Antiprotons Annihilation in the Galaxy
As A Source of Diffuse Gamma Background

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Abstract

The existence of antimatter domains in baryon asymmetrical Universe can appear as the cosmological consequence of particle theory in inflationary models with non-homogeneous baryosynthesis. Such a domain can survive in the early Universe and form globular cluster of antimatter stars in our Galaxy. The model of antimatter pollution of Galaxy and annihilation with matter gas is developed. The proton-antiproton annihilation gamma flux is shown to reproduce the observed galactic gamma background measured by EGRET. From comparison with observational data the estimation on the maximally allowed amount of antimatter stars, possibly present in our Galaxy, is found.

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1 Introduction

The generally accepted motivation for baryon asymmetric Universe is the observed absence of the macroscopic amounts of antimatter up to the scales of clusters of galaxies, which probably extends on all the part of the Universe within the modern cosmological horizon [1]. The modern cosmology relates this baryon asymmetry of the Universe to the process of baryosynthesis., i.e. to the creation of baryon excess in very early Universe [2, 3]. In the homogeneous baryon asymmetric Universe the Big Bang theory predicts exponentially small fraction of primordial antimatter. Therefore, any non exponentially small amount of antimatter in the modern Universe is the profound signature for new phenomena, related to the existence of antimatter domains and leads to the respective predictions for antinuclear component of galactic cosmic rays.

The most recent analysis finds that the size of possible antimatter domains in baryon symmetrical Universe should be only few times smaller than the modern cosmological horizon to escape the contradictions with the observed gamma ray background [4]. The distribution of antibaryon excess, corresponding to relatively small ($\lesssim 10^{-5}$) volume occupied by it, can arise in inflational models with baryosynthesis and is compatible with all the observational constraints on the annihilation of antimatter in the baryon dominated Universe [4]. The size and amount of antimatter domains is related to the parameters of models of inhomogeneous baryosynthesis (see for review [4, 5]). With the account for all possible mechanisms for inhomogeneous baryosynthesis, predicted on the base of various and generally independent extensions of the standard model, the general analysis of possible domain distributions is rather complicated. But the main point of the existing mechanisms of baryosynthesis, important for our aims, is that all of them can lead to inhomogeneity of baryon excess generation and even to generation of antibaryon excess in some regions of space, when the baryon excess, averaged over the whole space, being positive (see reviews in [4, 5, 6]).

On the other hand, EGRET data [7] on diffuse gamma background show visible peak around $E_{\gamma} \approx 70$ MeV in gamma spectrum, which fact can be naturally explained by the decays of $\pi^0$-mesons, produced in nuclear reactions. Interactions of the protons with gaseous matter in the Galaxy shift the position of such a peak to higher values of gamma energy due to 4-momentum conservation. At the same time the secondary antiprotons, produced in the cosmic ray interactions with interstellar gas, are too energetic [10] and their annihilation also cannot explain the observational data.

The above consideration draws attention to the model with antimatter globular cluster existing in our Galaxy, which cluster can serve as a permanent source of antimatter due to (anti)stellar wind or (anti)Supernova explosions. The isolated antimatter domain can not form astronomical object smaller than globular cluster [11]. The isolated anti-star can not be formed in the surrounding matter since its formation implies the development of thermal instability, during which cold clouds are pressed by hot gas. Pressure of the hot matter gas on the antimatter cloud is accompanied by the annihilation of antimatter. Thus anti-stars can be formed in
the surrounding antimatter only, what may take place when such surrounding has at least the scale of globular cluster. One can expect to find antimatter objects among the oldest population of the Galaxy [11], in the halo, since owing to strong annihilation of antimatter and matter gas the formation of secondary antimatter objects in the disk component of our Galaxy is impossible. So in the estimation of antimatter effects we can use the data on the spherical component of our Galaxy as well as the analogy with the properties of the old population stars in globular clusters and elliptical galaxies. The total mass of such cluster(s) is constrained from below by the condition of antimatter domain survival in the surrounding baryonic matter because small antimatter domains completely annihilate in the early Universe before the stage of galaxy formation. The upper limit on the total mass of antimatter can be estimated from the condition, that the gamma radiation from annihilation of antimatter with galactic matter gas does not exceed the observed galactic gamma background. The expected upper limit on cosmic antihelium flux from antimatter stars in our Galaxy was found [11, 12] only factor of two below the modern level of sensitivity in experimental cosmic antihelium searches [13]. In the first approximation the integral effect we study depends on the total mass of the antimatter stars and does not depend on the amount of globular clusters. The only constraint is that this amount does not exceed the observed number of galactic globular clusters (about 200).

Assume that antimatter globular cluster, moves along elliptical orbit in the halo. The observed dispersion of velocity of globular clusters is $<v> \sim 300$ km/s and of the long axis of their orbits is $<r> \sim 20$ kpc. This gives $T \sim 2 \cdot 10^{15}$ s as the order of the magnitude for the period of orbital motion of the cluster in the Galaxy. The period the cluster moves along the dense region of the disk with the mean half–width $D \sim 100$ pc depends on the angle at which the orbit crosses the plane of the disk and is of the order

$$t_d \sim \frac{D}{<v>} \sim 10^{13} \text{ s}.$$

This means that the cluster spends not more than 1% of the time in the dense region of galactic disk, where the density of gas is of the order of $n_{H}^{\text{disk}} \sim 1$ cm$^{-3}$, moving the most time in the halo with much lower density of the matter gas $n_{H}^{\text{halo}} \sim 5 \cdot 10^{-4}$ cm$^{-3}$. Therefore, we can neglect the probability to find the cluster in the disk region and consider the case when the source of the antimatter is in the halo.

One could expect two sources of the annihilation gamma emission from the antimatter globular cluster. The first one is the annihilation of the matter gas captured by the antimatter stars. Another source is the annihilation of the antimatter, lost by the antimatter stars, with interstellar matter gas. It is clear that the gamma flux originating from the annihilation of the matter gas on the antimatter stars surface is negligible. Really, an antimatter star of the Solar radius $R = R_{\odot}$ and the Solar mass $M = M_{\odot}$ captures matter gas with the cross section

$$\sigma \sim \pi R \left( R + \frac{2GM}{v^2} \right) \sim 4 \cdot 10^{22} \text{ cm}^2,$$
so that the gamma luminosity of cluster of $10^5$ stars does not exceed $L_{\gamma} \leq M_5 \cdot 10^{29} \text{erg/s}$, where $M_5$ is the relative mass of the cluster in units $10^5 \text{M}_\odot$, $M_\odot = M_5 \cdot 10^5 \text{M}_\odot$. Such a low gamma luminosity being in the halo at the distance of about 10 kpc results in the flux $F_{\gamma} \leq 10^{-13} \text{(ster} \cdot \text{cm}^2 \cdot \text{s})^{-1}$ of 1000 MeV gamma rays near the Earth, what is far below the observed background. This explains why the antimatter star itself can be rather faint gamma source elusive for gamma astronomy and shows that the main contribution into galactic gamma radiation may come only from the annihilation of the antimatter lost by the antistars with the galactic interstellar gas.

There are two sources of an antimatter pollution from the (anti-)cluster: the (anti-)stellar wind and the antimatter Supernova explosions. In both cases the antimatter is expected to be spread out over the Galaxy in the form of positrons and antinuclei. The first source provides the stationary in-flow of antimatter particles with the velocities in the range from few hundreds to few thousands km/s to the Galaxy. The (anti)Supernova explosions give antimatter flows with velocities order of $10^4$ km/s. The relative contributions of both these sources will be estimated further on the base of comparison with the observational data assuming that all the contribution into diffuse gamma background comes from the antimatter annihilation with the interstellar matter gas. We assume in present paper that the chemical content to be dominated by anti-hydrogen and consider the contribution from the annihilation of the antiprotons only.

We consider the quasi-stationary case, provided by the presence of a permanent source of the antimatter. The assumption about stationarity strongly depends on the distribution of magnetic fields in the Galaxy, trapping charged antiparticles, annihilation cross section and on the distribution of the matter gas. We shall see that the assumption about stationarity is well justified by existing experimental data and theoretical models.

We carried out a careful consideration of the possibility to reproduce the observed spectrum of diffuse gamma background, suggesting the existence of maximal possible amount of the antimatter in our Galaxy. We showed that the predicted gamma spectrum is consistent with the observations. In this case the integral amount of galactic antimatter can be estimated, which estimation leads to definite predictions for cosmic antinuclear fluxes [11, 12], accessible for cosmic ray experiments in the nearest future [13].

2 The model of galactic antimatter annihilation.

In this section we shall show that one can consider the antiproton annihilation in the halo as a stationary process and the distribution of the antiprotons does not depend practically on position and motion of the globular cluster of antistars.

One of the most crucial points for the considered model is the annihilation cross section of the antiprotons. In difference to the inelastic cross section of the $pp$ collisions, the cross section in the $\bar{p}p$ annihilation steeply grows as kinetic energy
of the antiprotons goes to zero. This growth leads to the obvious fact that the main contribution into gamma flux must come from the annihilation of the slowest antiprotons. Therefore we need to have reliable estimation for the annihilation cross section of the antiprotons at low kinetic energies. Existing theoretical models based mainly on the partonic picture of the hadronic interactions are definitely invalid for \( \bar{p}p \) annihilation at low energies and we used experimental data both for evaluation of the annihilation cross section as well as for the final state configuration.

At small energies the cross section must be proportional to the inverse power of the antiproton velocity. To find this dependence we have to match the available experimental data on \( \sigma_{ann} \) with this expected behavior. As it follows from data \([14, 15]\), obtained at CERN-LEAR, the dependence \( \sigma_{ann} \sim v^{-1} \) is valid already for laboratory antiproton momenta \( p_{lab} \leq 1000 \text{ MeV/c} \). The annihilation cross section is the difference between total and inelastic ones, \( \sigma_{ann} \approx \sigma_{tot} - \sigma_{el} \). Thus, at \( P_{lab} \geq 300 \text{ MeV/c} \) we used data from \([16]\) for the total and elastic cross sections and at momenta less than 300 MeV/c we used the dependence

\[
\sigma_{ann}(P < 300 \text{ MeV/c}) = \sigma_0 C(v^*)/v^* \\
\sigma_{el} = \text{const}, \tag{1}
\]

for annihilation and elastic cross sections, respectively, where \( v^* \) is the velocity of the antiproton in the \( \bar{p}p \) center-of-mass system. Additional Coulomb factor \( C(v^*) \) gives large increase for the annihilation cross section at small velocities of the antiproton and is defined by the expression \([17]\):

\[
C(v^*) = \frac{2 \pi v_c/v^*}{1 - \exp (-2 \pi v_c/v^*)}, \tag{2}
\]

where, \( v_c = \alpha c \), with \( \alpha \) and \( c \) being the fine structure constant and the speed of light, respectively.

Using the experimental data on the \( \bar{p}p \) annihilation cross section \([14, 15]\) we found that value \( \sigma_0 \) in (1) is equal to:

\[
\sigma_0 = \sigma_{ann}^{exp}(P = 300 \text{ MeV/c}) = 160 \text{ mb}.
\]

We used the spherical model for halo with \( z \) axis directed to North Pole and \( x \) axis directed to the Solar system. We parametrized the number density distribution of interstellar hydrogen gas \( n_H(r,z) \) along \( z \) direction as:

\[
n_H(z) = n_H^{\text{halo}} + \Delta_H(z),
\]

\[
\Delta_H(z) = \frac{n_H^{\text{disk}}}{1 + (z/D)^2}, \tag{3}
\]

with \( n_H^{\text{halo}} = 5 \cdot 10^{-4} \text{ cm}^{-3} \) being the hydrogen number density in the halo, \( n_H^{\text{disk}} = 1 \) \text{ cm}^{-3} \) being the hydrogen number density in the disk and \( D = 100 \text{ pc} \) being the
half-width of the gaseous disk. We chose here the hydrogen number density in
the halo in suggestion that $\sim 90\%$ of the halo mass is a non-baryonic dark matter. Such
a distribution of the matter gas is to large extent the worst case for our aims since
the matter density along $z$ axis falls slowly and visible fraction of the antiprotons
will annihilate sufficiently far of the galactic disk plane. Nevertheless, as we shall
see, even in this case the picture is still quasi-stationary and the antiproton number
density in the halo is practically not disturbed by the annihilation in the dense
regions.

The validity of the stationary approximation depends on the interplay of the life-
time of the antiprotons to the annihilation and their confinement time in the Galaxy.
To evaluate the antiproton confinement time we used the results of the ”two–zone”
leaky box model (LBM) [10]. The authors of [10] considered the spectra of secondary
antiprotons produced in collisions of the cosmic ray protons with interstellar gas. If
to compare the antiproton spectrum, obtained in [10], one easily observes that shape
of the spectrum beautifully reproduces the observational data on $\bar{p}/p$ ratio. But the
predicted total normalization is lower by factor $2 \div 3$ than the data. Owing to the
fact that confinement time enters as a common factor in the predicted $\bar{p}/p$ ratio, we
found necessary factor, performing the fit to the observational data. Experimental
points have been taken from [18] where references on the data can be found. The
data on $\bar{p}/p$ ratio we used have been collected in balloon experiments and region
of low kinetic energies, $E_{kin} \leq 100$ MeV, is strongly affected by the heliosphere
[19]. To avoid this influence we removed from the fit two the most left points in
Fig.1. Solid curve in Fig.1(a) represents the ”two-zone” LBM predictions for the
$\bar{p}/p$ ratio, multiplied by the fitted factor $K = 2.58$, which factor increases the
confinement time for slow antiprotons in the Galaxy up to $5.5 \cdot 10^8$ years. Dashed
curve is the phenomenological fit in the form $R(E) = a E^{b+c \ln E}$, which we plotted
for comparison. The shapes of both curves match fairly. Fig.1(b) shows the resulting
antiproton confinement times for Galaxy as whole (solid) and for disk only (dashed).

Fig.2 shows the antiproton life-time to the annihilation (a) and the free path
length of the antiprotons (b) versus their distance of the galactic plane, $z$ for three
values of the antiproton velocity. In the stationary case to compensate the annihila-
tion of the antiprotons with matter gas the number density of the antiprotons must
satisfy the equation:

$$\frac{d^2 n_{\bar{p}}}{dE dt} = I_{\bar{p}}(E) - v \sigma(v) n_H \frac{dn_{\bar{p}}}{dE}. \quad (4)$$

The solution of this equation is:

$$\frac{dn_{\bar{p}}}{dE} = I_{\bar{p}}(E) t_{ann}(E) \left(1 - e^{-t/t_{ann}}\right), \quad (5)$$

with $t_{ann} = [v \sigma(v) n_H]^{-1}$ being the life-time of the antiprotons relative to the
annihilation.
From Fig.2(a) we can conclude that for antiprotons with velocities $10^3$ km/s (stellar wind) the confinement time in the halo, starting from distances $z \sim 2$ kpc, is less than their annihilation time. Thus, from (5) we obtain for the halo:

$$n(E) \approx I\bar{p}(E) T_{conf}.$$  \hfill (6)

In the gaseous disk the situation is just opposite. The antiprotons annihilate with high rate and their life-time to the annihilation is much less than the time necessary to escape the Galaxy volume.

Other words, the antiprotons are storing in the halo during the confinement time $\approx 5 \cdot 10^8$ yrs increasing the gamma flux by factor $T_{conf}$. We can also conclude that during large confinement time the antiprotons are being spread over the halo with constant number density not depending on the position of the antistars cluster and under usual acceleration mechanisms in the halo their energy spectrum comes to the stationary form. Additionally from Fig.2(a) we see that the ”storing” volume is order of the volume of the halo $V_{halo} = 4\pi R_{halo}^3/3$ when the region with $T_{conf} \gg T_{ann}$ is restricted by $|z| \leq 2$ kpc. Thus intensive annihilation takes place within the volume $V_{ann} \approx \pi R_{halo}^2 4\text{kpc}$. The ratio of these two volumes is order of

$$\frac{V_{ann}}{V_{halo}} \sim \frac{4\text{kpc}}{4/3 R_{halo}} \leq 20\%$$

and the annihilation of the antiprotons in the gaseous disk practically does not affect the number density of the antiprotons in the Galaxy as whole.

The above consideration provides quasi-stationary distribution of antimatter in the halo and, as results, constant number density of the antiprotons in the galactic halo. Fig.2(b) shows $z$ dependence of free path length of the antiprotons at three values of their velocity.

### 3 Diffuse gamma flux.

The gamma flux arriving from the given direction is defined by the well known expression:

$$J_\gamma(E_\gamma) = \int_0^L dl \psi(E_\gamma, r, z).$$  \hfill (7)

The integration must be performed up to the edge of the halo $L = -\alpha_x R_\odot + \sqrt{R_{halo}^2 - R_\odot^2 (1 - \alpha_x^2)}$ with $\alpha_x$ being the cosine of the line-of-sight to the $x$ axis, directed from the Galaxy Center to the Sun and lying in the plane of the Solar orbit.

Function $\psi(E_\gamma)$ in (7) is the intensity of gamma sources along the observation direction $l$ in assumption of isotropic distribution of gamma emission. This function is defined as:
\[ \psi(E_{\gamma}, r, z) = \int_{E_{\text{min}}}^{\infty} dE \, v(E) \sigma_{\text{ann}}(E) \, n_H(r, z) \, n_{\bar{p}}(E, r, z) \, W(E_{\gamma}; E) \]

\[ W(E_{\gamma}; E) = \frac{dn_{\gamma}(E_{\gamma}; E)}{dE_{\gamma} \, dO}. \tag{8} \]

To simulate the gamma energy spectrum and angular distribution \( W(E_{\gamma}; E) \) we used the Monte Carlo technics. The experimental data \cite{20} on the \( \bar{p}p \) annihilation at rest (see Table) have been used to simulate the probabilities of different final states. In practice, the approximation of the annihilation at rest is valid with very good accuracy up to laboratory momenta of the incoming antiprotons about 0.5 GeV because at these laboratory momenta the kinetic energy of the antiproton is still order of magnitude less than the twice antiproton mass. The simulation of the distributions of final state particles has been performed according to phase space in the center-of-mass of the \( \bar{p}p \) system. PYTHIA 6.127 package \cite{21} has been used to perform the subsequent decays of all unstable particles. Momenta of stable particles (\( e^{\pm}, p/\bar{p}, \mu^{\pm}, \gamma \) and neutrinos) have been boosted in the laboratory reference frame. The resulting average number of \( \gamma \)'s per annihilation is

\[ < n_{\gamma} > = \int d\Omega \, dE_{\gamma} \, W(E_{\gamma}; E) = 3.93 \pm 0.24 \]

and agrees with experimental data.

In the stationary case we can put that annihilation rate in the halo is being constantly compensated by the permanent source of the antiprotons. But, owing to the fact that the antiprotons annihilation rate in the gaseous disk is much greater than in halo, we need to take into account the dependence of the antiproton density on \( z \) coordinate. Fig.2(b) demonstrates that free path length of the lowest antiprotons is comparable with half-width of the disk \( D \). To take this effect into account we have to consider the annihilation with disk gas. For given value of \( z \) we have:

\[ \frac{dn_{\bar{p}}(z, E)}{dz} = \sigma_{\text{ann}}(E) \Delta_H(z) \, n_{\bar{p}}(z, E). \tag{9} \]

The differential equation (9) can be easily solved and results the following antiproton number density distribution along \( z \) axis:

\[ n_{\bar{p}}(z, E) = n_0 \exp \left\{ -\sigma_{\text{ann}}(E) \int_{z}^{z_{\text{max}}} \Delta_H(z') \, dz' \right\}, \tag{10} \]

where, \( z_{\text{max}} = L \alpha_z \) is the maximal value of \( z \) coordinate, defined by the edge of the halo, and \( n_0 \) is the antiproton number density far from the disk.

The next point we need to consider is the antiproton energy spectrum. As it will be shown further, the stellar wind from antistars has to give more significant contribution in the antimatter pollution from the anticluster. The original distribution of
the stellar wind particles has a Gaussian form peaking at velocities $v \approx 500$ km/s [22]. The interplanetary shocks accelerate emitted particles and the resulting stellar cosmic rays flux becomes proportional to $J_{SW} \sim v E_{kin}^{-2}$ in the range of kinetic energies up to $\sim 100$ MeV [22]. Additional acceleration occurs in the interstellar plasma and, as we believe, produces the observable spectrum of the galactic cosmic rays $\sim v E_{kin}^{-2.7}$. Both the acceleration mechanisms are being defined by the collisionless shocks in interplanetary or Galaxy plasmas and are charge-independent. One has to take into account also the relative movement of the hypothetical antistars cluster with velocity $\sim 300$ km/s as well as the similar velocities of the matter gas defined by the gravitational field of the Galaxy. Thus, one can expect that minimal relative velocity of the antiprotons from (anti)stellar wind and the matter gas is something about $v_{min} \approx 600 - 700$ km/s. Following the above consideration, we chose the antiproton spectrum in the halo (far from regions with high matter gas density) to be similar to the galactic cosmic-rays proton spectrum in the whole range of the antiproton energies:

$$n_{\bar{p}}(E, z >> D) \sim \left(\frac{1 \text{GeV}}{E_{kin}}\right)^{2.7} ,$$  \hspace{1cm} (11)

with the normalization:

$$\int_{E_{min}}^{\infty} n_{\bar{p}}(E, z >> D) \, dE = n_0 .$$

Actually, reasonable variation of the form of the antiproton flux does not affect significantly the total normalization and changes only the gamma spectrum at higher energies. The main contribution in the integrated antiproton number density comes from the slowest antiprotons owing to fast growth of the annihilation cross section with decrease of the velocity. We don’t consider in present paper the contribution in the gamma flux from the annihilation of the secondary antiprotons produced in the collisions of the cosmic-ray protons with interstellar gas. This effect must give the main contribution at higher energies of gammas and needs careful investigation of the deceleration mechanisms in the halo.

If we assume that all the gamma background at high galactic latitudes is defined by the antiproton annihilation, we have the only free parameter in our model - the minimal velocity of the antiprotons $v_{min}$. Therefore, for given value $v_{min}$ the integrated number density of the antiprotons in the halo $n_0$ can be found from comparison with the observational data on diffuse gamma flux. If we choose the minimal velocity of the antiprotons order of the velocity of the stellar wind, $v_{SW} \approx 1000$ km/s, being equivalent to kinetic energy of the antiprotons $E_{kin}^{SW} \approx 5.2$ keV, we obtain the necessary integral number density of the antiprotons $n_0$ to be equal to:

$$n_0^{SW} \approx 5.0 \cdot 10^{-12} \text{ cm}^{-3} .$$  \hspace{1cm} (12)
Fig. 3(a, b) demonstrates the resulting differential gamma distribution in the Galactic North Pole direction in comparison with EGRET data \[9\] in the range \(10 \leq E_\gamma \leq 1000\) MeV. The peak of \(\pi^0\) decay is clearly seen both in calculations as well as in experimental distributions. Fig. 3(c) shows the charged multiplicity distribution in the annihilation model described above. The comparison with the experimental points taken from \[23, 24\] serves as additional confirmation of our calculations.

We also performed calculations for two other values of the minimal velocity of the antiprotons \(v_{\text{disp}} = 300\) km/s and for the velocity of the (anti)matter thrown out by the Supernovae, \(v_{SN} = 2 \cdot 10^4\) km/s. The respective necessary values of the integral antiproton number density are:

\[
\begin{align*}
    n_0^{\text{disp}} &\approx 2.0 \cdot 10^{-12} \text{ cm}^{-3} \\
    n_0^{\text{SN}} &\approx 6.0 \cdot 10^{-11} \text{ cm}^{-3}.
\end{align*}
\]

Thus, one can see that necessary integral antiproton density in the halo practically linearly depends on minimal velocity of the antiprotons in the range \(300 \leq v \leq 10^4\) km/s. Note, that the approximation about annihilation at rest is valid for all the range of above minimal velocities and the resulting gamma spectrum does not change its form at such a variation of \(v_{\text{min}}\).

4 Discussion and Conclusion

Let us estimate the intensity of the antiproton source and, as result, the total mass of the hypothetical globular cluster of antistars for three values of the minimal antiproton velocity: \(v_{\text{disp}}, v_{SW}\) and \(v_{SN}\). The first case assumes that antiprotons have been decelerated and travel in the halo with velocities equal to the velocity dispersion defined by the galactic gravitational field. The second value of \(v_{\text{min}}\) is the order of the speed of the fast stellar wind and the third case is the velocity of the particles blown off by the Supernova explosion without possible deceleration.

If we integrate over the volume of the whole halo and take into account the antiproton storing in the halo during the confinement time, we obtain for the integral intensity of the antiproton source \(\dot{M} \sim (n_0 m_p V_{\text{halo}})/t_{\text{conf}}\). For above three variants of the minimal velocity of the antiprotons and \(t_{\text{conf}} \sim 5 \cdot 10^8\) years from \(12\) and \(13\) we obtain the following values of the necessary antiproton source intensity:

\[
\begin{align*}
    \dot{M}^{\text{disp}} &\approx 3.0 \cdot 10^{-9} \, M_\odot/yr \\
    \dot{M}^{SW} &\approx 8.5 \cdot 10^{-9} \, M_\odot/yr \\
    \dot{M}^{SN} &\approx 1.0 \cdot 10^{-7} \, M_\odot/yr
\end{align*}
\]
From the analogy with elliptical galaxies in the case of constant mass loss due to stellar wind one has the mass loss $10^{-12} M_\odot$ per Solar mass per year. In the case of stellar wind we find for the mass of the anticluster:

$$M_{SW}^{clu} \approx 2 \cdot 10^4 M_\odot. \quad (15)$$

To estimate the frequency of Supernova explosions in the antimatter globular cluster the data on such explosions in the elliptical galaxies were used [11], what gives the mean time interval between Supernova explosions in the antimatter globular cluster $\Delta T_{SN} \sim 1.5 \cdot 10^{15} M_5^{-1}$ s. For $M_5 > 1$ this interval is smaller than the period of the orbital motion of the cluster, and one can use the stationary picture considered above with the change of the stellar wind mass loss by $\dot{M} \sim f_{SN} \cdot M_{SN}$, where $f_{SN} = 6 \cdot 10^{-16} M_5$ s$^{-1}$ is the frequency of Supernova explosions and $M_{SN} = 1.4 M_\odot$ is the antimatter mass blown off in the explosion. Following the theory of Supernova explosions in old star populations only the supernovae of the type I (SNI) take place, in which no hydrogen is observed in the expanding shells. In strict analogy with the matter SNI the chemical composition of the antimatter Supernova shells should include roughly half of the total ejected mass in the internal anti-iron shell with the velocity dispersion $v_i \leq 8 \cdot 10^8$ cm/s and more rapidly expanding $v_e \sim 2 \cdot 10^9$ cm/s anti-silicon and anti-calcium external shell. The averaged effective mass loss due to Supernova explosions gives the antinucleon flux $\dot{N} \sim 10^{42} M_5$ s$^{-1}$, but this flux contains initially antinuclei with the atomic number $A \approx 30 - 60$, so that the initial flux of antinuclei is equal to $\dot{A} \sim (2 - 3) \cdot 10^{40} M_5$ s$^{-1}$. Due to the factor $\sim Z^2 A^{2/3}$ in the cross section the annihilation life-time of such nuclei is smaller than the cosmic ray life-time, and in the stationary picture the products of their annihilation with $Z < 10$ should be considered. With the account for the mean multiplicity $\langle N \rangle \sim 8$ of annihilation products one obtains the effective flux $\dot{A}_{eff} \sim (1.5 - 2.5) \cdot 10^{41} M_5$ s$^{-1}$, being an order of magnitude smaller than the antiproton flux from the stellar wind.

If to take the antimatter stellar wind as small as the Solar wind ($\dot{M}_\odot = 10^{-14} M_\odot$ yr$^{-1}$) this corresponds to the antiproton flux by two orders of magnitude smaller than one chosen above in (14), and the antimatter from Supernova should play the dominant role in the formation of galactic gamma background. For the Supernova case we have for the mass of the anticluster the value

$$M_{SN}^{clu} \approx 4.0 \cdot 10^5 M_\odot,$$

which value agrees with the estimation [11]. If we assume that significant fraction of the antiprotons from stellar wind is decelerated up to $v_{disp}$ the respective mass of the globular cluster of antistars can be reduced up to

$$M_{disp}^{clu} \approx 7 \cdot 10^3 M_\odot.$$

It is necessary to make small remark. Namely, in principle, one cannot exclude that the secondary antiprotons produced in $pp$ collisions can be decelerated in the
halo magnetic fields up to velocities order of few hundreds km/s. In this case they will also give contribution in the diffuse gamma flux annihilating with the matter gas and the calculations performed in present paper are valid in this case also.

In conclusion we can say that the hypothesis on the existence of antimatter globular cluster in the halo of our Galaxy does not contradict to either modern particle physics models or observational data. Moreover, the Galactic gamma background measured by EGRET can be explained by antimatter annihilation mechanism in the framework of this hypothesis. If the mass of such a globular cluster is of order of $10^4 \div 10^5 M_\odot$, we can hope that other signatures of its existence like fluxes of antinuclei can be reachable for the experiments in the nearest future. The analysis of antinuclear annihilation cascade is important in the realistic estimation of antinuclear cosmic ray composition but seems to be much less important in its contribution into the gamma background as compared with the effect of antimatter stellar wind. This means that the gamma background and the cosmic antinuclei signatures for galactic antimatter are complementary and the detailed test of the galactic antimatter hypothesis is possible in the combination of gamma ray and cosmic ray studies.

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Table. Relative probabilities of $\bar{p}p$ annihilation channels.

| Channel          | Rel. prob., % | Channel          | Rel. prob., % |
|------------------|---------------|------------------|---------------|
| $\pi^+\pi^-\pi^0$ | 3.70          | $2\pi^+2\pi^-\eta$ | 0.60          |
| $\rho^-\pi^+$    | 1.35          | $\pi^0\rho^0$    | 1.40          |
| $\rho^+\pi^-$    | 1.35          | $\eta\rho^0$     | 0.22          |
| $\pi^+\pi^-2\pi^0$ | 9.30          | $4.99\pi^0$      | 3.20          |
| $\pi^+\pi^-3\pi^0$ | 23.30        | $\pi^+\pi^-$     | 0.40          |
| $\pi^+\pi^-4\pi^0$ | 2.80          | $2\pi^+2\pi^-$   | 6.90          |
| $\omega\pi^+\pi^-$ | 3.80          | $3\pi^+3\pi^-$   | 2.10          |
| $\rho^0\pi^0\pi^+\pi^-$ | 7.30        | $K\bar{K}0.95\pi^0$ | 6.82          |
| $\rho^+\pi^-\pi^+\pi^-$ | 3.20        | $\pi^0\eta'$     | 0.30          |
| $\rho^-\pi^+\pi^+\pi^-$ | 3.20        | $\pi^0\omega$    | 3.45          |
| $2\pi^+2\pi^-2\pi^0$ | 16.60        | $\pi^0\eta$      | 0.84          |
| $2\pi^+2\pi^-3\pi^0$ | 4.20         | $\pi^0\gamma$    | 0.015         |
| $3\pi^+3\pi^-\pi^0$ | 1.30          | $\pi^0\pi^0$     | 0.06          |
| $\pi^+\pi^-\eta$  | 1.20          |                  |               |
Figure 1: (a) Fit of the $\bar{p}/p$ ratio to experimental data. Solid line shows predictions of the two-zone leaky box model [10], increased by factor $K \approx 2.6$. Dashed curve is the phenomenological fit, described in the text. (b) The respective confinement times for the antiprotons in the Galaxy (solid) and in the disk (dashed). The curves are taken from [10] and multiplied by factor $K$. 
Figure 2: (a) The dependence of the antiprotons annihilation time on the $z$ coordinate. The horizontal dashed line is the antiproton confinement time in the Galaxy. (b) The dependence of free path length of the antiprotons. The horizontal dashed line is the halo edge $z = 20$ kpc. The curves are calculated for three values of the antiproton velocity: $300 \text{ km/s}$, $10^3 \text{ km/s}$ and $2 \cdot 10^4 \text{ km/s}$. Vertical dashed line shows the half-width of the disk $D = 100$ pc.
Figure 3: Comparison of the calculated differential fluxes of $\gamma$ quanta from $\bar{p}/p$ annihilation for the minimal antiproton velocity $v_{\text{min}} = 10^3$ km/s with experimental data $\text{EGRET}$ [9] on diffuse gamma background (a,b). The observational direction is to the North Pole of the Galaxy. There is also shown the comparison of the charged multiplicity distribution in the annihilation model described in the text with the existent experimental data (c). Circles - [23], squares - [24].