Anti-stars in the Milky Way and primordial black holes

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Summary. — Astronomical data of the several recent years which present an evidence in favour of abundant antimatter population in our Galaxy, Milky Way, are analysed. The data include: registration of gamma-rays with energy 0.511 MeV, which surely originate from electron-positron annihilation at rest, very large flux of anti-helium nuclei, discovered at AMS, and 14 stars which produce excessive gamma-rays with energies of several hundred MeV which may be interpreted as indication that these stars consist of antimatter. Theoretical predictions of these phenomena, made much earlier ago are described.

1. – Introduction

The story of the antimatter search in the Galaxy started probably in 1968 from the attempts initiated by B. P. Konstantinov to search for anti-comets in the Solar System [1,2], which were strongly criticised by Ya.B. Zeldovich despite very good personal relations between them.

Later activity referred mostly to cosmological antimatter but not to antimatter in our close neighbourhood, Antimatter effects in cosmology was probably first discussed in 1971 in ref. [3], followed by [4,5]. Antimatter domains in the universe were studied in [6]. Reviews on the state of art with antimatter in cosmology were done in [4,8]. Antimatter in the Galaxy was considered only in the last reference [8] based on the theoretical prediction [9], which was later elaborated in [10].

2. – Anti-evidence

2˙1. *Cosmic positrons*. – Observation of intense 0.511 line, a proof of abundant positron population in the Galaxy. In the central region of the Galaxy electron–positron annihilation proceeds at a surprisingly high rate, creating the flux [11-13]:

$$(1) \qquad \Phi_{511 \text{ keV}} = 1.07 \pm 0.03 \cdot 10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1}.$$

The width of the line is about $3\,\mathrm{keV}$. Emission mostly goes from the Galactic bulge and at much lower level from the disk. There are several preceding works where this phenomenon was observed, the references can be found in the above quoted papers.

Until recently the commonly accepted explanation was that e^+ [14] are created in the strong magnetic fields of pulsars but the recent results of AMS probably exclude this mechanism. The reason is the following. According to the AMS data the energy spectrum of antiprotons and positrons are exactly the same both in the form and in the absolute magnitude. This feature implies that the mechanisms of $\bar{p}$ and e^+ production are the same and since protons cannot be produced in the magnetic fields of pulsars, it means that neither positrons could be created by this mechanism.

$\mathbf{2^{\cdot}2.}$ *Cosmic antinuclei*. – In 2018 AMS-02 announced possible observation of six $\overline{\mathrm{He}}^3$ and two $\overline{\mathrm{He}}^4$ events [15,16]. Recent measurements reveal much more anti-events [14]. According to the data [14] the ratio of fluxes $\overline{\mathrm{He}}/\mathrm{He} \sim 10^{-9}$ is too high, if one assumes that $\overline{\mathrm{He}}$ is produced in the process of cosmic ray collisions. As we see below, such secondary creation of $\overline{\mathrm{He}}^4$ is negligibly weak in comparison with theoretical expectation. A simple possibility to explain so high value of the observed anti-flux is to assume an existence of primordial antimatter in the Galaxy. Possibly because of that S. Ting expressed hope to observe anti-silicon, $\overline{\mathrm{Si}}$.

It is not excluded that the flux of anti-helium is even much higher than the observed one, because the low energy $\overline{\mathrm{He}}$ may escape registration in AMS.

The expected rate of the secondary production of anti-nuclei in cosmic rays was calculated in ref. [17]. Anti-deuterium can be created in the collisions $\bar{p} + p$ or $\bar{p} + \mathrm{He}$, which would produce the flux of $\bar{\mathrm{D}} \sim 10^{-7}/\mathrm{m}^2/\mathrm{s}^{-1}/\mathrm{steradian}/\mathrm{GeV}/\mathrm{neutron}$, *i.e.*, 5 orders of magnitude below the observed flux of antiprotons. The fluxes of $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$, which could be created in cosmic ray collisions are respectively 4 and 8 orders of magnitude smaller than the flux of anti-D.

After AMS announcement of observations of anti-He^4 there appeared theoretical attempts to create anti-He^4 through dark matter annihilation, which does not look natural. A recent review on anti-nuclei in cosmic rays can be found in [18].

$\mathbf{2^{\cdot}3.}$ *Antistars in the Galaxy*. – A possible striking discovery of antistar population in the Milky Way was announced recently [19]. 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."

Of course additional confirmation of this result is necessary. A possible new way to identify antistats was suggested in ref. [20]. It was noticed there that prior to idirect $p\bar{p}$ contact and annihilation the formation of atomic-like excited states consisting from proton-antiproton, proton-antinucleous (or antiproton-nucleous), and at last nucleous-antinucleous could be formed, which are similar to positronium.

In astrophysically plausible cases formation of such quasi-atoms is possible in the process of the interaction of neutral atmospheres or winds from antistars with ionised interstellar gas, These atoms rapidly cascade down to low levels prior to annihilation giving rise to a series of narrow lines which can be associated with the hadronic annihilation gamma-ray emission. The most significant are L (3p-2p) $1.73\,\mathrm{keV}$ line (yield more than 90%) from $p\bar{p}$ atoms, and M (4-3) $4.86\,\mathrm{keV}$ (yield ~ 60 %) and L (3-2) $11.13\,\mathrm{keV}$ (yield about 25%) lines from $\mathrm{He}^4\bar{p}$ atoms. These lines can be probed in dedicated observations by forthcoming sensitive X-ray spectroscopic missions XRISM and Athena and
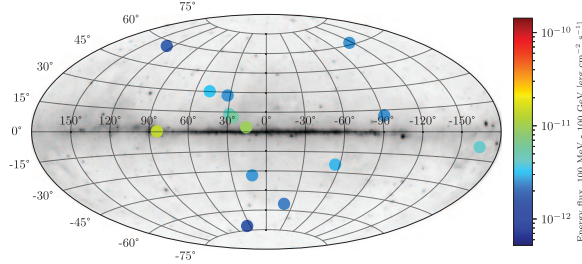
Fig. 1. – Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV.

in wide-field X-ray surveys like SRG/eROSITA all-sky survey.

The search of such objects could be facilitated by some unusual properties of antistars, *e.g.*, by high velocities or unusual chemical content, see below. According to the model of antistar-in-the-Galaxy prediction [9,10] such peculiarities are typical for antistars and can be good signatures to search for them.

2˙4. *Observational bounds on galactic antimatter*. – Possible evidence of admixture of antimatter in the Galaxy is surely beyond the usual expectations. Normally one may expect galaxies consisting purely either of matter or antimatter. Cosmologically large domains of matter and antimatter may be formed if C and CP symmetries are broken spontaneously. As a result the world would be symmeric with respect to matter and antimatter.

From the data on the cosmic gamma rays one can conclude that the nearest anti-galaxy could not be closer than at $\sim 10\,\mathrm{Mpc}$ [21]. Otherwise annihilation with protons from the common intergalactic cloud consisting of matter would be too intensive, violating existing observational limits.

The fraction of antimatter in Bullet Cluster should be below $< 3 \times 10^{-6}$ [22] based on the upper bounds to annihilation gamma-rays from galaxy clusters. Some limits on the fraction of antimatter at large scales can be obtained from the CMB data which excludes *large* isocurvature fluctuations at $d > 10\,\mathrm{Mpc}$, and from Big Bang Nucleosynthesis which does not allow large chemistry fluctuations at $d > 1\,\mathrm{Mpc}$.

According to ref. [23] the analysis of the intensity of gamma rays created by the Bondi accretion of interstellar gas to the surface of an antistar would create the luminosity

$$(2) \qquad\qquad L_\gamma \sim 3 \cdot 10^{35} (M/M_\odot)^2 v_6^{-3}.$$

It allows to put a limit on the relative density of antistars in the Solar neighbourhood: $N_{\bar{*}}/N_* < 4 \cdot 10^{-5}$ inside $150\,\mathrm{pc}$ from the Sun.

The presented above bounds are valid, if antimatter makes the same type objects as the observed matter. For example, compact stellar-like objects consisting of antimatter may be abundant in the Galaxy but still escape observations. The bounds on the density of galactic compact antistars are rather loose, because the annihilation proceeds only on the surface of antistars which are the objects with short mean free path of protons, as it is analysed in the papers [24-26].

3. – Antistar prediction

Based on the conventional approach no antimatter object is expected to be in the Galaxy. However, it was predicted in 1993 and elaborated in 2009 that noticeable amount of antimatter, even antistars might be present in the Galaxy and in its halo in non-negligible amount [9, 10].

The mechanism the papers [9, 10] was originally dedicated to the formation of primordial black holes (PBH). It predicts a large population of massive and supermassive PBH with log-normal mass spectrum in perfect agreement with observations. This is the only known to us mass spectrum of PBH which is tested by observational data.

The proposed mechanism [9, 10] also allows to solve multiple problems related to the observed black holes in the universe in all mass ranges, in particular, it explains the origin of supermassive BHs and black holes with intermediate masses, from $M \sim 10^2 M_\odot$. up to $10^5 M_\odot$, mysterious otherwise.

As a by-product of this mechanism compact stellar type objects, which are not massive enough to form BHs, made of matter and antimatter are predicted.

3˙1. *Predicted mass spectrum of PBH* . – The log-normal mass spectrum is determmned by three constant parameters and has the following very simple form:

$$(3) \qquad \frac{dN}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_0)\right].$$

The parameters μ and γ are determined by an unknown high energy physics but M_0 should be equal to the cosmological horizon mass at the QCD phase transition, so it is predicted to be $M_0 \approx (10 - 20) M_\odot$ [27]. This value perfectly fits the data. In partociular, the log-normal form of the mass spectrum of PBHs is confirmed by the chirp mass distribution of the LIGO events [28]. The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO runs are analysed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum. The inferred best-fit mass spectrum parameters, $M_0 = 17 M_\odot$ and $\gamma = 0.9$, fall within the theoretically expected range and shows excellent agreement with observations. On the opposite, binary black hole models based on massive binary star evolution require additional adjustments to reproduce the observed chirp mass distribution, see figs. 2, 3

Thus, PBHs with log-normal mass spectrum perfectly agree with the data obtained by LIGO, while astrophysical BHs seem to be disfavored. This agreement presents a very strong support in favour of the theoretical model [9, 10].

3˙2. *How reliable the galactic antimatter prediction.* – To summarise: why can we trust the prediction the population of antimatter in the Milky Way? In short the answer is because the it is a by-product of the mechanism of PBH formation which pretty well resolves multiple problems with the properties of observed BH in the early ($Z \sim 10$) and the present day universe, for a review see [29].

In particular, PBHs formed according to our scenario explain the peculiar features of the sources of GWs observed by LIGO/Virgo [30].

The existence of supermassive black holes (SMBH) discovered in all large and some small galaxies and even in almost empty environment is explained. Conventional models of SMBH formation demand time which is not enough by about two orders of magnitude.
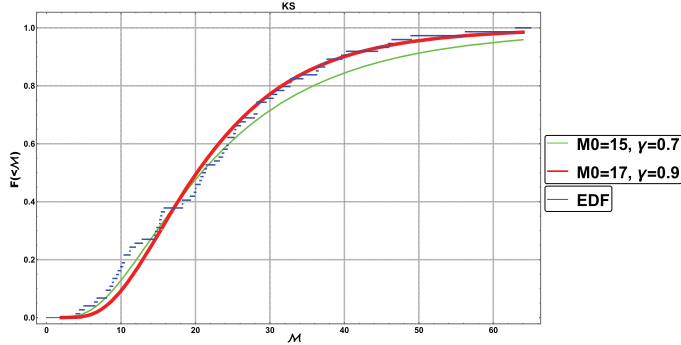
Fig. 2. – Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.
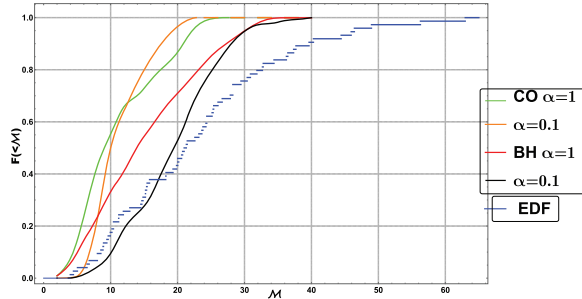

Fig. 3. – Cumulative distributions $F(< M)$ for some astrophysical models of binary BH coalescences.

The present day universe is full of SMBH with masses in the range $M = (10^6 - 10^{10})M_\odot$ as well as the intermediate mass black holes (IMBH), with $M = (10^2 - 10^5)M_\odot$ in unexpectedly high amount. Moreover the SMBH are abundant in the early, $z = 5 - 10$, universe. It is problematic to explain their formation through the canonical astophysical mechanisms but much more natural is to assume that they are primordial.

Since the predicted features of PBH in all mass ranges well agree with the data, one may expect that the underlying mechanism of their creation indeed operated in the early universe. This perfectly working model of PBH creation also predicts existence of primordial antimatter in our vicinity, so it is quite natural to expect that antimatter is indeed abundant in the Galaxy.

Theory predicts that the primordial stellar type compact objects have quite unusual chemical content enriched with metals, It is confirmed in particular, by observations of extremely old stars, even of a star which formally is older than the universe. The stars looks too old because their initial chemistry is enriched by heavy elements, which in the standard approach demand very long time for their synthesis. Also very high velocity stars can be present in the Galaxy and they are indeed observed.

4. – Mechanism of anti-creation

The suggestion of PBH (and antistar) creation proposed in refs. [9,10] is based on the SUSY motivated Affleck-Dine (AD) [31] scenario of baryogenesis. It is assumed that there

exists a scalar field χ with non-zero baryonic number, as suggested by supersymmetry. The potential of χ has, as a rule, the so called flat directions along which the potential does not change, remaining the same as in the origin at $\chi = 0$. All these properties are generically inherent to high energy supersymmetric models.

The field χ could reach very large magnitude moving along such flat directions either due to rising quantum fluctuations of massless fields at de Sitter (inflationary) stage, as in the original version of the AD baryogenesis model or, as in the present paper, because of negative effective mass squared of χ (higgs-like effect).

Our new input to the model is is an introduction of the interaction of χ with the inflaton field, such that the mass m^2_{eff} stays negative for some time. Due to this new interaction, the gate to the flat direction were closed during almost all inflationary epoch, except for a rather short period. When the gates are closed χ remained small, sitting near the origin. When the gates were open χ might reach large values and when the gates close again, χ returned to the origin carrying a large baryonic number but only inside the bubbles of cosmologically small but possibly astrophysically large size.

Thus the universe would look like the inverted Swiss cheese. In almost all space baryon number density is small except for relatively small bubbles with large B. Since the particles which carry baryonic number, *i.e.*, quarks were massless, the density contrast remained practically unnoticeable. The contrast became huge after the QCD phase transition when massless quarks turns into heavy protons and neutrons. Then these High-B Bubbles (HBB) turns into PBH or, if not massive enough, into compact (anti) stars. Depending upon the direction of the χ phase rotation in the complex χ plane such primordial stars or antistars. could be created.

When χ is large, its evolution is governed by the quartic part of the potential, at smaller χ the quadratic part dominates and if the flat directions of quartic and quadratic parts are different χ starts to rotate in the complex χ-plane either clock-wise or anticlockwise. As we see in what follows it leads either to creation of High-B-Bubble, HBB, or High-antiB-Bubbles, H$\bar{B}$B.

For a toy model we assume that the quartic part of the potential has the form:

$$(4) \qquad U_\lambda(\chi) = \lambda |\chi|^4 \left(1 - \cos 4\theta\right),$$

while the mass term can be written as $U_m = m^2 \chi^2 + m^{*\,2} \chi^{*\,2}$, or in a more convenient form:

$$(5) \qquad U_m(\chi) = m^2 |\chi|^2 \left[1 - \cos(2\theta + 2\alpha)\right],$$

where $\chi = |\chi| \exp(i\theta)$ and $m = |m| e^\alpha$. If $\alpha \neq 0$, C and CP would be broken.

In GUT SUSY baryonic number is naturally non-conserved. In our toy model this non-conservation is achieved due non-invariance of $U(\chi)$ with respect to phase rotation, $\chi \to e^{i\sigma} \chi$ with a constant phase σ.

In the conventional version of the AD-baryogenesis the field χ after inflation 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 of Newtonian mechanics with the Hubble friction term:

$$(6) \qquad \ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0.$$

Baryonic number of χ, $B_\chi = \dot{\theta}|\chi|^2$, is analogous to the mechanical angular momentum of rotation in the complex χ-plane. It is quite natural that this "angular momentum" could reach a large value and hence the baryon asymmetry, that is the ratio of the baryonic number density to the density of the CMBR photons could be very high $\beta = N_B/N_\gamma \sim 1$, much larger than the observed value $\beta_{obs} \approx 10^{-9}$. The B-conserving decays of χ would transfer its baryonic number to that of quarks.

Rotation could be either clockwise or anticlockwise for different bubbles with large χ depending upon relative locations of the flat directions in quartic and quadratic parts of the potential in the complex χ-plane. Large χ lives in quartic valley, but when χ drops down, it moves to the quadratic one starting to "rotate". So the angular momentum or, in other words B, is generated by possible different directions of the quartic and quadratic valleys at low χ. If CP-odd phase α is non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of one of them. Both matter and antimatter objects may exist but it is natural to expect a global dominance of one of them, so $B_{tot} \neq 0$.

We assume that the Affleck-Dine field χ has the potential:

$$(7) \quad U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda_{CW}|\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right) + \lambda(\chi^4 + h.c.) + (m^2\chi^2 + h.c.),$$

where the first term introduced in refs. [9, 10]. is the general renormalizable coupling of two scalar fields, χ and the inflaton Φ. The logarithmic term is is the Coleman-Weinberg potential [32], which originates from summing up one loop corrections to the quartic potential.

CP would be broken, if the relative phase of λ and m is non-zero, otherwise one can "phase rotate" χ and come to real coefficients, eliminating thus CP-violation.

The value of Φ_1 is chosen so that the Φ reached the value Φ_1 in the process of inflation but but relatively late, so that the duration of inflation after that made about 30-40 e-foldings. When the window to the flat direction is open, near$\Phi = \Phi_1$, the field χ slowly diffuses to a large value, according to quantum diffusion equation derived by Starobinsky, generalised to a complex field χ. When Φ turns large, it evolves classically, oscillating near the local minimum of the potential.

If the window to flat direction, when $\Phi \approx \Phi_1$ is open only during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$, created by small χ.

The mechanism of massive PBH formation 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 in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition.

The main features of the scenario can be summarised as follows:

- $\rho_\chi \ll \rho_\Phi$, even inside large χ bubbles.

- Bubbles with large χ occupy a small fraction of the universe volume.

- When $\Phi < \Phi_1$ but inflation still lasts, χ is large and oscillates fast. Hence it does not feel shallow valleys of $m^2\chi^2$. At this stage baryon asymmetry is not generated.

- Inflation ends and the oscillations of Φ heats up the universe.

- Ultimately the amplitude of χ drops down, the field starts to feel m^2-valley, and begins to rotate, generating large baryon asymmetry.

- The picture is similar to the original AD-scenario in the universe.

- With the chosen values of couplings and masses the density contrast between the bubbles and the rest of the world, before the QCD phase transition, could be rather small, at the per-cent level.

5. – Summary

Here we summarise some properties of the mechanism [9, 10] of PBH and antistar formation which are discussed above but not only them.

- The predicted significant antimatter population of Milky Way seems to be confirmed by observations.

- The Log-normal mass spectrum of PBH is verified by the numerous data and very well agrees with them.

- PBHs formed through the mechanism [9, 10] explain the peculiar features of the sources of GWs observed by LIGO.

- The considered mechanism solves the numerous mysteries of $z \sim 10$ universe: supermassive black holes, early created gamma-bursters and supernovae, early bright galaxies, and evolved chemistry including a high level of dust.

- Inverted picture of the galaxy formation is proposed when a supermassive PBH is first formed and subsequently seeds galaxy formation.

- It is predicted that globular clusters (GB) and dwarf galaxies are seeded by IMBHs, so there should be an intermediate mass BH in the center with mass about $2000 M_\odot$ in GBs and typically somewhat higher in dwarfs. An estimate of the density of GCs is made and agrees with the data.

- A large number of the recently observed intermediate mass black holes was predicted.

- An existence of supermassive black holes observed in all large and some small galaxies and in almost empty environment is explained.

- It is claimed that a large fraction of the cosmological dark matter up to 100% can consist of PBHs.

- Strange stars with unusual chemistry, enriched with metals and high velocities are predicted and observed. Extremely old stars are predicted and discovered. Even, an "older than the universe" star is found; the old age is mimicked by the unusual initial chemistry.

- In refs. [9,10] the new ideas of invoking inflation and Affleck-Dime baryogenesis for PBH creation were proposed, which were later repeated in a number of subsequent works.

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