BARYOGENESIS AND COSMOLOGICAL ANTIMATTER.

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Abstract

Possible mechanisms of baryogenesis are reviewed. Special attention is payed to those which allow for creation of astronomically significant domains or objects consisting of antimatter. Observational manifestations of cosmological antimatter are discussed.

1 Introduction

Theoretical prediction of antimatter made by Paul Dirac 80 years ago is one of the most impressive discoveries of quantum field theory [1]. A symmetry between matter and antimatter led Dirac to a natural suggestion that "maybe there exists a completely new universe made of antimatter". Surprisingly a very similar statement was done 30 years before Dirac by another English physicist Arthur Schuster who made a brilliant but at that time wildly speculative guess that there might be entire solar systems, made of antimatter and indistinguishable from our Solar system (probably by light) but capable to annihilate and produce enormous energy. To avoid abundant antimatter around us, Schuster assumed that world and antiworld were gravitationally repulsive.

Our present point of view on existence of such astronomically large systems is very much different, even opposite. Now we know for sure that antimatter exists but believe that there are very few antiparticles in the universe, except for antineutrinos, which, together with neutrinos, are the most abundant massive particles in the universe. As for "real" antimatter, i.e. antiprotons or positrons, the dominant point of view is that they are too rare to make any macroscopic objects.

However it is not excluded that Dirac and Schuster were right and there are whole antimatter worlds, or solar-like systems, or just macroscopically large antimatter objects. It is discussed below if there may exist whole galaxies made of antimatter or could galaxies or the Galaxy consist predominantly of matter with large clumps of antimatter which are potentially observable. It is argued that both natural theory and existing observations allow for that.

These lectures are based on the works with J. Silk [3], C. Bambi [4], M. Kawasaki and N. Kevlishvili [5], see also [6]. Recent theoretical activity was stimulated by the existing: Pamela, BESS, AMS, and future AMS-02 (2009), PEBS (2010), CAPS (2013) programs for search of cosmic antimatter, according to the talk by P. Picozza at TAUP 2007 [7].

The content of the lectures is the following. In the next section the basic ideas of baryogenesis are formulated and their ability to give birth to astronomically significant amount of antimatter is discussed. Different mechanisms of CP-violation which are favorable for antimatter creation are enumerated in sec. 3. Observational data are briefly described in sec. 4. A specific mechanism of creation of compact antimatter objects, which nevertheless may have a larger total mass than the observed baryons, is presented in sec. 5. Cosmological evolution of such (anti)baryonic bubbles is considered in sec. 6. Observational manifestations of abundant antimatter in the Galaxy is described in sec 7. At last, in sec. 8 we conclude.

2 Cosmological baryogenesis

It is strongly believed that the universe is populated by matter and that the observed antimatter is of the secondary origin. Observations and the simplest scenarios of baryogenesis do not contradict this assertion. The standard mechanism of baryogenesis is based on the following three principles as it was formulated in 1967 by A.D. Sakharov [8]:
1. Non-conservation of baryons. It is predicted theoretically by grand unification [9] and even by the standard electroweak theory [10]. Moreover, in a sense it is confirmed "experimentally" by cosmological inflation because the latter is impossible with the conserved baryonic density equal to the measured one. It is interesting how the same observational fact of our existence led to opposite conclusions: 30 years ago it was: "we exist, thus baryons are conserved.", while now it is: "we exist, thus baryons are NOT conserved.".
2. Breaking of symmetry between particles and antiparticles, i.e. of C and CP. CP-violation was observed in experiment in 1964 [11]. Breaking of C-invariance was found earlier immediately after discovery of parity non-conservation [12].
3. Deviation from thermal equilibrium. This is fulfilled in nonstationary, expanding universe for massive particles or due to possible first order phase transitions.

Neither of the three conditions is obligatory, and successful baryogenesis could be realized without any of them [13], but the corresponding scenarios are somewhat more complicated.

The list of the available baryogenesis scenarios is surely not a short one. There is plethora of models each being able to explain the single observed number:

$$\beta_{observed} = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \times 10^{-10} \tag{1}$$

The standard prediction of different models is $\beta = const$, which makes impossible to distinguish between the models. Much more interesting are the models withspatially varying asymmetry, $\beta = \beta(x)$ and especially with negative $\beta(x)$ in some astronomically large regions, i.e. with significant amount of antimatter, maybe not too far from us. The scenarios of baryogenesis include:

I. *Baryogenesis by heavy particle decays.* This was historically first model [8, 14]; the references to subsequent works can be found e.g. in reviews [13, 15]. Due to C and CP non-conservation the *partial* widths of decays into channels with different baryonic numbers should be different. For example:

$$\Gamma(X \to q\bar{l}) \neq \Gamma(\bar{X} \to \bar{q}l), \tag{2}$$

where X is a heavy particle and q and l are correspondingly a quark and a lepton. Such a mechanism can be realized in particular in grand unification models with X being a gauge boson of grand unification with $m_X \sim 10^{16}$ GeV.

Deviation from thermal equilibrium can be easily estimated from the kinetic equation in expanding universe and is equal to:

$$\frac{\delta f}{f_{eq}} = \frac{H m_X^2}{\Gamma T E} \approx \frac{10 m_X}{\alpha m_{Pl}}, \tag{3}$$

where H is the Hubble parameter and $g_* \sim 100$ is the number of particle species in the primeval plasma. The baryogenesis is most efficient at $T \sim m_X$ (in fact about an order of magnitude smaller) and an optimistic estimate of the resulting asymmetry is

$$\beta \approx \frac{\Delta\Gamma}{\Gamma} \frac{\delta f}{f_{eq}} \frac{n_X}{n_0} \sim \frac{10 m_X}{m_{Pl}} \frac{n_X}{n_0}, \tag{4}$$

where $n_0 \sim 0.1T^3$ is the number density of massless particles and m_{Pl} is the Planck mass.

II. *Electroweak baryogenesis [16].* The standard $SU(2)\times U(1)$ model possesses all the necessary ingredients for baryogenesis: C and CP violation, non-conservation of baryons (through the chiral anomaly) [10], and significant deviation from thermal equilibrium, if the phase transition from the electroweak symmetric phase to the phase with broken symmetry is 1st order. However, heavy Higgs boson, $m_H > 100$ GeV leads to the second order phase transition and to very weak deviation from thermal equilibrium. Moreover, CP violation in the minimal standard model is by far too weak to ensure efficient baryogenesis, see e.g. discussion in ref. [17]

A possible cure may be TeV scale gravity [18], with $m_{Pl} \sim$ TeV, which allows both significant deviation from thermal equilibrium, even without 1st order phase transition, see eqs. (3,4), and a stronger CP-violation [19].

III. *Baryo-through-lepto-genesis [20].* This is a combination of the scenarios I and II. First, at temperatures about 10^{10} GeV lepton asymmetry was generated in the decays of a heavy Majorana fermion and subsequently the lepton asymmetry was redistributed between baryon and lepton ones approximately in equal share by the equilibrium electroweak processes which conserve $(B-L)$ but break $(B+L)$. For a recent review see e.g. ref. [21].

IV. *SUSY condensate (Affleck-Dine) baryogenesis [22].* In supersymmetric models there must exist scalar superpartners of baryons or leptons χ. The potentials, $U(\chi)$, of such scalar fields have some flat directions along which the fields can develop a non-zero vacuum expectation values e.g. due to quantum fluctuations during inflation. After inflation is over and non-zero mass of χ is generated, χ evolves down to the mechanical equilibrium point $\chi = 0$. If the potential, $U(\chi)$ is not symmetric with respect to the phase rotation, $\chi \to \exp(i\Theta\chi)$, i.e. baryonic charge is not conserved in χ self-interaction, then in the process of relaxation of χ down to zero, the field starts to "rotate" around the origin, i.e. it acquires non-vanishing and typically large baryonic charge. Subsequent B-conserving decay of χ into quarks and/or leptons transform baryon (or lepton) asymmetry in the χ sector into that in the quark sector. For more detail see below Sec. 5. In contrast to other scenarios of baryogenesis, this one normally leads to quite high value of $\beta = n_B/n_\gamma \sim 1$ and theoretical efforts are needed to diminish it down to the observed value. This mechanism is especially favorable for creation of astronomically large antimatter domains.

V. *Spontaneous baryogenesis [23].* It is assumed that theory is symmetric with respect to spontaneously broken global $U(1)$ symmetry associated with B. In the broken phase there appears a massless or light Goldstone field θ. Its Lagrangian has the form:

$$\mathcal{L} = \eta^2(\partial\theta)^2 + \partial_\mu\theta j^B_\mu - V(\theta) + i\bar{Q}\gamma_\mu\partial_\mu Q + i\bar{L}\gamma_\mu\partial_\mu L + (g\eta\bar{Q}L + h.c.), \tag{5}$$

The time derivative of θ looks as a chemical potential but strictly speaking this is not so because chemical potential is introduced into Hamiltonian and such an addition to the Hamiltonian coincides with that to the Lagrangian only if it does not contain derivatives [24] which is surely not true in this case. Nevertheless the model may quite efficient for creation of cosmological baryon asymmetry. It is interesting that baryogenesis is possible in thermal equilibrium. This scenario is also favorable for creation of cosmologically significant amount of antimatter. However, as far as I know, all scenarios of antimatter creation based on spontaneous baryogenesis suffer from too large isocurvature density perturbations at large scales which are forbidden by CMBR.

VI. *Baryogenesis through evaporation of primordial black holes [25].* Though the Hawking process creates thermal equilibrium spectrum of the emitted particles at the black hole (BH) horizon, the particle propagation in the gravitational field of the BH distorts it. It makes possible to create an excess of particles over antiparticles. A concrete model of such generation of baryon asymmetry may be the following. Let BH emits a heavy X-boson which decays in the vicinity of the BH horizon into a light baryon and a heavy antibaryon and vise versa with different decay rates:

$$\Gamma(X \to L + \bar{H}) \neq \Gamma(X \to \bar{L} + H) \tag{6}$$

The probability of gravitational back-capture by the BH of H is larger than L and it would lead to an excess of baryons in external space.

VII. *Space separation of B and $\bar{B}$.* The idea that baryons and antibaryons are separated at cosmological scales due to mutual repulsion was suggested by Omnés in 1970 [26]. However, no repulsive interaction between baryons and antibaryons of sufficient strength is known and the mechanism seems to be excluded. A possibility of spatial separation of matter and antimatter was reconsidered in multidimensional cosmologies with matter and antimatter living on different branes which might be quite close to each other along the fourth dimension [27]. Another suggestion which does not demand new physics was proposed in ref. [28], according to which quarks and antiquarks at QCD phase transition can form astronomically small but macroscopic bubbles with large baryonic or antibaryonic numbers. Due to CP violation a small misbalance between quark and antiquark nuggets was created which is observed as the usual baryonic matter. Such (anti)quark nuggets may form cosmological dark matter. All these scenarios allow for baryonic charge conservation and as a result give rise to globally baryo-symmetric universe.

3 CP violation in cosmology

Creation of astronomically significant antimatter depends not only of the mechanism of baryogenesis but also on the mechanism of CP violation in cosmology. For a review of cosmological CP-violation see ref. [17]. There are several distinct possibilities of breaking symmetry between particles and antiparticles:

1.*The usual explicit, by complex constants in Lagrangian.* Is is assumed in majority of baryogenesis scenarios. In this case the baryon asymmetry is normally constant over space. However, under certain conditions the sign of the baryon excess is not prearranged by the sign of CP-symmetry breaking but is determined by the kinetics of the processes [29], and by intial conditions [30].

2. *Spontaneous, induced by a non-zero vacuum expectation value of a complex scalar field* [31]. Such a mechanism evidently leads to charge symmetric universe with mixed domains of matter and antimatter [32]. The original scenario, however, suffers from very small size of the domains. Observations either exclude it or demand the nearest antimatter domain to be beyond the present day horizon because of too high gamma ray background [33] and also due to the domain wall problem [34]. The first part of the problem can be resolved if the domains expanded exponentially after their formation [35] but the domain walls must be outside cosmological horizon.

3.*Dynamical or stochastic CP breaking, by a complex scalar field which was displaced out of mechanical equilibrium point during BS and relaxed down to equilibrium now* [13, 17]. Evidently the domain wall problem in this case is absent and the universe is not necessarily baryon-symmetric, though significant antimatter is allowed.

4.*A mixture of spontaneous and explicit CP-violation* [36]. It makes charge asymmetric universe with an arbitrary fraction of antimatter.

5.*A mixture of all above* - everything which is not forbidden is allowed.

4 Observations

Up to now no astronomically significant objects consisting antimatter have been detected. A little antiprotons and positrons in cosmic rays are most probably of the secondary origin. Quite suspicious is the observed intensive positron annihilation 0.511 MeV line from the galactic bulge [37] and possibly from the halo [38]. The abundant positrons may indicate to an existence of antimatter objects (see below), but most probably the annihilation line has less striking explanation.

As we have already mentioned, in charge symmetric universe the nearest antimatter domain should be practically at the present day horizon, $l_B >$ Gpc. An efficient annihilation on the domain boundaries at an early stage, due to positive feedback, would create too intensive cosmic gamma ray background [33].

No significant amount of antimatter is observed in the Galaxy. Observed colliding galaxies or galaxies in the common cloud of intergalactic gas are dominated by the same kind of matter (or antimatter?). The absence of the noticeable 100 MeV gamma radiation allows to limit the fraction of antimatter in the Bullet Cluster by $n_{\bar{B}}/n_B < 3 \times 10^{-6}$ [39]. Analogously the nearest galaxy dominated by antimatter could not be closer than at $\sim$10 Mpc [40]. However we cannot say much about galaxies outside of our supercluster.

However, one should keep in mind that these bounds are true if antimatter makes exactly the same type objects as the *observed* matter. For example, compact objects made of antimatter may escape observations and be quite abundant and almost at hand.

5 Anti-creation mechanism

A mechanism which leads to an abundant antimatter objects in the universe and, in particular in our Galaxy, was proposed in ref. [3] and developed recently in ref. [5]. According to the suggested model the bulk of baryons and (almost equal) antibaryons are in the form of compact stellar-like objects or possible primordial black holes (PBH), plus the observed sub-dominant practically homogeneous baryonic background, all created by the same baryogenesis mechanism. The amount of antimatter may be much larger than that of the *known* baryons, but such "compact" (anti)baryonic objects could escape direct observations or the observation through their impact on BBN and CMB, and even make all or significant part of dark matter in the universe.

To create compact high density baryonic and antibaryonic objects we rely on the Affleck-Dine baryogenesis discussed above in sec. 2. As we have mentioned, a scalar baryon χ could condense along flat directions of its potential and accumulate a high baryonic charge later released in the decays of χ into quarks. However, if the window to the flat direction is open only during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the cosmological volume, while the rest of the universe would have the normal baryon asymmetry (1).

When the window to the flat direction is open, the system could undergo a 2nd order phase transition. When the window is closed, the phase transition should be first order. Since by assumption the window is open for a short finite time, we call this phase transition 3/2 order.

To realize such rather unusual behavior, a very simple modification of the potential of the Affleck-Dine field χ is sufficient. We assume that χ has the usual Coleman-Weinberg potential [41] plus an additional general renormalizable coupling to inflaton field Φ:

$$U(\chi, \Phi) = \lambda_1 |\chi|^2 (\Phi - \Phi_1)^2 + \lambda_2 |\chi|^4 \, \ln(|\chi|^2/\sigma^2) + m_0^2 |\chi^2| + (m_1^2 \chi^2 + h.c.), \tag{7}$$

where Φ_1 is some constant value which Φ passes in the course of inflation but not too far from the end of inflation. The mass parameter m_1 may be complex but CP would be still conserved, because one can "phase rotate" χ to eliminate complex parameters in the Lagrangian. It is essential that the last term is not invariant with respect to $U(1)$ transformation, $\chi \to \exp(i\Theta)\,\chi$, and thus it breaks B-conservation. Potential (7) has one minimum at $\chi = 0$ for large and small Φ and has a deeper minimum at non-zero χ when Φ is close to Φ_1. At that time the chances for χ to reach a high value at the other minimum are non-negligible.

There is a simple mechanical analogy which allows to visualize the solution of the equation of motion and the evolution of the baryonic charge density of χ. For homogeneous field $\chi = \chi(t)$ its equation of motion is the equation of the Newtonian mechanics of a point-like particle in potential (7) with the liquid friction term $J_t^{(B)} = i\chi^\dagger \partial_t \chi + h.c.$, is in this language the angular momentum of the particle, $B = J_t^{(B)}$. Hence we can see that during the initial period of inflation when the Hubble parameter was large in comparison with the effective mass of χ, $H_I^2 > |m_\chi|^2$, the amplitude of the field was near zero. When $\Phi \approx \Phi_1$, the quantum fluctuations of χ should rise [42] and χ might reach another minimum and remained there till the minimum disappeared at sufficiently small Φ.

The probability for χ to reach the deeper minimum is determined by the quantum diffusion at inflationary stage. It is governed by the diffusion equation [43]:

$$\frac{\partial \mathcal{P}}{\partial t} = \frac{H^3}{8\pi^2} \sum_{k=1,2} \frac{\partial^2 \mathcal{P}}{\partial \chi_k^2} + \frac{1}{3H} \sum_{k=1,2} \frac{\partial}{\partial \chi_k} \left[\mathcal{P} \frac{\partial U}{\partial \chi_k} \right] \tag{8}$$

where $\chi = \chi_1 + i\chi_2$. The inflation may be not exact and H_I may depend upon time but this does not significantly influence the spectrum of the produced bubbles with high baryonic density.

Field χ can quantum fluctuate noticeably away from the origin when Φ is close to Φ_1 at moment $t = t_1$ and the effective mass of χ behave as $m_{eff}^2 \approx m_0^2 + m_1^4 (t - t_1)^2$. Correspondingly the dispersion is:

$$\langle \chi^2 \rangle \sim \left[m_0^2 + m_1^4 (t - t_1)^2 \right]^{-1}. \tag{9}$$

It can be shown the bubble distributions over length and mass have the log-normal form:

$$\frac{dn}{dM} = C_M \exp\left[-\gamma \ln^2 (M/M_0) \right] \tag{10}$$

where C_M, γ, and M_0 are constant parameters.

Field χ would keep its large amplitude till the second minimum remains, even if it becomes higher than the minimum at $\chi = 0$. When Φ becomes sufficiently small and the second minimum disappears, χ would evolve down to the minimum at $\chi = 0$. Due to an asymmetry of $U(\chi)$ with respect to rotation in the complex χ plane, χ would start to "rotate" acquiring high baryonic number density. Later the "rotation" of χ would be transformed into baryonic number of quarks by B-conserving decays of χ.

The magnitude of the baryon asymmetry inside the B-balls, and their size are stochastic quantities. The initial phase of χ is uniform in the interval $[0, 2\pi]$, due to the large Hubble driving force, $H \gg m$. The size of B-ball is determined by the remaining inflationary time after the inflaton passed the value Φ_1. The magnitude of the cosmological baryon asymmetry β could be large, especially if χ decayed much after the inflaton decay and the entropy dilution was absent.

In the simplest version of the model both positive and negative values of β in the baryon rich bubbles are equally probable. The background uniform baryon asymmetry with $\beta = 6 \cdot 10^{-10}$ in the main part of the universe may be created by the same field χ which did not penetrate to the second minimum of the potential but "lived" near zero. To this end an explicit CP-violation in the χ sector is necessary. Another possibility of creation of the small and homogeneous baryon asymmetry in the bulk of the universe is one of the mechanisms enumerated in sec. 2.

6 Baryonic inhomogeneities and their evolution

According to the scenario described above, the universe looks as a huge piece of swiss cheese or better to say, as "anti" swiss cheese because in the bulk with the normal baryon number density there are small dense bubbles with much larger baryon or antibaryon number density, with $|\beta| \sim 1$, but not empty holes as in the cheese. The mass of those high B objects can be of the order of stellar mass or even larger or much smaller, as we see below. Despite their small size the mass fraction of the bubbles could be comparable or even larger than the observed baryonic mass fraction.

Initially the density contrast between the bubbles with high values of χ and the bulk with $\chi \sim 0$ was small, if the energy density of χ was much smaller than the energy density of the inflaton. This density contrast remained constant while the matter inside and outside the B-bubbles were relativistic. Later when the mass of χ came into play, the matter inside the bubbles with a large amplitude of χ became nonrelativistic and the density contrast started to rise. The rise continued till χ decayed into light quarks and/or leptons and the matter inside became relativistic as in the bulk of the universe.

The second period of the rising perturbations took place after the QCD phase transition at $T = T_{QCD} \sim 100$ MeV, when relativistic quarks confined to make nonrelativistic nucleons.

If $\delta\rho/\rho = 1$ at horizon crossing, primordial black holes (PBH) would be formed. The mass inside horizon at cosmological time t is equal to:

$$M_{hor} \approx m_{Pl}^2 t \approx 10^{38}\mathrm{g}\,(\mathrm{t/sec}) \approx 10^5 \mathrm{M}_\odot (\mathrm{t/sec}), \tag{11}$$

where $M_\odot$ is the Solar mass. Time is related to the temperature by a simple approximate equation $t/\mathrm{sec} = (T/\mathrm{MeV})^{-2}$. Hence for $T = 10^8$ GeV the PBH mass would be 10^{16} g. Perturbations with $\delta\rho/\rho < 1$ might still make PBH due to subsequent matter accretion. If PBH had not been formed, the subsequent evolution of the B-bubble depends upon the relation between their mass and the Jeans mass, see below.

At the moment of QCD phase transition the mass inside horizon is about $M_\odot$, while during big bang nucleosynthesis (BBN) the mass inside horizon varies from $10^5 M_\odot$ to to $10^7 M_\odot$. One should keep in mind that compact objects (not BH) with smaller masses could be formed too.

Initial inhomogeneous χ and/or β led to large isocurvature perturbations. The amplitude of such perturbations is strongly restricted by BBN and by CMBR at about 10% level, but these bounds are valid at much larger scales, bigger than galactic size.

The amplitude of relative density perturbations, when they entered horizon after the QCD phase transition is equal to:

$$r_B = \frac{\delta\rho}{\rho} = \frac{\beta n_\gamma m_p}{(\pi^2/30) g_* T^4} \approx 0.07\beta\,\frac{m_p}{T}. \tag{12}$$

For $\beta = 1$ the density contrast at horizon crossing would be of the order of unity at $T \approx 70$ MeV, and $M_{hor} \approx 10^2 M_\odot$. In this way an early formation of very heavy PBH, up to superheavy ones observed in all large galaxies can be understood. At the present time the mechanism of their creation is unknown, for a review see ref. [44]

Thus the bubbles with high baryonic number density could naturally form PBH with masses either 10^{16} g, or somewhere in this region, or solar mass, or much heavier PBH. Of course BH made of matter or antimatter are indistinguishable because baryonic charge does not create any long range forces, for a review see [45]. However, anti-BH may be surrounded by anti-atmosphere if β slowly decreases. This makes them potentially observable antimatter objects.

If $M_0 \sim M_\odot$, eq. (10), some of the high β bubbles might form stellar type objects in the early universe, more or less at the era of BBN. Most probably these stars are now evolved and dead or have low luminosity. Both such stars and PBHs may make a considerable contribution into the cosmological dark matter.

Nonrelativistic baryonic matter started to dominate inside the bubbles at

$$T = T_{in} \approx 65\,\beta\,\mathrm{MeV} \tag{13}$$

The mass inside a baryon-rich bubble with radius R_B at the radiation dominated stage was

$$M_B \approx 2 \cdot 10^5\, M_\odot (1 + r_B) \left(\frac{R_B}{2t}\right)^3 \left(\frac{t}{\mathrm{sec}}\right) \tag{14}$$

The mass density at the onset of matter dominated (MD) stage was:

$$\rho_B \approx 10^{13} \beta^4 \ \mathrm{g/cm}^3\,. \tag{15}$$

The bubbles with $\delta\rho/\rho < 1$ but with

$$M_B > M_{Jeans}$$

at horizon would decouple from the cosmological expansion and form compact stellar type objects or lower density clouds which could survive against early annihilation.

For example, for a solar mass bubble the mass density is

$$\rho_B = \rho_B^{(in)} (a_{in}/a)^3 \approx 6 \cdot 10^5 \ \mathrm{g/cm}^3 \tag{16}$$

and the radius is $R_B \approx 10^9$ cm. The temperature when $M_J = M_\odot$ is:

$$T \approx T_{in} (a_{in}/a)^2 \approx 0.025 \ \mathrm{MeV}. \tag{17}$$

This bubble is similar to the red giant core and its evolution should be also similar, but with an important difference that initially the external pressure was larger then the internal one.

There are three sources of energy release by such objects at an early stage:
1. Cooling down because of high internal temperature, $T \sim 25$ keV.
2. Annihilation of surrounding matter on the surface.
3. Nuclear reactions inside.

1. The cooling time is determined by the photon diffusion time:

$$t_{diff} \approx 2 \cdot 10^{11}\,\mathrm{sec} \left(\frac{M_B}{M_\odot}\right) \left(\frac{\mathrm{sec}}{R_B}\right) \left(\frac{\sigma_{e\gamma}}{\sigma_{Th}}\right) \tag{18}$$

Correspondingly the luminosity is $L \approx 10^{39}$ erg/sec. With the thermal energy stored inside such B-ball equal to

$$E_{therm}^{(tot)} = 3 T M_B / m_N \approx 1.5 \cdot 10^{50} \mathrm{erg} \tag{19}$$

the life-time with respect to the cooling would be about 10^{11} s. In the extreme case of all DM made of such B-balls i.e. for $\Omega_{BB} = 0.25$, the thermal keV photons would make $10^{-4} - 10^{-5}$ of CMBR, red-shifted today to the background light.

2. Nuclear helium burning, (similar to a red giant core): $3He^4 \to C^{12}$, however with larger T by the factor ~ 2.5. Since the luminosity strongly depends upon the core temperature, $L \sim T^{40}$, the life-time with respect to this process would be very short. The total energy influx would be below 10^{-4} of CMBR if $\tau < 10^9$ s. However, such an intensive nuclear burning could lead to the B-ball explosion and creation of a solar mass anti-cloud.

3. Annihilation on the surface. (Anti)proton mean free path before recombination is small:

$$l_p = 1/(\sigma n) \sim m_p^2/(\alpha^2 T^3) = 0.1\, cm\ (MeV/T)^3 \tag{20}$$

After recombination the number of annihilation on one B-ball per unit time would be:

$$\dot{N} = 10^{31} V_p\, (T/0.1\ eV)^3 \left(R_B/10^9\ cm\right)^2, \tag{21}$$

With maximum allowed number of B-balls it could create the energy density of 100 MeV photons, properly red-shifted by today, not more than 10^{-15} of CMBR.

Thus we see that compact anti-objects could survive in the early universe, even if they are not PBHs. A kind of early dense stars might be formed with initial pressure outside larger than that inside. Such very first stars might evolve quickly and, in particular, make early SNs, enrich the universe with heavy (anti)nuclei and re-ionize the universe. The energy release from stellar like objects in the early universe is small compared to CMBR. Such objects are not dangerous for BBN since they occupy a very small fraction of the total cosmological volume.

7 Observational effects of antimatter in the Galaxy

Here we will discuss possible effects induced by antimatter objects in our neighborhood. The presentation is based on our paper [4]. For other works on similar issue see refs. [46]. We would not dwell on a particular theoretical model but still keep in mind the possibility of compact antimatter objects discussed in the previous sections. The list of possible astronomically significant antimatter objects, which may live in the Galaxy includes:
1. Gas clouds of antimatter.
2. Isolated anti-stars, maybe already dead
3. Anti stellar clusters.
4. Anti black holes with possible anti-atmosphere around.
These anti-objects may be inside galaxies or outside them. They can be concentrated in the galactic halos or be in the intergalactic space. All the options are open

The observational signatures of such objects are more or less trivial. They could be 100 MeV gamma background or compact sources of such gamma radiation from $\bar{p}p$ annihilation. There could be excessive antiprotons or positrons in the cosmic rays. The 0.511 MeV line from e^+e^-– annihilation may also be a signature of abundant cosmic antimatter. Probably the strongest indication for cosmic antimatter would be an observation of anti-nuclei starting from anti-^4He to heavier ones. Among more difficult to observe effects are the photon polarization from the synchrotron radiation and the fraction of neutrino versus antineutrino from supernova explosion.

The antimatter objects in the galaxy are floating in the galactic gas of protons which should annihilate with anti-protons in such objects. This would give rise to gamma-radiation from $\bar{p}p \to pions$ and $\pi^0 \to 2\gamma$ ($E_\pi \sim 300$ MeV) and from e^+e^--annihilation originating from $\pi^\pm$-decays and also 0.511 MeV photons from the "original" positrons in the B-ball.

The astronomically large antimatter objects can be separated into two classes: gas clouds and compact stellar-like objects. We define the gas clouds of antimatter as objects for which the mean free path of protons, l_p, is larger than the size of the (anti)cloud, $l_c \equiv l_B$.

$$l_p = 1/(\sigma_{tot} n_{\bar{p}}) = 10^{24}\,\mathrm{cm}\,\left(cm^{-3}/n_{\bar{p}}\right)\,(barn/\sigma_{tot})\,, \tag{22}$$

Here $n_{\bar{p}}$ is the number density of antiprotons in the cloud. According to the model discussed above it is natural to expect that $n_{\bar{p}} \gg n_p \approx 1/\mathrm{cm}^3$, where n_p is the average number density of protons in the Galaxy.

If the relative velocity, v, of the $\bar{p}p$ is small in comparison with the fine structure constant, $\alpha = 1/137$, the cross-section of the annihilation is amplified by the Sommerfeld-Sakharov [47] factor:

$$\sigma \to \sigma\,\frac{2\pi\alpha/v}{1 - \exp(-2\pi\alpha/v)} \tag{23}$$

Galactic protons would penetrate into an anti-cloud and annihilate inside its whole volume. It leads to a high efficiency of the annihilation. The number of annihilations per unit time is

$$\dot{n}_p = v\sigma_{ann} n_p n_{\bar{p}} \tag{24}$$

Correspondingly the total number of annihilations is equal to $\dot{N}_p = 4\pi l_c^3\,\dot{n}_p/3$. The total number of $\bar{p}$ in the cloud is $N_{\bar{p}} = 4\pi l_c^3 n_{\bar{p}}/3$. So a low density or small clouds would not survive in a galaxy, but they could survive in the halo. The life-time of an antimatter cloud submerged into a sea of protons with density n_p and velocity v_p is:

$$\tau = 10^{15}\ sec\,\left(\frac{10^{-15}cm^3/s}{\sigma_{ann}v}\right)\left(\frac{cm^{-3}}{n_p}\right), \tag{25}$$

if supply of galactic protons is sufficient. Indeed, the proton flux into an anti-cloud:

$$F = 4\pi l_c^2 n_p v = 10^{35}\ sec^{-1}\left(n_p/cm^3\right)(l_c/pc)^2 \tag{26}$$

This flux is sufficient to destroy the anti-cloud in 10^{17} sec if:

$$\left(n_{\bar{p}}/cm^3\right)(l_c/pc) < 3\cdot 10^4 \tag{27}$$

The luminosity for volume annihilation is quite high:

$$L_\gamma^{(vol)} \approx 10^{35}\,\frac{\mathrm{erg}}{\mathrm{s}}\left(\frac{R_B}{0.1\,\mathrm{pc}}\right)^3\left(\frac{n_p}{10^{-4}\,\mathrm{cm}^{-3}}\right)\left(\frac{n_{\bar{p}}}{10^4\mathrm{cm}^{-3}}\right). \tag{28}$$

It would create the flux of 100 MeV photons on the Earth at e.g. distance of one kpc $10^{-5}\gamma/\mathrm{s/cm}^2$ or $10^{-3}\mathrm{Mev/\,s/cm}^2$, similar to the observed cosmic background, $10^{-3}/\mathrm{MeV/s/cm}^2$.

If the density of antimatter inside a B-rich bubble is so high that the proton mean free path is smaller than the bubble size, $l_{free} < l_B$, the annihilation would proceed in a narrow shell near the surface. All that hits the surface annihilate, but the "surface-to-volume" ratio is very small and the annihilation is not efficient enough to destroy the object. The total luminosity with respect to the surface annihilation is:

$$L_{tot} = 2m_p\cdot 4\pi\,R_B^2\,n_p v \approx 10^{27}\,\frac{\mathrm{erg}}{\mathrm{sec}}\left(\frac{n_p}{cm^3}\right)\left(\frac{R_B}{l_\odot}\right)^2 \tag{29}$$

The fraction of the annihilation products into gamma-rays is about 20-30%.

Much more energetic may be the annihilation of galactic protons with antiprotons from the stellar wind produced by an anti-star. The mass loss by an anti-star can be parametrized as:

$$\dot{M} = 10^{12} W \text{ g/sec} \tag{30}$$

where $W = \dot{M}/\dot{M}_\odot$ is the mass loss of an anti-star in units of that for the Sun. If all "windy" particles annihilate, the luminosity per anti-star would be:

$$L = 10^{33} W \text{ erg/sec.} \tag{31}$$

These compact objects would be quite bright sources of energetic, ~ 100 MeV, photon radiation. The observational restrictions permit to impose the limit on the number density of anti-stars to that of the usual solar type stars:

$$N_{\bar{S}}/N_S \leq 10^{-6} W^{-1}, \tag{32}$$

from the total galactic luminosity in 100 MeV photons, $L_\gamma = 10^{39} erg/s$, and from the flux of the positron annihilation line $F \sim 3 \cdot 10^{-3}/cm^2/s$. It is natural to expect that $W \ll 1$ because the primordial anti-stars are, most probably, already evolved.

The stellar wind would populate galaxy with anti-nuclei. Their number density is bounded from above by the density of "unexplained" $\bar{p}$ and the fraction of anti-nuclei in stellar wind with respect to antiprotons. It may be the same as in the Sun, but if anti-stars are old and evolved, this number must be much smaller. Heavy anti-nuclei from primordial anti-SN explosion may be abundant but their ratio to $\bar{p}$ can hardly exceed the same for normal SN. Explosion of anti-SN would create a large cloud of antimatter, which should quickly annihilate producing vast energy - a spectacular event. However, most probably such stars are already dead and anti-SN might explode only in very early galaxies or even before them. The observational bounds on the antihelium-helium ratio [48] impose:

$$N_{\bar{S}}/N_S = (\bar{H}e/He) \leq 10^{-6}, \tag{33}$$

if anti-stars are similar to usual stars, though most probably they are not and the limit is weaker.

As we have already mentioned, the abundances of light elements created during BBN in baryon-rich bubbles should be significantly different from those produced in the bulk with normal β, eq. (1). If $\beta \gg 10^{-9}$, the light (anti)element abundances would be anomalous: much less anti-deuterium and more anti-helium should be produced. For the calculations of light and heavier element abundances in the bubbles with anomalously high β see ref. [49]. This opens a possibility for search of antimatter objects. If there are some regions in the sky with anomalous chemistry, they have a good chance to be made of antimatter. Of course, according to the discussed above mechanism of antimatter creation, there is 50% probability that such regions consist of normal matter with anomalously high ratio n_B/n_γ. Still if such a cloud or compact object is found, the search for annihilation there has non-negligible chance to be successful.

Compact objects made of antimatter could be efficient sources of cosmic positrons. Indeed, the gravitational proton capture by an anti-star is more efficient than the capture of electrons due to smaller mobility of the latter in the interstellar medium, see e.g. [50]. The anti-star would be neutralized by a forced positron ejection. The process would be most efficient in galactic center where the proton number density, n_p is large. The 0.511 MeV positron annihilation line must be accompanied by wide spectrum ~ 100 MeV radiation coming from $\bar{p}$–annihilation.

There could be also quite spectacular but rare event of star-antistar collisions. The collision of similar mass star-antistar would resemble γ-bursters. The energy release at this collision is

$$\Delta E \sim 10^{48}\,\mathrm{erg}\,\left(\frac{M}{M_\odot}\right)\left(\frac{v}{10^{-3}}\right)^2, \tag{34}$$

where v is the relative velocity of the colliding stars and M is their mass. The annihilation pressure would push the stars apart with the collision time being about 1 second. The radiation should be emitted in the narrow disk on the boundary of the colliding stars but not in jets.

The collision of a compact anti-star with a red giant would lead to penetration of the anti-star into the giant. The compact anti-star would travel inside creating an additional energy source. As a result the color and luminosity of the red giant would change. The characteristic time for such a process is about one month. The additional energy release during this period is $\Delta E_{tot} \sim 10^{38}$ erg. The presented estimates are very rude and more detailed calculations are in order.

Another two body violent phenomenon could be generated by the transfer of matter in a binary system of a star and an anti-star. It would lead to the effects similar to hyper-nova explosion with hard spectrum of emitted photons.

Among more subtle effects is the photon polarization from synchrotron radiation. Since positrons are predominantly "right handed", the same is transferred to the bremsstrahlung. Another potentially observable one is registration of neutrinos from supenova explosion: the first burst ν from SN consists of neutrinos while that from anti-supernova consists of antineutrinos.

The bubbles with high baryonic (and anti-baryonic) number density should contribute into cosmological dark matter. If their mass spectrum is centered near relatively small mass, say, from 10^{15} g to planet masses they would not emit light and would behave as normal cold dark matter. Some or many of them could form PBHs. They might even dominate in DM. For the observational bounds on PBH see e.g. ref. [51]. Heavier B-bubbles open much more exciting possibilities. They could make very first stars, which would enrich interstellar space with anti-elements. They may manifest themselves as MACHOs [52] and make a considerable contribution into dark matter. The bounds on the possible fraction of dark matter in the form of stellar (or similar) mass objects can be found in refs. [52, 53].

8 Conclusion

We have shown that there exists a realistic possibility that the amount of antimatter in the universe may be noticeably larger than the amount of the observed matter. Moreover, the antimatter objects can be not far away near horizon but may populate our Galaxy, as well as all other ones. They still escaped observations, because they are mostly compact, but with new more sensitive instruments the odds for their discovery are non-negligible.

As a by-product the suggested scenario presents a feasible mechanism of creation of super-heavy BH in the galactic centers which might be seeds for galaxy formation. To the best of my knowledge this is the only mechanism of early quasar formation with evolved chemistry, which is one of the mysteries of the standard cosmology.

As cold DM particles B-bubbles should be abundant in the galactic haloes. Since no shining stars are observed in the halo, it means that the high B compact objects are mostly dead or low luminosity stars. The stellar wind from them is low or absent. However, annihilation of background protons on their surface should exist and compact sources of 100 MeV radiation may be observed. Despite of low intensity of the stellar wind, the B-bubbles could eject anti-nuclei into interstellar space during early period of their evolution. Not only $^4\bar{H}e$ is worth to look for but also heavier anti-elements. Their relative abundances should be similar to those observed in SN explosions. Regions with an anomalous abundances of light elements are suspicious that they are dominated by antimatter and there may be anti-elements. These regions may be sources of gamma radiation from $\bar{p}p$ and e^+e^-–annihilation.

Discovery of cosmic antimatter looks as the unique chance to establish what baryogenesis scenario was realized in the universe. All the usual scenarios deal with only one number, β, and the measurement of this one number does not allow to distinguish between different mechanisms.

Possibly 0.511 MeV e^+e^-–annihilation line line from the galactic center and maybe even from the galactic halo [37, 38] are the first positive indications to cosmological antimatter.

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