Statistical analyses of antimatter domains, created by nonhomogeneous baryosynthesis in a baryon asymmetrical Universe

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O.M. Lecian
Sapienza University of Rome, Rome, Italy.

Authors: M.Yu. Khlopov, O.M. Lecian.

Abstract

Within the framework of scenarios of nonhomogeneous baryosynthesis, the formation of macroscopic antimatter domains is predicted in a matter-antimatter asymmetrical Universe.
The properties of antimatter within the domains are outlined; the matter-antimatter boundary interactions are studied. The correlation functions for two astrophysical objects are calculated.
The theoretical expression in the limiting process of the two-points correlation function of an astrophysical object and an antibaryon is calculated.

Summary[1]

- symmetry-breaking scenarios;
- spontaneous baryosynthesis;
- nucleon-antinucleon interaction studies;
- correlation functions

[1] Based

Introduction

In several cosmological scenarios, the appearance of domains with antibaryon excess can be predicted.
In non-trivial baryosynthesis frameworks, the formation of antimatter domains containing antibaryons, such as antiprotons, antinuclei, and both possibilities are studied according to their dependence on their antimatter densities within the domains.
The boundary conditions for antimatter domains are determined through the interaction with the surrounding baryonic medium.
Within the analysis, new classifications for antibaryon domains, which can evolve in antimatter globular clusters, are in order.

Differences must be discussed within the relativistic framework chosen, the nucleosynthesis processes, the description of the surrounding matter medium, the confrontation with the experimental data within the observational framework. The spacetime-evolution of antimatter domains and the correlation functions are described within the nucleon-antinucleon boundary interactions.

Symmetry-breaking scenario

V.A. Kuzmin, M.E. Shaposhnikov, I.I. Tkachev, Matter-antimatter domains in the Universe: a solution of the vacuum walls problem, Phys. Lett. B, 105, 1 (1981);
Ya. B. Zeldovich, L. B. Okun, L.Yu. Kobzarev, Cosmological Consequences of a Spontaneous Breakdown of a Discrete Symmetry, Zh. Eksp. Teor. Fiz. 40, 1 (1974);
V.M. Chechetkin, M.G. Sapozhnikov, M.Yu. Khlopov, Ya.B. Zeldovich, Astrophysical aspects of antiproton interaction with ^{4}He (antimatter in the universe) Phys. Lett. B 118, 329 (1982);
V.M. Chechetkin, M.G. Sapozhnikov, M.Yu. Khlopov, Antiproton interactions with light elements as a test of GUT cosmology, Riv. N. Cim. 5, 1 (1982);
V.A. Kuzmin, I.I. Tkachev, M.E. Shaposhnikov, Are There Domains of Antimatter in the Universe?, Zh. Eksp. Teor. Fiz. Lett. 33, 557 (1981).
spontaneous CP violation

$$V(\phi_1,\phi_2,\chi) = -\mu_1^2(\phi_1^+\phi_1+\phi_2^+\phi_2)+\lambda_1[(\phi_1^+\phi_1)^2+(\phi_2^+\phi_2)^2]+2\lambda_3(\phi_1^+ \phi_1)(\phi_2^+\phi_2)(\phi_1^+\phi_2)+2\lambda_4(\phi_1^+\phi_2)(\phi_2^+\phi_1)+\lambda_5[(\phi_1^+\phi_2)^2+h.c.]+ \lambda_6(\phi_1^+\phi_1+\phi_2^+\phi_2)(\phi_1^+\phi_2+\phi_2^+\phi_1)-\mu_2^2\chi^+\chi+\delta(\chi^+ \chi)^2+2\alpha(\chi^+\chi)(\phi_1^+\phi_1+\phi_2^+\phi_2)+2\beta[(\phi_1^+\chi)(\chi^+\phi_1)+(\phi_2^+\chi)(\chi^+\phi_2)]$$

effective low-energy electroweak $SU(2)\otimes U(1)$ theory.
GUT spontaneous CP violation

formation of vacuum structures separated from the rest of the matter universe by domain walls,

- whose size is calculated to grow with the evolution of the Universe. behavior calculated not to affect the evolution of the Universe if the volume energy $\rho(\tilde{V})$ density of the walls for
$\rho(\tilde{V}) \sim \sigma_\phi^2 T^4/\tilde{h}$,
$\tilde{h}$ value of the scalar coupling constant.

CP-invariant Lagrangian

$$L = (\partial\phi)^2 - \lambda^2(\phi^2 - \chi^2)^2 + \bar{\psi}(i\partial - m - ig\gamma_5\phi)\psi$$

vacuum characterized by $<\phi>=\sigma\eta$, with $\sigma = \pm 1$.

$$L = (\partial\chi)^2 - \frac{1}{2}m_\chi^2\chi^2 - 4\sigma\lambda 2\chi\eta^3 - \lambda^2\chi^4 + \bar{\psi}(i\hat{\partial} - M - i\frac{gm}{M}\gamma_5\chi - \frac{g^2\sigma\eta}{M}\chi)\psi.$$

CP violation can be achieved after the substitution $\phi = \chi + \sigma\eta$.

the domain wall problem can be solved after the Kuzmin-Shaposhnikov-Tkachev mechanism.

- research for antinuclei in cosmic rays;
- research for annihilation products;

- annihilation at rest on Relativistic background;
- annihilation of small-scale domains
  - thin-boundary approximation;
  - at different times, the diffusion of the baryon charge is determined after different processes.

Spontaneous baryosynthesis

allowing for the possibility of sufficiently large domains through proper combination of effects of inflation and baryosynthesis

$\chi \equiv \frac{f}{\sqrt{2}} e^{\theta}$

variance

$< \delta\theta >= \frac{H^3 t}{4\pi^2 f^2}$

$\tilde{N}(t) - \tilde{N}(t_0) \equiv \int_{t_0}^{t_\iota} P(\chi) \ln \chi d\chi(t), \quad P(\chi)$ including variance

$\tilde{H}$ Hubble-radius function,

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

$f_{eff} = f\sqrt{1 + \frac{g_{\phi\chi} M_{Pl}}{12\pi\lambda}(N_c - N)}$

N e-foldings at inflation

M.Yu. Khlopov, S.G. Rubin, A.S. Sakharov, Possible origin of antimatter regions in the baryon dominated universe, Phys. Rev. D 62, 083505 (2000);

M.Yu. Khlopov, S.G. Rubin, A.S. Sakharov, Antimatter regions in the baryon dominated universe, 14th Rencontres de Blois on Matter- Anti-matter Asymmetry [hep-ph/0210012].

If the density is so low that nucleosynthesis is not possible, low density antimatter domains contain only antiprotons (and positrons).
High density antimatter domains contain antiprotons and antihelium.
Heavy elements can appear in stellar nucleosynthesis, or in the high-density antimatter domains.
Strong non-homogeneity in antibaryons might imply (probably as a necessary condition) strong non-homogeneity for baryons, and produce some exotic results in nucleosynthesis.

Antimatter domains and antibaryons interactions

radiation-dominated era

within the cosmological evolution, the dominant contribution to the total energy is due to photons.

low density antimatter domains:
the contribution of the density of antibaryons $\rho_{\overline{B}}$ is smaller than the contribution due to the radiation ρ_γ even at the matter-dominated stage.

in a FRW Universe, within its thermal history, for $T < 100keV$ only photons as a dominant components are considered.

matter-dominated era and following

within a *non-homogeneous* scenario,
$\rho_{DM} > \rho_B$, with $\rho \equiv \rho(x)$.

the creation of high density antibaryon domains can be accompanied by similar increase in baryon density in the surrounding medium. Therefore outside high density antimatter domain baryonic density may be also higher than DM density

$\rho_B(x) > \rho_{DM}(x)$.

low density antimatter domains:

total density $\rho_{\overline{B}} + \rho_\gamma$

$\rho_{\overline{B}} < \rho_\gamma$

$\rho_{dm} > \rho_B$

Nucleon-antinucleon interaction studies

a study: **proton-antiproton annihilation probability: limiting process- theoretical formulation**

- $P(\bar{p})$ probability of existence of one antiproton of mass m_p, m_p being the proton mass, in the spherical shell, of section r_I, of (antimatter)-density ρ_I, delimiting the antimatter domain, in which the interaction takes place $P(\bar{p}) \equiv 3Nm_p/(r_I \rho_I)$

- $\tilde{P}_i \equiv \tilde{P}_{\bar{p}\to(d.c._i)}$ probability of antiproton $\bar{p}$ interaction with a proton p in a chosen i annihilation channel *a.c.*, possibly also depending on the chemical potential;

- Δt time interval considered,

under the most general hypotheses (most stringent constraint), $\Delta t \pm \delta t$,
$\Delta t \simeq t_U \simeq 4 \cdot 10^{17} s$
t_U age of the universe, δt to be set according to the particular phenomena considered;
$\bar{P}_{\bar{p},i}(t, \Delta t)$ probability of antiproton interaction, i.e. antiproton-proton annihilation (density)

$$\bar{P}_{\bar{p},i} \simeq \frac{1}{\Delta t} P_{\bar{p}} \tilde{P}_i$$

a study: **nucleon-antinucleon interaction (annihilation) probabilities**
antinucleus $\bar{M}$ interaction probability $\bar{P}_{\bar{M},j}(t, \Delta t)$ through the annihilation channel(s) k

$\bar{P}_{\bar{M},k}(t, \Delta t) \simeq \frac{1}{\Delta t} P_{\bar{A}} \tilde{P}_{\bar{A},k}$ $[\mathrm{t}^{-1}]$

to be further specified for:

- non-trivial Relativistic scenarios

such as perturbed FRW
with the thermal history of the Universe
i.e., also, according to the Standard Cosmological Principle

at large scales asymptotically isotropic and homogeneous;

- non-trivial nucleosynthesis;
- possibilities of surrounding media;
- antibaryon-baryon annihilation:

most stringent constraint: $\bar{P}$ evaluated for present times in the description of reducing density in the limiting process of a low-density antimatter domain.

An example

Low-density antimatter domains:
- non-interacting antiprotons;
- boundary interactions;
- interaction with surrounding medium.

Low-density antimatter domains can be surrounded by low-density matter regions.

Correlation functions

two-point correlation functions $\tilde{C}_2$ for two antimatter domains α_1 and α_2 of size $> 10^3 M_\odot$ each
- on (homogeneous, isotropic) Minkowski-flat background
- antimatter densities $\rho \equiv \tilde{N}/V$ following a Poisson space-time statistical distribution

$d\tilde{C}_2(\alpha_1, \alpha_2) \equiv \rho^2(1 + \xi(\mid \vec{r}_{\alpha_1\alpha_2} \mid))dV_1 dV_2$

estimator $\xi(\mid \vec{r}_{\alpha_1\alpha_2} \mid) \equiv \mid \vec{r}_{\alpha_1\alpha_2} \mid$
$\vec{r}_{\alpha_1\alpha_2}$ distance of the two antimatter domains
for the two antimatter domains
of volume $V_{\alpha_l} \equiv \frac{4}{3}\pi r_l^3$
separated of a distance $\mid \vec{r}_{\alpha_1\alpha_2} \mid$

analytical solution for the two-point correlation functions for two antimatter domains

analytically integrated:

$$\tilde{C}_2(\alpha_1, \alpha_2) = 2\pi \tilde{n}(n, k; \Delta f_{eff}, \tilde{H}; \Delta t) \mid \vec{r}_{\alpha_1 \alpha_2} \mid \left(\frac{1}{r_2} + \frac{1}{r_1} \right) \tilde{H_c}^{2k} t^{4k-4}$$

evaluated at the present time t

$\tilde{H_c}$ effective Hubble-radius function *an example*: **two-point correlation functions for an antimatter domain and another object**

limiting example:

correlation function between an antimatter domain α_1 and an antibaryon α_3

Davies-Peebles estimator

for the macroscopic objects described in terms of density distribution and temperature distribution

$\xi_{l,l'} \equiv \frac{\tilde{N}_{bin}}{\tilde{N}} \frac{D_l(|\vec{r}|)}{D_{l'}(|\vec{r}|)} - 1$

$\tilde{N}$ number of antibaryons in a low-density antimatter domain

$\tilde{N}_{bin}$ number of antibaryons in a low-density antimatter domain where the antimatter is distributed according to a binomial space-time statistical distribution,

$D_l(|\ \vec{r}\ |)$ number of pairs of low-density appropriate-mass antimatter domains

within the geodesics (coordinate) interval distance $\left[r - \frac{dr}{2}, r + \frac{dr}{2}\right]$

$D'_l(|\ \vec{r}\ |)$ number of pairs of objects between an antimatter domain and an (*Poisson-distributed*) antibaryon on the coordinate geodesics

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

within the use of statistical estimators, 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

- $\tilde{H}$ Hubble-radius function, and on
- Δf_{eff} effective (time-dependent) phase function.

Hamilton estimator

the Hamilton estimator

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

- antimatter domains separated in a small angular distance
  - Rubin-Limber correlation functions for small angles

V.C. Rubin, Fluctuations in the space distribution of galaxies, Proc. Natl. Acad. Sci. USA 40, 541 (1954);
D.N. Limber, The Analysis of Counts of the Extragalactic Nebulae in Terms of a Fluctuating Density Field. II., Astrophys. J. 119, 655 (1954).

- analysis of the metric requiring a time evaluation after the time of the surface of last scattering A. Pontzen, A. Challinor, Linearization of homogeneous, nearly-isotropic cosmological models, Class. Quant. Grav. 28, 185007 (2011), Eq. (52).

Thank You for Your attention

Binomial distribution

$$\tilde{N}(k) - \tilde{N}_0(k) \simeq \sum_k \frac{1}{(k!)(1-k)!}\frac{\chi_{t_a}}{\chi_{t_0}}\frac{2}{\Delta f_{eff}(t;t_a,t_i,t_0)}\left(\frac{(-2)}{4\pi^2}\cdot\right.$$

$$\left.\left[ln\frac{L_u e^{H_c(t_c-t_0)} - e^{H_0 t_0}}{l}\right]^k (t)^{k-3}\right.$$

J. Bernoulli, Ars Conjectandi, Opus Posthumum. Accedit Tractatus de Seriebus infinitis, et Epistola Gallice scripta de ludo Pilae recticularis; Impensis Thurnisiorum, Fratrum, Basel (1713).

Poisson space-time antimatter statistical distribution

antibaryon gas with positrons in the FRW Universe within the thermal history
low density domains: neither nucleosynthesis, nor recombination takes place

k Poisson probability of the existence of two neighboring domains with antibaryons
$\tilde{N}$ number of antibaryons

$$\tilde{N}(k) - \tilde{N}_0(k)(\Delta t) \simeq \sum_n \sum_k \frac{k^n e^k}{n!} \frac{\chi_{t_a}}{\chi_{t_0}} \frac{2}{\Delta f_{eff}(t; t_a, t_i, t_0)} \cdot \left(\frac{(-2)}{4\pi^2} \left[ln \frac{L_u e^{\tilde{H}_c(t_c - t_0)} - e^{\tilde{H}_0 t_0}}{l} \right] \right)^k (t)^{k-3},$$

Bernoulli distribution

$$\tilde{N}(k) - \tilde{N}_0(k) \simeq \frac{1}{(k!)(1-k)!}\frac{\chi_{t_a}}{\chi_{t_0}}\frac{2}{\Delta f_{eff}(t; t_a, t_i, t_0)}\left(\frac{(-2)}{4\pi^2}\cdot\right.$$
$$\left.\left[ln\frac{L_u e^{H_c(t_c-t_0)} - e^{H_0 t_0}}{l}\right]^k (t)^{k-3}\right.$$

V.A. Kuzmin, M.E. Shaposhnikov, I.I. Tkachev, Matter-antimatter domains in the Universe: a solution of the vacuum walls problem, Phys. Lett. B, 105, 1 (1981);

- three scalar fields
- CP violation achieved with complex vev's
- vacuum domain structures appear with opposite CP violation signs
- $\Rightarrow$ massive walls
- $\Rightarrow$ the size of the domains should grow

V.A. Kuzmin, M.E. Shaposhnikov, I.I. Tkachev, Matter-antimatter domains in the Universe: a solution of the vacuum walls problem, Phys. Lett. B, 105, 1 (1981);

- rotation $\psi \rightarrow e^{i\alpha\gamma_5}\psi$, $tg2\alpha = -g\sigma\eta/m$
- $\Rightarrow$ appearence in the Lagrangean density of two terms with opposite CP symmetry,
  the sign of the phase depending on σ
- $\lambda \leq\simeq 1$
- $\Rightarrow 1 \leq\simeq \eta$

M.Yu. Khlopov, S.G. Rubin, A.S. Sakharov, Possible origin of antimatter regions in the baryon dominated universe, Phys. Rev. D 62, 083505 (2000);

$$V(\chi) = -m_\chi^2 \chi^* \chi + \lambda_\chi (\chi^* \chi)^2 + V_0$$

$$\chi = \frac{f}{\sqrt{2}} e^{\frac{i\alpha}{f}}$$

- $U(1)$ symmetry breaking
- $\theta = \alpha / f$