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Antimatter in the Universe

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Cosmological models which predict a large amount of antimatter in the Universe are reviewed. Observational signatures and searches for cosmic antimatter are briefly considered. A short discussion of new long range forces which might be associated with matter and antimatter is presented.

1. Introduction

The world in our neighbourhood, as we observe it, is 100% charge asymmetric. We see only matter and any considerable amount of antimatter nearby is excluded [1,2]. A small number of antiprotons and positrons in the cosmic rays (to say nothing of those produced in accelerators) can be prescribed to the secondary origin. Charge asymmetry in terms of *visible* massive matter defined as $\beta_B = (n_B - n_{\bar{B}})/(n_B + n_{\bar{B}})$ is close to one. Here n_B and $n_{\bar{B}}$ are the number density of baryons and antibaryons respectively. However, the cosmologically more natural quantity

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 3 \times 10^{-10} \tag{1}$$

is surprisingly small. Here $n_\gamma \approx 400/\mathrm{cm}^3$ is the number density of photons in electromagnetic background radiation with temperature $T = 2.7\,\mathrm{K}$. The smallness of β implies that β_B was also small and of the same order of magnitude as β at an early stage of the Universe evolution when the temperature was about or above the proton mass and antibaryons were abundantly produced in the primeval plasma. (To be more exact the characteristic temperature is that of the QCD phase transition, $T_{QCD} \approx 100\,\mathrm{MeV}$, when free quarks are confined to hadrons.)

At the present day we are able to directly observe only a minor fraction (of order of a few per cent) of the total mass of the Universe. Nothing is known about the physical nature of the dark matter and, in particular, if it is charge asymmetric or not. If the dark matter consists of massive ($m = O(10\ \mathrm{eV})$) neutrinos then most naturally the neutrino asymmetry $\beta_\nu = (n_\nu - n_{\bar{\nu}})/(n_\nu + n_{\bar{\nu}})$ is tiny, $\beta_\nu = 10^{-9}$–10^{-10}, though $\beta_\nu = O(1)$ is not excluded. Astronomical data disfavor very much the neutrino dark matter hypothesis and other candidates are being looked for. If the latter is a neutral particle (like Majorana type neutralino in supersymmetric models or axion), the charge asymmetry in the dark matter sector is zero by definition. In other cases nothing is known about charge asymmetry of dark matter.

Here I will address the following questions:

(1) Why is there a charge asymmetry in the Universe?

(2) Why is it so small?

(3) May the Universe be charge asymmetric locally an charge symmetric globally?

(4) What would be the size of domains with a definite sign of the charge asymmetry?

(5) What are the possibilities of observation of antimatter?

(6) Can there be any difference in gravitational interactions of matter and antimatter and can there be new long range forces different for matter and antimatter?

This paper is not intended to be a review on cosmology though a knowledge of some cosmological material is desirable. It would be hard to give all the appropriate references here and a reader can find them as well as necessary detail in numerous review papers and textbooks. (see e.g. refs. [4–6]).

2. Baryogenesis

The origin of the baryon asymmetry, i.e. charge asymmetry in baryonic sector, was understood after the paper by Sakharov [3], where three basic principles of baryogenesis were formulated. They are:

(1) Breaking of charge (C) and combined charge–parity (CP) invariance.

(2) Deviation from thermal equilibrium in the primeval plasma.

(3) Baryonic charge (B) nonconservation.

It was known that under these conditions a charge (baryonic) asymmetry is developed from practically arbitrary initial state.

These three principles stay on rather different footing. Thermal nonequilibrium is induced by the nonadiabaticity created by the Universe expansion. This is true for massive particles but usually is rather small if some special conditions are not realized. The breaking of C and CP is well established experimentally but not well understood theoretically, and not much is known about charge asymmetry breaking at high energies at which baryonic charge is presumably nonconserved. A nonconservation of the latter was not observed in direct experiments despite hard attempts to discover the proton decay. Theoretically it looks at least very natural, not to say strictly proven. First, the models of grand unification which put quarks and leptons into the same particle multiplet (like SU(5) [7]) predict transition between quarks and leptons with corresponding nonconservation of baryonic and leptonic charges. The characteristic energy scale of such processes is huge,

$m_{GUT} = 10^{15}$–10^{16} GeV, so in these models baryogenesis took place at very high temperatures very close to the initial singular state of the Universe.

A more interesting possibility is the baryonic charge nonconservation in the standard electroweak SU(2)×U(1) theory [8]. This phenomenon is really striking because the classical Lagrangian conserves baryonic charge and the nonconservation arises as a result of quantum corrections and proceeds as some kind of quantum tunnelling process. It opens the possibility of baryogenesis in the standard model, though the resulting size of the asymmetry is very small [9] (see, however, review paper [6]).

Thus baryonic charge nonconservation is predicted theoretically though we still lack experimental confirmation. The only evidence in favor of B-nonconservation is given by cosmology. This is not only the baryon asymmetry itself but also an impossibility to realize inflationary universe scenario if B is conserved. Since at the present time inflation gives the only way to create the observed Universe and in that sense can be considered as an experimental fact, one may think that baryon nonconservation is also proven experimentally. Though it is possible to invent some counterexamples to this statement (see review paper [6]), they seem to be much more exotic than baryon nonconservation.

The majority of baryogenesis scenarios give a very low value of β and special efforts are taken to get the observed value (1). The reasons for getting a small β are the following. First, even if the CP-violating amplitudes are not suppressed with respect to CP-even ones still their observational manifestations are rather weak and arise only in a high order in a small coupling constant because CP-violation becomes observable only through interference effects with CP-conserving processes. Second, the deviation from thermal equilibrium in the early Universe is typically small because the expansion is mostly slow in comparison with the characteristic reaction rates. And last, but not least, there is a danger of a large entropy generation after baryogenesis (by the first order phase transition or by heavy particle annihilation) which can considerably dilute a previously generated charge asymmetry. There is only one example known to me [10] when the calculated value of the baryon asymmetry happened to be (much) larger than the observed value (1) and one had to invent a way to dilute it by the entropy production in the course of the expansion and cooling down of the Universe.

In short the model of ref. [10] is the following. It is assumed that there exists a scalar field χ with a nonzero baryonic charge. Such fields naturally appear in supersymmetric theories. They are scalar superpartners of quarks. During inflationary stage all the matter fields, except for scalar ones, exponentially die out, while scalar fields are even amplified due to rising quantum fluctuation if their mass is smaller than the Hubble parameter, $m_\chi < H_I$ [11]. If this is true for χ one would expect that a condensate of baryonic charge (stored in χ) should be developed during inflation with a large (generically of the order of H_I^3) baryonic charge density. When inflation is over and χ relaxes to the equilibrium state, its coherent oscillations produce an excess of quarks over antiquarks or vice versa depending upon the initial sign of the baryonic charge condensate. The latter is generated stochastically and is zero if averaged over a large volume. In this model the Universe is charge symmetric as a whole, while it might have a significant charge asymmetry locally. Note that this scenario is effective even without CP-violation in the Lagrangian. In a more traditional approach the similar Universe structure appears in the models with spontaneous CP-violation [12].

3. CP-violation and a charge asymmetry of the Universe

If the symmetry between particles and antiparticles is broken explicitly in the Lagrangian, the charge asymmetry should have the same sign all over the Universe. There might be, however, counterexamples to this statement: as was argued in ref. [13] in some models the sign of the asymmetry may be different depending upon the rate of cooling. So if the cooling was not homogeneous there could be domain of matter and antimatter in the Universe even if CP is broken explicitly. The effect is much more profound, however, in the models with spontaneous symmetry breaking. In this case there should be an equal amount of matter and antimatter in the Universe.

Spontaneous symmetry breaking means that the Lagrangian is invariant with respect to the symmetry transformation while the vacuum state is not. Still the symmetry manifests itself by the presence of several (or infinitely many) degenerate vacuum states related by the symmetry transformations.

Spontaneous CP-violation can be realized in the model with a complex scalar field ϕ having the potential

$$U(\phi) = -m^2|\phi|^2 + \lambda_1|\phi|^4 + \lambda_2(\phi^4 + \phi^{*4}) + g^2T^2|\phi|^2. \tag{2}$$

The last, temperature dependent term comes from the interaction with particle in the thermal bath, g being the coupling constant of the interaction. One sees that at high temperatures the potential has the only minimum at $\phi = 0$ and CP is unbroken over this minimum. With decreasing temperature two new minima arise while that at $\phi = 0$ turns into maximum. The field ϕ should evolve down to one of those two minima where it would have a nonzero vacuum expectation value. A nonzero complex field condensate results in the breaking of charge invariance. In particular through Yukawa coupling to fermions it gives them complex masses which are equivalent to complex angles in the Kobayashi–Maskawa matrix and correspondingly to CP-violation.

It is evident that the relaxation of ϕ to the minimum of the potential would proceed with equal probability to the complex conjugate states and so both signs of the CP-odd amplitude are equally probable. In this model we would expect domain of matter and antimatter equally probably in the Universe [14].

Two problems arise in this case. First, the size of the domains should be very small in the standard Friedman cosmology. Indeed the characteristic size of the domains at the moment of their formation should be smaller than the horizon at this moment, $l \leqslant t_i$. After that, if it expanded as the scale factor, it grew to the present time as $(T_i/2.7\text{ K})$, where T_i is the temperature at the moment of the formation and 2.7 K is the temperature of the cosmic microwave radiation now. T_i should be larger than 1 GeV since there is no baryon nonconservation at this small temperature. Since $t \approx m_{\text{Pl}}/T^2$ (where $m_{\text{Pl}} = 1.22 \times 10^{19}$ GeV is the Planck mass) the present-day size of the domains, l_B, is definitely smaller than 10 light years. To be more precise, the domain walls could move with the speed close to that of light, but since this motion is chaotic, the average increase of their size does not differ much from the above given estimate. This problem can be solved if there existed a period of exponential expansion (inflation) $a(t) \sim \exp(Ht)$ which could inflate the domains up to arbitrary large sizes [15]. As a result the domain sizes would be exponentially poorly known. They can be larger than the present-day horizon and so we effectively return to the charge symmetric Universe as in the models with explicit CP-violation. The size of the domains might be much smaller than that and so we live in the Universe with equal amount of matter and antimatter inside the present-day horizon. Of course the domain size cannot be too small, otherwise the bright results of $p\bar{p}$-annihilation would be observed. The absence of antiprotons in cosmic ray implies the bound $l_B > 10$ Mpc.

Another problem connected with this model is the existence of domain walls separating different vacua. Usually they have a large mass and produce unacceptable density perturbations [16]. For the solution of the latter a low temperature inverse phase transition is necessary. Note that the domain wall problem does not appear in the model of baryogenesis with baryonic charge condensate discussed above.

Thus we see that there is a solid theoretical framework permitting to expect that the Universe contains an equal amount of matter and antimatter. In the case of the domain size being smaller than the horizon we may hope to observe antimatter in the Universe.

4. More exotic models with abundant antimatter in the Universe

The period of the exponential expansion of the Universe together with the CP-violation induced by a scalar field condensate may result in a particular pattern of matter–antimatter distribution in the Universe. To start with we consider a model which gives rise to a strictly periodic distribution of baryons with possible alternation of baryonic and antibaryonic layers [17]. Although it looks very much exotic, the scenario can be realized with a few very natural assumptions: first, the existence of a complex scalar field ϕ with the mass which is smaller than the Hubble parameter at the inflationary stage, $m_\phi < H_I$. Second, nonharmonic terms should be present in the potential of ϕ like e.g. $\lambda|\phi|^4$. Third, a condensate of ϕ should be developed during inflation which is not spatially constant but a slowly varying function of space, $\phi(r)$. The first two assumptions are perfectly natural, while the third one, though natural too, deserves some explanatory remarks. A scalar field condensate is generically formed in the de Sitter background due to rising quantum fluctuations of ϕ [11] which produce a spatially nonuniform but effectively classical field $\phi(r)$. Another possibility to get $\phi(r)$ is a first order phase transition as result of which a bubble of ϕ is formed described by a function $\phi(r)$. The concrete form of this function depends on the details of the phase transition but, what is certain, their shape is not constant in space. Once the bubble is formed it may remain frozen till inflation goes on and only when it is over the field ϕ starts to oscillate around the minimum of the potential. If the baryogenesis proceeds prior to the complete relaxation of ϕ, the space distribution of the baryons in this model should be periodic. Indeed the size of the baryon asymmetry is proportional to the amplitude of CP-violation and the latter is given by the complex field ϕ. Initially ϕ was a very slowly varying function of r, but in the course of the evolution when ϕ quickly oscillates at each space point as a function of time, a large wave periodic distribution in space would be developed. The latter is induced by nonharmonic terms in the potential because the period of oscillations in time depends upon the initial amplitude. Such model naturally explains periodic distribution of the visible matter observed in the recent pencil beam measurements [18]. The distance between the layers of matter is about 100 Mpc and five layers were observed both in the direction to the North and South galactic poles. If ϕ oscillates around zero (though it is not obligatory) the baryonic layers should alternate with antibaryonic ones separated by regions with a smaller matter density.

Another model [19] of abundant generation of antimatter in the Universe was stimulated by an attempt to save the hypothesis of baryonic dark matter. It is known that the bulk of matter in the Universe (from 90 to 99%) is invisible and is observed only by its gravitational action. What's more, the invisible (or dark matter) is most probably nonbaryonic. There are several pieces of data in favor of these statements. The velocity of gas around galaxies does not decrease with the distance from the luminous center but tends to a constant value (of the order of few hundred km/s). The observations have been done up to distances almost an order of magnitude larger than the size of galaxies. Such so-called flat rotational curves indicate that the mass is not concentrated in the luminous central part but increases proportionally to the distance from the center. The fraction of the invisible mass is different for different galaxies but typically it is an order of magnitude larger than the visible part. It is not easy to conceal all this matter if it is of the usual baryonic staff. The option which is not excluded is that the dark matter consists of large planets ("Jupiters"), or dead stars, or black holes though the mechanism of their production is not clear. There are, however, strong arguments against the hypothesis that all the dark matter is baryonic. They are based on the theory of large scale Universe structure formation and primordial nucleosynthesis. Large scale Universe structure was formed from initially small perturbations in the matter/energy density due to gravitational instability. The growth of the perturbations in the baryonic matter could only start rather late when the temperature dropped below that of the hydrogen recombination, $T \approx 4000$ K. Above that temperature the light pressure prevents electrically charged massive matter from gravitational clumping. In the course of the expansion the inhomogeneities could rise at most by the factor $z_{rec} = T_{rec}/T_{now} \approx 1.5 \times 10^3$, where T_{now} is the present-day temperature of the background radiation. The initial (at $T = T_{rec}$) density inhomogeneities are imprinted on the angular fluctuations of the background radiation temperature. The quantity $\Delta T/T$ remains unchanged after the recombination in the standard cosmological scenario and is known from many observations at different angular scales to be very small, $\Delta T/T \leqslant 10^{-5}$. Until recently, there were only upper bounds on $\Delta T/T$ and the first positive indication for the nonzero value of it was presented only a few months ago by COBE [20]. In view of that it is very hard (if possible) to get developed density perturbations from the time of the recombination to the present epoch. The existence of the dark (noninteracting with light) matter makes things easier, since the perturbations in the latter may start earlier (before the recombination) when the Universe became dominated by nonrelativistic (dark) matter.

Another argument against baryonic dark matter is based on a good agreement of the calculated abundances of light elements, created when the Universe was only several minutes old, with observations (for a recent review on the subject see, e.g., ref. [21]). One of the parameters which determine the production of light elements is the ratio of baryon-to-photon number densities $\beta = n_B/n_\gamma$. Its value inferred from the data on the light nuclei abundances is very close to that obtained by the direct observation of the visible matter. There is some discrepancy (like the factor of two) between these two values indicating that some dark matter might be baryonic. Still the bulk of dark matter is most probably nonbaryonic. It is convenient to characterize the density of matter in the Universe ρ by the parameter $\Omega = \rho/\rho_c$, where ρ_c is the closure of critical energy density given by the expression

$$\rho_c = 3H^2/8\pi G \approx 2 \times 10^{-29}\ \text{g/cm}^3\ (H/100\ \text{km/s/Mpc})^2, \tag{3}$$

where G is the Newton gravitational constant and H is the present-day value of the Hubble parameter. The latter is known with a rather bad accuracy, $H = 50$–100 km/s/Mpc. For the visible baryonic matter $\Omega_B^{vis} \approx 10^{-2}$, which is close to that obtained from the observed abundances of light elements (maybe a factor 2–3 smaller). Analysis of the rotational curves gives $\Omega_{DM}^{clustered} \approx 0.2$–$0.3$. This number refers to the matter clustered around galaxies since the data are not sensitive to the uniformly distributed matter. With the latter included Ω can be as large as 1 which is strongly favored by the inflationary scenario. Since this scenario presents the only now known way to resolve long-standing cosmological problems, inflation can be considered as an experimental fact and we have to conclude that 95–99% of matter in the Universe is made of some unknown stuff.

At the first glance, the most natural candidate for the latter is the massive neutrino with $m = O(10\ \text{eV})$. This particle is known to exist and we do not see any reason why it should be massless. Unfortunately, the Universe structure in the model with massive neutrinos differs very much from what is observed. The next possibility is the lightest supersymmetric particle which most probably should be stable. These particles have the generic name neutralinos and should be rather heavy, above a few tens of GeV.

The observed picture supports the idea of two forms of dark matter, one being clustered around galaxies (with $\Omega = 0.2$–0.3) and another uniformly distributed all over the Universe (with $\Omega = 0.7$–0.8). This might mean that both light and heavy particles give a contribution into dark matter, though it might be as well that the uniformly distributed dark matter is the so-called cosmological term or, in other words, the vacuum energy.

One more particle which is theoretically predicted and might provide dark matter is the axion which ensures a natural CP-conservation in quantum chromodynamics. Though very light ($m_a \leqslant 10^{-5}$ eV), the axion by some funny reason behaves as heavy particles from the point of structure formation creating the so-called cold dark matter, the same type as the lightest SUSY particles.

Dark matter in the Universe should not necessarily be in the form of gas of elementary particles but can be made of stable macroscopical field configurations which maintain their stability by topological reasons. These are so-called topological solitons or topological defects which arise in theories with spontaneously broken symmetries. They include domain walls separating different degenerate vacuum states, cosmic vortices or strings, global monopoles, and three-dimensional textures. The latter are unstable but their lifetime is long enough to make them cosmologically interesting.

All these possibilities are certainly unusual (except for the neutrino which is almost for sure excluded) and demand a new physics beyond the standard model. Supersymmetric particles may be in the best shape since supersymmetry is a very appealing extension of the standard model. Still it is very interesting to pursue the possibility of dark matter being made of usual baryons (and as we shall see in what follows of antibaryons as well). This can be realised with a special model of baryogenesis which gives rise to relatively small bubbles of very high baryonic or antibaryonic number density with $|\beta| = O(1)$ in the homogeneous baryonic background with $\beta = 10^{-9}$–10^{-10} [19]. An interesting feature of this model is that it predicts an equal number of baryonic and antibaryonic bubbles, so the Universe is practically charge symmetric. At first sight such a picture strongly contradicts observations but, since the regions of high $|\beta|$ would mostly collapse into black holes, one can make the model compatible with the astronomical data. In the limiting (and noninteresting) case of 100% of these high density baryon bubbles forming black holes there would be no observational signatures characteristic to the model, except for the conclusion that dark matter consists of black holes with masses about two orders of magnitude around the Solar mass. A more exciting possibility is that some of those bubbles did not collapse, so that there are some "naked" compact objects made from antimatter in the Universe. Depending upon the relation between the

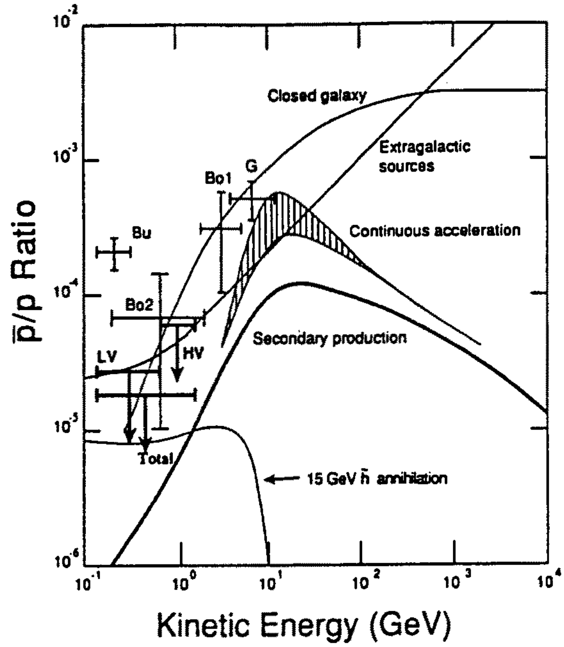

Fig. 1. Bounds on p̄/p-ratio from ref. [24]. These results are labeled LV, HV, and Total. Also presented are results of other experiments as well as theoretical predictions for different mechanisms of antiproton production.

Jeans wavelength and the horizon, at the moment when the latter is equal to the size of the bubble, the bubble could form either a star (antistar) or a disperse, though well localized cloud of high density baryons or antibaryons. They can be observed by fluxes of γ-rays from the annihilation on their boundaries, though it is hard to make a certain prediction of their intensity. An unambiguous proof of the existence of a large amount of antimatter would be an observation of antinuclei in cosmic rays. The secondary production of the latter is practically impossible. Another interesting phenomenon is a collision of a star with an antistar. It would produce a powerful burst of gamma-radiation. The isotropically distributed γ-bursts observed during a BATSE experiment of Gamma Ray Observatory are most probably explained by another mechanism, though no completely satisfactory model is known at the moment.

5. Search for cosmic antimatter

There are three possible ways to detect the cosmic antimatter by looking for antiprotons, antinuclei, and energetic ($\sim$ 100 MeV) gamma-quanta in cosmic rays. For the review of the possibilities of the detection see refs. [22,23]. There were some data indicating an excess of cosmic antiprotons over the theoretical expectations

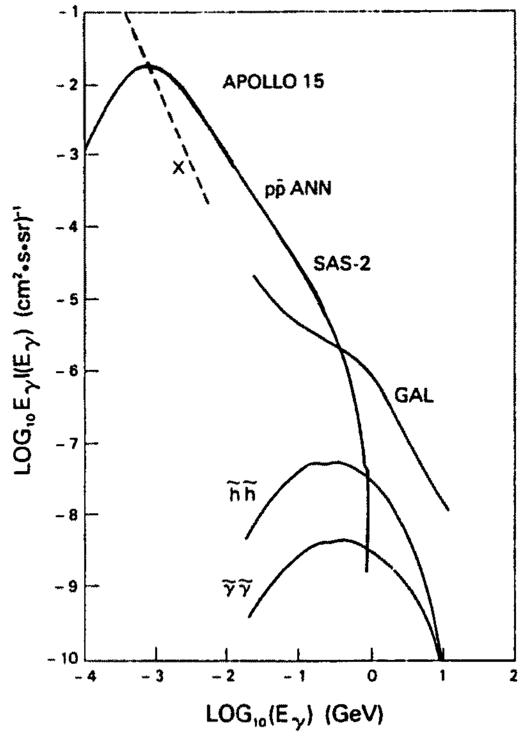

Fig. 2. The gamma-ray background spectrum from pp̄-annihilation as is calculated in ref. [25]. Also presented are the extrapolated X-ray background component (X), the galactic high latitude cosmic ray produced background, and spectra from 15 GeV photino and higgsino annihilation.

based on the assumption of their secondary production. Unfortunately, the most recent and most accurate experiment [24] does not confirm the previous data and gives only the upper bound 2×10^{-5} at 95% CL for the p̄/p-ratio. This bound does not contradict the expectation for the secondary produced p̄ in the standard model as well as to their production by cosmic neutralinos with $m > 20$ GeV. The data of ref. [24] together with the results of other experiments as well as the theoretical expectations for p̄/p-ratio are presented in fig. 1.

An observation even of a single antinucleus in cosmic rays would be a decisive evidence in favor of existence of a large amount of antimatter in the Universe, because the probability of their secondary production is negligible. No compelling evidence indicating the existence of antinuclei in the cosmic rays has been found though there are a few strange events which might be interpreted this way (see ref. [22]).

pp̄-annihilation into π^0's with the subsequent decay of the latter into 2γ may be observed in cosmic γ-rays at the Earth. In particular the antimatter annihilation might explain the observed isotropic cosmic γ-ray background. Though this explanation is rather speculative, there is no other known satisfactory mechanism and the origin of this background radiation remains weird. The flux of cosmic γ-rays from $p\bar{p}$-annihilation as well as from neutralino annihilation was calculated in ref. [25]. Its results are presented in fig. 2.

At the moment none of the observations can be considered as a confirmation of the existence of any considerable amount of antimatter in the Universe but they neither can reject the hypothesis. Evidently it can never be rejected since the observations can only put a lower limit on the distance to the antimatter-rich region. The flux of cosmic $\bar{p}$ shows that this distance is larger than 10 Mpc.

6. Gravitational interaction of antimatter and new long range forces

Long range forces are known to be created by massless particle exchange which can result in the potential $U(r) \sim 1/r$ and the force $U'(r) \sim 1/r^2$. An exchange of massive particles gives rise to the Yukawa type potential $U \sim \exp(-mr)/r$. There are only two known massless particles in nature: the photon and the graviton. The latter strictly speaking is not discovered experimentally but it is hard to believe that gravitons do not exist. Zero mass of photons is maintained by the gauge invariance of electromagnetism while that of gravitons is maintained by the general covariance. If not for that, quantum corrections should definitely give rise to nonvanishing masses even if they were zero at the classical level. Zero mass of both photon and graviton are experimentally established with a very good accuracy. (One may ask, how it is possible to put a bound on the graviton mass if it is not experimentally proven that the particle exists. The answer is that, if we assume that graviton exists, then the data shows that its mass should be very small or exactly zero.) A good agreement of the Newton law at the scale of the Solar system with astronomical data implies that the Compton wavelength of the graviton $\lambda_g \equiv m_g^{-1}$ is larger than the size of the Solar system and the recent observations of the gravitational lenses shows that $\lambda_g > 10$ Kpc. Analogously the observation of the Jupiter magnetic field means that $\lambda_\gamma > 10^4$ km while the existence of the galactic magnetic fields demands $\lambda_\gamma > 10$ Kpc.

A modification of gravitational interaction which breaks general covariance should generically result in nonzero m_g and so be theoretically disfavored. One can mimic a breaking of the equivalence principle by introduction of new long range forces and correspondingly new massless particles. Introduction of new massless tensor particles (that is those with spin 2) is not possible because there is only one conserved tensor quantity (energy–momentum tensor) which can be the source of such particles and this source is already occupied by gravitons.

Long range forces due to exchange of scalar particles are not theoretically supported. There is no symmetry which can maintain $m = 0$ in the scalar case. For this reason the Brans–Dicke modification of gravity would be effective only at a short distance. The dilation field associated with conformal symmetry should be massive because the symmetry is known to be badly broken. It is known that there should appear massless scalar bosons if a global symmetry is spontaneously broken (the so-called Goldstone bosons), but it can be shown that the coupling of these bosons to matter is of pseudoscalar form, like $\phi\bar{\psi}\gamma_5\psi$, so that their exchange gives rise to the force falling as $1/r^3$.

The only remaining possibility is vector particle exchange. One can invent a number of conserved vector currents (with the corresponding gauge symmetry) which might be sources for massless vector particles. In particular currents connected with baryonic (B) and leptonic (L) charges are interesting. However, B and L are not conserved because of quantum chiral anomaly. Still their sum is conserved and there may be a massless vector boson coupled to the corresponding current. A high accuracy with which the equivalence principle is fulfilled demands that the corresponding gauge coupling constant is very small, $\alpha_{B+L} < 10^{-43}$. For comparison the electromagnetic coupling constant is $\alpha_{em} \approx 10^{-2}$.

Thus one may expect that there may be new long range forces associated with the exchange of new massless vector bosons. These forces should be attractive between matter and antimatter and repulsive between the same kind of matter in contrast to forces induced by tensor (graviton) exchange which are always attractive.

7. Conclusions

(1) The Universe may be charge symmetric having an equal amount of matter and antimatter.

(2) The size of matter–antimatter domains is absolutely unknown and can be as small as 10 Mpc or be larger than the present-day horizon. In the latter case no observation of antimatter is possible in any foreseeable future.

(3) A noticeable amount of uniformly distributed compact objects made of antimatter in the background of the baryonic Universe is possible theoretically and permitted by observations.

(4) No evidence of cosmic antimatter is found by looking for $\bar{p}$-flux.

(5) Search of antinuclei in cosmic rays is of great importance and any positive result would be an unambiguous proof of the existence of antimatter in considerable amount.

(6) Gamma-ray background might be an indication of cosmic antimatter.

(7) Gravitational interaction of matter and antimatter are most likely the same but new long range forces associated with the exchange of a new massless vector particle are not excluded.

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