PHYSICAL REVIEW D 92, 023516 (2015)

# Antimatter and antistars in the Universe and in the Galaxy

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(Received 12 October 2014; published 13 July 2015)

Possible existence of baryo-dense (BD) stars and antistars, which might be created in the very early Universe in the frameworks of a slightly modified Affleck–Dine scenario of baryogenesis is studied. We discuss phenomenology, observational manifestations, and bounds on such antistars and show that they are allowed to be abundant in the Galaxy. New constraints on the possible number of compact antimatter objects are derived. We point out that explosion of an antistar as a type Ia supernova produces a remnant with relatively low annihilation signal. Another important conclusion is the strong reduction of the annihilation flux from antistars in the gaseous disk of the Galaxy due to the high velocities of BD stars in general, and antistars in particular. The contemporary observational data do not exclude significant amount of antimatter in the Galaxy (and in other galaxies) in the form of the BD stars with relatively low mass.

DOI: 10.1103/PhysRevD.92.023516 PACS numbers: 98.80.Cq

## I. INTRODUCTION

Despite almost identical properties of particles and antiparticles, all matter observed in our neighborhood consists only of particles, i.e. of protons, neutrons, and electrons. A small fraction of antiprotons in cosmic rays, about $10^{-4}$ with respect to protons, most probably can be explained by their secondary origin. Predominance of matter over antimatter was beautifully explained by Sakharov [1] as a result of breaking of $C$- and $CP$-invariance, nonconservation of baryonic number, and deviation from thermal equilibrium which occurred in the early Universe.

On the other hand, there are plenty of theoretical possibilities leading to noticeable creation of antimatter in the universe. For example, if $CP$-invariance is broken spontaneously [2], the universe would be equally populated by matter and antimatter. However, in this case the nearest antimatter domain should be practically at the cosmological horizon, at a few Gigaparsec distance [3]. Still less pessimistic scenarios are possible, and independently of the theory, a search for real (not secondary produced) cosmic antimatter should be done and is being performed by several detectors, including BESS [4], PAMELA [5], and AMS [6]. More detectors are in project.

An unambiguous proof of existence of the primordial antimatter would be an observation of sufficiently heavy antinuclei, starting from $^4$He. According to theoretical estimates [7] antideuterium could be created in the energetic cosmic ray reactions of $\bar{p}p$ or $\bar{p}$He collisions with an intensity of $\sim 10^{-7}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,(\mathrm{GeV/n})^{-1}$, where GeV/n is the kinetic energy in GeV per nucleon. This is 5 orders of magnitude lower than the observed intensity of antiprotons. The intensities of the secondary-produced $\overline{^3\mathrm{He}}$ and $\overline{^4\mathrm{He}}$ are predicted to be much smaller, respectively 4 and 8 orders of magnitude below that of antideuterium. An experimental search of antinuclei production is performed at the LHC by the ALICE Collaboration. The results can be found in Ref. [8] and were reported at a seminar by A. P. Kalweit [9]. Though the production rate looks significant, with the suppression factor about 1/300 per each extra (anti)nucleon added to a nucleus, such events are quite rare in cosmology, and their contribution to the total cosmological production is very small.

As for cosmic ray observations, at the present time, there are only upper bounds on the flux of cosmic anti-helium-4 [4]: $\overline{\mathrm{He}}/\mathrm{He} < 3\times 10^{-7}$. In the nearest future, this bound is expected to be improved down to $\overline{\mathrm{He}}/\mathrm{He} < 3\times 10^{-8}$ [5] and $\overline{\mathrm{He}}/\mathrm{He} < 10^{-9}$ [6].

There is another direction of the search for cosmic antimatter through analysis of cosmic electromagnetic radiation, in particular of $\sim$100 MeV photons from $\bar{p}p$-annihilation and of the 0.511 MeV-line from $e^+e^-$ annihilation at low energies. According to these data, the bounds on the fraction of antimatter in several galaxies, in particular on the amount of antistars, is generally below $10^{-6}$ of the total amount of matter there. The absence of

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excessive gamma radiation allows one to conclude that the nearest antigalaxy could not be closer than $\sim$10 Mpc [10]. The mass fraction of antimatter in two observed colliding galaxies in the Bullet cluster cannot be larger than $10^{-6}$ [11]. As for our Galaxy, it is shown in Ref. [12] that the amount of antistars is bounded by $N_{\bar{*}}/N_{*} < 4 \times 10^{-5}$ within 150 pc from the Sun.

The quoted limits are valid if the antimatter objects are of the same kind as those made of the ordinary matter. However, they may be essentially different, as argued in Refs. [13,14], where an efficient mechanism of the cosmological antimatter creation was suggested and studied. According to this model, which is discussed below to make the paper self-contained, the antistars could be formed in the very early Universe as compact objects, which may be predominantly dead now. They are not concentrated in galaxies but distributed in a larger volume, in the halo, and have larger velocities than the normal stars. In this sense, they are similar to cold dark matter particles. In such a case, the restrictive limits derived for the "normal" antistars are not applicable, and these new type antimatter objects may abundantly populate the Galaxy. Phenomenology of such antimatter objects is discussed in Ref. [15]. Since antistars may be abundant in the Galaxy, it is of interest to consider the possibility of their registration by terrestrial detectors, which at the present time are sensitive only to relatively close objects. It was shown in Ref. [16] that the width of different atomic lines are different for atoms and antiatoms, but the effect is too weak to be observed in the foreseeable future. More promising for a registration of antistars in the Galaxy are measurements of polarization of some lines of the stellar electromagnetic radiation, especially in the nuclear transitions or of neutrino vs antineutrino fluxes [17]. There is no chance to see antistars in distant galaxies except for a lucky case of a star-antistar collision which would be energetic enough to be observed on Earth.

In Ref. [18] we applied the mechanism of the early star formation, which is used below for creation of antimatter, for an explanation of existence of quasars/supermassive black holes, gamma-ray bursters, and supernovae at high redshifts, as well as of the stars in the Galaxy which look older than the Universe.

Some other models of the antimatter creation can be found in reviews [19–22]. The current observational bounds are also extensively reviewed in Refs. [12,23].

The standard scenarios of baryogenesis deal with only one number, namely with the ratio of the baryonic number density to the density of photons in the microwave background radiation. Their usual outcome is a homogeneous baryon asymmetry all over the universe. Therefore, there is no way to discriminate between different models having only one number in possession. In this connection the models of baryogenesis which lead to noticeable isocurvature perturbations and especially to domains with negative asymmetry, i.e. antimatter domains, are of great interest, and astronomical searches for cosmic antimatter and studies of theoretical scenarios of antimatter creation become of primary importance in the attempts to understand the generation of cosmological matter-antimatter asymmetry.

The paper is organized as follows. In Sec. II, to make the presentation self-contained, we discuss the main features of the model leading to an efficient production of antimatter objects (such as antistars, or dense clouds of antimatter) which may "live" in the Galaxy in a significant amount. Section III is devoted to estimates of possible abundance of antimatter in diffusive interstellar state. We derive new constraints on the possible number of compact antimatter objects in Sec. IV. Discussion and conclusions are presented in Sec. V.

## II. MECHANISM OF STAR AND ANTISTAR FORMATION IN THE EARLY UNIVERSE

All scenarios of baryogenesis, but one, normally predict rather low values of the baryon asymmetry, so theoretical efforts are aimed at amplification of the predictions up to the largest possible value to obtain the observed magnitude of the baryon asymmetry, which according to the recent determination of the cosmological parameters by the Planck mission [24] is

$$\beta_{\rm obs} = n_B/n_\gamma \approx 6 \times 10^{-10}. \tag{2.1}$$

The only exception is the model of baryogenesis suggested by Affleck and Dine (AD) [25]. This model normally predicts the cosmological baryon asymmetry much larger than the observed value, and efforts should be made in the opposite direction to diminish it down to (2.1).

The AD scenario of baryogenesis is based on high-energy supersymmetric (SUSY) model which naturally possesses flat directions (valleys) in the potential of scalar superpartner of baryons. Such a scalar field has nonzero baryonic number and could acquire a large vacuum expectation value during inflation, if its mass is smaller than the Hubble parameter at that period. After inflation is over, the baryonic number density accumulated in the rotational motion of the Affleck–Dine field, $\chi$, i.e. in its time-dependent phase, was transformed into baryonic number of quarks through baryo-conserving decays of $\chi$.

The essential features of the potential of $\chi$ can be described by the following toy model expression:

$$U(\chi) = \lambda(2|\chi|^4 + \chi^4 + \chi*^4) + (m_1^2\chi^2 + {\rm H.c.}) + m_2^2|\chi|^2. \tag{2.2}$$

According to the original AD scenario, the characteristic scale of the underlying SUSY model is about $10^8$–$10^{10}$ GeV, i.e. much above the low-energy minimal SUSY. The coupling constants are supposed to have the normal supersymmetric values at a level of $10^{-2}$. However, we will not confine ourselves to particular values of the masses and coupling constants keeping in mind an absence of knowledge of physics at the relevant high energies. The mass parameter $m_1$ may be complex, leading to $C$ and $CP$ violation if $\lambda \neq 0$. Guided by an explicit SUSY model used by AD, we take $m_2$ equal to $2|m_1|$ to avoid a nonzero vacuum expectation value of $\chi$. A positive $m_2^2$ may appear as a result of some spontaneous symmetry breaking at later stages of cosmological evolution. This is analogous to the well -known Higgs phenomenon. The first two terms in the potential have flat directions, along which the potential does not grow, but for complex $m_1$ the flat directions of the quadratic term do not coincide with quartic ones. Because of one-loop radiative corrections, the quartic terms can acquire a logarithmic factor, called the Coleman–Weinberg potential [26]:

$$U_{\rm CW} = \lambda_2 |\chi|^4 \ln(|\chi|^2/\sigma^2). \tag{2.3}$$

During inflation, when the Hubble parameter was much larger than $|m_1|$ and $|m_2|$, the amplitude of the field $\chi$ was able to reach a high magnitude, and when inflation was over and the Hubble parameter became smaller than the slope of the potential, $\chi$ started evolving down to the origin, and on the way it could acquire a large "angular momentum" in the complex $[{\rm Re}\chi, {\rm Im}\chi]$-plane due to misalignment of the quartic and quadratic flat directions. The angular momentum is essentially the baryonic number accumulated by $\chi$:

$$n_B(\chi) = i[\chi^*(\partial_t \chi) - (\partial_t \chi^*)\chi]. \tag{2.4}$$

If there is no phase difference between $m$ and $\lambda$ and a quadratic flat direction coincides with a quartic one, then there would be no misalignment, but nevertheless a nonzero angular momentum could be induced due to quantum fluctuations of $\chi$ in the direction orthogonal to the valley. In this case baryonic density would be also created but with different signs in different space domains because of the chaotic behavior of quantum fluctuations. Therefore, on average the baryon asymmetry would be zero.

This simple AD scenario was slightly modified in Ref. [13] by an addition of the general renormalizable coupling of $\chi$ to the inflaton field $\Phi$:

$$\delta U(\chi, \Phi) = g|\chi|^2 (\Phi - \Phi_1)^2. \tag{2.5}$$

Indeed, the general renormalizable coupling between $\chi$ and $\Phi$ is a polynomial of power not larger than 4: $\delta U = |\chi|^2 (m^2 + g_1 \Phi + \lambda_{\Phi\chi} \Phi^2)$. To ensure the conservation of the baryonic number of $\chi$, the latter enters as $|\chi|^2$. Evidently, this interaction potential can be rewritten in the form (2.5). Parameter $\Phi_1$ is supposed to be equal to the value which $\Phi$ passed during inflation sufficiently far from its end, such that the size of the bubbles with high baryon asymmetry would be astronomically large. This is the only tuning parameter of the model. An essential effect created by the addition of $\delta U$ to the potential of $\chi$ is that the window to the flat directions was open only for a short period of time when $\Phi$ was close to $\Phi_1$. During this period the slope of the total potential of $\chi$ near $\chi = 0$ becomes close to zero along the flat directions, or even negative, due to the presence of the Coleman–Weinberg correction (2.3). One can see it from the form of the total potential of $\chi$:

$$\begin{aligned} U_{\rm tot}(\chi, \Phi) = {} & \lambda(2|\chi|^4 + \chi^4 + \chi*^4) + (m_1^2 \chi^2 + {\rm H.c.}) \\ & + m_2^2 |\chi|^2 + g|\chi|^2 (\Phi - \Phi_1)^2 \\ & + \lambda_2 |\chi|^4 \ln(|\chi|^2/\sigma^2). \end{aligned} \tag{2.6}$$

When $\Phi$ approaches $\Phi_1$, this potential has two minima: one at $\chi = 0$ and the other, initially higher, one at $\chi \neq 0$. When $\Phi \approx \Phi_1$, the logarithmic term dominates for $\chi \to 0$ near the flat directions, and the minimum at $\chi = 0$ turns into a local maximum. At the inflationary (quasi-de Sitter) period, $\chi$ quantum-fluctuates with the effective amplitude $\delta\chi \sim H/(2\pi)$. The equation governing the evolution of the quantum fluctuations of a real scalar field was derived in Ref. [27]. It was generalized for a complex field [13,14]. Based on that we may say that the effective mass near zero is roughly $\delta m_\chi^2 \sim \lambda_2 H^2 \ln(H^2/\sigma^2)$. This effective mass squared would be negative if $H < \sigma$. However, this condition is not necessary because at small $\chi$ near the flat directions the negative logarithmic term dominates anyhow. Analytical estimates and numerical calculations of $\chi$ evolution and the proper references are presented in the paper [14]. During the period when $\chi$ had the negative mass squared, it would exponentially rise with time along the flat directions of potential (2.2) as $\exp(|\delta m|\Delta t)$. If time $\Delta t$, during which the effective mass of $\chi$ is imaginary, is sufficiently short (it is determined by the inflaton potential and can be easily arranged), the probability to reach a high value for $\chi$ would be small. Correspondingly $\chi$ would be large only in a small fraction of space. In this case cosmologically small but possibly astronomically large bubbles with high $\beta$ could be created, occupying a small part of the universe volume, while the rest of the universe would have the normal $\beta \approx 6 \times 10^{-10}$, created by a small $\chi$, which occupied the bulk of space. Nevertheless, the fraction of baryonic and antibaryonic matter in these compact objects may exceed that of the observed baryons. In the simplest version of the model, the amount of baryons and antibaryons in high $\beta$ regions would be equal, but in the more general case, their ratio is model dependent and may be arbitrary. Numerical calculations of Ref. [14] prove this picture.

The bubbles with high values of $\chi$ after B-conserving decay of $\chi$ into fermions would form domains with a large baryonic number density in the form of usual quark/baryon matter. The rest of the universe would have normal small baryon asymmetry. Initially the density contrast between the regions with low and high values of $\chi$ was zero or very small (isocurvature perturbations). After formation of the domains with large $\chi$, the equation of state inside and outside the bubbles became different because the matter inside the bubbles was more nonrelativistic than the matter outside. This would create some initial density contrast between inner and outer parts of the high-B bubbles. This and the following (see the next paragraph) conclusion would be valid if the baryon diffusion length was very short. It was indeed true in the primeval plasma.

The second period of generation of the density contrast inside and outside the bubbles, $\delta_Q$, took place after the QCD phase transition at temperatures somewhat above 100 MeV, when quarks formed nonrelativistic protons. At this stage a whole family of compact stellarlike objects with baryon number density much higher than the background baryon density were formed. Depending upon the relation between their mass and the corresponding Jeans mass, they could be very early stars, progenitors of supernovae, or primordial black holes. As shown in Refs. [13,14], the mass distribution of these objects has the log-normal form

$$\frac{dN}{dM} = C_M \exp\left[-\gamma \ln^2(M/M_0)\right], \qquad (2.7)$$

where $C_M$, $\gamma$, and $M_0$ are constant model-dependent parameters. The form of the spectrum is practically model independent, since it was essentially determined by the exponential expansion during the inflationary epoch. We call these regions baryo-dense ones, and the stars formed in such regions can be called BD stars and even BD black holes.

In particular, primordial black holes with masses from a few solar masses up to $10^{6–7} M_\odot$, or even more (on the tail of the distribution), could be created. Such supermassive black holes might be the seeds of galaxy formation. It is easy to choose the parameters of the model such that there would be one supermassive black hole (BH) for any existing large galaxy. This scenario offers a new mechanism of the early supermassive BH (quasar) formation and an explanation of existence of ultracompact dwarf galaxies, where the central BH contains more than 10% of the mass of the whole galaxy [28]. Indeed, more and more supermassive black holes are being discovered. One of the most massive objects [29] is an ultraluminous quasar, SDSS J010013.02 + 280225.8, at redshift $z = 6.30$. From the near-infrared spectrum, its mass is estimated to be $\sim 1.2 \times 10^{10} M_\odot$, which is consistent with the value $1.3 \times 10^{10} M_\odot$ derived by assuming the Eddington-limited accretion rate. This discovery presents a weighty argument in favor of our model of the very early black hole formation.

Presently, there is no satisfactory explanation of the early formation of supermassive BHs and ultracompact dwarf galaxies with large BHs in the framework of the conventional theories. On the other hand, the model considered here also provides a natural explanation of the existence of high red-shift gamma-ray bursters, early supernovae, the metal-enriched chemistry in the vicinity of those early formed objects, and the stars which are formally older than the universe. Modern surveys of old bulge/halos stars (see e.g. Ref. [30]) reveal an unusually large scatter of metal abundances in some of the stars, which is difficult to reconcile with the standard chemical evolution, but it seems possible to realize in the scenarios leading to the formation of BD stars. These problems are discussed in an earlier publication by two of us [18]. Recent developments in observational astrophysics gives more hints on the reality of the AD scenario and natural existence of BD stars. For example, the discovery of the fast moving He-star US 708 in our Galaxy is interpreted as an ejection of the star by a thermonuclear supernova [31]. With the Galactic rest-frame velocity of $1157 \pm 53$ km s$^{-1}$, this star is the fastest known unbound star in the Galaxy. While the interpretation in the ejection scenario is feasible, it puts severe constraints on the SNIa progenitor system, and its difficulties are pointed out by the authors of the discovery [31]. It seems to us that the interpretation of US 708 as a BD star (an intergalactic "straggler") is more likely. As discussed in Ref. [18], the BD stars must be He-rich and fast moving in galaxies made of ordinary stars.

In this work we dwell on phenomenology, observational manifestations, and bounds on antistars, which were born in the early Universe and might be abundant in the Galaxy.

Of course, the big bang nucleosynthesis (BBN) in the regions with high $\beta$ would be significantly different from the standard one with low $\beta$; much heavier elements could be produced there. The calculations of the element abundances created at BBN with high $\beta$ have been done in Ref. [32], but unfortunately only with $\beta \ll 1$, though with $\beta \gg \beta_{\rm obs}$. It would be very interesting to extend such calculations up to $\beta \geq 1$. One immediate effect is that the primordial hydrogen to helium ratio would significantly decrease because for large $\beta$ the neutron-proton freezing took place at higher temperatures when $n/p$ ratio was close to one. Therefore, the stars formed after BBN in high-$\beta$ bubbles should mostly consist of $^4$He plus some metals which are normally absent in the first stars. Since in the simplest version of the scenario the baryo-dense objects consist of matter and antimatter in roughly an equal amount, an anomaly in elemental abundances somewhere in the Galaxy could be an indicator of antimatter there with a 50% probability. On the other hand, the observed abundances of light elements created during BBN would not be significantly different from the predictions of the standard theory with low $\beta$, because the low-$\beta$ volume is much larger than that with high $\beta$, and the clouds with anomalous abundances are quite rare.

As is well known, the spectrum of angular fluctuations of cosmic microwave background (CMB) measures $\beta$ quite close to (2.1). However, it does not exclude the existence of BD objects considered here because the anomalies in the baryonic number density would appear at very low scales, much shorter than a few Megaparsecs, i.e. outside the range of sensitivity of the CMB measurements. At scales that small, the angular fluctuations of the CMB temperature are erased by the diffusion (Silk) damping.

In what follows we put aside theory and consider possible observational manifestations of antimatter in the Galaxy, not restricting ourselves to any particular form of antimatter objects, using the principle "everything which is not forbidden is allowed."

## III. CONSTRAINTS FROM DIFFUSE ANTIMATTER

Diffuse clouds of antimatter can be probed through registration of the products of nucleon-antinucleon annihilation in the process of collision of such an antimatter cloud with the surrounding interstellar or intergalactic matter (see reviews [10,12] for discussion and references). The best signature of this process would be an observation of the gamma-ray emission produced by the decays of $\pi^0$, which were created in the annihilation. The gamma-ray photons from $\pi^0$ decays have a broad spectrum peaked around 100 MeV, so the 100 MeV diffuse gamma-ray background can be used as an appropriate indicator of the antimatter annihilation. The observed isotropic EGRET gamma-ray background intensity [33] in the ∼100 MeV energy range can be approximately represented as

$$I_{\rm CGRB} = \nu I_\nu(100\ {\rm MeV}) \approx 1000\ [{\rm eV\,cm^{-2}\,s^{-1}\,ster^{-1}}]. \tag{3.1}$$

This corresponds to the energy density of 100 MeV photons:

$$\epsilon_{\rm CGRB}(100\ {\rm MeV}) = \frac{4\pi}{c} I_{\rm CGRB} \approx 4\times 10^{-7}\ [{\rm eV\,cm^{-3}}]. \tag{3.2}$$

Baryons in stars amount to the cosmological fraction of matter equal to $\Omega_b^* \simeq 10^{-3}$ [34] (in units of the critical density in the Universe), which corresponds to the energy density

$$\epsilon^* = \Omega_b^* \varrho_{\rm cr} \sim 5.2\ [{\rm eV\,cm^{-3}}]. \tag{3.3}$$

For the sake of a simple estimate, let us assume that most of the stars, including the BD ones, are similar to the Sun, so they lose about 50% of their mass in due course of evolution. Adopting an equal amount of BD antimatter stars, $\Omega_{\tilde b} = \Omega_b^*$, and allowing for the maximum annihilation of matter and antimatter over the Hubble time, we get a rough upper limit on the spatial mixing of diffuse matter/antimatter,

$$f_{\rm m} < \frac{\epsilon_{\rm CGRB}(100\ {\rm MeV})}{\epsilon^*} \simeq 3\times 10^{-8}, \tag{3.4}$$

in order to respect the observed gamma-ray background. We point to the difference between this estimate and the estimate of the fraction of antimatter derived in Ref. [12] from the analysis of the *Fermi* gamma-ray telescope observations of nearby galaxies and clusters of galaxies ($f_{\rm ISM}$ and $f_{\rm c}$ in the notations of that paper): here we explicitly *assume* an equal amount of stars and antistars and the similarity of their evolution and that all antimatter have annihilated into gamma-ray photons over the Hubble time, while in the paper [12] the gamma-ray flux from diffuse antiproton annihilation with the average interstellar density ($n_{\rm H} = 1\ {\rm cm^{-3}}$) and annihilation cross-section ($\sigma_{\rm ann} v \simeq 10^{-10}\,{\rm cm^3\,s^{-1}}$) was calculated. In addition to the gamma-ray annihilation signal, antihydrogen emission in the magnetic field can be probed by 21 cm radio line polarimetry, as was recently suggested in Ref. [35].

Note that, unlike the usual stars, the BD stars can initially be compact and consist mostly of antihelium, so their evolutionary mass loss can be different from that by the ordinary stars (see Refs. [36,37] and the discussion below). Moreover, this mass loss took place at high redshifts, probably at the redshifts $z > 10$, and the flux of the photons from matter and antimatter annihilation would be strongly reduced and shifted to smaller energies. Therefore, it is interesting to consider another limiting case where the primordial antimatter survived in the form of compact objects.

## IV. CONSTRAINTS FROM COMPACT ANTIMATTER OBJECTS

### A. Annihilation during accretion

Let us consider the compact remnants of BD-star evolution. Whichever peculiar the chemical composition of a BD star might be, the remnant should be in the form of a white dwarf, a neutron star, or a black hole. Clearly, only white dwarfs or neutron stars composed of antimatter are of interest. The mass of a white dwarf or neutron star is around one solar mass. A compact remnant of the BD star with mass $M$ passing through diffuse interstellar or intergalactic medium with number density $n_0$ will accrete baryonic matter. According to the well-known Bondi–Hoyle–Littleton formula, the accretion rate is

$$\dot M \simeq \left(\frac{2GM}{v^2}\right)^2 m_p n_0 v \approx 10^{11}\ [{\rm g/s}] \left(\frac{M}{M_\odot}\right)^2 \left(\frac{n_0}{1\ {\rm cm^{-3}}}\right) \left(\frac{v}{10\ {\rm km\,s^{-1}}}\right)^{-3}. \tag{4.1}$$

This accretion rate exactly corresponds to the widely used formula (23) from Ref. [10] for gamma-ray luminosity due to annihilation of the accreting matter.

As mentioned in Sec. I, compact BD stars can be treated as cold dark matter particles. Thus, they should have virial velocities in galactic halos about $v_{\rm BD} \sim 500\ {\rm km\,s^{-1}}$.

Unfortunately, the Galactic escape velocity and hence the virial velocity are not well known [38,39]. For a recent review, see Ref. [40]. The value $v_{\rm esc} = 650\ {\rm km\,s^{-1}}$ (90% upper confidence limit) from Ref. [41] is usually taken. Reference [42] finds an updated escape velocity in the range $498\ {\rm km\,s^{-1}} < v_{\rm esc} < 608\ {\rm km\,s^{-1}}$ at 90% confidence level, with the median likelihood being $v_{\rm esc} = 544\ {\rm km\,s^{-1}}$.

Therefore, the gas accretion rate onto a rapidly moving compact BD star is dramatically decreased relative to the Bondi–Hoyle formula applied for usual stars with the typical velocity dispersion of tens km s$^{-1}$, $\dot{M}_{\rm BD} \sim 10^6\ {\rm g\,s^{-1}}$, if we take the safe realistic values of the BD-star velocity $v_{\rm BD} \sim 300$–$500\ {\rm km\,s^{-1}}$. This implies that a prolific amount of local BD stars does not violate the accretion constraints on the fraction of antistars considered in Ref. [12], $f_* = N_{\bar{*}}/N_* < 4 \times 10^{-5}$; with a velocity of 300 km s$^{-1}$, this limit becomes $f_* \times (300/10)^3 \sim 1$.

At this low accretion luminosity ($\sim 10^{27}$–$10^{28}$ erg s$^{-1}$), which may be even lower than their intrinsic luminosity, BD stars are very difficult to discover. They may appear as rapidly moving dim cold objects, which can be searched, for example, in the forthcoming infrared surveys, e.g. WFIRST or *Euclid* and in JWST observations. A distinctive feature of such BD stars in contrast to hypervelocity stars, which can be potentially ejected from the Galaxy by different mechanisms, is their peculiar chemical composition.

### B. Binary BD stars

Consider now a possible binary BD star consisting of antimatter. The stars in the system would coalesce due to gravitational wave emission and produce an explosive event like the ordinary type Ia supernova. This explosion would inject around 1–2 solar masses of antimatter into the interstellar medium and produce an expanding supernova remnant (SNR). In addition to ordinary thermal shock-wave emission (mostly in the keV range), in this case one should expect a high flux of hard photons from $e^+e^-$ and proton-antiproton annihilation produced by interaction of the SNR with the interstellar medium.

Let us consider the interaction of an SNR consisting of antimatter (anti-SNR) with interstellar medium (ISM) in more detail. In realistic astrophysical plasmas, the mean free path of a charged (anti)baryon is determined by the magnetic field which is inevitably generated behind the shock front [43–47]. For an estimate, assume the typical magnetic field strength $B \equiv 10^{-5}\ {\rm G} \times B_{-5}$. The proton Larmor radius is

$$r_L = (v/c) m_p c^2/eB = 10^{10}\ [{\rm cm}] B_{-5}^{-1} v_9, \qquad (4.2)$$

where the shock velocity, $v_9$, is normalized to the typical value $10000\ {\rm km\,s^{-1}} = 10^9\ {\rm cm\,s^{-1}}$.

For example a young anti-SNR with the radius $R = 10^{18}\ [{\rm cm}] R_{18}$ has the mass inside the layer of active annihilation equal to

$$\Delta M = 4\pi R^2 r_L m_p n_0, \qquad (4.3)$$

where $n_0 \sim 1\ {\rm cm^{-3}}$ is the ambient ISM number density.

In realistic situations the density of matter colliding with the antimatter ejecta from the supernova might be a few times larger than $n_0$ due to compression of the ISM by the supernova shock wave. The annihilation time is $t_{\rm ann} = 1/(n_0 \sigma v)$, where the annihilation cross-section is inversely proportional to the center-of-mass velocity of the colliding proton-antiproton pair, and for sufficiently high relative velocity of colliding protons-antiprotons, $v/c > 0.03$, it is equal to $\sigma v \sim 10^{-15}\ {\rm cm^3/s}$; see e.g. Ref. [10].

At smaller velocities the annihilation can be enhanced due to Coulomb attraction between protons and antiprotons (the Sommerfeld enhancement). The annihilation cross section with account for the Sommerfeld enhancement factor at low velocities is

$$\sigma v \simeq 10^{-15} (\pi\alpha/v)\ {\rm cm^3\,s^{-1}}, \qquad (4.4)$$

where $\alpha = 1/137$ and it is assumed that $\pi\alpha/v > 1$.

Thus, for large relative velocities the annihilation time would be

$$t_{\rm ann} = 1/(\sigma v n_0) \approx 10^{15}\ [{\rm s}] (n_0/1\ {\rm cm^{-3}})^{-1}, \qquad (4.5)$$

and correspondingly the annihilation luminosity becomes

$$L_{\rm ann} = \frac{\Delta M c^2}{t_{\rm ann}} \approx 2 \times 10^{29}\ [{\rm erg\,s^{-1}}] R_{18}^2 B_{-5}^{-1} (n_0/1\ {\rm cm^{-3}})^2. \qquad (4.6)$$

The absolute upper limit on the annihilation luminosity is $\sim M_\odot c^2/t_{\rm ann} \approx 10^{39}\ {\rm erg\,s^{-1}}$, but, of course, the estimate (4.6) is much closer to reality.

In the case of mixed gas of protons and antiprotons with temperature $T$, the average proton-antiproton relative velocity is $v \sim (3T/m_p)^{1/2}$, and the Sommerfeld enhanced annihilation cross section would be larger by the factor $\sim 300\ ({\rm eV}/T)^{1/2}$. However, we expect that in the shock wave the relative proton-antiproton velocity is much larger.

If protons or antiprotons form hydrogen or antihydrogen atoms capturing electrons or positrons respectively, then one might think that the annihilation rate would be determined by the large atomic cross section which is equal to the geometrical size of the atoms, $\sigma_{\rm H\bar{H}} \sim 10^{-16}\ [{\rm cm^2}]$. However, such collisions lead only to dissociation of the atoms with subsequent normal $p\bar{p}$-annihilation, while formation of the bound $p\bar{p}$ state is strongly suppressed; see e.g. Ref. [10].

Since the predicted luminosity from annihilation (4.6) appears to be rather low, it is hard to find the fraction of anti-SNIa among the bulk of the distant ordinary SNIa events. Nevertheless, if a population of binary antistars existed in an appreciable amount, the rate of SNIa produced by them (or by BD stars in general) should be non-negligible at much higher redshifts than the rate of the ordinary SNIa production. Current searches [48] have found supernovae of all types up to $z = 2.5$, when the Universe was only ~3 Gyr old. The rate of SNIa explosions at $2 < z < 2.5$ was even higher than now, at $0 < z < 0.5$, although the errors are quite large. If the modified AD scenario leads to production of the BD binary stars in appreciable amounts, then the type Ia events could be observed even at higher $z$.

There could be also binaries formed by a star and an antistar through the gravitational capture via three-body interaction with another star. The probability of such binary formation is possibly much smaller than the probability of the formation of a binary consisting of two antistars from the same primordial cloud with high baryon density. Still it is nonzero, and the merging of an antistar and a star might lead to a spectacular explosion (hypernova?).

### C. Microlensing

Compact BD stars can be also found by the effect of gravitational microlensing which may be caused by both visible and invisible stars. These objects are called now Machos for "massive astrophysical compact halo objects." This phenomenon was first discussed in relation with dark matter (DM) candidates made of the so-called mirror matter by Berezhiani, Dolgov, and Mohapatra [49] and Blinnikov [50]).

#### *1. MACHO, EROS, AGAPE, MEGA, OGLE—Contradicting results*

The MACHO group [51] has revealed 13—17 microlensing events in the Large Magellanic Cloud (LMC), a significantly higher number than that expected from the known stars but not enough to explain all DM in the halo. The fractional contribution of the objects, which produced the lensing, into the dark matter density is usually denoted as $f$. Such objects were dubbed Machos. The MACHO group concluded that compact objects in the mass range $0.15M_\odot < M < 0.9M_\odot$ have a fraction $f$ in galactic halo in the range $0.08 < f < 0.50$ (95% C.L.). So Bennett [52] has concluded (based on the results of the MACHO group) that Machos have really been found.

The EROS collaboration has placed only an upper limit on the halo fraction, $f < 0.2$ (95% C.L.) for the objects in the specified above MACHO mass range, while EROS-2 [53] gives $f < 0.1$ for $10^{-6}M_\odot < M < 1M_\odot$.

The AGAPE collaboration [54], working on microlensing in the M31 (Andromeda) galaxy, finds the halo Macho fraction in the range $0.2 < f < 0.9$. while the MEGA group marginally conflicts with them with an upper limit $f < 0.3$ [55].

Detailed analysis of the controversial situation with the results of different groups is given in Ref. [56]. Newer results [57] for EROS-2 and OGLE in the direction of the Small Magellanic Cloud are $f < 0.1$ obtained at 95% confidence level for Machos with the mass $10^{-2}M_\odot$ and $f < 0.2$ for Machos with the mass $0.5M_\odot$.

Recent data and other aspects of the microlensing are discussed in Ref. [58,59]. The general belief now is that the fraction $f$ of Machos in DM halos is rather small. Contrary to this, an interesting conclusion is reached by Hawkins [60]. He claims that the mass of the DM halo may be lower than generally assumed, and all-Macho halos cannot be ruled out on the basis of the observations, because for a given number of Macho events and a lower DM halo mass, the parameter $f$ evidently becomes larger.

It would be exciting if all DM were constituted by BD stars (and BD black holes) with masses in still allowed intervals, but more detailed analysis of this possibility has to be done. In particular, further analysis of microlensing events with unidentified lensing star is needed. To prove that those lensing objects are the BD antistars, accurate gamma-ray and x-ray observations of the corresponding regions in the sky are necessary.

Perhaps a more realistic explanation of the paradoxical situation with Machos is discussed in papers [61,62]. They suggest that the LMC is surrounded by a large cloud of objects sufficient to reproduce the observed microlensing signal by the background source stars: "a shroud composed of dark or dim material, such as low-mass stars or compact objects." The main problem with this idea is that all known stellar populations in the LMC have too small velocity dispersion for such a cloud; there are no known LMC populations with a line-of-sight velocity dispersion exceeding 33 $\mathrm{km\,s^{-1}}$ [63]. Evans and Kerins [62] wrote, "One possibility is that the shroud stars belong to an old, metal-rich population that could have evaded detection… A shrouded LMC may not dispense with the need for compact dark matter. It merely relocates it from the Milky Way halo to the LMC, although of course a much lower total mass budget in compact objects is implied." It is tempting to suggest that this population of the old stars that evaded detection can well be the BD stars discussed in Ref. [18]. Those stars should be older than any kind of the oldest standard stellar populations. They will meet both criteria: they should be very weak, and their cloud should have such a high velocity dispersion as needed. There is an intriguing possibility that some of those BD stars may be antistars discussed in the current paper.

#### *2. Destruction of wide pairs of visible stars*

Paper [64], which appeared in the series "End of MACHO Era (1974–2004)," asserts that wide pairs of visible stars must be destroyed by invisible Machos flying near them. The same effect may take place in the case of BD stars (which are visible, but weak). In addition to the criticism of paper [64], put forward in Ref. [65], one can point out that it is necessary to consider not only the process of destruction but also a reverse process of creating pairs of visible stars from single individual stars, not bound previously by the mutual gravity.

The probability of microlensing [66,67] is naturally measured by the so-called optical depth $\tau$. Evans and Belokurov [65] confirmed a lower number of compact objects in the direction to the LMC than that obtained by the MACHO group; i.e. they got $\tau < 0.36 \times 10^{-7}$ in agreement with EROS results [53]. Later, however, a paper of the same Cambridge group [68] was published where, on the basis of studies of binary stars, arguments in favor of the real existence of Machos and against the pessimistic conclusions of Ref. [64] were presented.

### D. Reionization and CMB

Energy influx from matter-antimatter annihilation at high redshift, $z > 10$, could be a source of the cosmological reionization, for which not enough energy is found in the standard model. Another way around, we can derive a bound on the amount of antimatter annihilating at high redshifts, if no energy injection is observed. A simple constraint can be derived as follows. According to Eq. (4.5), the annihilation time in the early Universe is

$$t_{\rm ann}(z) \sim 0.5 \times 10^{23}\ [\mathrm{s}](1+\mathrm{z})^{-3}. \tag{4.7}$$

Here we took for the baryon number density the value $n = \Omega_b \varrho_c / m_p \approx 2 \times 10^{-7} (\mathrm{z}+1)^3$. The Sommerfeld enhancement, which is effective at low velocities, $v < 10^{-3}$, could increase the cross section by an order of magnitude and correspondingly diminish $t_{\rm ann}$ by the same factor.

At redshift $z = 10$ the annihilation time is about $t_{\rm ann} \simeq 4 \times 10^{19}$ seconds, which is much longer than the Hubble time at this redshift, $t_U(z=10) \approx 10^{16}$ s. Therefore, one may expect that the fraction of all diffuse antimatter which resulted from the evolution of BD stars would be of the order of $t_{\rm ann}/t_U \sim 10^{-3}$–$10^{-4}$. The annihilation at this epoch would produce mostly 100 MeV photons, energetic electrons, and positrons. In principle, this process could provide more than enough energy to reionize the Universe, but more detailed calculations of the rate of energy degradation down to atomic resonance are necessary, which are outside of the scope of the present work.

The age of the Universe becomes comparable to the annihilation time near the hydrogen recombination era at $z \approx 1100$ or earlier. The antimatter annihilation could distort the CMB frequency spectrum if the annihilation occurred later than $z = 10^6$. However, the energy of photons produced by $p\bar{p}$ or even $e^- e^+$ annihilations is by far above the CMB energy at these epochs. Moreover, in the model considered here, virtually all antimatter was confined inside BD stars, and very little annihilation occurred on the star surface. However, e.g., a helium BD star with mass $M_{\rm He} \sim 2.5 M_\odot$, would evolve only about $5 \times 10^5$ years, so most of the mass loss would occur shortly after recombination, when the age of the Universe was comparable to the annihilation time. This implies that the energy produced by annihilation of antimatter expelled from such stars would interfere with the recombination dynamics, which may lead to some observable effects worth of further investigation.

### E. Meteor observations

As it was mentioned above in Sec. II, (some of) the BD stars may potentially have anomalous chemical abundances due to high value of the (anti)baryon-to-photon ratio $\beta$ during primordial nucleosynthesis. If $\beta$ is low, no significant differences as compared to the standard BBN abundances are expected. Such "metal-free" BD stars should be similar to the first Population III stars. Not much dust is expected to be formed during evolution of these stars. However, in domains with large $\beta$, the initial metal abundance can be higher. These "metal-rich" BD stars in due course of the evolution can produce a certain fraction of solids mostly in the form of dust particles. These dust particles should move with the virial halo velocities, $v \sim 500\ \mathrm{km\,s^{-1}}$, and can be observed as "antimeteors." An antimeteor with mass $m$ intruding the Earth's atmosphere should produce a prolific gamma-ray emission with a fluence of about $F_\gamma \sim 10(m/1\mathrm{mg})\ \mathrm{erg\,cm^{-2}}$ on a time scale of the Earth atmosphere crossing ~0.1–1 s. The brightest gamma-ray bursts observed by the BATSE gamma-ray detector have a fluence of $\sim 10^{-3}\ \mathrm{erg\,cm^{-2}}$ [69]. The nondetection of much brighter flares by all-sky gamma-ray monitors from the Earth's atmosphere and from the Moon led Fargion and Khlopov [70] to infer the upper bound on the antimatter fraction in meteors to be $f_c < 10^{-8}$–$10^{-9}$, by assuming the complete symmetry between matter and antimatter. (Note that short, millisecond, intensive hard gamma-ray flashes with energy $10^8$–$10^9$ ergs are frequently observed from the atmosphere, the so-called "terrestrial gamma-ray flashes" [71], and are thought to be associated with atmospheric electricity [72]).

An extragalactic meteor intruding the Earth's atmosphere with a velocity of at least $300\ \mathrm{km\,s^{-1}}$ was reported in Ref. [73]. The spectrum of this faint meteor was similar to the standard metal-rich chondrite. The authors [73] concluded that the space number density of such rapid dust particles, apparently of extragalactic origin, in the vicinity of the Earth could be as high as $n_d \sim 4 \times 10^{-26}\ \mathrm{cm^{-3}}$. The (very model-dependent) estimate of the observed meteor mass is $m \sim 10^{-6}$ g. The prolific metal-rich extragalactic dust particles is quite enigmatic from the point of view of standard stellar evolution. If this event were an antimeteor, the associated gamma-ray fluence, assuming a 500 km distance to the space detector, would be about $10^{-2}\ \mathrm{erg/cm^2}$, which is still several orders of magnitude higher than the brightest BATSE flashes.

According to the standard belief, the first stars ejected molecules and dust. To form larger pieces of matter (meteors), such gas should be compressed e.g. by a shock wave from supernova explosion or by a collision with another molecular cloud. As a result, the dust particles could be squeezed forming larger stones or pieces of ice, which subsequently form protoplanetary or protostar clouds. However, the BD stars not necessarily passed through such cycles but most probably remained primordial (PopIII) stars. In this case one should not expect a large number of meteors from them in our neighborhood.

Thus, in the context of BD stars under scrutiny, the antimatter restrictions derived in Ref. [70] from meteor observations cannot be directly applied. Indeed, most of the cosmic antidust produced by mass loss from metal-rich BD stars is expected to be in the form of small micron-size grains with a mass of $10^{-6}$ g and smaller, like the ordinary interstellar dust. Estimates made in Ref. [70] show that these small antidust grains should completely annihilate when moving through the interstellar gas, contributing to the diffusive gamma-ray background. Guided by the analogy with the ordinary matter, the fraction of dust in the total galactic stellar mass should be smaller than $\sim 1\%$ [34], thus providing only a minor contribution to the observed gamma-ray background discussed above.

## V. DISCUSSION AND CONCLUSIONS

We conclude that the contemporary observational data do not exclude a significant amount of antimatter in the Galaxy (and in other galaxies), especially in the form of the baryo-dense low-mass stars created in the very early Universe. The total mass of these antimatter objects could be comparable with the total mass of the Galaxy. They would populate the Galactic halo and might make a noticeable contribution to dark matter and, in particular, to Machos observed through microlensing. The BD stars should have an unusual chemical composition because they were formed in the regions with a very high baryon-to-photon ratio, where BBN proceeded with more efficient synthesis of heavy elements. Thus, a (rapidly moving) low-mass star with chemical anomaly may present a good possibility to be an antimatter star.

As we have shown above, the diffusive gamma-ray background may impose stringent constraints on the BD-star fraction because of the inevitable mass loss during the evolution of the antihelium stars. The precise amount of mass lost during evolution of an (anti)helium star depends upon its mass and metal abundance (see e.g. Ref. [36] for more detail). For example, for solar metal abundance, if $M_{\rm He} \leq 0.3 M_\odot$, the helium ignition into carbon is impossible, and the star simply cools down to form an antihelium white dwarf without mass loss. It is also known that for $M_{\rm He} \leq 0.8 M_\odot$ no significant mass loss is expected, and the star is evolved to form a hybrid CO-He white dwarf [36]. Helium stars with the initial masses $0.8 < M_{\rm He}/M_\odot \leq 2.2$ evolve to form a CO white dwarf with a mass up to $1.2\, M_\odot$; i.e. the mass loss from helium stars in this mass interval increases from zero to about 45%. Cores of more massive helium stars are expected to collapse to form a neutron star or black hole (for the most massive stars). Whether the collapse into a black hole is accompanied by substantial mass loss is unclear. The nuclear evolution of more massive helium stars occurs on the time scale $\tau_{\rm He} \sim 10^{7.15} (M_{\rm He}/M_\odot)^{-3.7}$ yr [37]. Therefore, for interesting He-star masses $M_{\rm He} \gtrsim 0.8 M_\odot$, most of the possible mass loss is expected to occur in the first 60 mln yr, i.e. at redshifts $z \gtrsim 43$ (for the standard cosmology), long before the formation of first structures in the universe. Assuming a homogeneous medium with density $n(z) = n_0 (1+z)^3$, where $n_0 = \varrho_b/m_p \sim 2 \times 10^{-7}$ cm$^{-3}$ is the present-day mean baryon number density, taking the annihilation cross section to be $\sigma_{\rm ann} \sim 10^{-24} (c/v)$ cm$^2$ (without account for the Sommerfeld low-velocity enhancement), and using the thermal velocity $v_{\rm th} \sim 10^5 \sqrt{T/10^4 {\rm K}}$ cm s$^{-1}$ in adiabatically cooling ideal monoatomic gas with $T(z) = 3 \times 10^3 [(1+z)/10^3]^2$ K, we can estimate the annihilation time $t_{\rm ann} \sim 1/(n \sigma_{\rm ann} v)$ to be much longer than the Hubble time at the corresponding $z$. This implies that most of the antimatter from BD-stellar winds is likely to survive until the present time. Even at the present time, in dense intercluster gas with baryon number density $n \sim 10^{-3}$ cm$^{-3}$, such antiparticles moving with virial velocities of a few 1000 km s$^{-1}$ can annihilate only very slowly.

The physics of BD stars is quite poorly studied and may be very much different from the usual astrophysics because the initial states of such stars quite often were different from the initial states of the usual stars. For example, BD stars could be formed in the state when the external pressure was larger than the internal one. Moreover, they start from an already dense and hot state but not from cold disperse gas cloud. In particular, there could be BD stars which are similar to the core of red giants but without external layers and some other strange objects; see the discussion in Ref. [15].

We also note that allowing some fraction of the antimatter to annihilate at high redshifts may contribute to the hard radiation continuum which is necessary to the secondary ionization of the Universe at $z > 10$.

As discussed in the previous papers, BD stars may have age comparable to that of the universe, and due to an anomalous initial chemical abundance, they even might look older than the universe if their age is determined by the conventional methods and by assuming the standard initial elemental abundance. This problem is under investigation. The observed high-redshift supernovae and gamma-ray bursts also nicely fit into the frameworks of the model.

As a byproduct, the model considered here can explain the formation of supermassive black holes and suggests an inverted process of the galaxy formation: first, a supermassive BH was born, which served as a seed for the subsequent collection of matter making a galaxy.

## ACKNOWLEDGMENTS

We are grateful to A. V. Zasov for useful comments on dark matter literature and to M. S. Pshirkov, L. R. Yungelson, and Peter Höflich for fruitful discussions. S. B. and A. D. acknowledge the support of the grant of the Russian Federation government, Grant No. 11.G34.31.0047. The work of K. P. was supported by the Russian Science Foundation Grant No. 14-12-00203. We would like to thank the anonymous referee for his/her helpful comments.



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