(\vec{r}, p, t) - \frac{n_{\bar{b}}}{t_d} + F_i(p, \dot{p}; \ldots) - \mu\nabla^2 n_{\bar{b}} - \frac{3d_i}{R_i} < \hat{\sigma}_i\hat{v}_i > n_{\bar{b}}n_{bi} - \mu_i\nabla^2 n_{\bar{b}} \tag{19}$$

3.5. Antibaryon Domain Containing Baryon Sub-Domains

As a generalization of the previous description, it is achievable to delineate the physical characterization of one antimatter domain containing several matter domains, as a 'Swiss-cheese' structure, as

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \tilde{\sigma}\tilde{v} >_{ext}\ n_{\bar{b}}n_b - \beta n_{\bar{b}} + Q(\vec{r}, p, t) - \frac{n_{\bar{b}}}{t_d} + \sum_i \left(F_i(p, \dot{p}; \ldots) - \mu\nabla^2 n_{\bar{b}} - \frac{3d_i}{R_i} < \hat{\sigma}_i\hat{v}_i > n_{\bar{b}}n_{bi} - \mu_i\nabla^2 n_{\bar{b}} \right) \tag{20}$$

3.6. Swiss-Cheese Structures

It is therefore now possible to implement the delucidation of the 'Swiss-cheese' structure of antimatter domains as

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext}\ n_{\bar{b}}n_b - \beta n_{\bar{b}} + Q(\vec{r}, p, t) - \frac{n_{\bar{b}}}{t_d} + \sum_i F_i(p, \dot{p}; \ldots) - \mu\nabla^2 n_{\bar{b}} + \sum_i [-\frac{3d_i}{R_i} < \sigma_v >_{i\ \ ext}\ n_{\bar{b}}n_{bi} - \mu_i\nabla^2 n_{\bar{b}}] \tag{21}$$

3.7. 'Chinese-Boxes' Structures

It is realizable to determine the characterization of 'Chinese-boxes' structures for antimatter domains. Such structures are describes as an antimatter domain containing a matter domain, which, on its turns, contain an antimatter domain, and so on, according to the baryosynthesis process. Such structures are characterized as follows

$$\frac{dn_{\bar{b}}}{dt} = -\frac{3d}{R} < \sigma v >_{ext} n_{\bar{b}} n_b - \beta n_{\bar{b}} + Q(\vec{r}, p, t) - \frac{n_{\bar{b}}}{t_d} - \mu \nabla^2 n_{\bar{b}} - \sum_{i=1}^{i=I} \Big[F_i(p, \dot{p}; \ldots) - \mu \nabla^2 n_{\bar{b}i} - \frac{3d_i}{R_i} < \sigma_v >_{i \ \ ext} n_{\bar{b}} n_{bi} \Big] + + \sum_{j=1}^{j=J} \Big[F_j(p, \dot{p}; \ldots) - \mu \nabla^2 n_{\bar{b}j} - \frac{3d_j}{R_j} < \sigma_v >_{j \ \ ext} n_{\bar{b}} n_{bj} \Big] \tag{22}$$

3.8. Non-Relativistic Perfect-Fluid Equation

It is now possible to write the solution of the diffusion equation of the non-relativistic characterization as

$$ln[\frac{r_f}{r_i} + (\tilde{\mu})] \simeq -\int_{t_i}^{t_f} \frac{3d}{a} \simeq -\frac{-d}{3R}(t_f - t_i) \tag{23}$$

i.e., under the hypothesis of a non-relativistic characterization of the radius of the domain.

4. Relativistic FRW Solutions of Dense Antimatter Domains

It is now possible to write the solution of the Relativistic FRW diffusion equation of dense antimatter domains.

One poses

$$-\frac{\mu}{n_\gamma} \nabla^2 n_{\bar{b}} \equiv \tilde{\mu} \tag{24}$$

with

$$\tilde{\mu} << 1, \tag{25}$$

i.e., the chemical-potential term is physically characterised; as a result (i) Equation (4) is solved as

$$ln[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)] = -\frac{1}{3}\left(\frac{4\pi}{3}\right)^{1/3} < \sigma v >_{ext} r n_\gamma \int_{t_i}^{t_\tau} \frac{\delta(t)}{(a(t))^{1/3}} dt \tag{26}$$

with $a(t) = 4\pi R(t)^3/3$ and $d = \delta(t)$, from which

$$\frac{d}{dt_\tau}(ln[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)]) = -\frac{1}{3}\left(\frac{4\pi}{3}\right)^{1/3} < \sigma v >_{ext} r n_\gamma \frac{\delta(t_\tau)}{(a(t_\tau))^{1/3}} \tag{27}$$

The expression of the spherical shell δ reads

$$\delta(t_\tau) \sim -\left(\frac{3}{4\pi}\right)^{1/3} \frac{3(a(t_\tau))^1/3}{< \sigma v >_{ext} r n_\gamma} \frac{\frac{d}{dt_\tau}[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)]}{[\frac{r_\tau}{r_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)]} \tag{28}$$

The expression of the radius of the antimatter domain reads

$$(a(t_\tau))^{1/3} = -\left(\frac{3}{4\pi}\right)^{1/3} \frac{< \sigma v >_{ext} r n_\gamma \delta(t_\tau)}{3} \frac{[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)]}{\frac{d}{dt_\tau}[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)]} \tag{29}$$

The expression of the interaction width of the antimatter domain depends therefore also on the domain's radius in a non-trivial manner, i.e., as a prefactor.

(ii)

$$ln[\frac{\bar{r}_\tau}{\bar{r}_0} + < \tilde{\sigma}\tilde{\mu} >_{int \ \ j} r n_\gamma \bar{r} - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)] = -\frac{1}{3}\left(\frac{4\pi}{3}\right)^{1/3} \int_{t_i}^{t_\tau} \frac{\delta(t)}{(a(t))^{1/3}} dt \tag{30}$$

with $a(t) = 4\pi R(t)^3/3$ and $d = \delta(t)$, from which

$$\frac{d}{dt_\tau}(ln[\frac{\bar{r}_\tau}{\bar{r}_0} + < \tilde{\sigma}\tilde{\mu} >_{int \ \ j} r n_\gamma \bar{r}(t_\tau - t_0) - (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0)]) = -\frac{1}{3}\left(\frac{4\pi}{3}\right)^{1/3} \frac{\delta(t_\tau)}{(a(t_\tau))^{1/3}} \tag{31}$$

The expression for the spherical shell δ reads

$$\delta(t_\tau) \sim -\left(\frac{3}{4\pi}\right)^{1/3} \frac{3(a(t_\tau))^1/3}{<\sigma v>_{ext}\ rn_\gamma} \frac{\frac{d}{dt_\tau}[\frac{\bar{r}_\tau}{\bar{r}_0} + <\tilde{\sigma}\tilde{\mu}>_{int\ j}\ rn_\gamma \bar{r}(t_\tau - t_0) - (\tilde{\beta}+\tilde{\mu})(t_\tau - t_0)]}{[\frac{\bar{r}_\tau}{\bar{r}_0} + <\tilde{\sigma}\tilde{\mu}>_{int\ j}\ rn_\gamma \bar{r}(t_\tau - t_0) - (\tilde{\beta}+\tilde{\mu})(t_\tau - t_0)]} \tag{32}$$

The expression for the radius of the antimatter domain reads

$$(a(t_\tau))^{1/3} = -\left(\frac{3}{4\pi}\right)^{1/3} \frac{<\sigma v>_{ext}\ rn_\gamma \delta(t_\tau)}{3} \frac{[\frac{\bar{r}_\tau}{\bar{r}_0} + <\tilde{\sigma}\tilde{\mu}>_{int\ j}\ rn_\gamma \bar{r}(t_\tau - t_0) - (\tilde{\beta}+\tilde{\mu})(t_\tau - t_0)]}{\frac{d}{dt_\tau}[\frac{\bar{r}_\tau}{\bar{r}_0} - + <\tilde{\sigma}\tilde{\mu}>_{int\ j}\ rn_\gamma \bar{r}(t_\tau - t_0) - (\tilde{\beta}+\tilde{\mu})(t_\tau - t_0)]} \tag{33}$$

The expression of the spherical-shell interaction width of the antimatter domain depends therefore also on the radius in a non-trivial manner, i.e., as a prefactor.

(iii)

$$ln[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\mu})(t_\tau - t_0)] = -\frac{1}{3}\left(\frac{4\pi}{3}\right)^{1/3} <\sigma v>_{ext}\ rn_\gamma \int_{t_i}^{t_\tau} \frac{\delta(t)}{(a(t))^{1/3}} dt \tag{34}$$

with $a(t) = 4\pi R(t)^3/3$ and $d = \delta(t)$, from which

$$\frac{d}{dt_\tau}(ln[\frac{\bar{r}_\tau}{\bar{r}_0} - (\tilde{\mu})(t_\tau - t_0)]) = -\frac{1}{3}\left(\frac{4\pi}{3}\right)^{1/3} <\sigma v>_{ext}\ rn_\gamma \frac{\delta(t_\tau)}{(a(t_\tau))^{1/3}} \tag{35}$$

The expression for the spherical shell δ reads

$$\delta(t_\tau) \sim -\left(\frac{3}{4\pi}\right)^{1/3} \frac{3(a(t_\tau))^1/3}{<\sigma v>_{ext}\ rn_\gamma} \frac{\frac{d}{dt_\tau}[\frac{\bar{r}_\tau}{\bar{r}_0} - \tilde{\mu}(t_\tau - t_0)]}{[\frac{\bar{r}_\tau}{\bar{r}_0} - \tilde{\mu}(t_\tau - t_0)]} \tag{36}$$

The expression for the radius of the antimatter domain reads

$$(a(t_\tau))^{1/3} = -\left(\frac{3}{4\pi}\right)^{1/3} \frac{<\sigma v>_{ext}\ rn_\gamma \delta(t_\tau)}{3} \frac{[\frac{\bar{r}_\tau}{\bar{r}_0} - \tilde{\mu}(t_\tau - t_0)]}{\frac{d}{dt_\tau}[\frac{\bar{r}_\tau}{\bar{r}_0} - \tilde{\mu}(t_\tau - t_0)]} \tag{37}$$

The expression of the spherical-shell interaction width of the antimatter domain depends therefore also on the radius of domain in a non-trivial manner, i.e., as a prefactor.

4.1. Conditions and Evolution of Different Types of of Strong Primordial Inhomogeneities in Non-Homogeneous Baryosynthesis

In the case of non-homogeneous primordial baryosynthesis, various types of scenarios can accomplish: antimatter consisting of axion-like particles; closed walls for baryogenesis with excess of antibaryons; phase fluctuations such that a baryon excess is created everywhere and with non-homogeneous distribution.

In order to avoid large-scale fluctuations, fluctuations must be imposed to be small.

In the latter cases,

$$\frac{3B}{4\pi R(t)^3} >> \rho_B \tag{38}$$

before recombination. The excess of antibaryon B therefore interacts with the antimatter domains as in the following picture. Three regions can be outlined: (1) the dense antimatter domain of antibaryon number density n_{b1} of radius $R \leq R_1$ and chemical potential μ_1; (2) the outer spherical shell region of antibaryon number density n_{b2}, of radius $R_1 \leq R \leq R_2$ and chemical potential μ_2, where diffusion process happens; and (3) the outmost region of antibaryon number density n_{b3} of radius $R_3 \geq R_2$ of low antimatter density, as from Equation (38).

From this picture, the following system of equations is set for the three regions: in Region (1)

$$\frac{n_{b1}}{dt} = -\mu_1 \nabla^2 n_{b1} \sim \tilde{\mu_1} n_{b1}; \tag{39}$$

in Region (2)

$$\frac{n_{b2}}{dt} = -\mu_2 \nabla^2 n_{b2} \sim \tilde{\mu_2} n_{b2}; \tag{40}$$

and in Region (3)

$$\frac{n_{b3}}{dt} = -\mu_3 \nabla^2 n_{b3} \sim \tilde{\mu_3} n_{b3} \tag{41}$$

The hypotheses $\tilde{\mu_1} << 1$, $\tilde{\mu_2} << 1$, and $\tilde{\mu_3} << 1$ are supposed to hold.

The diffusion process is described through the three regions as follows. In Region (1)

$$n_{b1}(t) = n_{b1(t_0)} \tilde{\mu_1}(t - t_0) \tag{42}$$

in Region (2)

$$n_{b2}(t) = n_{b2(t_0)} \tilde{\mu_2}(t - t_0) \tag{43}$$

Region (3)

$$n_{b3}(t) = n_{b3(t_0)} \tilde{\mu_3}(t - t_0) \equiv e^{N_0 \ \ 3(t-t_0)}. \tag{44}$$

The physical setting system is therefore clarified after the imposition of the continuity conditions

$$n_{b1}(t, R_1) = n_{b2}(t, R_1) \tag{45}$$

on the boundary of Region (1), and

$$n_{b2}(t, R_2) = n_{b3}(t, R_2) \tag{46}$$

on the boundary of Region (2) the antibaryon number densities n_{b1}, n_{b2}, n_{b3} being functions of the radii R_1, R_2 and R_3.

4.2. Domains Survival to the Epoch of Galaxy Formation

The features of the relativistic densities of the surviving antimatter domains at the epoch of galaxy formation are here further delineated.

In the case of ultra-high density antimatter domains (i), the expression of the cross section reduces to the case

$$< \sigma v >_{int} r = 0, \tag{47}$$

with

$$\tilde{\mu}(t_\tau - t_0) n_\gamma << 1, \tag{48}$$

$$\tilde{\beta}(t_\tau - t_0) n_\gamma << 1, \tag{49}$$

$$(\tilde{\mu} + \tilde{\beta})(t_\tau - t_0) n_\gamma << 1, \tag{50}$$

i.e.,such that

$$\frac{\bar{r}_\tau n_\gamma}{a(t_\tau)} = \frac{1}{a(t_\tau)} \frac{n_\gamma}{\frac{1}{\bar{r}_0} + (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0) n_\gamma} e^{\frac{1}{3}} \left(\frac{4\pi}{3}\right)^{1/3} < \sigma v >_{ext} r_0 n_\gamma \int_{t_0}^{t_\tau} \frac{\delta t}{a(t)} dt. \tag{51}$$

In the case of very-high density antimatter domains (ii), the diffusion equation is characterized as

$$\frac{\bar{r}_\tau n_\gamma}{a(\tau)} = \frac{1}{a(t_\tau)} \frac{n_\gamma}{\frac{1}{\bar{r}_0 n_\gamma} + (\tilde{\beta} + \tilde{\mu})(t_\tau - t_0) n_\gamma} e^{\frac{1}{3}} (\frac{4\pi}{3}^{1/3}) < \sigma v >_{ext} r_0 n_\gamma \int_{t_0}^{t_\tau} \frac{\delta t}{a(t)} dt. \tag{52}$$

In the case of high-density antimatter domains (iii), the diffusion equations is further delineated as

$$\frac{\bar{r}_\tau n_\gamma}{a(\tau)} = \frac{1}{a(t_\tau)} \frac{1}{\frac{n_\gamma}{\bar{r}_0} + \tilde{\mu}(t_\tau - t_0) n_\gamma} e^{\frac{1}{3}} (\frac{4\pi}{3}^{1/3}) < \sigma v >_{ext} r_0 n_\gamma \int_{t_0}^{t_\tau} \frac{\delta t}{a(t)} dt \tag{53}$$

5. Experimental Verification Purposes

In the present Section, some of the the experimental verification methods for the existence of antimatter domains are recapitulated, according to the different domains-creation mechanisms.

In [12], the properties of $p\bar{p}$ atoms are studied.

In [13], the γ-ray spectrum originated after the $p\bar{p}$ annihilation in liquid Hydrogen is analysed by means of two BGO spectrometers. No exotic narrow peaks are detected, and the upper limit is calculated.

In [8], the results were used to estimate the γ-ray signal due to matter-antimatter annihilation on the boundary of antimatter domains in the case of a matter/antimatter symmetric Universe. In the case of a matter/antimatter symmetric Universe, more γ-rays than the observed quantities are predicted. As a conclusion, a matter/antimatter symmetric Universe is postulated to be possible if and only if the present Universe is one consisting of the matter quantity.

It is our purpose to study the results obtained in [8] to investigate the γ-ray signal from a matter/antimatter asymmetric Universe.

More in detail, the $p\bar{p}$ interaction process is examined as resulting in photons after the π^0 decay. With $\bar{g}$ the mean photon multiplicity, each of the $p\bar{p}$ annihilation processes are judged to resolve in $\bar{g} \simeq 3.8$ electrons and positrons, and an approximately similar number of photons. The features of the annihilation electrons are considered at a redshift y estimated as $20 < y < 1100$; and the mechanisms that rule the electrons motion are taken into account. As a result of the investigation, the mechanisms that rule the annihilation electrons motions are summarized as being the cosmological redshift, the collision with cosmic background radiation (CBR) photons, and the collision with ambient plasma electrons. At the considered redshift values, a more important control mechanism consists of the collisional energy loss. As far as collisional energy losses are concerned, collisions with CBR photons is considered to be the more important control mechanism ruling the electron trajectory. Being L the width of the reheated zone, where the electrons produced after the annihilations directly deposit energy into the fluid, i.e., the electron range, for initially-Relativistic electrons of energy $E_0 = \gamma_0 m_e$, the dependence of L on γ_0 is calculated as negligible.

The inclusive photon spectrum in the $p\bar{p}$ process is normalized to $\bar{g}$; the average number of photons made per unit volume is quantified. The transport equation of the photons scatter and redshift, which conducts to a spectral flux of annihilation photons, is calculated. The conservative lower limit for the γ-ray signal is estimated.

Comparison with Other Celestial Bodies—Antistars

In [14], the presence of antimatter in the Milky Way Galaxy is reviewed in its several manifestations.

The bounds of antistars densities were posed after the study of the boundaries of antistars, where the matter/antimatter annihilation takes place (as a function of the mean free path before annihilation) [15–17].

6. Outlook and Perspectives

The nontrivial feature of an ultra high density domain is that we can consider the antibaryon chemical potential in it to be so high that it makes antimatter in the domain relativistic degenerated Fermi gas of quarks. We aim to correctly describe the properties of relativistic gas of excessive quarks. It is our aim to testify that if $\mu > T > T_{EW}$, where T_{EW} is the critical temperature of EW phase transition, we have relativistic degenerated Fermi gas of massless quarks dominating in the domain (the number of other species should be taken into account to determine the value of μ properly for this case). The conditions inside such a domain and at its border should be specified and analysed.

Phenomenological analysis should correctly take into account specific conditions of evolution of the ultra high density domain. This evolution leads to degenerated relativistic antiquark gas, so that we should correctly take into account phase transitions, which take place not at high temperature but at high density of antibaryonic matter (both electroweak phase transition and the QCD one).

7. Concluding Remarks

The presence of antimatter domains at present times can be ascribed also at a geometrical origin; in particular, non-standard geometrical objects can lead to axion-fields background to the inflationary field during the inflationary epoch [18].

Matter domains and antimatter domains are predicted in [19], in which case matter domains and antimatter domains (where the latter have negative gravitational mass) are predicted to exhibit a repulsion which can be responsible of the expansion of the universe.

A model in which domain walls are predicted in the early universe only is presented in [20]; more in detail, antimatter domains are predicted to exist, and to populate the universe as separated at cosmological distances.

CP violation is described as responsible of the existence of large antimatter domains even at present times in [21].

The presence of cosmologically-large baryon domains and antibaryon domains can be ascribed also to C violation in the early universe [22].

The formalism developed in the present paper will be used to elaborate cosmological scenarios, which will be aimed to link such processes in very early Universe to the predicted forms and properties of the macroscopic antimatter component of the Milky Way.

In the present analysis, the features of antimatter domains according to the density characterization are expressed in Equation (47), Equation (52), and Equation (53). These obtained solutions can provide the basis for the further analysis of physical evolution of antimatter within dense domains, involving specifics of nucleosynthesis and formation of gravitationally bound objects. The predicted properties of these objects will shed light on the expected forms of antimatter signal accessible to detection at the AMS02 experiment and in particular clarify the significance of the search for the antihelium component of cosmic rays.

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