PRIMORDIAL ANTIMATTER IN THE CONTEMPORARY UNIVERSE

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Abstract

In some baryogenesis scenarios, the universe acquires a non-vanishing average baryonic charge, but the baryon to photon ratio is not spatially constant and can be even negative in some space regions. This allows for existence of lumps of antimatter in our neighborhood and the possibility that very compact antimatter objects make a part of cosmological dark matter. Here I discuss the peculiar signatures which may be observed in a near future.

One can conclude from simple considerations that there is much more matter than antimatter around us [1]. However, the origin of matter–antimatter asymmetry in the universe is unknown: the Standard Model of particle physics is certainly unable to explain it and new physics is necessary [2]. Assuming a homogeneous and isotropic universe, from the Big Bang Nucleosynthesis
one can determine the baryon to photon ratio \( \beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10} \) (1)

where \( n_B \gg n_{\bar{B}} \). On the other hand, the freeze-out abundances in a homogeneous baryo-symmetric universe would be \( n_B/n_\gamma = n_{\bar{B}}/n_\gamma \sim 10^{-18} \) [5].

However, Eq. (1) may not be the end of the story. One can indeed distinguish three main types of cosmological matter–antimatter asymmetry:

1. **Homogeneous matter dominated universe.** Here \( \beta \) is constant and the universe is 100% matter dominated. This is certainly the most studied case (see e.g. Refs. [6, 7]) but it is not very interesting for astrophysical observations, because there is only one observable quantity, \( \beta \), which cannot contain much information on high energy physics.

2. **Globally B-symmetric universe.** Such a possibility appears quite reasonable and “democratic”: the universe would consist of equal amount of similar domains of matter and antimatter. However, it seems observationally excluded or, to be more precise, the size of the domain where we live should be at least comparable to the present day cosmological horizon [8]. So, even in this case observations cannot determine nothing but \( \beta \).

3. **Inhomogeneous matter dominated universe.** In this case the universe has a non-vanishing baryonic charge, but \( \beta \) is not spatially constant and can even be negative in some space regions. Lumps of antimatter can be scattered throughout the universe.

Here I will discuss possible observational signatures of the third case: even if at first glance such a picture may appear strange, just because we are used to think about ordinary matter around us, there are no theoretical and experimental reasons to reject it. At present, the source of CP violation responsible for the observed B-asymmetry in the universe is unknown, so generation of lumps of antimatter is not so exotic as one may naively think. Moreover, compact antimatter objects can easily survive in a matter dominated universe up to the present days. The talk is based on a work made in collaboration with Alexander Dolgov [9]. The reference baryogenesis mechanism is the one in [10]. The phenomenology of other scenarios can be found in Refs. [11] [12].

1 **Baryogenesis framework**

Let us now briefly review the baryogenesis framework suggested in Ref. [10]. The basic ingredient is the Affleck-Dine mechanism [13], where a scalar field
\( \chi \) with non-zero baryonic charges have the potential with flat directions, that is directions along which the potential energy does not change. Due to the infrared instability of light fields in de Sitter spacetime [14], during inflation \( \chi \) can condense along the flat directions of the potential, acquiring a large expectation value. In the course of the cosmological expansion, the Hubble parameter drops down and, when the mass of the field exceeds the universe expansion rate, \( \chi \) evolves to the equilibrium point and the baryonic charge stored in the condensate is transformed into quarks by \( B \)-conserving processes. Since here CP is violated stochastically by a chaotic phase of the field \( \chi \), then during the motion to the equilibrium state the matter and antimatter domains in a globally symmetric universe would be created. An interesting feature of the model is that regions with a very high \( \beta \), even close to one, could be formed.

If the scalar field \( \chi \) is coupled to the inflaton \( \Phi \) with an interaction term of the kind \( V(\chi, \Phi) = \lambda |\chi|^2 (\Phi - \Phi_1)^2 \), the “gates” to the flat directions might be open only for a short time when the inflaton field \( \Phi \) was close to \( \Phi_1 \). In this case, the probability of the penetration to the flat directions is small and \( \chi \) could acquire a large expectation value only in a tiny fraction of space. The universe would have a homogeneous background of baryon asymmetry \( \beta \sim 6 \cdot 10^{-10} \) generated by the same field \( \chi \), which did not penetrate to larger distance through the narrow gate, or by another mechanism of baryogenesis, while the high density matter, \( \beta > 0 \), and antimatter, \( \beta < 0 \), regions would be rare, although their contribution to the cosmological mass density might be significant or even dominant. In the simple model of Ref. [10], such high density bubbles could form clouds of matter or antimatter and more compact object like stars, anti-stars or primordial black holes. In the non-collapsed regions, primordial nucleosynthesis proceeded with large \( |\beta| \), producing nuclei heavier than those formed in the standard BBN [15].

2 Phenomenology

In what follows I will not dwell on possible scenarios of antimatter creation, but simply consider phenomenological consequences of their existence in the present day universe, in particular in the Galaxy. Some considerations on the cosmological evolution of lumps of antimatter in a baryon dominated universe can be found in Refs. [9, 12].

2.1 Indirect detection

The presence of anti-objects in the Galaxy today should lead to the production of the gamma radiation from matter–antimatter annihilation. Hence we would expect \( \sim 100 \text{ MeV} \gamma \) from the decay of \( \pi^0 \) mesons produced in \( pp \) annihilation, with an average of 4 \( \gamma \) per annihilation, and 2 \( \gamma \) from \( e^+e^- \) annihilation with \( E = 0.511 \text{ MeV} \), if \( e^+e^- \) annihilate at rest. In addition to the slow background
positrons, there should be also energetic secondary positrons produced by pion decays from $p\bar{p}$ annihilation. Astronomical observations are seemingly more sensitive to $p\bar{p}$ annihilation because the total energy release in $p\bar{p}$ annihilation is 3 orders of magnitude larger than that in $e^+e^-$ annihilation and the galactic gamma ray background at 100 MeV is several orders of magnitude lower than the one at 0.5 MeV. On the other hand, $e^+e^-$ annihilation gives the well defined line which is easy to identify.

For compact anti-objects like anti-stars, one find that the size of the anti-object, $R$, is much larger than the proton or electron mean free path inside the anti-object, $\lambda_{free} \sim 1/(\sigma_{ann} n_{\bar{p}})$, where $\sigma_{ann}$ is the annihilation cross section for $p\bar{p}$ or $e^+e^-$ (they have similar order of magnitude) and $n_{\bar{p}}$ is the antiproton number density in the anti-object. In this case, the annihilation takes place on the surface, all the protons and electrons that hit the surface of the anti-object annihilate and the annihilation cross section is given by the geometrical area of the anti-object, that is $\sigma = 4\pi R^2$. The gamma ray luminosity of such a compact anti-object is

$$L_\gamma \approx 10^{27} \left( \frac{R}{R_\odot} \right)^2 \left( \frac{n_{\bar{p}}}{\text{cm}^{-3}} \right) \left( \frac{v}{10^3} \right) \text{erg/s},$$

where $R_\odot \sim 7 \cdot 10^{10}$ cm is the Solar radius and $n_{\bar{p}}v$ is the proton flux. With this luminosity, a solar mass anti-star would have the life time of the order of $10^{27}$ s (considering only matter–antimatter annihilation), if all the factors in Eq. (2) are of order unity. For an anti-star in the galactic disc, the $\gamma$ flux observable on the Earth would be

$$\phi_{Earth} \sim 10^{-7} \left( \frac{R}{R_\odot} \right)^2 \left( \frac{1 \text{pc}}{d} \right)^2 \text{cm}^{-2} \text{s}^{-1},$$

where $d$ is the distance of the anti-star from the Earth. Such a flux should be compared with the point source sensitivity of EGRET [16], at the level of $10^{-7}$ photons cm$^{-2}$ s$^{-1}$ for $E_\gamma > 100$ MeV, and of the near-future GLAST [17], which should be about two order of magnitude better, i.e. $\sim 10^{-9}$ photons cm$^{-2}$ s$^{-1}$. So, anti-stars should be quite close to us in order to be detectable point-like sources and their observation would result difficult if they were very compact objects, as e.g. anti-neutron stars. On the other hand, if such an anti-star lived in the galactic center, where $n_{\bar{p}} \gg 1/\text{cm}^3$, its luminosity would be larger. Anomalously bright lines of 0.5 MeV are observed recently in the galactic center [18], galactic bulge [19] and possibly even in the halo [20]. Though an excess of slow positrons is explained in a conventional way as a result of their creation by light dark matter particles, such a suggestion is rather unnatural, because it requires a fine-tuning of the mass of the dark matter particle and the electron mass. More natural explanation is the origin of these positrons from primordial antimatter objects.
The existence of primordial antimatter in the Galaxy would increase the galactic diffuse gamma ray background as well. Standard theoretical predictions and observational data agree on a galactic production rate of $\gamma$ in the energy range $E_\gamma > 100$ MeV \cite{9}

$$\Gamma_\gamma^{\text{tot}} \sim 10^{43} \text{ s}^{-1}.$$ (4)

Requiring that annihilation processes on anti-stars surface cannot produce more than 10\% of the standard galactic production rate \cite{11}, we obtain the following bound on the present number of anti-stars

$$N_{\bar{S}} \lesssim 10^{12} \left( \frac{R_\odot}{R} \right)^2,$$ (5)

where, for simplicity, we assumed that all the anti-stars have the same radius $R$. However the constraint is not very strong: for solar type anti-stars, their number cannot exceed the one of ordinary stars!

Let us now consider the annihilation of antimatter from the anti-stellar wind with protons in the interstellar medium. Since the number of antiprotons reached a stationary value, the production rate of 100 MeV $\gamma$ in the Galaxy has to be proportional to $N_{\bar{S}}$. The luminosity of the Galaxy in 100 MeV $\gamma$ rays from anti-stellar wind would be $L_{\bar{S}} \sim 10^{44} W N_{\bar{S}}/N_S$ erg/s, where $W$ is the anti-stellar wind to solar wind flux ratio. Since from Eq. (4) we find that the total Galaxy luminosity in 100 MeV $\gamma$ is $L_{\gamma}^{\text{tot}} \sim 10^{39}$ erg/s, the related bound on the anti-star to star number ratio is $N_{\bar{S}}/N_S \lesssim 10^{-6} W^{-1}$, always assuming that the contribution from new physics cannot exceed 10\% of $L_{\gamma}^{\text{tot}}$. A similar restriction can also be obtained from the 0.511 MeV line created by $e^+e^-$ annihilation with positrons from the anti-stellar wind.

On the other hand, if anti-stars were formed in the very early universe in the regions with a high antimatter density \cite{10}, such primordial stars would most probably be compact ones, like white dwarfs or neutron stars. The stellar wind in this case would be much smaller that the solar one, $W \ll 1$. Their luminosity from the annihilation on the surface should be very low, because of their small radius $R$, and their number in the Galaxy may be even larger than the number of the usual stars. This possibility is not excluded by the previous bounds. Such compact dark stars could make a noticeable part of the cosmological dark matter.

### 2.2 Direct detection

It is common belief that the abundances of most elements in the cosmic rays reflect relative abundances in the Galaxy. Hence, as the simplest working hypothesis we can assume that the antimatter–matter ratio in cosmic rays is more or less equal to the anti-star–star ratio $N_{\bar{S}}/N_S$, at least if the anti-stars are of the same kind as the stars in the Galaxy.
As for antiprotons and positrons, they cannot be direct indicators for the existence of primordial antimatter, because they can be produced in many astrophysical processes. For example, the observed $\bar{p}/p$ ratio is at the level of $10^{-4}$ and is compatible with theoretical predictions for $\bar{p}$ production by the high energy cosmic ray collisions with the interstellar medium. A possible contribution of $\bar{p}$ from primordial lumps of antimatter is not more than about 10% of the total observed $\bar{p}$ flux, so $N_S/N_S \lesssim 10^{-5}$ and the number of anti-stars $N_S$ has to be no more than $10^6$, since the number of ordinary stars in the Galaxy is $N_S \sim 10^{11}$.

On the other hand, the possibility of producing heavier anti-nuclei (such as anti-helium) in cosmic ray collisions is completely negligible and a possible future detection of the latter would be a clear signature of antimatter objects. At present there exists an upper limit on the anti-helium to helium ratio in cosmic rays, at the level of $10^{-6}$ [21], leading to the constraint $N_S \lesssim 10^5$. Such an upper limit can probably be lowered by 2 or 3 orders of magnitude in a near future, thanks to AMS [22] and PAMELA [23] space missions. I would like to stress that here we are not assuming that these possible anti-helium nuclei were produced by nuclear fusion inside anti-stars, but that original anti-helium abundance inside anti-stars is roughly equal to the helium abundance inside ordinary stars. This is certainly a conservative picture, since anti-stars were formed in high density regions of the early universe, where the primordial nucleosynthesis produced much more anti-helium and heavier anti-nuclei [15]. On the other hand, if anti-stars were compact ones from the very beginning, the stellar wind from them and the shortage of anti-supernova events would spread much less anti-helium than the normal stars.

2.3 More exotic events

The presence of anti-stars in the Galaxy could lead to extraordinary events of star–anti-star annihilation. As a matter of fact, the radiation pressure produced in the collision prevents their total destruction. Still the released energy can be huge.

The most spectacular phenomenon is a collision between a star and an anti-star with similar masses $M$. A simple estimate of the amount of the annihilated matter in such a collision is $m_{\text{ann}} \sim Mv^2$ [9], where $v$ is the typical value of the relative velocity and is about $10^{-3}$. The total energy release would be $E \sim 10^{48}\text{erg}(M/M_\odot)(v/10^{-3})^2$. Most probably the radiation would be emitted in a narrow disk along the boundary of the colliding stars. The collision time is $t_{\text{coll}} \sim R$ and for the solar type star this time is about 3 s. The energy of the radiation should be noticeably smaller than 100 MeV, because the radiation should degrade in the process of forcing the star bounce. This makes this collision similar to gamma bursts, but unfortunately some other features do not fit so well: the released energy should be much larger, about
\(10^{53} \sqrt{\tau} \) erg and it is difficult to explain the features of the afterglow.

3 Conclusion

Unfortunately there are no true conclusions because we are unable to make clear predictions. However this is the problem of all the baryogenesis models: the physics responsible for the matter–antimatter asymmetry in the universe is unknown and common approaches are based on the construction and investigation of toy-models which contain free parameters that we can only partially constrain with the observed asymmetry. Moreover, most baryogenesis scenarios are based on physics at very high energy, which will be hardly tested in a near future by man-made colliders. On the other hand, if we are lucky and able to get evidences of the existence of primordial antimatter object, the latter will tell us much interesting information on high energy physics (CP violation, B violation, etc.) and, maybe, even on cosmological open questions such as the nature of dark matter.

Gamma rays from \( p\bar{p} \) annihilation may be observable with future or even with existing \( \gamma \)-telescopes. Quite promising for discovery of cosmic antimatter are point-like sources of gamma radiation; the problem is to identify a source which is suspicious to consist of antimatter. The 100 MeV gamma ray background does not have pronounced features which would unambiguously tell that the photons came from the annihilation of antimatter. The photons produced as a result of \( p\bar{p} \) annihilation would have a well known spectrum but it may be difficult to establish a small variation of the conventional spectrum due to such photons. In contrast, the 0.511 MeV line must originate from \( e^+e^- \) annihilation and it is tempting to conclude that the observed excessive signal from the Galaxy and, especially, from the galactic bulge comes from astronomical antimatter objects. If an anti-star happens to be in the galactic center, its luminosity from the surface annihilation of the background matter should be strongly enhanced due to the much larger density of the interstellar matter there. So the search of the antimatter signatures in the direction of the center is quite promising. There is also a non-negligible chance to detect cosmic anti-nuclei and not only light anti-helium but also much heavier ones, especially if anti-stars became early supernovae.

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