Matter-antimatter domains in the universe

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Abstract

A possible existence of cosmologically large domains of antimatter or astronomical “anti-objects” is discussed. A brief review of different scenarios of baryogenesis predicting a noticeable amount of antimatter is given. Though both theory and observations indicate that the universe is most possibly uniformly charge asymmetric without any noticeable amount of antimatter, several natural scenarios are possible that allow for cosmologically (astronomically) interesting objects in close vicinity to us. The latter may be discovered by observation of cosmic ray antinuclei.

1 INTRODUCTION

It is well known that the world of elementary particles is doubled - for each particle there exists an antiparticle with the same mass, \( m = \bar{m} \), and life-time (if unstable), \( \tau = \bar{\tau} \), but with opposite signs of charges associated with any conserved vector current, \( Q_v = -\bar{Q}_v \). Scalar or tensor charges have the same signs for particles and antiparticles. These are the results of invariance of any “normal” theory with respect to combined transformation of charge conjugation (C), mirror reflection (P), and time-reversal (T), that follows from famous CPT-theorem. Despite this symmetry the universe is seemingly populated only by particles, at least in our neighborhood. However, neither C-transformation, nor combined CP-parity one are symmetries of the theory. Hence properties of particles and antiparticles (or even mirror reflected antiparticles) are slightly different. This small difference together with a possible non-conservation of baryonic charge and a deviation from thermal equilibrium in the course of cosmological expansion created an overwhelming dominance of matter with respect to antimatter \(^1\). In the simplest versions of the baryogenesis scenario (for the review see \(^2\)) the cosmological baryon asymmetry

\[
\beta = \frac{(N_B - N_{\bar{B}})}{N_\gamma}
\]  

\(^1\) Also: ITEP, Bol. Cheremushkinskaya 25, Moscow 113259, Russia.
is a universal constant and there is no room for astronomically large antimatter domains. However in more complicated models the baryon asymmetry may be non-uniform, \( \beta = \beta(x) \), creating the so called isocurvature perturbations and, moreover, it might change sign so that large parts of the universe would be built of antimatter. Unfortunately there is no definite theory so neither the characteristic size of the domains nor the distance to them can be predicted with any certainty. Still the idea that there can exist cosmic domains of antimatter or even that the universe is globally charge symmetric, is very attractive and the question if there is any cosmological antimatter remains with us for several decades after it was discovered that antimatter in principle exists.

2 OBSERVATIONAL LIMITS

There are two possible ways to search for cosmic antimatter. First, one may look for it in the cosmic rays. There is a small amount of energetic antiprotons at the level of \( 10^{-4} \) with respect to protons. It can be explained by the secondary production of \( \bar{p} \) in proton collisions. It is very difficult to create antinuclei in proton-proton or proton-nucleus collisions. Their registration in the cosmic rays would be a strong indication to the existence of cosmic antimatter. With a small probability antideuterons may be produced in annihilation of neutralino dark matter \( \bar{\chi} \) but secondary production of heavier elements is practically impossible. The recent preliminary data obtained by Alpha Magnetic Spectrometer \( \bar{\chi} \) give the following upper limits for the flux of antihelium and heavier elements;

\[
\Phi (^4\bar{He})/\Phi (^4He) < 2 \cdot 10^{-6}
\]

\[
\Phi (Z > 2)/\Phi (Z > 2) < 2 \cdot 10^{-5}
\]

More activity is expected in this area and more restrictive bounds will be obtained or maybe even a discovery of antinuclei will be made in the nearest future.

In the absence of definitive theoretical predictions we will discuss logical possibilities for the behavior of \( \beta \) and reasonable scenarios for realization of one or other logical option. The simplest (and dullest) model is that \( \beta = \text{const} \). In this case all the universe is homogeneously populated with baryonic matter and the search for antimatter would be fruitless. Another option is that the baryon asymmetry is a varying function of space points, \( \beta = \beta(x) \) but \( \beta > 0 \) everywhere. In this model isocurvature density perturbations created by the different chemical (baryonic) content might be quite essential but still no antimatter domains would exist. If \( \beta \neq \text{const} \), then it is quite natural that it might have somewhere negative values so these parts of the universe would be filled by antimatter. A particular case of globally symmetric universe, when there is an equal amount of matter and antimatter:

\[
\int \beta dV = 0
\]
is aesthetically attractive. However there exist scenarios when the universe is dominated by matter while relatively small amount of antimatter in the form of gas clouds or separate anti-stars or even rare anti-galaxies is possible \[5\]. Such small admixtures of antimatter may be relatively close to us.

There are several ways in which cosmic antimatter may become visible. First, $p\bar{p}$-annihilation into $\pi$-mesons would produce $\sim 100$ MeV cosmic $\gamma$-rays coming from the decay $\pi^0 \rightarrow 2\gamma$ or from annihilation of energetic positrons from the sequence of the decays $\pi^+ \rightarrow \mu^+ \rightarrow e^+$. 

The old analysis of reference \[6\] permits to conclude that if antimatter in large amount exists, it should be at least at the distance 10 Mpc. This conclusion was revised recently in ref. \[7\] where a much stronger limit was obtained that a possible anti-world should be very far away from us at a distance larger than $\sim$ Gpc. This result was obtained under assumption of baryo-symmetric universe. It was also assumed that matter and antimatter domains are in close contact. The last assumption is justified by the smoothness of the cosmic microwave background radiation (CMBR). The latter demands that there cannot be density contrast above $10^{-4}$ at the scale larger than 15 Mpc. On the other hand, according to the calculations of ref. \[7\] the photon diffusion would drag matter to a larger distance. Hence even if the matter-antimatter domains were originally spatially separated (but less than for 15 Mpc) they would come to a close contact due to the photon drag. After annihilation would start its products would efficiently carry energy far away from the annihilation region because a bulk of the produced particles are energetic electrons or positrons and neutrinos whose mean free path is large in comparison with the annihilation region. Hence contrary to naive expectations, the energy and pressure density in the region of annihilation becomes smaller and it would increase the diffusion of matter and antimatter towards each other and amplify the efficiency of annihilation. Such annihilation after hydrogen recombination would be a source of a very strong gamma ray background. Non-observation of this background permits to obtain a very restrictive limit that any abundant cosmic antimatter should be near or beyond the horizon. However this result is not valid for the case of isocurvature fluctuations (see discussion below).

Another possible effect of matter-antimatter annihilation is a distortion of energy spectrum of CMBR if the annihilation takes place before recombination. This could happen for large size domains. This effect was considered in refs. \[8, 9\]. At the present time this phenomenon does not permit to obtain any interesting limit.

The limits discussed above should be very much weaker in the case of isocurvature fluctuations. In this case initial density contrast was zero and started to rise only relatively late. Baryon (antibaryon) rich regions cooled faster so photons would diffuse there from hotter baryon poor regions and this diffusion would drag matter and antimatter away so baryons and antibaryons would go out of contact. This picture is opposite to the one considered above. In this model annihilation would be very weak and one would expect the universe consisting of possible large matter and antimatter domains sepa-
rated by relatively narrow baryon(antibaryon) voids. If the angular size of this voids is sufficiently small then the limits from angular fluctuations of CMBR are not applicable and we may expect to have antimatter domains almost at hand.

3 THEORETICAL MODELS

As has been already mentioned for generation of baryon asymmetry three principles of baryogenesis [1] should be fulfilled:

1. Non-conservation of baryonic charge.
2. Breaking of C and CP invariance.
3. Deviation from thermal equilibrium.

There are several workable scenarios of baryogenesis. They all are based on the assumption of explicit C and CP violation and give $\beta = const$ and no cosmic antimatter. However if charge symmetry is broken spontaneously [11], then in different CP-domains the universe would be either baryonic or anti-baryonic [12]. The size of these domains may be cosmologically large if after their formation the universe passed through a period of exponential expansion (inflation) [13]. A review of the earlier ideas on the subject can be found in [14]. If C and CP are indeed broken spontaneously, then the universe should be globally charge symmetric with equal number of baryonic and anti-baryonic domains separated by domain wall with enormous mass. Such domain walls would create serious cosmological problems [15]. So either the size of the domains should be larger than the present day horizon and the antimatter would be unobservable or there should exist a mechanism of domain wall destruction maintaining homogeneity and isotropy of the universe. However even if all this works, the discussed mechanism would create matter-antimatter domains in close contact with each other and with vanishingly small isocurvature density perturbations (because the baryon asymmetries in different domains have differ by sign but have equal magnitude). This corresponds to the case considered in ref. [7] and, as we discussed above, permits cosmic antimatter to be only very far away from us.

This pessimistic conclusion can be avoided in some more complicated versions of baryogenesis scenario, in particular in the model of spontaneous baryogenesis [16] or in the model of scalar baryon condensation [17]. In the model of spontaneous baryogenesis non-conservation of baryonic current is induced by a spontaneous breaking of $U(1)$-symmetry associated with baryonic charge. The corresponding (pseudo)goldstone field satisfies the equation of motion:

$$D^2 \theta + U'(\theta) = f^{-2} \partial_\mu J^\mu_{bar}$$

(4)
where \( f \) is the scale of symmetry breaking and \( J_{\mu}^{\text{bar}} \) is the baryonic currents of fermions (quarks). In the case that the symmetry is broken only spontaneously the potential \( U(\theta) \) vanishes and the baryon charge density created by the evolution of the Goldstone field \( \theta \) is evidently given by

\[
B = f^2 \dot{\theta}_{in}
\]  

(5)

In the case that the potential \( U \) is non-vanishing (pseudo-goldstone field), e.g. \( U(\theta) = m^2 \theta^2 \), the asymmetry is given by

\[
B = f^2 \Gamma f^2 \theta_{in}^3,
\]  

(6)

where \( \Gamma = g^2 m / 16\pi \) is the width of the decay of \( \theta \) into quarks.

One sees that the result for the asymmetry depends upon the initial value of the field \( \theta \) (or its derivative) and may have an arbitrary sign. The asymmetry can be generated without any explicit C and CP violation. The proper asymmetry between matter and antimatter is created by charge asymmetric initial conditions and can be generated stochastically. This type of C, CP - violation can be called stochastic [2]. It is normally assumed that the initial conditions are formed during inflation when a massless or light scalar field \( \phi \) was infrared unstable and rose as

\[
\langle \phi^2 \rangle \sim H^4 t
\]  

(7)

reaching the average value \( \sim H^4 / m^2 \) [19]. This models permits to have spatially varying \( \beta(x) \) and even domains of matter and antimatter at cosmologically large scales. A more detailed discussion can be found in the refs. [2] [11] [21] or in a recent paper [21]. However this model suffers from a large magnitude of isocurvature perturbation that may to be too high to be compatible with CMBR data [22].

Similar picture of charge asymmetry generation may take place in the Affleck-Dine model [17]. In this model a condensate of a bosonic field with a non-zero baryonic charge might be formed along a flat direction of the potential during inflationary stage. When inflation was over the field evolved down to the equilibrium point of the potential and due to stochastic initial conditions started to “rotate” clockwise or anti-clockwise, creating respectively baryons or antibaryons. In this respect the model is similar to spontaneous baryogenesis discussed above, however the asymmetry in this model might be much larger than in the previously considered case. Moreover, the model may be combined with the explicit C and CP breaking in such a way that the bulk of the space would be filled with baryons with normal uniform density, and simultaneously relatively small bubbles with a much larger asymmetry, \( \beta \), may be formed [3]. Most probably such bubbles form primordial black holes with log-normal mass distribution,

\[
dN/dM = \exp[-\gamma \ln^2 M/M_0]
\]  

(8)
with unknown constant parameters $\gamma$ and $M_0$. The remnants that did not underwent gravitational collapse could be anti-stars, clouds of antimatter, or even small isolated galaxies. Since the volume occupied by this abnormal bubbles could be sufficiently small, their existence is not forbidden and cosmological antimatter may be quite close to us.

4 CONCLUSION

First and possibly rather gloomy conclusion is that most natural is to expect that the universe is uniformly filled with baryons with a constant asymmetry $\beta$ and there is no cosmologically noticeable antimatter. However the idea that the universe may be charge symmetric is quite attractive and there are natural theoretical frameworks for such cosmology. Simple versions of realization of charge symmetric world comes into contradiction with observations of gamma-ray background and with the data on CMBR. However some quite natural models with specific isocurvature density perturbations allow for large and relatively close astronomical objects consisting of antimatter. They may be sources of antinuclei in cosmic rays and the search for them could put stronger limits on existence of cosmic antimatter or make a seminal discovery of anti-worlds.

References

[1] A.D. Sakharov, Pis’ma Zh. Eksp. Teor. Fiz. 5 (1967) 32.
[2] A.D. Dolgov, Phys. Repts. 222 (1992) No. 6.
[3] F. Donato, N. Fornengo, and P. Salati, Phys.Rev. D62 (2000) 043003.
[4] R. Battiston, Invited talk at XIIIth Rencontres de Physique La Thuile, February 22-27, 1999; astro-ph/9907152.
[5] A.Dolgov and J.Silk, Phys. Rev. D47 (1993) 4244.
[6] G. Steigman, Annu. Rev. Astr. Ap. 14 (1976) 339.
[7] A.G. Cohen, A. De Rujula, and S.L. Glashow, Astrophys.J. 495 (1998) 539; A. De Rujula, astro-ph/9705043. Based on a talk at the Jan. 1998 Moriond Meeting at Les Arcs, France.
[8] W.H. Kinney, E.W. Kolb, and M.S. Turner, Phys.Rev.Lett. 79 (1997) 2620.
[9] A. G. Cohen and A. De Rujula, astro-ph/9709132.
[10] A.D.Dolgov, Hyperfine interactions, 76 (1993) 201.
[11] T.D. Lee, Phys. Rev. D8 (1973) 1226.
[12] R.W. Brown and F.W. Stecker, Phys. Rev. Lett. 43 (1979) 315.
[13] K. Sato, Phys. Lett. 99B (1981) 66.
[14] F.W. Stecker, Nucl. Phys. B252 (1985) 25.
[15] Ya.B. Zel’dovich, I.Yu. Kobzarev, and L.B. Okun, ZhETF, 67 (1974) 3.
[16] A. Cohen and D. Kaplan, Phys. Lett. 199B (1987) 251.
[17] I. Affleck and M. Dine, Nucl. Phys. B249 (1985) 361.
[18] A.D. Dolgov and K. Freese, Phys.Rev. D51 (1995) 2693;
   A. Dolgov, K. Freese, R. Rangarajan, and M. Srednicki, Phys.Rev. D56 (1997) 6155.
[19] T.S. Bunch and P.C.W. Davies, Proc. Roy. Soc. (London) A360 (1978) 117;
   A. Vilenkin and L.H. Ford, Phys. Rev. D26 (1982) 1231;
   A.D. Linde, Phys. Lett. 116B (1982) 335.
[20] A.D. Dolgov, International Workshop on Baryon Instability, Oak Ridge, Tennessee,
   March 28-39; [hep-ph/9605280].
[21] M.Yu. Khlopov, S.G. Rubin, and A.S. Sakharov, Phys.Rev. D62 (2000) 083505.
[22] K. Enqvist, H. Kurki-Suonio and J. Valiviita, Phys.Rev. D62 (2000) 103003;
   M. Bucher, K. Moodley, and N. Turok, [astro-ph/0012141].