Antistars in the Galaxy

A. D. Dolgov$^{1,2*}$

$^1$Physics Department, Novosibirsk State University, Novosibirsk, Russia
$^2$Bogolyubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Moscow oblast, Russia

Received January 16, 2022

Abstract—Possible existence of antimatter in our Galaxy, in particular, of antistars is discussed and the mechanism of their creation is described.

Keywords: baryogenesis, antimatter, Galaxy

DOI: 10.3103/S0027134922020308

1. BARYOGENESIS AND C AND CP VIOLATION IN COSMOLOGY

The excess of matter over antimatter in the universe is explained by the famous Sakharov mechanism [1] based on three cornerstones:

- Nonconservation of baryonic number.
- C and CP (explicit) violation.
- Deviation from thermal equilibrium.

Depending upon the model these principles allow calculating the magnitude of the baryonic number density normalised to the density of the photons of CMBR:

$$\beta = \frac{N_B}{N_\gamma} = \text{const.}$$  \hspace{1cm} (1)

In the simplest versions of the scenario no antibaryons are created by the Sakharov mechanism and $\beta$ is predicted to be constant over all the universe. There is no room for antimatter in this simple scenario. However, the outcome depends upon the mechanism of C and CP breaking in cosmology. They can be separated into three possible groups [4]:

1. Explicit, which is achieved by complex coupling constants or masses in the fundamental Lagrangian of particle physics. In this case $\beta = \text{const}$ and has fixed sign, so no primordial antimatter is created.

2. Spontaneous [2], realised by a non-zero expectation value of a (complex) scalar field, which can have different signs in different space regions. In this case the universe would contain an equal amount of matter and antimatter with matter-antimatter domains separated by cosmologically large distances of the order of ggyaparsecs [3].

3. Dynamical, which operated only in the early universe if a classical complex scalar field somehow originated at the early stage of the cosmological evolution, but disappears later leaving no trace. If it happened simultaneously with baryogenesis, then the regions with different values and signs of $\beta$ can be created. This mechanism left behind neither domain walls nor any effects in particle physics.

In versions 2 and 3 stars and antistars can be created but far away from each other, in different galaxies. None of these, more or less conventional, scenarios allows for abundant antimatter in a galaxy predominantly consisting of matter or vice versa.

2. ANTIMATTER IN THE MILKY WAY

Possible discovery of several antistars in the Galaxy was recently reported [5]. Quoting the authors “We identify in the catalog 14 antistar candidates not associated with any objects belonging to established gamma-ray source classes and with a spectrum compatible with baryon-antibaryon annihilation.”

Somewhat earlier a striking idea was put forward that dark matter may consist of compact antistars [6]. The authors noted that such anti-DM may be easier to spot than other forms of macroscopic DM. However, detailed consideration of the observational limits is in order.

*E-mail: dolgov@fe.infn.it
Bounds on the antistar density in the Galaxy were studied in [7–9]. As is argued there, the fractional density of compact antistars in the universe and even in the Galaxy at the level of about 10% does not violate existing observational limits. The relatively weak limit is explained by the fact that the annihilation of the interstellar gas with antistar antimatter takes place either on the antistar surface or in the antistellar wind. Surface annihilation on a compact object is much less efficient than volume annihilation, e.g., inside gas cloud of antimatter. Such diffuse clouds of antimatter are also predicted by the theory, discussed below, but they could not survive to our time.

After this conference another method of antistar identification was suggested [10]. It was noticed that prior to $p\bar{p}$-annihilation the Coulomb-bound atomic like state could be formed analogous to positronium. Similar states $He^-$, $p\bar{He}$, or $He\bar{He}$ could also be formed. All such “atoms” were created, at highly excited states and in the process of de-excitation they would emit narrow X-ray lines with the energies in the range 1–10 keV. Which might be registered by Roentgen observatories.

3. ANTISTAR PREDICTION
AND ANTI-CREATION MECHANISM

Possible existence of antistars in the Galaxy was predicted many years ago in [11, 12]. In these works a new mechanism of primordial black holes (PBHs) was worked out and an appearance of antistars in the Galaxy was a natural by-product of the proposed mechanism. This mechanism of massive PBH formation predicted, in particular, the very simple mass spectrum of PBH, the so called lognormal mass spectrum:

$$\frac{dN}{dM} = \mu^2 \exp[-\gamma \ln^2(M/M_0)].$$  

(2)

Two out of three constant parameters, $\mu$ and $\gamma$, are model dependent and cannot be reliably predicted without information about the properties of high energy particle interactions. However, the value of the central mass $M_0$ should be equal to the mass inside the cosmological horizon at the QCD phase transition which took place in the very early universe at the temperatures about 100 MeV. So, according to the estimate of [13], $M_0 \approx 10 M_\odot$. The chirp mass distribution of LIGO events very well agrees with the lognormal form of the PBH spectrum [14]. This is the only known mass spectrum of PBH verified by observations.

The observed numbers of supermassive black holes ($M = (10^6–10^{10}) M_\odot$), intermediate mass BHs $M = (10^2–10^5) M_\odot$, and of BHs with masses of tens solar masses are well described by lognormal spectrum. The massive PBHs created by the mechanism of [11, 12] allow curing the multiple inconsistencies related to their origin in the conventional cosmology and astrophysics. Unusual stellar type compact objects observed in the Galaxy, including abundant antistars in the Galaxy, too quickly moving stars, too old stars, and stars with nontypical chemistry [15], can also be created by the mechanism [11, 12]. Dark matter made out of PBHs with lognormal spectrum may be a viable option [16].

In short, the basic features of the mechanism are the following. It is essentially based on the SUSY motivated baryogenesis or Axleke–Dine (AD) baryogenesis [17]. SUSY predicts existence of scalar field $\chi$ with non-zero baryonic number, $B \neq 0$. Such bosons may condense along the flat directions of the potential of $\chi$. We assume that the potential contains the quartic and quadratic terms:

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

(3)

where $\chi = |\chi| \exp(i\theta)$ and $m = |m|e^{i\alpha}$. If $\alpha \neq 0$, C and CP are broken. In GUT SUSY baryonic number is naturally non-conserved. Thus is expressed through the non-invariance of $U(\chi)$ with respect to the phase rotation of $\chi$.

Initially, just after inflation, the classical field $\chi(t)$ was away from the origin and, when inflation was over, it started to evolve down to the equilibrium point, $\chi = 0$, according to the equation analogous to that of the Newtonian mechanics with liquid (Hubble) friction:

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

(4)

Baryonic number of $\chi(t)$, equal to $B_\chi = \dot{\theta} |\chi|^2$, is analogous to mechanical angular momentum. At some later epoch the decay of $\chi$ transferred its baryonic number to that of quarks in B-conserving process. In contrast to other baryogenesis scenarios, the AD baryogenesis could lead to baryon asymmetry of order of unity, much larger than the observed value $\beta \sim 10^{-9}$. If necessary, with mild modification, the baryon asymmetry can be reduced to a much smaller value.

If $m \neq 0$, the angular momentum, $B_\chi$, could be generated by different directions of the quartic and quadratic valleys at low $\chi$. If CP-odd phase $\alpha$ is small but non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of one of them. Matter and antimatter domains may exist but globally $B \neq 0$.

The essential feature of the mechanism [11, 12] is the introduction of the general renormalizable cou-
pling of $\chi$ field to the inflaton $\Phi$, the first term in the equation below:

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda |\chi|^4 \ln \left( \frac{|\chi|^2}{\sigma^2} \right)$$

$$+ \lambda_1 (\chi^4 + \text{h.c.}) + (m^2 \chi^2 + \text{h.c.}),$$

(5)

where $\Phi_1$ is the value which $\Phi$ passed during inflation, some time before its end. The logarithmic term in this expression is a result of one-loop contribution to the potential, i.e., the Coleman–Weinberg potential[18].

When $\Phi$ is close to $\Phi_1$, the window to the flat direction is open and the field $\chi$ can diffuse to a large value. If the window to flat direction is open only during a sufficiently short period, cosmologically small but possibly astronomically large bubbles with high $\beta$ could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \times 10^{-10}$, created by small $\chi$.

This mechanism of massive PBH formation is quite different from all others. The fundament of PBH creation is build at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations. Initial isocurvature perturbations are contained in a large excess of quarks over antiquarks (or vice versa). Since quarks at this stage are massless the density perturbations are practically absent. Density perturbations are generated rather late after the QCD phase transition. The emerging universe looks like a piece of Swiss cheese, where holes are high baryonic density objects occupying a minor fraction of the universe volume. Since $\chi$ could rotate in the complex $\chi$-plane clockwise or anticlockwise around the origin, both bubbles with high baryonic or antibaryonic numbers could be created. Mostly they would turn into PBHs, but those which are not massive enough remain compact stars or antistars.

A competing suggestion on galactic antimatter was proposed recently in [19]. According to the statement of the author, the oscillation of the neutron $n$ into mirror neutron $n'$, its partner from dark mirror sector, can gradually transform from an ordinary neutron star into a mixed star consisting in part of mirror dark matter. The implications of the reverse process taking place in the mirror neutron stars depend on the sign of baryon asymmetry in mirror sector. Namely, if it is negative, as predicted by certain baryogenesis scenarios, then $n'^{-} - \bar{n}$ transitions create a core of our antimatter gravitationally trapped in the mirror star interior. The annihilation of accreted gas on such antimatter cores could explain the origin $\gamma$-source candidates, with unusual spectrum compatible to baryon-antibaryon annihilation [5], after the mergers of mirror neutron stars can produce the flux of cosmic antihelium and also heavier antimatter which are hunted in the AMS–02 experiment.

**FUNDING**

This work was supported by the Russian Science Foundation, project no. 20–42–09010.

**CONFLICT OF INTEREST**

The author declares that he has no conflicts of interest.

**REFERENCES**

1. A. D. Sakharov, “Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe,” JETP Lett. 5, 24 (1967); Sov. Phys. Usp. 34, 392 (1991).
2. T. D. Lee, “A theory of spontaneous T violation,” Phys. Rev. D8, 1226 (1973);
3. A. G. Cohen, A. de Rujula, and S. L. Glashow, “A matter – antimatter universe?” Astrophys. J. 495, 539 (1998); astro-ph/9707087.
4. A. D. Dolgov, “CP violation in cosmology,” in Proceedings of the International School of Physics Enrico Fermi, Course CLXII, Verenna, July 19–29, 2005, Ed. by M. Giorgi (IOS, Netherlands, Soc. Ital. Fis., Bologna, Italy, 2006), p. 407; arXiv: hep-ph/0511213.
5. S. Dupourqué, L. Tibaldo, and P. von Ballmoos, “Constraints on the antistar fraction in the Solar System neighborhood from the 10-year Fermi Large Area Telescope gamma-ray source catalog,” Phys. Rev. D 103, 083016 (2021); arXiv: 2103.10073 [astro-ph.HE]
6. J. S. Sidhu, R. J. Scherrer, and G. Starkman, “Antimatter as macroscopic dark matter,” arXiv: 2006.01200 [astro-ph.CO].
7. C. Bambi and A. D. Dolgov, “Antimatter in the Milky Way,” Nucl. Phys. B 784, 132 (2007); astro-ph/0702350.
8. A. D. Dolgov and S. I. Blinnikov, “Stars and black holes from the very Early Universe,” Phys. Rev. D 89, 021301 (2014); arXiv: 1309.3395.
9. S. I. Blinnikov, A. D. Dolgov, and K. A. Postnov, “Antimatter and antistars in the Universe and in the Galaxy,” Phys. Rev. D 92, 023516 (2015); arXiv: 1409.5736.
10. A. E. Bondar, S. I. Blinnikov, A. M. Bykov, A. D. Dolgov, and K. A. Postnov, “X-ray signature of antistars in the Galaxy,” arXiv: 2109.12699 [astro-ph.HE].
11. A. Dolgov and J. Silk, “Baryon isocurvature fluctuations at small scale and baryonic dark matter,” Phys. Rev. D 47, 4244 (1993).
12. A. Dolgov, M. Kawasaki, and N. Kevlishvili, “Inhomogeneous baryogenesis, cosmic antimatter, and dark matter,” Nucl. Phys. B 807, 229 (2009); arXiv: 0806.2986 [hep-ph].

13. A. Dolgov and K. Postnov, “Why the mean mass of primordial black hole distribution is close to 10 \( M_\odot \),” J. Cosmol. Astropart. Phys. 07, 063 (2020); arXiv: 2004.11669.

14. A. D. Dolgov, A. G. Kuranov, N. A. Mitichkin, S. Porey, K. A. Postnov, et al., J. Cosmol. Astropart. Phys. 12, 017 (2020); arXiv: 2005.00892.

15. A. D. Dolgov, “Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics,” Phys. Usp. 61, 115 (2018); arXiv: 1705.06859 [astro-ph.CO].

16. B. Carr and F. Kuhnel, “Primordial black holes as dark matter candidates,” in Contribution to Les Houches Summer School on Dark Matter, arXiv: 2110.02821 [astro-ph.CO].

17. I. Affleck and M. Dine, “A new mechanism for baryogenesis,” Nucl. Phys. B 249, 361 (1985).

18. S. R. Coleman and E. J. Weinberg, “Radiative corrections as the origin of spontaneous symmetry breaking,” Phys. Rev. D 7, 1888 (1973).

19. Z. Berezhiani, “Antistars or antimatter cores in mirror neutron stars?,” arXiv: 2106.11203 [astro-ph.HE].