When clusters collide: constraints on antimatter on the largest scales

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Abstract. Observations have ruled out the presence of significant amounts of antimatter in the Universe on scales ranging from the solar system, to the Galaxy, to groups and clusters of galaxies, and even to distances comparable to the scale of the present horizon. Except for the model-dependent constraints on the largest scales, the most significant upper limits to diffuse antimatter in the Universe are those on the ∼Mpc scale of clusters of galaxies provided by the EGRET upper bounds to annihilation gamma rays from galaxy clusters whose intracluster gas is revealed through its x-ray emission. On the scale of individual clusters of galaxies the upper bounds to the fraction of mixed matter and antimatter for the 55 clusters from a flux-limited x-ray survey range from 5×10^{-9} to <1×10^{-6}, strongly suggesting that individual clusters of galaxies are made entirely of matter or of antimatter. X-ray and gamma-ray observations of colliding clusters of galaxies, such as the Bullet Cluster, permit these constraints to be extended to even larger scales. If the observations of the Bullet Cluster, where the upper bound to the antimatter fraction is found to be <3×10^{-6}, can be generalized to other colliding clusters of galaxies, cosmologically significant amounts of antimatter will be excluded on scales of order ∼20 Mpc (M ∼ 5×10^{15} M_{⊙}).

Keywords: high energy photons, baryon asymmetry

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1. Introduction

Had the Universe been matter–antimatter (baryon–antibaryon) symmetric during the later stages of its early evolution, when the temperature was below that of the quark–hadron transition (and well below the nucleon mass), it would have experienced an ‘annihilation catastrophe’ in the sense that the number of post-annihilation nucleons would be a billion—or more—times less abundant than is observed in our present Universe (for a review and an extensive list of references, see [1]). Even worse, for a symmetric universe the annihilation which ceased during its early evolution due to the low density of the surviving nucleon–antinucleon pairs would resume when gravitationally collapsed objects formed (if, indeed, collapsed objects could form in such a baryon-poor universe), further reducing the baryon density and inhibiting the formation of stars, planets, etc. The problems of a symmetric Universe were appreciated by Sakharov [2], who outlined the necessary conditions for generating a matter–antimatter asymmetry during the early evolution of the Universe. Later, when it was understood that grand unified theories, along with the expected, early evolution of the standard, hot big bang cosmological model, contained the ingredients of Sakharov’s recipe for generating a baryon asymmetry [3]–[6], it became generally accepted that our Universe is matter–antimatter asymmetric, consisting predominantly of ordinary matter (by definition!) and containing, at most, only trace amounts of antimatter. For a recent, contrary point of view, see [7]–[9]. Over the years, the theoretical expectations of a baryon asymmetric Universe have been tested and confirmed by a wide variety of observations which strongly limit the observationally allowed amount of cosmological antimatter [1], [7]–[11].

During the collapse of stars and, in particular, of the pre-solar nebula, any relic antimatter would have annihilated to extremely low levels. Even so, it is useful to note that the absence of annihilation gamma rays, which could have been produced as the solar wind sweeps over the planets, strongly restricts the presence of significant amounts of antimatter in the solar system [1]. Beyond the solar system, only the cosmic rays provide direct evidence of the composition of the stars and gas in the Galaxy. The absence of complex antinuclei (e.g., antihelium) in the cosmic rays at a level $<10^{-6}$ [12] provides an interesting upper bound to antimatter in the Galaxy. New cosmic ray experiments such as PAMELA [13] and AMS [14] have the potential to reduce this limit further or to find...
When clusters collide: constraints on antimatter on the largest scales

Evidence for antimatter from observations of galactic or extragalactic cosmic ray antinuclei. While a collapsed object, such as a star, may hide appreciable amounts of antimatter\(^1\), stars are formed from interstellar gas, and in the course of their evolution and at the end of their evolution, they return substantial amounts of material to the interstellar medium. Since an antinucleon (or antinucleus) in the diffuse interstellar medium (ISM) of the Galaxy has a very short lifetime against annihilation, \(\sim 300 \text{ yr} - 200 \text{ kyr} \)\(^2\), any antimatter present when the Galaxy formed would not have survived to the present epoch. Indeed, the observed Galactic gamma rays indirectly limit the ratio of antimatter to matter in the ISM to \(< 10^{-15} \)\(^1\). On scales larger than that of the Galaxy, upper bounds to the observed gamma-ray flux provide indirect limits on the presence of diffuse regions of mixed matter and antimatter.

In section 2, the gamma-ray limits on matter–antimatter annihilation in the hot, x-ray emitting gas of clusters of galaxies are reviewed, leading to bounds on the antimatter fraction in systems of size \(\sim \) a few Mpc and mass \(\sim 10^{15} M_\odot \). In section 3 it is noted that observations of the ‘Bullet Cluster’\(^{15}\) and of other colliding clusters of galaxies\(^{16} - 18\) permit these bounds to be extended to larger distance/mass scales. The results presented here are summarized in section 4.

2. Antimatter constraints on the scale of clusters of galaxies

In clusters of galaxies most of the baryons (matter) are in the hot, x-ray emitting, intracluster gas. If a fraction, \(f\), of this gas were to consist of antibaryons (antimatter) mixed with the dominant baryons (or vice versa), then the two-body collisions responsible for creating the x-rays via thermal bremsstrahlung emission would ensure the production of high energy gamma rays from matter–antimatter annihilation\(^1\). As a result, the predicted annihilation gamma-ray flux is directly tied to—proportional to—the observed x-ray flux. The absence of observed gamma rays bounds the fraction of mixed matter and antimatter in the intracluster gas\(^1\). The best constraints to the presence of antimatter on some of the largest scales in the Universe \((M \sim 10^{14} - 10^{15} M_\odot ; R \sim \) a few Mpc) are provided by a comparison of the upper bounds to the cluster gamma-ray flux, \(F_\gamma = F_\gamma(>100 \text{ MeV}) \text{ photons cm}^{-2} \text{ s}^{-1}\), to the observed cluster x-ray flux, \(F_X \equiv F_X(2-10 \text{ keV}) \text{ erg cm}^{-2} \text{ s}^{-1} \)\(^1\). For a cluster at a distance \(R\), whose intracluster gas fills a volume \(V\) and is at a temperature \(T_\text{s} \equiv T/10^8 \text{ K}\), the x-ray and the annihilation-predicted gamma-ray fluxes are\(^1\)

\[
F_X = 1.4 \times 10^{-23} T_\text{s}^{1/2} \int \frac{n_B^2 \, dV}{4\pi R^2}
\]

\(^1\) In its journey through the Galaxy, an antistar would accrete interstellar gas, leading to the production of annihilation gamma rays. Observations of discrete Galactic gamma-ray sources limit the fraction of antistars in the Galaxy to \(< 10^{-4} \)\(^1\).

\(^2\) The \(\sim 3-5\) order of magnitude longer lifetime in Bambi and Dolgov\(^7\), while still very small compared to the age of the Galaxy, fails to account for the \(\sim 3-5\) order of magnitude enhancement of the annihilation cross section at the very low collision energies in the ISM. As a consequence, the Bambi and Dolgov gamma-ray flux estimates\(^7\) may need to be corrected upwards by \(3-5\) orders of magnitude.

\(^3\) Note that the numerical coefficient in equation (2) differs from that in\(^1\), due to a more careful accounting for the temperature-dependent enhancement of the low energy annihilation cross section.
When clusters collide: constraints on antimatter on the largest scales

Figure 1. The upper limits to the galaxy cluster antimatter fractions, $f_{\text{max}}$, inferred from the absence of $\gamma$-rays [20], as a function of the observed x-ray fluxes [19], $F_X$, for 55 clusters of galaxies (red triangles) and for the Bullet Cluster [15, 22] (blue square).

\[
F_G = 5.4 \times 10^{-14} \frac{f}{T_8^{1/2}} \int \frac{n_B^2 \, dV}{4\pi R^2}.
\]

(2)

Since not all the observed $\gamma$-rays will have been produced by annihilation, the ratio of $F_\gamma$ to $F_X$ provides an upper bound to $f$,

\[
f \leq 2.6 \times 10^{-10} T_8 \left( \frac{F_\gamma}{F_X} \right) = 3.0 \times 10^{-8} T_{\text{keV}} \left( \frac{10^8 F_\gamma}{10^{11} F_X} \right),
\]

(3)

where $T_{\text{keV}} \equiv kT$ measured in keV ($T_{\text{keV}} = 8.6 T_8$).

The flux-limited x-ray survey by Edge et al [19] identifies 55 clusters emitting at a level $F_X \geq 1.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The upper bounds to the cluster antimatter fraction, $f_{\text{max}}$, which follow from the EGRET upper bounds to the $\gamma$-ray flux [20] for these 55 x-ray clusters, are shown by the red triangles in figure 1, along with the corresponding upper bound (blue square) inferred from observations of the Bullet Cluster (see section 3). These observations limit the fraction of mixed matter and antimatter on the scale of clusters of galaxies to be smaller than $f < 1 \times 10^{-6}$. The best constraints (the smallest upper bounds) to the antimatter fraction on the scale of galaxy clusters are from observations of the Perseus and Virgo clusters, where $M \sim 10^{15} h_{50}^{-1} M_\odot$. For Perseus, $f < 8 \times 10^{-9}$, and
for Virgo an even lower upper bound of $f < 5 \times 10^{-9}$ is derived. For the slightly larger scales of the Coma and Ophiuchus clusters ($M \sim 2–3 \times 10^{15}h_{50}^{-1}M_\odot$), the observations lead to the somewhat weaker, but still very strong, constraints $f < 3–4 \times 10^{-8}$. Indeed, since $f \ll 1$ for all 55 clusters, each of these clusters likely consists entirely of matter (or of antimatter). If there are significant antimatter-dominated regions in the Universe, they must be separated from matter-dominated regions on scales greater than the $\sim$Mpc ($M \sim 10^{15}h_{50}^{-1}M_\odot$) scale of clusters of galaxies. It is of interest to extend the cluster bounds to these larger scales.

3. The bullet cluster

It is clear from the data provided by the x-ray and $\gamma$-ray observations of a large sample of galaxy clusters [19, 20] that if regions of diffuse antimatter do exist on large scales in the Universe, they must be separated from regions of ordinary matter by distances at least of order of the $\sim$Mpc sizes of clusters of galaxies. Can the above constraints from the x-ray and $\gamma$-ray observations of galaxy clusters be extended to even larger distance/mass scales? For example, how would it be known if there were significant amounts of diffuse antimatter in regions where the fraction of ordinary matter is very small (e.g., entire galaxy clusters of antimatter)? Such regions would reveal themselves through the annihilation $\gamma$-rays when the matter and antimatter clusters collide. The only way to probe this possibility of separated clusters and anti-clusters is to search for correlated x-rays and $\gamma$-rays from colliding clusters of galaxies. Observations of the so-called ‘Bullet Cluster’ [15] provide just such an opportunity.

According to Nusser (private communication and [21]), $M_{\text{Bullet}} \sim 6 \times 10^{15}h_{50}^{-1}M_\odot$ and, at maximum, the colliding clusters were separated by $\sim 20$ Mpc. For the Bullet cluster, $F_X = 4.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, $T_{\text{keV}} = 14$ [15] and, at 95% confidence, $F_\gamma < 3.5 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ (Thompson, private communication and [22]), so that $f_{\text{Bullet}} < 3 \times 10^{-6}$. While somewhat weaker than the constraints on $f$ from the individual clusters discussed in section 2 above, this upper bound to the antimatter fraction shows that the colliding galaxy clusters which constitute the Bullet Cluster consist predominantly, if not entirely, of matter (or of antimatter!) If the Bullet Cluster is typical, then recent evidence for other clusters in collision [16]–[18] raises the possibility of further extending these constraints on antimatter in the Universe to scales of tens of Mpc.

4. Conclusions

Direct observations in the solar system and of the galactic cosmic rays set stringent constraints on antimatter in our local vicinity. Gamma rays produced when matter and antimatter meet and annihilate provide indirect evidence for regions of mixed matter and antimatter. There is no evidence for such mixed regions on scales from galaxies to groups and clusters of galaxies, limiting the antimatter fraction to $< 1 \times 10^{-6}$, or smaller, on scales up to $\sim$Mpc and $M \sim 10^{15}M_\odot$. Recent observations of clusters in collision [15]–[18] permit the x-ray cluster bounds on the fraction of antimatter in the Universe to be extended to even larger scales. Observations of the colliding galaxy clusters which constitute the Bullet Cluster limit the antimatter fraction to $f_{\text{Bullet}} < 3 \times 10^{-6}$, on a scale of $M \sim 6 \times 10^{15}h_{50}^{-1}M_\odot$. If, indeed, there are regions of antimatter in the Universe, they
must be separated from regions of ordinary matter by distances on the order of tens of Mpc (mass scales of order $10^{16} M_\odot$). Evidence for galaxy clusters in collision suggest that these scales could be probed in the near future.

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