Antimatter around us

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Cosmological revolution

Striking discoveries of the last several years.

The universe is full of black holes in all mass ranges from a fraction of the solar mass up to a hundred billion solar masses. In the conventional scenario there are plenty of problems with their formation in particualr, but not all, there is by far not enough time for their formation.

Moreover, supermassive black holes are also observed in the very young universe at redshifts of the order of 10 or even exceeding that, when the universe was about 0.5 billion years old, i.e. 20 times younger than today.

Even more striking are indications that our Galaxy, Milky Way, may be quite abundantly populated by antimatter, positrons, antinuclej and even antistars.

Predictions

These unexpected phenomena were in fact predicted many years ago: A. Dolgov, J.Silk, PRD 47 (1993) 4244 (DS) "Baryon isocurvature fluctuations at small scale and baryonic dark matter. A.Dolgov, M. Kawasaki, N. Kevlishvili (DKK), Nucl. Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, cosmic antimatter, and dark matter". In these works a new mechanism of primordial black hole (PBH) formation was suggested with the predicted mass spectrum of PBHs, which very well agrees with the observations made in the recent years. The successful prediction of the PBH properties implies possible success of another striking prediction of DS and DKK, namely existence of antimatter in the Milky Way, in particular of compact stellar-like objects consisting from antimatter i.e. antistars.

Classification by mass:

1) solar mass BHs; masses from a fraction of the solar mass M_{\odot} up to a hundred M_{\odot} ;

2) intermediate mass BHs: $M \sim (10^2 - 10^5) M_{\odot};$

3) supermassive BHs: masses exceeding hundreds thousand solar masses, **observed up to 100 billions solar masses**.

Types of BH by creation mechanism:

I. Astrophysical: created by stellar collapse, when star exhausted its fuel. Masses expected just above the neutron star masses, $3M_{\odot}$, and normally quite close to it.

Instead the mass spectrum of BH in the Galaxy has maximum at

 $M \approx 8 M_{\odot}$ with the width: $\sim (1-2) M_{\odot}$.

These BHs usually have non-vanishing spins, $a \sim 1$.

They may acquire some electric charge by predominant capture of surrounding protons.

BH, what's that

II. Accretion of matter to regions with excessive density. There is a supermassive BH (SMBH) in all(?) large galaxies. Masses are in the range: $M \sim 10^9 M_{\odot}$ in elliptic and lenticular galaxies and $M \sim (10^6 - 10^7) M_{\odot}$ in elliptic galaxies, like Milky Way. Is the type of the galaxy determined by the mass of BH and not vice versa? However, the known mechanisms of accretion is not efficient enough to create such monsters during the universe age $t_{II} \approx 15$ Gyr, more than by an order of magnitude Moreover SMBH are found in very small galaxies and one SMBH lives even in almost empty space. SMBH are also discovered recently in quite young universe with the age about 0.5 -1 Gyr. Their formation is multifold less probable. Q and a are normally small (?). For creation of SMBH some massive seeds are necessary, however their origin is unknown.

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BH, what's that

III. Primordial black holes (PBH) created in pre-stellar epoch in the very early universe.

The canonical picture: the density excess might accidentally happen to be large, $\delta \varrho / \varrho \sim 1$, at the cosmological horizon scale. Then this piece would be inside its gravitational radius i.e. it becomes a BH, and decouple from the cosmological expansion. (Zeldovich and Novikov mechanism, elaborated later by Carr and Hawking). Usually this mechanism created PBH with rather low masses and with sharp almost delta-function mass spectrum.

A different mechanism (AD and J.Silk, 1993) could make PBH with masses exceeding millions solar masses and with extended mass spectrum (log-normal) which became quite popular recently. PBH spins are normally very small, since vorticity perturbations in the early universe are negligible.

Anti-evidence

Astronomical data of the several recent years present strong evidence in favour of abundant antimatter population in our Galaxy, Milky Way. The data include:

- Observation of gamma-rays with energy 0.511 MeV, which surely originate from electron-positron annihilation at rest.
- Very large flux of anti-helium nuclei, observed at AMS.

• Several stars are found which produce excessive gamma-rays with energies of several hundred MeV which may be interpreted as indication that these stars consist of antimatter.

Anti-evidence: 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:

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

The width of the line is about 3 keV. Emission mostly goes from the Galactic bulge and at much lower level from the disk, "Great Annihihilator" in the Galactic bulge.

G. Weidenspointner et al., Astron. Astrophys. 450, 1013 (2006);

J. Knodlseder et al., Astron. Astrophys. 441, 513 (2005);

P. Jean et al., Astron. Astrophys. 445, 579 (2006).

Until recently the commonly accepted explanation was that e^+ are created in the strong magnetic fields of pulsars but the recent results of AMS probably exclude this mechanism, since the spectrum of \bar{p} and e^+ at high energies are identical. L'Aquila Joint Astroparticle Colloquium, 10th November, 2021 by S. Ting.

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Anti-evidence: cosmic antinuclei

- Registration of anti-helium: In 2018 AMS-02 announced possible observation of six \overline{He}^3 and two \overline{He}^4 .
- A. Choutko, AMS-02 Collaboration, "AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018).
- S. Ting, Latest Results from the AMS Experiment on the International Space Station. Colloquium at CERN, May, 2018.
- Recent registration of more events L'Aquila Joint Astroparticle Colloquium, 10th November by S. Ting: fraction $\overline{He}/He \sim 10^{-9}$, too much.
- Secondary creation of \overline{He}^4 is negligibly weak.
- Nevertheless Ting expressed hope to observe \overline{Si} !!!
- It is not excluded that the flux of anti-helium is even much higher because low energy \overline{He} may escape registration in AMS.

Antinuclei creation in cosmic rays

Expected secondary produced anti-nuclei:

Anti-deuterium can be created in the collisions $\bar{p} p$ или $\bar{p} He$ (Duperray et al, 2005). which would produce the flux of $\bar{D} \sim 10^{-7}/m^2/s^{-1}/\text{steradian/GeV/neutron}$, i.e. 5 orders of magnitude below the observed flux of antiprotons. The fluxes of \overline{He}^3 and \overline{He}^4 , which could be created in cosmic rays 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. Quite unnatural.

Recent review on secondary anti-nuclei creation in cosmic rays: P. von Doetinchem, K. Perez, T. Aramaki, et al "Cosmic-ray Antinuclei as Messengers of New Physics:..." 2002.04163v1

Anti-evidence: antistars in the Galaxy

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 103 (2021) 083016 "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."

Possible discovery of anti-stars in the Galaxy



Figure: 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

X-ray signatures of antistars

"X-ray signature of antistars in the Galaxy" A.E. Bondar, S.I. Blinnikov, A.M. Bykov, A.D. Dolgov, K.A. Postnov e-Print: 2109.12699 [astro-ph.HE], JCAP, Sep 26, 2021, In astrophysically plausible cases of the interaction of neutral atmospheres or winds from antistars with ionised interstellar gas, the hadronic annihilation will be preceded by the formation of excited $p\bar{p}$ and $He\bar{p}$ atoms. 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 keV line (yield more than 90%) from $p\bar{p}$ atoms, and M (4-3) 4.86 keV (yield \sim 60%) and L (3-2) 11.13 keV (yield about 25%) lines from $He^4\bar{p}$ atoms. These lines can be probed in dedicated observations by forthcoming sensitive X-ray spectroscopic missions XRISM and Athena and in wide-field X-ray surveys like SRG/eROSITA all-sky survey.

Observational bounds on antimetter

From cosmic gamma rays:

Nearest anti-galaxy could not be closer than at ~10 Mpc (Steigman, 1976), from annihilation with p in common intergalactic cloud. Fraction of antimatter Bullet Cluster $< 3 \times 10^{-6}$ (Steigman, 2008). CMB excludes LARGE isocurvature fluctuations at d > 10 Mpc. BBN excludes large "chemistry" fluctuations at d > 1 Mpc.

Review: P. von Ballmoos, arXiv:1401.7258 Bondi accretion of interstellar gas to the surface of an antistar:

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

put a limit $N_{\bar{*}}/N_{*} < 4 \cdot 10^{-5}$ inside 150 pc from the Sun.

The presented bounds are true if antimatter makes the same type objects as the OBSERVED matter.

For example, compact stellar-like objects made of antimatter may be abundant in the Galaxy but still escape observations.

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Antimatter in the Galaxy

Antimatter in cosmology

Based on the conventional approach no antimatter object is expected to be in the Galaxy.

However, there are crazy predictions of 1993 (DS) and 2006 (DKK) that noticeable amount of antimatter, even antistars, might be abundant in the Galaxy and in its halo.

Bounds on the density of galactic antistars are rather loose, because the annihilation proceeds only on the surface of antistars, objects with short mean free path of protons, as analyzed in:

C.Bambi, A.D. Dolgov, "Antimatter in the Milky Way", Nucl.Phys.B 784 (2007) 132-150 • astro-ph/0702350,

A.D. Dolgov, S.I. Blinnikov, "Stars and Black Holes from the very Early Universe", Phys.Rev.D 89 (2014) 2, 021301 • 1309.3395, S.I.Blinnikov, A.D. Dolgov, K.A.Postnov, "Antimatter and antistars in the universe and in the Galaxy", Phys.Rev.D 92 (2015) 023516 • 1409.5736.

Antimatter fraction at a few per cent level seems to be allowed.

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Antimatter in the Galaxy

Matter versus antimatter in cosmology

Canonical picture, (A.D. Sakharov, 1967):

- Non-conservation of baryonic number.
- **2** Explicit C and CP violation.
- Over the second seco

Allows to explain the observed baryon baryon asymmetry

$$eta = rac{N_B}{N_\gamma} = 6 imes 10^{-9},$$

where $N_{\gamma} = 411/\text{cm}^3$ - number density of CMB photons. According to this model β is a universal "cosmological constant", the same over all the universe. No antimatter at all, except for secondary produced antiparticles: antiprotons, positrons, antinuclei. Spontaneous C and CP breaking, induced by a nonzero vacuum value of a complex scalar field acquiring different signs in different patches of space (T.D. Lee, 1974) leads to cosmologically huge domains of matter and antimatter with with equal absolute values of the asymmetries. Double well potential:

$$\boldsymbol{U}(\phi) = -\boldsymbol{m}^2 \phi^2 + \lambda \phi^4$$

leads to formation of domains of matter and antimatter. They should be much larger than the galactic size, otherwise diffusion and subsequent annihilations would destroy them. Absence of the MeV gamma background demands that domains of antimatter should be far away. $I_B \gtrsim \text{Gpc}$ (A. Cohen, A. De Rujula, and Sh. Glashow, 1996). Domain wall problem. The mechanism DS and DKK predicts a large population of massive and supermassive primordial black holes (PBH) with log-normal mass spectrum in perfect agreement with observations. It also allows to solve multiple problems related to the observed black holes in the universe in all mass ranges, in particular, the origin of supermassive BHs and black holes with intermediate masses, from $M \sim 10^2 M_{\odot}$. up to $10^5 M_{\odot}$, otherwise mysterious. As a by-product compact stellar type objects, which are not massive enough to form BHs, made of matter and antimatter are predicted.

The predicted mass spectrum of PBHs

The model predicts the log-normal mass spectrum of PBH:

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

and predicts $M_0 \approx 10 M_{\odot}$. A.Dolgov, K.Postnov, "Why the mean mass of primordial black hole distribution is close to $10 M_{\odot}$ ". JCAP 07 (2020) 063 e-Print: 2004.11669 . In excellent agreement with observations. **The log-normal form of the mass spectrum of primordial black holes** is strongly confirmed by the chirp mass distribution of the LIGO events, AD, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, I.V. Simkin, **"On mass distribution of coalescing black holes,"** JCAP 12 (2020) 017

Chirp mass

Two rotating gravitationally bound massive bodies are known to emit gravitational waves. If the back reaction is neglected, the radius of the orbit and the rotation frequency are constant and the GW frequency is twice the rotation frequency. The luminosity of the GW radiation is:

$$\boldsymbol{L} = \frac{32}{5} \, \boldsymbol{m}_{\boldsymbol{P}\boldsymbol{I}}^2 \left(\frac{\boldsymbol{M}_{\boldsymbol{c}} \, \boldsymbol{\omega}_{\boldsymbol{o}\boldsymbol{r}\boldsymbol{b}}}{\boldsymbol{m}_{\boldsymbol{P}\boldsymbol{I}}^2} \right)^{10/3} \,,$$

where M_c is the so called chirp mass:

$$M_c = rac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}},$$

and

$$\omega_{orb}^2 = \frac{M_1 + M_2}{m_{PI}^2 R^3} \,.$$

The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/ runs are analyzed 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. This is the only known model of PBH creation which agrees with the data without special tuning.

On the other hand, binary black hole models based on massive binary star evolution require additional adjustments to reproduce the observed chirp mass distribution.

Chirp mass distribution

Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.



Chirp mass distribution, astrophysical BHs

Cumulative distributions F(< M) for several astrophysical models of binary BH coalescences.



Conclusion: PBHs with log-normal mass spectrum perfectly fit the data. Astrophysical BHs seem to be disfavored.

Creation of rich population of BBH and **antistars** is based on SUSY motivated baryogenesis, Affleck and Dine (AD), which in our case operated in the very early universe in a relatively small fraction of space.

SUSY predicts existence of scalars with $B \neq 0$. Such bosons may condense, reaching very large values, along flat directions of the quartic potential:

$$U_{\lambda}(\chi) = \lambda |\chi|^4 (1 - \cos 4\theta)$$

and of the mass term, $\boldsymbol{U_m} = \boldsymbol{m}^2 \chi^2 + \boldsymbol{m}^{*\,2} \chi^{*\,2}$:

$$\boldsymbol{U}_{\boldsymbol{m}}(\chi) = \boldsymbol{m}^2 |\chi|^2 [1 - \cos\left(2\theta + 2\alpha\right)],$$

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

Initially (after inflation) χ was away from 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:

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

Baryonic number of χ :

 $B_{\chi} = \dot{\theta} |\chi|^2$

is analogous to mechanical angular momentum. χ decays transferred its baryonic charge to that of quarks in B-conserving process. AD baryogenesis could lead to baryon asymmetry of order of unity, much larger than the observed 10^{-9} . Rotation could be either clockwise or anticlockwise for different bubbles with large χ depending upon locations of the flat directions in quartic and quadratic parts of the potential. Large χ lives in quartic valley, smaller χ goes to the quadratic one starting to "rotate", creating huge B

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Antimatter in the Galaxy

If $m \neq 0$, the angular momentum, B, is generated by 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.

Matter and antimatter objects may exist but globally $B \neq 0$.

Affleck-Dine field χ with CW potential coupled to inflaton Φ (DS/DKK):

$$U = g|\chi|^2 (\Phi - \Phi_1)^2 + \lambda |\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right)$$
$$+\lambda_1(\chi^4 + h.c.) + (m^2\chi^2 + h.c.).$$

Coupling to inflaton is the general renormalizable one. When the window to the flat direction is open, near $\Phi = \Phi_1$, the field χ slowly diffuses to large value, according to quantum diffusion equation derived by Starobinsky, generalized to a complex field χ .

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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 emerging universe looks like a piece of Swiss cheese, where holes are high (anti)baryonic density objects occupying a minor fraction of the universe volume. If they are not sufficiently massive to make a PBH, they form stellar-kind object consisting of matter or antimatter.

Why can we trust the antistar creation model

How reliable is the prediction of antistars in the Galaxy? The mechanism predicts the log-normal mass spectrum of PBH, observed by LIGO/Virgo, well confirmed by the observations: AD, K.A.Postnov et al, JCAP 07 (2020) 063, 2004.11669 and JCAP 12 (2020) 017, 2005.00892. PBHs formed according to this scenario explain the peculiar features of the sources of GWs observed by LIGO/Virgo, S. Blinnikov, AD, N. Porayko, K. Postnov, Solving puzzles of GW150914 by primordial black holes, JCAP 11 (2016) 036.

The proposed mechanism of massive PBH creation allow to cure multiple inconsistencies with the standard cosmology and astrophysics. Review of astrophysical problems in A.D. "Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics," Usp. Fiz. Nauk 188 (2018) 2, 121; Phys. Usp. 61 (2018) 2, 115.

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

Why can we trust the antistar creation model

The universe is full of supermassive black holes (SMBH), $M = (10^6 - 10^{10})M_{\odot}$ and intermediate mass black holes (IMBH), $M = (10^2 - 10^5)M_{\odot}$.

Unexpectedly high amount in the present day and the early, z = 5 - 10 universe. Are they primordial?

The predicted features of PBH in all mass ranges well agree with the data, thus 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 creation of primordial antistars, so it is quite natural to see a population of antistars in the Galaxy.

Unusual stellar type compact objects could also be created, in particular, extremely old stars, even a star formally older then the universe, are observed. It looks too old because its initial chemistry is enriched by heavy elements. In a recent publication a striking idea was put forward that dark matter may consist of compact anti-stars: J. S. Sidhu, R.J. Scherrer, G. Starkman, "Antimatter as Macroscopic Dark Matter", arXiv:2006.01200, astro-ph.CO. Such anti-DM may be easier to spot than other forms of macroscopic DM. If anti-stars make dark matter, they should populate the galactic halo, as any other form of dark matter, i.e. they must be primordial, or at least pregalactic, anti-stars. Exactly as is predicted in our publications, the only but important difference is that in our scenario DM predominantly consists of PBHs

Results of (Anti-)Creation

- Log-normal mass spectrum is confirmed by the data.
- β may be negative leading to creation of (compact?) antistars which could survive annihilation with the homogeneous baryonic background.
- Disperse hydrogen and helium clouds with (much) higher than average n_B density. Similar anti-clouds already annihilated in matter dominated background and did not survive to our time.
- Strange stars with unusual chemistry and velocity larger than the virial one are observed.
- Extremely old stars would exist even, "older than the universe" are found; the old age is mimicked by the unusual initial chemistry. Several such stars are observed.

The mechanism of PBH formation is strongly supported by astronomical observation and thus the chances another prediction of this mechanism of abundant population of the Galaxy by antistars has high chance to be true. New data present strong indication to that.

CONFIRMATION OR EXCLUSION ARE COMING !?

APPENDIX. Antimatter in cosmology

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leads to formation of domains of matter and antimatter. They should be much larger than the galactic size, otherwise diffusion and subsequent annihilations would destroy them. $I_B \gtrsim \text{Gpc}$ (A. Cohen, A. De Rujula, and Sh. Glashow, 1996). Domain wall problem.

Dynamical or stochastic C(CP) violation (AD, 1992, 2005) a complex scalar field pushed away from the equilibrium point by quantum instability of massless, $m_{\phi} \ll H$, scalar at inflationary stage. Domain structure but no domain wall problem,

$$\boldsymbol{U}(\phi) = \boldsymbol{m}^2 \phi^2 + \lambda \phi^4.$$

In all the cases large structures consisting either of matter or antimatter, much larger than galaxies are formed, while galaxies consist solely of one form of (anti)matter.

If $m \neq 0$, the angular momentum, B, is generated by 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. Matter and antimatter objects may exist but globally $B \neq 0$.

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Evolution of AD-field

- $\varrho_{\chi} \ll \varrho_{\Phi}$, even inside large χ bubbles.
- $\bullet\,$ 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 started to feel m^2 -valley, and started 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 bubles and the rest of the world can be rather small, at the per-cent level.