Anti-stars in the Milky Way and primordial black holes

A. D. Dolgov

Novosibirsk State University, Novosibirsk, Russia
BLTP, JINR, Dubna, Russia

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Russian Scientists protest against the invasion to Ukraine

A large group of Russian scientists, science journalists, and other people joined signing the petition demanding to stop attack at Ukraine.

The petition can be seen at https://trv-science.ru/en/2022/02/we-are-against-war-en/

Content

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.**

Predicted in 1993 **A. Dolgov and J. Silk, PRD 47 (1993) 4244**
"Baryon isocurvature fluctuations at small scale and baryonic dark matter".
and further elaborated in 2009: A.Dolgov, M. Kawasaki, N. Kevlishvili, Nucl.Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter**, and dark matter".

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:

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

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 L'Aquila Joint Astroparticle Colloquium, 10th November, 2021 by S. Ting.

Anti-evidence: cosmic antinuclei

Registration of anti-helium: **In 2018 AMS-02 announced possible observation of six $\bar{H}e^3$ and two $\bar{H}e^4$.**
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 $\bar{He}/He \sim 10^{-9}$, too much.**
Secondary creation of $\bar{He}^4$ is negligibly weak.
Nevertheless Ting expressed hope to observe $\bar{S}i$!!!
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 $\bar{\boldsymbol{p}}\,\boldsymbol{p}$ или $\bar{\boldsymbol{p}}\,\boldsymbol{He}$ (Duperray et al, 2005). which would produce the flux of $\bar{D}$ $\sim 10^{-7}/\boldsymbol{m}^2/\boldsymbol{s}^{-1}/$**steradian/GeV/neutron)** ,

i.e. 5 orders of magnitude below the observed flux of antiprotons.

The fluxes of $^3\bar{\boldsymbol{H}}\boldsymbol{e}$ and $^4\bar{\boldsymbol{H}}\boldsymbol{e}$, 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 anti-nuclei 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

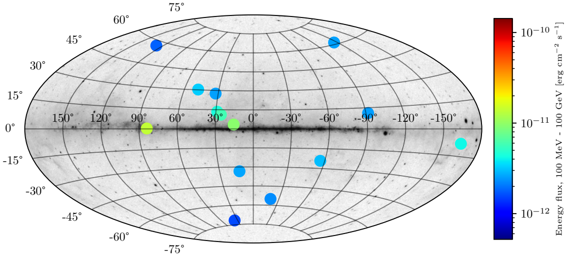


Figure: Positions and energy flux in the 100 MeV - 100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the Fermi 5-year all-sky photon counts above 1 GeV

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 antkimetter

From cosmic gamma rays:

Nearest anti-galaxy could not be closer than at $\sim$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 (discussed below).

Antimatter in cosmology

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 in the Galaxy and in its halo:

A. Dolgov and J.Silk, PRD 47 (1993) 4244 "Baryon isocurvature fluctuations at small scale and baryonic dark matter.

A.Dolgov, M. Kawasaki, N. Kevlishvili, Nucl.Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, **cosmic antimatter,** and dark matter".

Bounds on the density of galactic antistars are rather loose, because the annihilation proceeds only on the surface of antistars 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., K.A.Postnov, **"Antimatter and antistars in the universe and in the Galaxy",** Phys.Rev.D 92 (2015) 023516 • 1409.5736.

Antistar prediction

The mechanism AD-JS and AD-MK-NK 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:

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

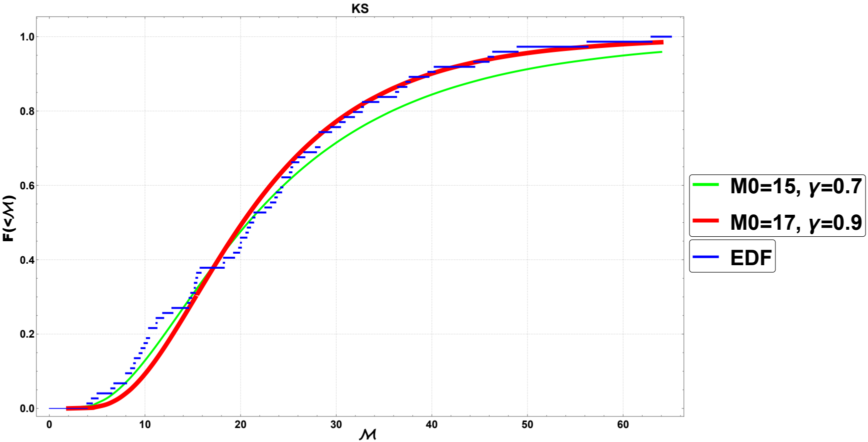
and predicts $M_0 \approx 10 M_\odot$. A.Dolgov, K.Postnov, "Why the mean mass of primordial black hole distribution is close to $10 M_\odot$". JCAP 07 (2020) 063 e-Print: 2004.11669 . In excellent agreement with observations.
The log-normal form of the mass spectrum of primordial black holes is strongly 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 distribution

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

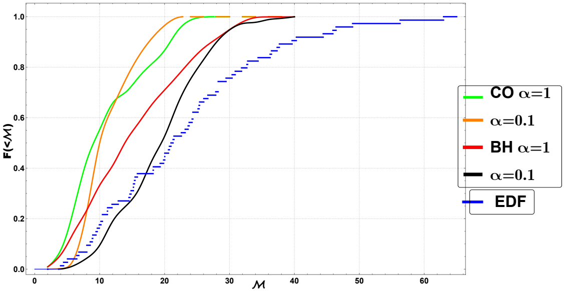
Chirp mass distribution

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.

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 multipie 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.

Dark antimatter

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
- Strange stars with unusual chemistry and velocity 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.

MORE DATA WILL PROBABLY COME SOON

APPENDIX. Antimatter in cosmology

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

1. Non-conservation of baryonic number.
2. **Explicit C and CP violation.**
3. Deviation from thermal equilibrium.

Allows to explain the observed baryon baryon asymmetry

$$\beta = \frac{\boldsymbol{N_B}}{\boldsymbol{N_\gamma}} = 6 \times 10^{-9}$$

where $N_\gamma = 411/\mathrm{cm}^3$ - 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.

Antimatter in cosmology

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). Double well potential:

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

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. $l_B \gtrsim$ **Gpc** (A. Cohen, A. De Rujula, and Sh. Glashow, 1996).

Domain wall problem.

Antimatter in cosmology

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,

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

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.

Anti-Creation Mechanism

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 (AD and Silk; AD, Kawasaki, Kevlishvili):

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

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.

Anti-Creation Mechanism

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 baryonic density objects occupying a minor fraction of the universe volume.

Evolution of AD-field

- $\varrho_\chi \ll \varrho_\Phi$, 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 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.