COSMIC ANTIMATTER: MODELS AND OBSERVATIONAL BOUNDS

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Abstract

A model which leads to abundant antimatter objects in the Galaxy (anti-clouds, anti-stars, etc) is presented. Observational manifestations are analyzed. In particular, the model allows for all cosmological dark matter to be made out of compact baryonic and antibaryonic objects.
1 Introduction

The origin of the observed excess of matter over antimatter in the universe is believed to be pretty well understood now. As formulated by Sakharov 1):

1) nonconservation of baryonic number,
2) breaking of C and CP, and
3) deviation from thermal equilibrium

lead to different cosmological abundances of baryons and antibaryons. The cosmological baryon asymmetry is characterized by the dimensionless ratio of the difference between the number densities of baryons and antibaryons to the number density of photons in the cosmic microwave background radiation:

$$\beta = \frac{n_B - n\bar{B}}{n_\gamma} \approx 6 \cdot 10^{-10}$$  \hspace{1cm} (1)

There are many theoretical scenarios which allow to “explain” this value of the baryon asymmetry, for the review see 2). Unfortunately “many” means that we do not know the single one (or several?) of the suggested mechanisms which was indeed realized. Usually in such cases experiment is the judge which says what is right or wrong. However, it is impossible to distinguish between competing mechanisms having in one’s disposal only one number, the same for all the scenarios. We would be in much better situation if $\beta$ is not a constant over all the universe but is a function of space point, $\beta = \beta(x)$. So it is interesting to study the mechanisms which might lead to space varying $\beta$ and especially, in some regions of space, to $\beta < 0$, i.e. to possible generation of cosmological antimatter.

There is an increasing experimental activity in search for cosmic antimatter. In addition to the already existing detectors, BESS, Pamella, and AMS, a few more sensitive ones shall be launched in the nearest years, AMS-02 (2009), PEBS (2010), and GAPS (2013), see the review talk 3) at TAUP 2007. To the present time no positive results indicating an astronomically significant cosmic antimatter have been found but still the bounds are rather loose and as we see in what follows, it is not excluded that the amount of antimatter in the universe may be comparable to that of matter and astronomically large antimatter objects can be in our Galaxy quite close to us.

If this is the case, one should search and may hope to observe cosmic antinuclei starting from $^4$He to much heavier ones, excessive antiprotons and positrons, flux of energetic gamma rays with energies about 100 MeV from $p\bar{p}$–annihilation and 0.511 MeV from $e^-e^+$–annihilation, violent phenomena from antistars and anticlouds, and some other more subtle ones.

We cannot say, of course, if there is any reasonable chance to find all that, but at least there is a simple theoretical model according to which galaxies, including the Galaxy, though possibly dominated by matter, may include
astronomically significant clumps of antimatter on the verge of possible detection.

This talk consists of the following two main parts:
I. The mechanism of the antimatter creation leading to considerable amount of antimatter in the Galaxy in the form of compact objects or clouds.
II. Antimatter phenomenology, observational signatures, and bounds.

The talk is based on several papers written in collaboration with C. Bambi, M. Kawasaki, N. Kevlishvili, and J. Silk, where a detailed discussion and more complete list of references can be found.

2 Standard homogeneous baryogenesis and bounds on antimatter

Up to now we have observed only matter and no antimatter, except for a little antiprotons and positrons most probably of secondary origin. However, the observed intensive 0.511 MeV line from the galactic center, which surely originated from the electron-positron annihilation, $e^+e^- \rightarrow 2\gamma$, may be a signature of cosmic antimatter. Still astronomical data rather disfavor cosmologically significant amount of antimatter. In our neighborhood the nearest anti-galaxy may be at least at the distance of 10 Mpc. This result can be obtained as follows. At such distance the antigalaxy should be in the same cloud of intergalactic gas as e.g. our Galaxy. The number of annihilation per second of the intergalactic gas inside such antigalaxy can be estimated as:

$$\dot{N} = \sigma_{ann} v N_{gal} \langle n_p \rangle = 10^{47} \text{/sec}$$

where $\sigma_{ann} v = 10^{-15} \text{ cm}^3/\text{s}$, $N_{gal} \sim 10^{67}$ is the total number of antiprotons in the gas which is contained in the antigalaxy, $\langle n_p \rangle \sim 10^{-5} \text{/cm}^3$ is the number density of protons in the intergalactic gas. The gamma ray luminosity produced by the annihilation is $L = 10^{45} \text{erg/s}$. It would create the constant in time energy flux on the Earth, $F = 10^{-3} \text{MeV/cm}^2/\text{s}$, which is excluded by observations. For comparison, the typical (short-time) flux from the gamma-bursters is about $10^2 \text{MeV/cm}^2/\text{s}$.

There are observed colliding galaxies at larger distances. They should consist of the same kind of matter (or antimatter?). If galaxy and antigalaxy collide the gamma-ray luminosity would be 5 orders of magnitude higher (proportional to the number density of gas inside galaxies) than the luminosity in the case of antigalaxy washed by the intergalactic gas. This allows to conclude that colliding galaxy and antigalaxy should be at 300 times larger distance, i.e. at or outside the present day cosmological horizon.

Esthetically attractive is the charge symmetric cosmology, with equal weight of cosmologically large domains of matter and antimatter. Such situation is almost inevitable if CP is spontaneously broken. It was shown,
however, that in charge symmetric universe the nearest antimatter domain should be at the distance larger than a Gpc \(10^{10}\), because the matter-antimatter annihilation at the domain boundaries would produce too intensive gamma ray background.

So we have to conclude that an asymmetric production of matter and antimatter is necessary. In the model considered below it is almost symmetric but the bulk of baryonic and/or antibaryonic matter can escape observations if antimatter “lives” in compact high density objects. Observational restrictions on astronomically large but subdominant antimatter objects/domains, anti-stars, anti-clouds, etc, are rather loose and strongly depend upon the type of the objects.

### 3 Anti-creation mechanism

The model which leads to creation of an almost baryosymmetric universe with the bulk of matter in the form of relatively compact objects consisting of baryons and antibaryons was put forward in ref. [14] and recently further developed in [15]. The model is based on the slightly modified version of the Affleck-Dine (AD) baryogenesis scenario [11]. According to AD scenario a very large baryon asymmetry of the universe might be generated due to accumulation of baryonic charge along flat directions of the potential of a scalar field \(\chi\) with nonzero baryonic number. Normally very high \(\beta \sim 1\) is predicted and theoretical efforts are needed to diminish the result. However, if the window to the flat directions is open only during a short period, cosmologically small but possibly astronomically large bubbles with high \(\beta\) could be created, while the rest of the universe would have the normal \(\beta \approx 6 \cdot 10^{-10}\). Such high \(B\) bubbles would occupy a small fraction of the universe volume, but may make a dominant contribution to the total mass of the baryonic matter. They can even make all cosmological dark matter in the form of compact already dead (anti)stars or primordial black holes (PBH).

To achieve this goal one should add a general renormalizable coupling of the scalar baryon \(\chi\) to the inflaton \(\Phi\):

\[
U_\chi(\chi, \Phi) = \lambda_1 (\Phi - \Phi_1)^2 |\chi|^2 + \lambda_2 |\chi|^4 \ln \left( \frac{|\chi|^2}{\sigma^2} \right) + m_0^2 |\chi|^2 + m_1^2 \chi^2 + m_1^2 \chi^2.
\]

(3)

where \(\Phi_1\) is some value of the inflaton field which it passes closer to the end of inflation. Its value is chosen so that after passing \(\Phi_1\) inflation is still significant to make large B-bubbles. The second term in the potential is Coleman-Weinberg potential [12], which is obtained by summation of one loop corrections to the quartic potential, \(\lambda_2 |\chi|^4\). The last two mass terms are not invariant with
respect to the phase rotation:

\[ \chi \rightarrow e^{i\theta} \chi \]  

(4)

and thus break baryonic current conservation. It can be seen from the following mechanical analogy. The equation of motion of homogeneous field \( \chi(t) \):

\[ \ddot{\chi} + 3H \dot{\chi} + \frac{\partial U(\chi, \Phi)}{\partial \chi^*} = 0 \]  

(5)

is just the equation of motion of point-like particle in potential \( U \) with the liquid friction term proportional to the Hubble parameter \( H \). In this language the baryonic number, which is the time component of the current

\[ J_{\mu}^{(B)} = i\chi^\dagger \partial_\mu \chi + h.c., \]  

(6)

is the angular momentum of this motion. If the potential is spherically symmetric i.e. it depends upon \( |\chi| \), angular momentum is conserved. The last two terms break spherical symmetry and give rise to B-nonconservation.

Depending upon the value of \( \Phi \), potential \( U(\chi, \Phi) \) has either one minimum at \( \chi = 0 \), or two minima: at \( \chi = 0 \) and some \( \chi_2(\Phi) \neq 0 \), or again one minimum at \( \chi_2(\Phi) \), see fig. 1.

The behavior of \( \chi \) in this potential is more or less evident. When the potential well near the minimum at \( \chi = 0 \) becomes low, the field can quantum fluctuate away from zero and if \( \chi \) reaches sufficiently large magnitude during period when the second deeper minimum at \( \chi_2 \) exists, it would live there till this second minimum disappears. Otherwise \( \chi \) would remain at \( \chi = 0 \). Choosing the parameters of the potential we can make the probability to fluctuate to the second minimum sufficiently small. When the minimum at \( \chi_2 \) disappears \( \chi \) would move down to zero oscillating around it with decreasing amplitude. The decrease is due to the cosmological expansion and to particle production by the oscillating field \( \chi \). The evolution of \( \chi \) is presented in fig. 2, according to numerical calculations of ref. [1].

An important feature of the solution is the rotation of \( \chi \) around the point \( \chi = 0 \), induced by the non-sphericity of the potential at low \( \chi \). As is argued above, this rotation is just non-zero baryonic charge density of \( \chi \). Baryonic number stored in this rotation is transformed into excess of quarks over antiquarks or vice versa by B-conserving \( \chi \) decays.

The magnitude of the baryon asymmetry, \( \beta \), inside the bubbles which were filled with large \( \chi \) (B-balls) and the bubble size are stochastic quantities. The initial phase, \( \theta \), is uniform in the interval \( [0, 2\pi] \) since due to the large Hubble term, \( H \gg m_1 \), quantum fluctuations equally populate the circle of the second minimum of \( U(\chi, \Phi) \) [3] where \( \chi = \chi_2 \). The generated baryonic number (angular momentum) is proportional to the displacement of the phase
with respect to the valley where $m_2^2 \chi^2 + m_1^2 \chi^2$ has minimal value. Evidently the bubbles with negative and positive $\beta$ are equally probable. The magnitude of the asymmetry inside B-bubbles is also uniformly distributed in the interval $[-\beta_m, \beta_m]$, where $\beta_m$ is the maximum of the asymmetry which may be of the order of unity. The baryon asymmetry inside the bubbles can be especially large if $\chi$ decayed much after the inflaton decay. In this case the cosmological energy density would be dominated by non-relativistic $\chi$ prior to its decay and all the baryonic number would be normalized to photons produced by $\chi$ decay products only.

A simple modification of the potential $U(\chi, \Phi)$ can shift the matter-antimatter symmetry of B-bubble population in either way and magnitude, see e.g. 13. In this way the universe with the homogeneous background baryon asymmetry $\beta = 6 \cdot 10^{-10}$ and small regions with $\beta \sim 1$ of both signs can be created. Despite a small fraction of the volume, B-bubbles may dominate in the cosmological energy density.

The size of B-ball is determined by the remaining inflationary time after
Figure 2: Evolution of $|\chi|$ because of the shift of the position of the second minimum in $U(\chi, \Phi)$.

The inflaton field passed $\Phi_1$ and can be as large as the solar mass or even much larger, or as small as $10^{15} - 10^{20}$ g or even smaller.

According to the calculations of refs. [4, 6] the initial mass spectrum has a very simple log-normal form:

$$\frac{dN}{dM} = C \exp \left[ -\gamma \ln^2 \left( \frac{M}{M_1} \right) \right],$$

where $C$, $\gamma$, and $M_1$ are unknown constant parameters. If $M_1 \sim M_\odot$ some of these high $\beta$ bubbles might form stellar type objects and primordial black holes (PBH). With much smaller $M_1$ light PBHs, but still with sufficiently large masses to save them from the Hawking evaporation during the universe life-time, could be created. Relatively light PBH with $M \approx 10^{17}$ g and mass spectrum (7) may be the source of 0.511 line from $e^+e^-$–annihilation [13], observed in the galactic center. In all the cases of heavy or light PBH and/or evolved, now dead or low luminosity, stars, they could make (all) cosmological dark matter.
Due to subsequent accretion of matter the initial spectrum (7) would be somewhat distorted. The calculations are in progress but here in phenomenological application we assume that the spectrum is not modified.

4 Inhomogeneities

In this scenario there are two mechanisms of creation of density perturbations at small scales:

1. After formation of domains with large $\chi$ the equation of state inside and outside of the domains would be different. Inside the domains $\langle \chi \rangle \neq 0$ and the equation of state approaches the nonrelativistic one, while outside the domains the equation of state remains relativistic for a long time. As is known, in this case isocurvature perturbations are generated which in the course of evolution are transformed into real density perturbations with $\delta \rho \neq 0$.

2. After the QCD phase transition at $T \sim 100$ MeV, when quarks made nonrelativistic protons, the matter inside B-balls would quickly become nonrelativistic and a large density contrast could be created.

As we just have mentioned the initially inhomogeneous $\chi$ and/or $\beta$ lead to isocurvature perturbations. The amplitude of such perturbations is restricted by CMBR at about 10% level, but the bounds from CMBR are valid at quite large wave lengths, larger than $\sim 10$ Mpc.

If $\delta \rho / \rho = 1$ at horizon crossing, PBHs could be formed. The mass inside the horizon as a function of the cosmological time is:

$$M_{\text{hor}} = 10^{38} \text{g (t/sec)}$$

For relativistic expansion regime time is related to temperature as $t(\text{sec}) \approx 1/T^2(\text{MeV})$. Thus for $T = 10^8$ GeV at the horizon crossing the PBH mass would be $10^{16} \text{g}$. At the QCD phase transition and below the mass inside the horizon can be from the solar mass up to $10^{6-7} M_\odot$ on the tail of the distribution. This presents a new mechanism of an early quasar formation which naturally explains their large masses already at high red-shifts and their evolved chemistry.

Anti-BH may be surrounded by anti-atmosphere if $\beta$ slowly decreases. There is no observational difference between black holes and anti black holes but the atmosphere may betray them.

The masses may be even larger than millions solar masses, but we assume that $M_0$ in eq. (7) does not exceed a few solar masses, so the formation of BHs much more massive than indicated above is strongly suppressed. Compact objects (not BH) with smaller masses might be formed too depending upon the relation between their mass and the Jeans mass (see below).

The density contrast created by an almost instant transformation of rel-
ativistic quarks into nonrelativistic baryons is equal to:

\[
\frac{\delta \rho}{\rho} = \frac{\beta n_e m_p}{(\pi^2/30)g_s T^4} \approx 0.07 \beta \frac{m_p}{T^4}.
\]  
(9)

The nonrelativistic baryonic matter started to dominate inside the bubble at the temperature:

\[
T = T_{in} \approx 65 \beta \text{MeV}
\]  
(10)

The mass inside a baryon-rich bubble at the radiation dominated stage is

\[
M_B \approx 2 \cdot 10^5 M_\odot (1 + r_B) \left( \frac{R_B}{2t} \right)^3 \left( \frac{t}{\text{sec}} \right)
\]  
(11)

The mass density in such a bubble at the onset of matter domination is

\[
\rho_B \approx 10^{13} \beta^4 \text{g/cm}^3.
\]  
(12)

When a B-bubble entered under horizon its evolution in the early universe is determined by the relation between its radius, \(R_B\) and the Jeans wave length, \(\lambda_J\). The latter at the onset of MD-dominance is

\[
\lambda_J = c_s \left( \frac{\pi M_{Pl}^2}{\rho} \right)^{1/2} \approx 10 t \left( \frac{T}{m_N} \right)^{1/2}
\]  
(13)

where the speed of sound is taken as \(c_s \approx (T/m_N)^{1/2}\).

The bubbles with \(\delta \rho/\rho < 1\) but with \(R_B > \lambda_J\) and correspondingly \(M_B > M_{\text{Jeans}}\) at horizon would decouple from cosmological expansion and form compact stellar type objects or "low" density clouds. For further implication it is important to know what anti-objects could survive against an early annihilation?

The initial value of the Jeans mass is equal to:

\[
M_J \approx 135 \left( \frac{T}{m_N} \right)^{3/2} M_{Pl} t \approx 100 M_\odot \beta^{1/2}
\]  
(14)

Taken literally this expression leads to a slow, as \(1/\sqrt{T}\), increase of \(M_J\) and \(\lambda_J\). However, this is not so because in a matter dominated object with a high baryon-to-photon ratio the temperature drops as \(T \sim 1/a^2\) and \(M_J\) decreases too: \(M_J \sim 1/a^{3/2}\). For example, for B-balls with approximately solar mass \(M_B \sim M_\odot\) and the radius \(R_B \approx 10^9\) cm at horizon crossing the mass density behaves as:

\[
\rho_B = \rho_B^{(in)} (a_{in}/a)^3 \approx 6 \cdot 10^5 \text{g/cm}^3.
\]  
(15)
The temperature inside such a B-ball at the moment when $M_J = M_{\odot}$ is equal to:

$$T \approx T_{\text{in}}(a_{\text{in}}/a)^2 \approx 0.025 \text{ MeV}. \quad (16)$$

Such an object is similar to the red giant core.

5 Universe heating by B-balls

There are three processes of energy release which are potentially important for B-ball survival and for the physics of the early universe (BBN, CMBR, reionization, etc):

1. Cooling down of B-balls because of their high internal temperature.
2. Annihilation of the surrounding matter on the surface.
3. Nuclear reactions inside.

We will briefly discuss them in what follows.

1. Initially the temperature inside B-balls was smaller than the outside temperature because of faster cooling of nonrelativistic matter. So such stellar-like object were formed in the background plasma with higher temperature and higher external pressure. It is in a drastic contrast with normal stars where the situation is the opposite.

After the B-bubble mass became larger than the Jeans mass, the ball expansion stopped and the internal temperature gradually became larger than the external one and B-balls started to radiate into external space. The cooling time is determined by the photon diffusion:

$$t_{\text{diff}} \approx 2 \cdot 10^{11} \text{ sec} \left( \frac{M_B}{M_{\odot}} \right) \left( \frac{\text{sec}}{R_B} \right) \left( \frac{\sigma_{e\gamma}}{\sigma_{Th}} \right) \quad (17)$$

The thermal energy stored inside B-ball is

$$E_{\text{therm}}^{(\text{tot})} = 3T M_B/m_N \approx 1.5 \cdot 10^{50} \text{ erg} \quad (18)$$

and the luminosity determined by the diffusion time $t_{\text{diff}}$ would be $L \approx 10^{39} \text{ erg/sec}$.

If B-balls make all cosmological dark matter, their fraction cannot exceed $\Omega_{DM} = 0.25$. Hence the thermal keV photons would make $(10^{-4} - 10^{-5}) \Delta$ of CMBR, red-shifted today to the background light. Here $\Delta$ is the fraction of B-balls with solar mass and $\sim$keV internal temperature.

2. If B-ball is similar to the red giant core the nuclear helium burning inside would proceed through the reaction $3He^4 \rightarrow C^{12}$, however with larger $T$ by the factor $\sim 2.5$. Since the luminosity with respect to this process strongly depends upon the temperature, $L \sim T^{40}$, the life-time of such B-ball would be
very short. The total energy influx from such B-ball would be below $10^{-4}$ of CMBR if $\tau < 10^9$ s. The efficient nuclear reactions inside B-balls could lead to B-ball explosion and creation of solar mass anti-cloud which might quickly disappear due to matter-antimatter annihilation inside the whole volume of the cloud. It is difficult to make a qualitative conclusion without detailed calculations.

3. For compact objects, in contrast to clouds, the annihilation could proceed only on the surface and they would have much longer life-time. The (anti)proton mean free path before recombination is small:

$$l_p = \frac{1}{\sqrt{\sigma n}} \sim \frac{m_p^2}{\alpha^2 T^3} = 0.1 \text{ cm} \left(\frac{\text{MeV}}{T}\right)^3$$  \(19\)

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

$$\dot{N} = 10^{31} V_p \left(\frac{T}{0.1 \text{ eV}}\right)^3 \left(\frac{R_B}{10^9 \text{ cm}}\right)^2,$$  \(20\)

The energy release from this process would give about $10^{-15}$ of the CMBR energy density.

6 Early summary

1. Compact anti-objects mostly survived in the early universe.
2. A kind of early dense stars might be formed with initial pressure outside larger than that inside.
3. Such “stars” may evolve quickly and, in particular, make early SNs, enrich the universe with heavy (anti)nuclei and re-ionize the universe.
4. The energy release from stellar like objects in the early universe is small compared to CMBR.
5. B-balls are not dangerous for BBN since the volume of B-bubbles is small. Moreover, one can always hide any undesirable objects into black holes.

For more rigorous conclusion detailed calculations are necessary.

7 Antimatter in contemporary universe

Here we will discuss phenomenological manifestations of possible astronomical anti-objects which may be in the Galaxy. We will use the theory discussed above which may lead to their creation as a guiding line but will not heavily rely on any theory for the conclusions. We assume that anything which is not forbidden is allowed and consider observational consequences of such practically
unrestricted assumption.
Astronomical objects which may live in our neighborhood include:
1. Gas clouds of antimatter.
2. Isolated antistars.
3. Anti stellar clusters.
4. Anti black holes.
5. Anything else not included into the list above.
Such objects may be: inside galaxies or outside galaxies, inside galactic halos or in intergalactic space. We will consider all the options.

7.1 Photons from annihilation

The observational signatures of these (anti)objects would be a 100 MeV gamma background, excessive antiprotons and positrons in cosmic rays, antinuclei, compact sources of gamma radiation, and probably more difficult, a measurement of photon polarization from synchrotron radiation and fluxes of neutrino versus antineutrino in neutrino telescopes.

Astronomically large antimatter objects is convenient to separate into two different classes: clouds of gas and compact star-like or smaller but dense clumps of antimatter. The boundary line between this two classes is determined by the comparison of the mean free path of protons inside them, \( l_p \), and their size, \( R_B \). If \( l_p > R_B \) the annihilation of antimatter in the cloud proceeds in all the volume of such B-bubble. In the opposite case the annihilation takes place only on the surface. The proton mean free path can be estimated as:

\[
l_p = \frac{1}{\sigma_{\text{tot}} n_{\bar{p}}} = 10^{24} \text{cm} \left( \frac{\text{cm}^{-3}}{n_{\bar{p}}} \right) \left( \frac{\text{barn}}{\sigma_{\text{tot}}} \right) \]

(21)

If the number density of antiprotons inside the bubble, \( \bar{n} \), is much larger (which is typically the case) than the number density of protons in the background, i.e. \( n_{\bar{p}} \gg n_p \), then it is possible that for B-ball smaller than \( l_{\text{gal}} = 3 - 10 \text{ kpc} \) both limiting cases can be realized: volume annihilation \( l_{\text{free}} > R_B \), i.e. clouds, and surface annihilation, \( l_{\text{free}} < R_B \), i.e. compact (stellar-like) objects.

One should expect that typically an anti-cloud could not survive in a galaxy. It would disappear during

\[
\tau = 10^{15} \text{ sec} \left( \frac{10^{-15} \text{ cm}^3/\text{s}}{\sigma_{\text{ann}} V} \right) \left( \frac{\text{cm}^{-3}}{n_p} \right),
\]

(22)

if the supply of protons from the galactic gas is sufficient. The proton flux into an anti-cloud is equal to:

\[
F = 4\pi l_c^2 n_p v = 10^{35} \text{ sec}^{-1} \left( \frac{n_p}{\text{cm}^3} \right) \left( \frac{l_c}{\text{pc}} \right)^2,
\]

(23)
where $l_c$ is the cloud size, previously denoted as $R_B$. The total number of $\bar{p}$ in the cloud is $N_\bar{p} = 4\pi l_c^3 n_\bar{p}/3$. The flux of protons form the galactic gas is sufficient to destroy the anti-cloud in less than the universe age, i.e. $3 \cdot 10^{17}$ seconds, if:

$$\left(\frac{n_\bar{p}}{cm^3}\right) \left(\frac{l_c}{pc}\right) < 3 \cdot 10^4$$  \hspace{1cm} (24)

Thus very large clouds might survive even in a galaxy. Almost surely they would survive in the halo.

In the case of volume annihilation, i.e. for $l_{free} > l_c$ the number of annihilation per unit time and volume is

$$\dot{n}_p = v\sigma_{ann} n_p n_\bar{p}$$  \hspace{1cm} (25)

The total number of annihilation per unit time is: $\dot{N}_p = 4\pi l_c^3 \dot{n}_p/3$. The total number of $\bar{p}$ in the cloud is equal to: $N_\bar{p} = 4\pi l_c^3 n_\bar{p}/3$. Comparing these two expressions we find the life-time (22) of the cloud.

The luminosity for volume annihilation is equal to:

$$L^{(vol)}_\gamma \approx 10^{45} \frac{erg}{s} \left(\frac{R_B}{0.1 \text{ pc}}\right)^3 \left(\frac{n_p}{10^{-4} \text{ cm}^{-3}}\right) \left(\frac{n_\bar{p}}{10^4 \text{ cm}^{-3}}\right)$$  \hspace{1cm} (26)

and the flux of gamma rays on the Earth from anti-cloud at the distance of $d=10$ kpc would be: $10^{-7} \gamma/\text{s/cm}^2$ or $10^{-5} \text{Mev/ s/cm}^2$, to be compared with cosmic background $10^{-3} / \text{MeV/s/cm}^2$. Still such annihilating cloud can be observed with a sufficiently good angular resolution of the detector.

The compact stellar type objects for which $l_s \gg l_{free}$ experience only the surface annihilation - all that hits the surface annihilate. There should be different sources of photons with quite different energies. The gamma-radiation from $pp \to pions$ and $\pi^0 \to 2\gamma$ ($E_\pi \sim 300$ MeV) would have typical energies of hundreds MeV. The photons from $e^+ e^-\text{-annihilation}$ originating from $\pi^\pm$ decays $\pi \to \mu\nu$, $\mu \to e\nu\bar{\nu}$, would be mostly below 100 MeV, while those from the ”original” positrons in the B-ball would create a pronounced 0.511 MeV line.

The total luminosity with respect to surface annihilation is proportional to the number density of protons in the Galaxy and to their velocity, $L_{tot} = 8\pi m_p l_s^2 n_p v$.

From this we obtain:

$$L_{tot} \approx 10^{27} \frac{erg}{sec} \left(\frac{n_p}{\text{cm}^3}\right) \left(\frac{l_s}{l_\odot}\right)^2$$  \hspace{1cm} (27)

from which the fraction into gamma-rays is about 20-30%.
7.2 Antimatter from stellar wind

Surprisingly the luminosity created by the annihilation of antiprotons from the stellar wind may be larger than that from the surface annihilation. The flux of particles emitted by an antistar per unit time can be written as:

\[ \dot{M} = 10^{12}W \, g/sec \]  

(28)

where parameter \( W \) describes the difference of matter emission by solar type star and the anti-star under consideration: \( W = M/M_\odot \). For solar type anti-star \( W \approx 1 \), while for already evolved antistar \( W \ll 1 \). If all “windy” particles (antiprotons and heavier antinuclei) annihilate, the luminosity per antistar would be \( L = 10^{33}W \, \text{erg/sec} \).

One sees that the luminosity of compact antimatter objects in the Galaxy is not large and it is not an easy task to discover them. However such objects may have an anomalous chemical content which would be an indication for possible antimatter. According to the discussed above scenario of generation of cosmic antimatter objects they should have anomalously large baryon-to-photon ratio. This leads to anomalous abundances of light elements in this regions, for example such domains should contain much less anti-deuterium and more anti-helium than in the standard case with \( \beta = 6 \cdot 10^{-10} \). Moreover, some heavier primordial elements in the regions with high \( \beta \) can be formed 115). So the search for antimatter should start from a search of cosmic clouds with anomalous chemistry. If such a cloud or compact object is found, one should search for a strong annihilation there. With 50% probability this may be, however, the normal matter with anomalous \( n_B/n_\gamma \) ratio, i.e. B-bubble with positive baryonic number.

Stellar wind and explosions of antistars would lead to enrichment of the Galaxy with low energy antiprotons. The life-time of \( \bar{p} \) with respect to annihilation in the Galaxy can be estimated as:

\[ \tau = 3 \cdot 10^{13} \, \text{sec} \left( \frac{\text{barn}}{\sigma_{ann} \, v} \right). \]  

(29)

The total number of antiparticles in a galaxy is determined by the equation:

\[ \dot{N} = -\sigma_{ann} \, v \, n_p \, \bar{n}_p \, V_{gal} + S \]  

(30)

where \( S \) is the source, i.e. \( S = W \epsilon (N_s/10^{12}) \, 10^{48} / \text{sec} \), \( N_s \) is the number of stars in the galaxy, \( \epsilon \) is the fraction of antistars. The stationary solution of the above equation is

\[ n_{\bar{p}} = \left( \frac{3 \cdot 10^{-5}}{\text{cm}^3} \right) \epsilon W \left( \frac{N_s}{10^{12}} \right) \left( \frac{\text{barn}}{\sigma_{ann} \, v} \right). \]  

(31)
The number density of antinuclei is bounded by the density of “unexplained” \( \bar{p} \) and the fraction of antinuclei in stellar wind with respect to antiprotons. It may be the same as in the Sun but if antistars are old and evolved, this number may be much smaller. Heavy antinuclei from anti-supernovae may be abundant but their ratio to \( \bar{p} \) cannot 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 SN might explode only in very early galaxies or even before them.

7.3 Cosmic positrons

Antistars can be powerful sources of low energy positrons. The gravitational proton capture by an antistar is more efficient than capture of electrons because of a larger mobility of protons in the interstellar medium. A positive charge accumulated by the proton capture should be neutralized by a forced positron ejection. It would be most efficient in galactic center where \( n_p \) is large. The observed 0.511 MeV annihilation line must be accompanied by wide spectrum \( \sim 100 \) MeV radiation.

7.4 Violent phenomena

A collision of a star with an anti-star of comparable mass would lead to a spectacular event of powerful gamma radiation similar to \( \gamma \)-bursters. The estimated energy release would be of the order of:

\[
\Delta E \sim 10^{48} \text{erg} \left( \frac{M}{M_\odot} \right) \left( \frac{v}{10^{-3}} \right)^2
\]

Since the annihilation pressure pushes the stars apart, the collision time would be quite short, \( \sim 1 \) sec. The radiation would be most probably emitted in a narrow disk but not in jets.

Another interesting phenomenon, though less energetic, is a collision of an anti-star with a red giant. In this case the compact anti-star would travel inside the red giant creating an additional energy source. It could lead to a change of color and luminosity. The expected energy release is \( \Delta E_{\text{tot}} \sim 10^{38} \) erg during the characteristic time \( \Delta t \sim \) month.

The transfer of material in a binary star-antistar system would lead to a very energetic burst of radiation similar to a hypernova explosion.

More difficult for observation and less spectacular effects include the photon polarization. Since positrons are predominantly “right handed”, the same helicity is transferred to bremsstrahlung photons. Indeed, neutron decay creates left-handed \( e^- \) and antineutron creates right-handed positrons. The first
burst from SN explosion consists predominantly of antineutrinos while that from anti-SN consists of neutrinos.

7.5 Baryonic and antibaryonic dark matter

The model considered above opens a possibility that all cosmological dark matter is made out of normal baryonic and antibaryonic stuff in the form of compact stellar-like objects as early formed and now dead stars or primordial black holes, either with mass near solar mass or much smaller, e.g. near $10^{20}$ g.

Such objects could make all cold dark matter (CDM) in the universe but in contrast to the usually considered CDM they are much heavier and have a dispersed (log-normal) mass spectrum. Very heavy ones with $M > 10^8 M_\odot$ which might exist on the high mass tail of the distribution could be the seeds of large galaxy formation. Lighter stellar type objects would populate galactic halos as usual CDM.

The bounds on stellar mass object in the halo of the Galaxy is presented in Fig. 3, taken from ref. 16. No luminous stars are observed in the halo. It means that all high B compact objects are mostly already dead stars or PBH. So the stellar wind must be absent. However, annihilation of background protons on the surface should exist and lead to gamma ray emission.

7.6 Observational bounds

The total galactic luminosity of the 100 MeV photons, $L_\gamma = 10^{39}$ erg/s, and the flux of the $e^+e^-$-annihilation line, $F \sim 3 \cdot 10^{-3}$ cm$^2$/s, allow to put the following bound on the number of antistars in the Galaxy from the consideration of the stellar wind:

$$N_{\bar{S}}/N_{S} \leq 10^{-6} W^{-1}. \quad (33)$$

It is natural to expect that $W \ll 1$ because the primordial antistars should be already evolved.

From the bound on the antihelium-helium ratio (see e.g. review 3) follows:

$$N_{\bar{S}}/N_{S} = (\bar{He}/He) \leq 10^{-6}, \quad (34)$$

if the antistars are similar to the usual stars, though they are most probably not.

The only existing now signature in favor of cosmic antimatter is the observed 0.511 MeV photon line from galactic center and probably even from the galactic halo. However, other explanations are also possible (for the list of references see 14).
8 Conclusion

1. The Galaxy may possess a noticeable amount of antimatter. Both theory and observations allow for that.
2. Theoretical predictions are vague and strongly model dependent.
3. Not only $^4\text{He}$ is worth to look for but also heavier anti-elements. Their abundances should be similar to those observed in SN explosions.
4. The regions with anomalous abundances of light elements suggest that they consist of antimatter.
5. A search of cosmic antimatter has non-vanishing chance to be successful.
6. Dark matter made of BH, anti-BH, and dead stars is a promising candidate. There is a chance to understand why $\Omega_B = 0.05$ is similar by magnitude to $\Omega_{DM} = 0.25$. 

Figure 3: Micro-lensing bounds on compact objects in the galactic halo as a function of their mass
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