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Effects of Baryon-Antibaryon Annihilation in the Evolution of Antimatter Domains in Baryon Asymmetrical Universe

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Abstract: The mechanisms of baryosynthesis, which involve the three Sakharov's conditions, admit a possibility of nonhomogeneous generation of baryon excess. It may take place in the case of spatial variation of CP violating phase or of the baryon generating field in the early Universe. In the extreme case this nonhomogeneity can lead to the change of sign of baryon excess and formation of antibaryon domains in baryon asymmetrical Universe. Surrounded by the baryon matter, evolution of antibaryon domains is strongly influenced by effect of baryon and antibaryon diffusion to the border of domain and their annihilation. It leads to change of size of domains and antibaryon density in them. The consequence of antibaryon-baryon annihilation at the border of antimatter domains in baryon-asymmetrical Universe is investigated. The successive evolution in the expanding Universe strongly depends on antibaryon density within domain. At low density it is not sufficient to provide separation from cosmological expansion. Such separation can, however, be provided by effects of dark matter, which we briefly discuss. Low-density antimatter domains are further classified with the account for the border interactions. Differently, a similar classification scheme is also proposed for higher-densities antimatter domains. The effects of antinuclei-nuclei-interaction-patterns are investigated and taken into account in the analysis of antimatter domain evolution.

Keywords: baryosynthesis; antimatter; Classical general relativity; fundamental problems and general formalism; Classical general relativity: exact solutions; antibaryons

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1. Introduction

Formation of antimatter domains in baryon asymmetrical Universe can take place in several cosmological scenarios with nonhomogeneous baryosynthesis. Successive evolution of such domains depends on antibaryon density within them and on effects of baryon-antibaryon annihilation with the surrounding matter [1–12]. The interaction of antimatter from antimatter domains with matter in the surrounding medium is studied to determine the boundary conditions also in the case of the non-disappearance of the antimatter domains in the limiting processes.
As a consequence, new classifications for the antimatter domains are set.
The implied differences are to be analyzed within the framework of the relativistic processes chosen, the nucleosynthesis processes occurring, the comparison with the existing experimental data, as implied from the confrontation within the Standard Cosmological Principle.
Space-time evolution of antimatter domains is studied after the analytical integration of the differential equation for the number of baryons, and the two-point correlation functions are analytically integrated within the nucleon-antinucleon boundary interactions.
A dependence on the Relativistic densities and on the effective antibaryon-antibaryon

distances is rendered as effective in the schematization of a lattice for the definition of first neighbours and second neighbours. A description of the phenomenon as a function of the diffusion length for the radiation-dominated epoch is described to be also appropriate. The results can be compared with the implications of a Relativistic Mean Field Theory and its low-energy limit implications.
Antibaryon-baryon interactions are studied within the definition of the boundary interaction of the antimatter domains.

The space-time evolution of antimatter domains is analyzed after the analytical solution of the equation for the number of antibaryons after the definition of the diffusion coefficient as a function of the (integrated) Thomson cross section for different antimatter space-time statistical distributions, and the width of the spherical shell of the antimatter-domain boundary is further classified.
Two-point correlation functions are analytically integrated in the case of a Minkowsky-flat background under the hypothesis of isotropy and homogeneity in the case of two antimatter domains in the case of a trivial estimator; the two-point correlation functions if further analytically integrated for the choice of the Davies-Peebles estimators; the implications of the Hamilton estimators are discussed.
The implications of the models are compared with those of the study of the condition for the survival of ifferent celestial objects, such as dm clumps, and, in particular, of neutralino clumps; the limiting processes are analyzed.

2. Methods: Introductory statements

2.1. Time evolution of antimatter domains

The time evolution of antimatter domains can be studied through the baryon/photon ratio s

$$s \equiv n_b / n_{\tilde{\gamma}}$$

, which obeys the differential equations

$$\frac{\partial s}{\partial t} = D(t)\frac{\partial^2 s}{\partial x^2}, \tag{1}$$

where $D(t)$ is the diffusion coefficient, and with the initial-data conditions $s(\mathbf{R}, t_0) = r_0, x < 0,\ \ r(\mathbf{R}, t_0) = 0, x > 0,$
to compute the geodesics coordinate distance run across by atoms after the recombination age until the present time
within a suitable photon thermalization process

The number of antibaryons in the boundary spherical shell in which the antibaryon-baryon interaction takes place is determined as

$$\frac{dn_{\bar{b}}}{dt} \simeq -\frac{R_d}{3} n_{\bar{b}}(< \sigma v > n_b - \beta) \tag{2}$$

with R_d radius of the spherical antimatter domain For the evaluation of the number density of antiprotons, by taking into account both the annihilation processes and the expansion of the Universe, the study is performed at a temperature T, $4 \cdot 10^4 K < T < 10^9 k$; for low-density antimatter domains, the density of antimatter within a domain is 3 orders of magnitude less than the baryon density.
The study of the interaction $\overline{n} + \overline{p} \rightarrow \overline{d} + \gamma$ is accomplished as its cross section $< \sigma v >$ does not depend on the temperature if below $1 Mev$ and implies the antideuterium production in the reaction only if the reaction rate exceeds the expansion rate of the Universe; the (integrated) Thomson cross section is therefore studied through the diffusion coefficient $D(t)$. Analytical solution of the equation for the number density of antiprotons as a function of annihilation and expansion of the Universe is here found.

Antibaryons within the domain can be schematized as a ling on the point of a lattice of edges of length l_d: the picture is compatible with the scenario of an expanding Universe

as soon as the antinucleon-antinuclei interactions are expressed as a function of the (Relativistic) volume densities.
The results can also be expressed as a function of the diffusion length for times ranging within the radiation-dominated epoch, or free streaming after the recombination epoch.

2.2. Antimatter space-time statistical distributions

It is possible to evaluate the (Relativistic) density of the antimatter domains by evaluating the number of antibaryons contained in the antimatter domains: to do so, it is necessary to individuate a suitable antimatter space-time statistical distribution obeyed by the antibaryons on the relativistic background. In the case of low-density antimatter domains, several antimatter space-time statistical distributions are possible to be evaluated: the case of a Bernoulli distribution, the case of a Binomial distribution, the case of a Poisson distribution, the case of a matter/antimatter symmetric Universe, the case a a Gaussian distribution, the case of a two-parameter Gauss minus distribution, the case of a Fishe's modified non-central hypergeometric distribution, the case of a Wallenius' non-central modified hypergeometric distribution, the case of a generalized modified non-central hypergeometric distribution; in the case of low-density antimatter domains, the different antimatter space-time statistical distributions are demonstrated not to converge to a Gaussian distribution. The results can be nevertheless compared through the Heinrich theorem, which, by means of linear mapping and (in the appreciated case) auxiliary parameters, which redistribute the (standard) errors and allow one to compare the results also on non-trivial relativistic backgrounds.

3. Results and Discussion

3.1. Low-density antimatter domains: antinucleon-nucleon interactions

3.1.1. Antiproton-proton interaction

First-neighbours Antiproton-proton-interaction approximations and second-neighbours Antiproton-proton-interaction ones can allow for a classification of boundary interactions for low-density antimatter domains. First-neighbours interaction approximation at the boundary of the antimatter domain of mass M and radius R_D holds in the case $l_{Pl} \leq H_1 \leq 2F$, $R_D - \vec{X}\bar{p} \leq H_1$, after which the condition $\Delta M > \Delta E_{\bar{p}H}$ for the antimatter domain not to disappear in the limiting process.S Second-neighbours antiproton-proton interactions approximations at the domain boundary hold in the case $\mid \vec{R_D} - \vec{X}\bar{p} \mid \geq H_1$.

3.1.2. antinucleus-nucleon interaction

First-neighbours antinucleus-interactions approximaions hold for antimatter domains $\tilde{d}$ for the study of the boundary interactions, which approximation holds in the case $R_D - (\vec{X} + \tilde{R}A^{1/3}) \leq V_1$, $l_{Pl} \leq V_1 \leq 2F - \tilde{R}A^{1/3}$, for A nucleus with A nucleons, with V_1 a dimensionfull function, depending on the antinucleon-antinucleon (centers distances on the lattice) $l_{\tilde{d}}$ and on the (Relativistic) density $V(t, \vec{x})/\tilde{N}$. For an antimatter domain consisting of antinuclei $\overline{A}$ of mass $m_{\overline{A}}$, the total mass change is

calculated as $\Delta M \simeq 6U_1 \Delta m_{\overline{A}}$
at the boundary.
Second-neighbours antinucleons-nucleon interaction domains are categorized for boundary interactions when the following majorization holds $R_D - (\vec{X} + \tilde{R}A^{1/3}) \geq V_1$, for which the total mass change is evaluated as

$$\Delta M \simeq 6U_1 \Delta m_{\overline{A}} + 4\sqrt{2}U_2 \Delta m_{\overline{A}}.$$

3.2. low-density antimatter domain: two-point correlation functions

Two-point correlation functions for low-density antimatter domains, α_1 and α_2, resp., of size $> 10^3 M_\odot$ each, on (homogenous, isotropic) Minkowski-flat background, for which an timatter densities $\rho \equiv \tilde{N}/V$ follow a Poisson space-time statistical distribution are integrated by means of the estimator $\xi_{12}(\vec{r}) \equiv \vec{r} \equiv \vec{r_{\alpha_2}} - \vec{r_{\alpha_1}}$ as

$$dC_2(\alpha_1, \alpha_2) \equiv \rho^2(1 + \xi(\mid \vec{r_{\alpha_2}} - \vec{r_{\alpha_1}} \mid))dV_1 dV_2 = 2\pi\tilde{n}(n, k; \Delta f_{eff}, \tilde{H}; \Delta t)\left(\frac{1}{r_2} + \frac{1}{r_1}\right)\tilde{H_c}^{2k} t^{4k-4} \quad (3)$$

with Δf_{eff} the effective (time-dependent) phase function.

3.2.1. Low-density antimatter domains: Davies-Peebles estimator

The correlation function between an antimatter domain α_1 and an antibaryon α_3 by means of the Davies-Peebles statistical estimator is integrated as

$$\xi_{l,l'} \equiv \frac{\tilde{n}_{bin}(n,k;\Delta f_{eff},\tilde{H};\Delta t)}{\tilde{n}(n,k;\Delta f_{eff},\tilde{H};\Delta t)} \frac{D_l(|\vec{r}|)}{D_l(|\vec{r}|)} - 1. \tag{4}$$

It is crucial to remark that the time dependence $\tilde{H_c}^{2k} t^{4k-4}$ is suppressed, and the *time dependence*is expressed after the ratio $\frac{\tilde{n}_{bin}(n,k;\Delta f_{eff},\tilde{H};\Delta t)}{\tilde{n}(n,k;\Delta f_{eff},\tilde{H};\Delta t)}$, i.e. on the different statistical antimatter space-time distributions and on their dependence on the Hubble-radius function $\tilde{H}$, and on the effective (time-dependent) phase function Δf_{eff}.

3.2.2. Hamilton estimator

The Hamilton statistical estimator $\tilde{\xi}_{l,l'}$ takes into account the difference in distances among the Binomial distribution and the Poisson distribution.

3.3. Low-density antimatter domains: evaluation of the number of antinucleons after the diffusion equation

It is possible to evaluate the number of antinucleons $n_{\bar{b}}$ in the spherical shell within which the boundary interactions take plaace after the diffusion equation Eq. (2), which can be solved analytically for the different antimatter space-time statitical distributions. In the case of a Bernoulli space-time statistical distribution of antimatter, the number of the antinucleons interacting in the spherical shell is calculated after Eq. (2) as

$$n_{\bar{b}} \simeq -\frac{R_d}{3}\tilde{n}(k;\Delta f_{eff},\tilde{H};\Delta t)\frac{1}{k-2}t^{k-1}(<\sigma v> n_b - \beta) \tag{5}$$

In the case of a Poisson space-time statistical distribution of antimatter, the number of the antinucleons interacting in the spherical shell is calculated after Eq. (2) as

$$n_{\bar{b}} \simeq -\frac{R_d}{3}\tilde{n}(n,k;\Delta f_{eff},\tilde{H};\Delta t)\frac{1}{k-2}t^{k-1}(<\sigma v> n_b - \beta) \tag{6}$$

In the case of a Binomial space-time statistical distribution of antimatter, the number of the antinucleons interacting in the spherical shell is calculated after Eq. (2) as

$$n_{\bar{b}} \simeq -\frac{R_d}{3}\tilde{n}_{bin}(n,k;\Delta f_{eff},\tilde{H};\Delta t)\frac{1}{k-2}t^{k-1}(<\sigma v> n_b - \beta) \tag{7}$$

In the case of a Gaussian space-time statistical distribution of antimatter, the number of the antinucleons interacting in the spherical shell is calculated after Eq. (2) as

$$n_{\bar{b}} \simeq -\frac{R_d}{3}\tilde{n}_{Gauss}(\Delta t-1)e^{\Delta t}(\Delta f_{eff},\tilde{H};\Delta t)(<\sigma v> n_b - \beta) \tag{8}$$

after treating the number of baryons n_b as not changing with the number of antibaryons $n_{\bar{b}}$, it is possible to evaluate the boundary of the antimatter domain as a spherical shell in which the baryon-antibaryon annihilation takes place as depending on whether the antibaryons in the low-density antimatter domains are not interacting, or interacting (as first-neighbours interaction or second-neighbours interactions), i.e. on the antibaryon-antibaryon interaction distances, on the mass of the baryons M_b, and on the mass of the antibaryons $M_{\bar{b}}$.

4. Conclusions

Comparison with Dark Matter (DM) objects of different masses would allow one to register the differences in the survival of such objects of cosmological origin, according to the different (limiting) processes. Neutralino clumps of mass M_{cl} are estimated to survive the Galaxy evolution if their mass is within the range $10^{-8}M_\odot \leq M_{cl} \leq 10^{-6}M_\odot$ in [13], [14]; further classifications of neutralino clumps also allow for further comparison with the case of antimattter domains [15].
Analyses of the limiting processes of disappearence of the antimatter domains are possible, after [16], and the characterization of the results follow [17].
The space-time evolution of antimatter domains separated in a small angular distance can be further

studied through the Rubin-Limber correlation functions for small angles [18], [19].
The antinucleon interactions investigated within the framework of a fully-ionized plasma are to be compared with those achieved in a Relativistic Mean Field Theory [20].
Further interactions examples can be therefore schematized.
We hope that the development of our approach and revealing of the observational signatures of antimatter domain structure in the baryon asymmetrical Universe would shed light on the origin of matter in the Universe, specifying the physical nature of the three Sakharov's conditions in the context of physics beyond the Standard model.

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