ANTIMATTER IN THE UNIVERSE

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Abstract

Different scenarios of baryogenesis are briefly reviewed from the point of view of possibility of generation of cosmologically interesting amount of antimatter. It is argued that creation of antimatter is possible and natural in many models. In some models not only anti-helium may be produced but also a heavier anti-elements and future observations of the latter would be critical for discovery or establishing stronger upper limits on existence of antimatter. Incidentally a recent observation of iron-rich quasar may present a support to one special model of antimatter creation.
1 Introduction

Our region of the universe is certainly dominated by matter, protons, electrons, and nuclei consisting of protons and neutrons. No antimatter in any significant amount is observed. A little of antiprotons and positrons in cosmic rays can be explained by their secondary origin in collisions of protons, electrons or photons with usual matter. Cosmological excess of matter over antimatter is described by the ratio

$$\beta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \cdot 10^{-10}$$ (1)

where $N_{B,B,\gamma}$ are respectively the cosmic number densities of baryons, antibaryons, and photons in microwave background radiation (CMBR). At the present day $N_\gamma = 412$/cm$^3$ and $N_B \gg N_{\bar{B}}$ (at least in our neighborhood.). It is believed that in the early universe, at high temperatures, $T > 100$ MeV, the number densities of baryons and antibaryons (at these temperatures they were in quark state) were almost equal with relative accuracy of the order of $\beta$.

According to simple models of baryogenesis, pioneered by Sakharov in 1967, baryon asymmetry is homogeneous, i.e. $\beta$ does not depend on space points, and the total baryonic charge of the universe is non-zero:

$$B_{tot} = \int \beta \, d^3x \neq 0$$ (2)

Still it is not excluded neither theoretically nor observationally that this may be not so and we face the following big questions:

1. Is $\beta = \text{const}$ or it could be a function of space point, $\beta = \beta(x)$?

2. If $\beta = \beta(x)$ what is the characteristic scale $L_B$ of its variation? Especially interesting is if $L_B$ may be smaller than the present-day horizon $L_{hor} \sim 3$ Gpc, or it is possible that $L_B < L_{hor}$?

3. If $\beta$ indeed varies, may it be that in some astronomically sizable regions $\beta < 0$, that is some parts of the universe are antimatter dominated?

4. If $\beta < 0$ is allowed what is the global baryonic charge of the universe? Is $B_{tot} \neq 0$, so the universe is globally charge asymmetric or $B_{tot} = 0$ and the universe is globally charge symmetric.

In this talk I will discuss the present observational bounds on existence of antimatter and scenarios of baryogenesis that might lead to astronomically interesting antimatter domains or antimatter objects.
2 Observational limits

Antimatter may be observed by the energetic gamma rays produced by $pp$-annihilation in the regions where matter and antimatter domains are in contact. According to the analysis made in the 70th, the level of gamma ray flux in the 100 MeV energy range demands that the nearest anti-galaxy should be at the distance larger than $10^{-15}$ Mpc, as reviewed in ref. 2). A discussion of possible search for cosmological antimatter can be found in refs. 3, 4).

More recently the bound quoted above was strongly improved in ref. 4) up to Gigaparsec range. It was argued there that the matter-antimatter domains could not be too far separated because, otherwise, density deficit in baryon poor regions between the domains would be noticeable by angular fluctuations of CMBR. The minimum observable scale is about 20 Mpc. Moreover, below approximately this scale fluctuations are strongly smoothed down by photon diffusion 4). Fluctuations at smaller scales may escape observations in angular spectrum of CMBR but in this case proton/antiproton diffusion would bring them into contact at later stage and there would be a burst of annihilation which might be observable in cosmic gamma rays. One would naively expect that the annihilation, when starts, would produce excessive pressure in the the region of annihilation which would push matter-antimatter domains apart. Hence the efficiency of the process would be low and large antimatter domains in our neighborhood would be allowed. In fact, as shown in ref. 5), the situation is opposite: energy and extra pressure produced by the annihilation would be released far away from the annihilation region because of a large mean-free path of the annihilation products. As a result matter and antimatter would be pushed towards stronger contact and the annihilation would be more and more efficient. This mechanism allowed to obtain a very strong bound quoted above.

As mentioned by the authors 4) the bound is valid in the case of baryo-symmetric cosmology when matter and antimatter are equally abundant in the universe and for the case of adiabatic density perturbations. For isocurvature perturbations the behavior could be different. Initially density contrast was absent, so the energy densities of baryonic and antibaryonic domains and the baryon-poor boundary between them were the same. When baryons became non-relativistic energy density of the regions with larger baryon (or antibaryon) numbers became larger than in baryon-poor regions. On the other hand, the temperature of photons in baryon-poor regions became higher than in (anti)baryon rich regions because nonrelativistic matter cools faster. Higher photon temperature would lead to an excessive
pressure which would put baryons and antibaryons apart diminishing probability of annihilation. This may allow antibaryonic domains to be much closer to us than Gigaparsec, especially if the universe is not baryo-symmetric and the amount of cosmic antimatter is noticeably smaller than amount of matter. Unfortunately qualitative results for this case are not yet available.

An unambiguous proof of existence of cosmic antimatter would be observation of anti-nuclei in cosmic rays. An observation even of a single $^4\overline{He}$-nuclei or a heavier one would demonstrate that primordial antimatter indeed exists not too far from us. The present-day upper limits are not too restrictive. They are summarized in ref. [7] and presented in Fig. 1.

A stronger limit, though rapidity dependent, is presented in ref. [8], see Fig. 2. Future AMS mission on International Space Station may improve the bound by three orders of magnitude.

3 Generation of cosmological baryon asymmetry: general features

The mechanism of dynamical creation of excess of particles over antiparticles in the early universe was suggested in 1967 by Sakharov [1] and is accepted now as one of the cornerstones of the modern cosmology. The well known three principles of

Figure 1: The upper limit of $\bar{He}/He$ flux ratio of ref. [7] together with previous limits.
baryogenesis are:

1. Non-conservation of baryonic charge.

2. Breaking of symmetry between particles and antiparticles (violation of C and CP invariance).

3. Deviation from thermal equilibrium in the primeval plasma.

In fact none of these conditions are absolutely obligatory (see discussion in the review \cite{9} and in what follows) but in simple models they all should be fulfilled.

At the time when the model of baryogenesis was suggested the hypothesis of baryon non-conservation was probably the weakest one. 40 years ago the common belief was: “we exist, so proton must be stable”. Now the point of view is exactly opposite: “we exist, so proton must be unstable”. Justification for the latter is that the universe with suitable for life conditions might emerge only if baryons were not conserved. In particular, inflation would not be possible if baryonic charge was conserved. So at the present day existence of the universe is the strongest “experimental” fact in favor of baryon non-conservation. Theory also evolved in the favorable direction. Models of unification of strong and electro-weak interactions
predict non-conservation of baryons \[^{[10]}^{[11]}\]. Moreover it was shown that even the standard electro-weak theory, which respects baryon conservation in the Lagrangian, breaks this law by quantum corrections \[^{[12]}\].

Deviation from thermal equilibrium in primeval plasma, stressed in ref. \[^{[13]}\], is usually small but non-vanishing for massive particles. It is roughly equal to:

\[
\frac{\delta f}{f} \sim \left( \frac{H}{\Gamma} \right) \left( \frac{m}{T} \right) \tag{3}
\]

where \(f\) is the distribution function of the massive particles with mass \(m\), \(\delta f\) is its deviation from equilibrium, \(\Gamma\) is the characteristic rate of the reaction with particles in question, and \(H\) is the Hubble parameter. One sees that for \(m \ll T\) the deviation can be very big but for low temperatures the number density of massive particles is Boltzmann suppressed and the net effect is small. So usually the most favorable period for generation of asymmetry is when \(T \sim m\). A large deviation from thermal equilibrium might also take place in the case of strongly first order phase transition with large supercooling and coexistence of two phases.

Breaking of symmetry between particles and antiparticles is established at experiment but theory of the effect is still uncertain. There are many possible theoretical models but we do not yet know which mechanism or several different ones is/are realized.

The simplest and generally accepted is explicit C(CP)-violation which is realized by introducing complex coupling constants or masses into fundamental Lagrangian. In the models of baryogensis based on this assumption cosmological baryon asymmetry has a definite sign determined by the particle physics and usually \(\beta\) is space point independent.

However charge symmetry may be broken spontaneously as suggested in ref. \([^{[14]}\]. In such a model vacuum state is degenerate and a complex scalar field acquires different vacuum expectation values corresponding to different vacuum states. The sign of C(CP)-violation is different there and baryogenesis would end up either with baryons or antibaryons. It was argued in ref. \([^{[14]}\] that if this type of charge symmetry breaking is realized in nature the universe would be globally charge symmetric with chaotically distributed baryonic and antibaryonic domains. However the size of the domains happened to be too small and some moderate period of exponential expansion was necessary \([^{[14]}\) to make the model consistent with the data. Still the model encounters serious problems. First, there must be domain walls with huge energy density separating different vacuum states. Existence of such walls contradicts the observed homogeneity and isotropy of the universe \([^{[14]}\) and one should invoke a mechanism to avoid formation of such walls or to destroy
them at a later stage. Second, the model predicts charge symmetric universe with close contact of matter-antimatter domains and according to ref. 5 discussed above the size of domains should be close or larger than horizon to avoid contradiction with the observed gamma ray background. One can however “create” charge asymmetric universe dominated by baryons but with some antibaryonic domains if both explicit and spontaneous mechanisms of C(CP) violation are operative 18).

One more mechanism of breaking the symmetry between particles and antiparticles which might be effective only in the early universe can be called stochastic 9). We believe that there exist many complex scalar fields with the mass smaller than the Hubble parameter at inflation; the latter could be as large as \(10^{-5} m_{Pl} \approx 10^{14} \text{ GeV}\). Such “light” fields are infrared unstable in De Sitter spacetime 19) and because of that they acquire non-zero vacuum value

\[
\langle \phi^2 \rangle = \frac{3H^4}{8\pi^2 m^2}
\]

(4)
The field tends to this asymptotic value as \(\langle \phi^2 \rangle = H^3 t/ (2\pi)^2 \) 20). Thus the field could be displaced from (mechanical) equilibrium by quantum fluctuations during inflation and if it did not relax to equilibrium before baryogenesis its non-zero amplitude acted as the vacuum condensate of the field that induced spontaneous breaking of charge symmetry in the model discussed above. An important difference with respect to the model of spontaneous C(CP)-breaking is that the field \(\phi\) would ultimately relax down to equilibrium point \(\phi = 0\) and no cosmic domain walls would remain. Similar type of C(CP)-violation is present in some models of baryogenesis described below.

Since stochastic C(CP) breaking would not survive to the present day the observed CP-violation in particle physics should be prescribed to another mechanism, e.g. to the explicit one. Correspondingly, if both mechanisms are operating and if the amplitude of the stochastic one is larger than the explicit, there could be domains of antimatter in the universe but their fraction would be smaller than 50%. In this scenario large isocurvature fluctuations can be expected.

4 Models of baryogenesis

4.1 Heavy particle decays

It is historically first model of baryogenesis 1, 21 which later received robust theoretical foundation based on GUTs - grand unified theories 22) (for more references and development see e.g. reviews 23, 24, 9, 25, 26). The mechanism is quite simple: if there are GUT heavy bosons, \(X\), out of thermal equilibrium, then e.g. the
decays $X \to 2q$ and $\bar{X} \to 2\bar{q}$, where $q$ is a quark, may have different probabilities due to C(CP)-breaking and as a result an excess of baryons over antibaryons may be created by these decays. In ref. 21) the decays of Majorana fermion were considered, so the same particle may decay into charge conjugated channels with different branching ratios.

If GUT scale is about $10^{16}$ GeV, as indicated by the recent data, then the deviation from equilibrium at $T \sim m_X$ is large (see eq. 3) and the model is capable to supply the necessary excess of baryons over antibaryons. However it is questionable if the universe ever reached temperatures about $10^{16}$ GeV and if such heavy bosons were abundantly produced.

In the standard versions the model does not lead to creation of antimatter, the asymmetry $\beta$ is determined by elementary particle physics and $\beta$ is predicted to be a universal constant over all the universe. To avoid this conclusion one needs to include additional fields and interactions which are not present in the usual GUTs.

4.2 Electroweak baryogenesis

The standard electroweak (EW) theory possesses all the features necessary for baryogenesis: breaking of symmetry between particles and antiparticles, non-conservation of baryonic charge (by chiral anomaly) and may lead to a strong deviation from thermal equilibrium. Breaking of equilibrium due to particle masses is very weak, according to eq. (3), but the cosmological phase transition from EW-unbroken to EW-broken phase might be first order and, if this was the case, thermal equilibrium could be strongly broken.

The possibility to create baryon asymmetry of the universe in frameworks of known physics makes the model very attractive and after the pioneering paper 27) the model became the most popular one. However with strengthening of the lower bound on the Higgs boson mass presented by LEP the first order phase transition (which could take place only for sufficiently light Higgs) became less and less probable and now electro-weak baryogenesis has lost a considerable part of its attraction. For more detail one can see the reviews 26, 28).

Creation of antimatter in electroweak scenario was not discussed but seemingly the situation in simplest versions of the model is similar to the GUT case: the baryon asymmetry is positive and uniform.
4.3 Baryo-thru-lepto-genesis

This scenario was suggested in ref. and combines the ideas of the two discussed above. First, a lepton asymmetry is generated in decays of heavy Majorana neutrino, \( \nu_M \), with the mass about \( m_M \sim 10^{10} \text{ GeV} \). Later, electroweak processes which conserve the difference of baryonic and leptonic charges, \( B - L \), would equilibrate them and as a result there would be generated baryon asymmetry equal to a fraction of the initially produced lepton asymmetry. The necessity of noticeable deviation from thermal equilibrium demands \( \nu_M \) to have very weak interactions. On the other hand, since the asymmetry could be produced by \( \nu_M \) decays only in the second order in the L-non-conserving interaction (see e.g. discussion in ref. ), it cannot be large. Subsequent entropy dilution could bring the baryon asymmetry down to unacceptably low value. A more optimistic point of view shared by majority working in the field is that baryo-thru-lepto scenario can supply the necessary amount of baryons in the universe. For a recent review see e.g. ref. . As for antimatter production, this approach is in the same bad shape as the other two described above.

4.4 Black hole evaporation

An excess of baryons over antibaryons could be produced by the evaporation of low mass black holes . A concrete mechanism was suggested in the paper and the calculations of the effect were performed in ref. . In the process of evaporation all the particles with the mass smaller than black hole temperature, \( T_{BH} = m_{Pl}^2 / (8\pi M_{Pl}) \) can be produced. A massive meson, still in gravitational field of black hole could decay into a light baryon and heavy antibaryon (e.g. \( u \) and \( \bar{t} \) quarks) or vice versa. The decay probabilities may be different because of C(CP) violation. Since back capture of heavy particles by the black hole is more probable that of light ones, such process could create a net flux of baryonic charge into external space, while equal antibaryonic charge would be hidden inside disappearing black hole. This mechanism could explain the observed value of the baryon asymmetry of the universe if at some early stage the total cosmological energy density was dominated by those black holes.

Evaporating black holes may not disappear completely. The process may stop when their mass drops down to the Planck value. In this case such stable Planck mass remnants would contribute into cosmological dark matter (see e.g. ). (In the case of theories with large extra dimension the mass may be as small as TeV.)

Without special efforts this model is also not good for creation of cosmologically significant amount of antimatter.
4.5 Spontaneous baryogenesis

The model was proposed in ref. 36 and is based on the assumption that \( U(1) \)-symmetry, related to baryonic or some other non-orthogonal charge, is spontaneously broken. A toy-model Lagrangian can be written as:

\[
\mathcal{L} = -|\partial \phi|^2 + \lambda \left(|\phi|^2 - f^2\right) + \sum_a \bar{\psi}_a \left(i \partial + m_a\right) \psi + \sum_{a,b} \left(g_{ab} \phi \bar{\psi}_b \psi_a + h.c.\right)
\]  

(5)

where some fermionic fields \( \psi_b \) possess non-zero baryonic charge, while some other do not. The theory is invariant with respect to simultaneous phase rotation:

\[
\phi \leftarrow \phi \exp(i \theta) \quad \text{and} \quad \psi_b \rightarrow \psi_b \exp(i \theta)
\]  

(6)

which ensures conservation of “baryonic” charge. In the broken symmetry phase where \( |\phi| = f \) the conservation of baryonic current of fermions also breaks down (due to presence of the last term in the Lagrangian above) and the Lagrangian takes the form:

\[
\mathcal{L} = -f^2 \left(\partial \theta\right)^2 + \partial_\mu \theta \bar{\psi}_b \gamma^\mu \psi_b + ...
\]  

(7)

where \( \theta \) is the massless Goldstone field induced by the breaking of the global \( U_b \)-symmetry. If there are some additional terms in the Lagrangian producing an explicit symmetry breaking then \( \theta \) would be massive and is called pseudo-Goldstone field. Baryogenesis would be much more efficient in the latter case.

In the homogeneous case when \( \theta = \theta(t) \) the second term in expression (7) looks like \( \dot{\theta} n_b \) where \( n_b \) is the baryonic charge density. So it tempting to identify \( \dot{\theta} \) with chemical potential of baryons 36. Though it is not exactly so 37, still this term shifts equality between number densities of quarks and antiquarks even in thermal equilibrium.

The sign of the created baryon asymmetry is determined by the sign of the \( \dot{\theta} \) and could be both positive or negative producing baryons or antibaryons. To create the matter/antimatter domain of astronomically large size the \( U(1) \)-symmetry should be broken during inflation and in this case the sign of \( \dot{\theta} \) would be determined by the chaotic quantum fluctuations at inflationary stage. The analysis of density perturbations created by fluctuating field \( \theta \) was done in ref. 38.

In this scenario C(CP)-violation is not necessary for generation of baryon asymmetry. As a whole the universe would be charge symmetric. We know however that an explicit C(CP)-violation is also present. If it also participate in creation of baryon asymmetry, then the amount of matter and antimatter in the universe would be different with unknown ratio that should be determined from observations.
4.6 SUSY condensate baryogenesis

If supersymmetry (broken of course) exits in nature then together with baryon-fermions there should be baryon-scalars. A scalar field, $\chi$, with non-zero and non-conserved baryonic charge could develop vacuum condensate during inflation according to the mechanism discussed at the end of Sec. 3 if its mass is smaller than the Hubble parameter at inflation. After the end of inflation this condensate can decay liberating the accumulated baryonic charge into usual baryons (quarks). This is the essence of the model, proposed in ref. 39, which can be very efficient for generation of baryon asymmetry. All features specified above are typical for SUSY models. In particular, the self-potential of $\chi$ possesses the so called flat directions (or valleys) along which the potential energy of the field does not rise.

As a toy model let us consider the potential energy of the form:

$$U(\chi) = \lambda \left[ |\chi|^4 - \left( \chi^4 + \chi^*^4 \right) / 2 \right] = \lambda |\chi|^4 (1 - 4 \cos \theta)$$

where $\chi = |\chi| \exp(i\theta)$. This potential has four valleys $\theta = \pi n/2$ with $n = 0, 1, 2, 3$ and is not invariant with respect to rotation in two-dimensional (Re$\chi$, Im$\chi$)-plane. This leads to non-conservation of baryonic current of $\chi$. The latter is defined as

$$J^B_\mu(\chi) = (-i/2) \left( \chi^* \partial_\mu \chi - \partial_\mu \chi^* \chi \right) = \partial_\mu \theta |\chi|^2$$

In the homogeneous case when $\theta = \theta(t)$ only time component of the current (i.e. baryonic charge density) is non-vanishing. There is a very convenient mechanical analogy in this case. The equation of motion for $\chi$

$$\ddot{\chi} + 3H \dot{\chi} + U'(\chi) = 0$$

describes classical mechanical motion of point-like particle in the potential $U(\chi)$. The second term induced by the cosmological expansion presents liquid friction force. In this language the baryonic charge of $\chi$ is simply angular momentum of the particle in this potential. If the potential is spherically symmetric (in two dimensions) then baryonic charge is conserved, otherwise is not.

The field $\chi$ should generically possess a non-zero mass. It could be either produced by some soft symmetry breaking after inflation was over or might be non-zero even at inflationary stage due to explicit mass term in the Lagrangian, $m^2 |\chi|^2$. During inflation the “particle” was deep along the valley and when inflation stopped and the Hubble parameter became smaller than $m$ it starts to roll down to the origin along the potential slope. The “particle” may be displaced a little from the minimum in the valley and hence some orthogonal oscillations between the walls of the valley.
would be superimposed on its motion down. These fluctuations were damped by the Hubble friction and, what’s more important, by the particle production by the time dependent field $\chi(t)$. The average value of the angular momentum at this stage was zero and no baryonic charge was produced by the decay of $\chi(t)$. However, when $\chi$ comes closer to the origin the potential becomes dominated by the spherically symmetric mass term and the oscillating behavior would change into rotation around the origin. This corresponds to non-zero baryonic charge which all would be transferred to the light particles produced by the decay of $\chi$. (We assume that interaction of $\chi$ with light particles conserves baryonic charge.)

It is evident that the sign of the baryon asymmetry is determined by the direction of the rotation, which could be either clock-wise or anti-clock-wise depending upon chaotic initial conditions. The latter introduce also an initial breaking of charge asymmetry, so no C(CP)-violation is necessary as in the example considered in the previous subsection.

The asymmetry generated according to this scenario can be very small because the orthogonal motion (which carries a non-zero angular momentum) might be strongly damped by the particle production (see also [1]). The frequency of the oscillations is determined by the slope of the potential in the direction orthogonal to the valley, $m_{\text{eff}} = \sqrt{\lambda\chi}$, and could be large for large displacement from the origin. Hence particle production could be very strong and the baryon asymmetry originated from the orthogonal motion would be small.

This conclusion can be avoided if there is an explicit C(CP)-breaking in the theory. One can introduce it assuming that there is a non-zero relative phase, $\alpha$, between the coupling constant $\lambda$ and mass $m$. The potential of $\chi$ in this case have the form:

$$U(\chi) = \lambda|\chi|^4(1 - \cos 4\theta) + m^2|\chi|^2[1 - \cos(2\theta + 2\alpha)]$$

The evolution of field $\chi$ in this potential would proceed as follows. Let us first consider the case of $\alpha = 0$. If the field $\chi$ was inside one of the valleys $\theta = 0, \pi$ then these valleys coincide with mass valleys and the field would evolve down to zero along these lines and no baryon asymmetry would be produced. The picture would be very much different if the field was initially in one of the valleys with $\theta = \pm \pi/2$ which are orthogonal to mass valleys. When the field approaches the origin and the mass term in the potential becomes dominating, the motion along the line $\theta = \pm \pi/2$ would be unstable and the field would start to move in direction of one or other mass valleys acquiring a non-zero (and possibly large) angular momentum. The choice between clock-wise or anti-clock-wise directions would be chaotic and the universe
would equally consist of baryonic and antibaryonic domains and would be globally baryo-symmetric. The size of the domains would be astronomically large if the trend to mass valleys would begin still at inflation.

If \( \alpha \neq 0 \) and \( C(CP) \) is explicitly broken then depending on the value of \( \alpha \) the fraction of antimatter in the universe may be anything from vanishingly small to completely dominant.

5 Models of anti-baryogenesis

As follows from the discussion in the previous section the necessary conditions for creation of cosmological antimatter are:

1. Different sign of \( C(CP) \) breaking amplitude in different space points. It could be either achieved by spontaneous breaking of charge symmetry or by a stochastic one created by fluctuations.

2. Exponential but moderate blow-up of regions with a definite sign of charge symmetry breaking. In the case of too large expansion domains of antimatter could exist but far beyond the present day horizon, while without inflation their size would be too small and they would mix producing locally charge symmetric universe with extremely small amount of baryons and antibaryons, \( N_B = N_{\bar{B}} = 10^{-19} N_\gamma \).  

Many models of this kind were considered in the literature, see e.g. and, as one can see, the last two models of the previous section are quite capable to create a considerable amount of cosmological antimatter. In addition to them I would like to discuss a rather special one proposed in ref. The model is essentially based of Affleck and Dine scenario discussed in Sec. Assume that an additional interaction between the field \( \chi \) and the inflaton \( \Phi \) is introduced:

\[
\mathcal{L}_{int} = \lambda \Phi |\chi|^2 (\Phi - \Phi_1)^2
\]  

(12)

It is a general renormalizable interaction and its appearance is quite natural. When the inflaton field is close to some value \( \Phi_1 \) the effective mass of \( \chi \) reaches minimum and the transition from one valley to another would be easier. If on the other hand, the time when \( \Phi \) is close to \( \Phi_1 \) is not very long then such transition would take place only in a relatively small fraction of space. Correspondingly in the dominant part of the universe volume baryogenesis would create a normal small baryon asymmetry at the level of \( 10^{-9} \), while in a small part of the universe the asymmetry can be very
large, even close to unity. The sign of baryon asymmetry in those high-B domains may be arbitrary and roughly an equal number of baryonic and antibaryonic domains with large $|\beta|$ should be created.

According to the calculations made in the paper the mass distribution of domains was of log-normal form:

$$\frac{dN}{dM} \sim \exp \left[ -c \ln^2 \frac{M}{M_0} \right]$$  \hspace{1cm} (13)

A large part of those (anti)baryon-rich regions would form primordial black holes. They may be quite heavy with the masses up to $10^9 M_\odot$, where $M_\odot$ is the solar mass. The very heavy black holes may be the observed today quasars or central black holes in large galaxies. But of course not all the matter (or antimatter) would be hidden inside these black holes and a part of it can exist non-collapsed.

About of a half of all such primordial black holes would emerge from anti-baryon rich regions. Hence some 50% of central black holes in galaxies might be made of antimatter. Of course there is no observational difference between a black hole and an anti black hole. However, some anti-matter around such black holes may be non-collapsed and, depending on the amount of the latter, there could be a flux of radiation from annihilation with the surrounding matter. It is tempting to explain the switch-off of quasars around $z = 2$ by this mechanism but to this end an optically thick medium around them is necessary, so the spectrum of annihilation could degrade down.

In this model clouds of antimatter, or separate stellar objects may exist even not too far from us. Especially interesting is that the primordial nucleosynthesis in this scenario would not stop on production of light elements, essentially $^4\text{He}$, but because of a large $\beta$ much more heavy elements could be produced, even possibly (anti)iron. This hypothesis may explain observed high abundances of metals around quasars at high red-shifts and is supported by the recent observation of high iron abundance around the Quasar APM 08279+5255.

If we believe the model discussed here, there is a 50% chance that central black hole in our galaxy was made of anti-matter. Moreover, there should be plenty of lighter ones floating around and not only in galactic disk but also in halo, like any other form of cold dark matter. The parameters of the model can be fixed if we assume that all dark matter in the universe consists of such primordial black holes. However, it is not clear if such cold dark matter with a rather wide mass distribution of the particles (black holes) can give a reasonable description of the observed large scale structure. To answer this question a new type of numerical simulation is necessary.
6 Conclusion

It seems that creation of astronomically interesting amount of antimatter is not only possible but quite natural in many scenarios of baryogenesis. In particular, the conditions for creation of antimatter are especially favorable if a condensate of a complex scalar field existed in the early universe which was a source of temporary charge parity breaking.

Theory allows globally charge symmetric universe which, however may have already problems with the existing observation. On the other hand, a dominance of matter or antimatter looks equally natural and a ratio, $\epsilon$, of the amount of cosmic antimatter to matter is an unknown parameter of the theory. At the present day we cannot exclude neither small not large $\epsilon$ and it even possible that we live in a relatively small matter domain in antimatter dominated universe. Still more detailed and accurate theoretical calculations in concrete models are necessary since they could already provide sensible bounds on the possible abundance and the distance to the nearest antimatter domains or astronomical objects. As we discussed in Section 5 antimatter may even live in the halo of our Galaxy.

A search for cosmic antimatter is a very exciting, though extremely difficult, challenge for the future observations. Its discovery would indicate to an unusual mechanism of charge symmetry breaking in cosmology and might be an additional proof of inflationary scenario. At the moment it seems that the most promising way to search for cosmic antimatter is to look for anti-nuclei in cosmic rays. According to the discussed above models those could be not only anti-helium but heavier ones up to anti-iron.

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