CONFRONTATION OF ANTIMATTER COSMOLOGIES WITH OBSERVATIONAL DATA

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Abstract. The presence of large amounts of antimatter in the Universe would be detectable directly via the cosmic rays and indirectly via the annihilation γ-rays. The observational data is reviewed. There is no evidence whatever indicating the presence of astrophysically interesting amounts of antimatter in the Universe. From the available data we may conclude that the Galaxy is made entirely of ordinary matter and that if any antimatter at all is present in the Universe, it must be very well separated from ordinary matter. Furthermore, we show that the observational constraints on various symmetrical cosmological models strengthen the case against antimatter in the Universe.

1. Introduction

The previous speakers have presented cosmological models which are symmetric in the sense that the Universe described contains exactly equal numbers of particles and antiparticles. Do such universes bear any relation to our observed Universe? It is fitting and proper at this symposium that we address ourselves to this question by considering the observational data.

There is a distinction to be made between two different questions to be answered. The first asks, 'Must the Universe be symmetric?', while the second enquires, 'Is the Universe symmetric?' Whatever the answer to the first question, we must, especially at this symposium, concern ourselves primarily with the second question. However, before turning to the observational situation for our Universe, a few remarks relating to the first question may be of value.

It is well known that the elementary particles come in pairs and that at the level of micro-physics there is a symmetry between particles and their antiparticles. Must this symmetry manifest itself on the macroscopic scale in the Universe; must the Universe contain exactly equal numbers of particles and antiparticles?

It is useful to recall that there are many cases where the symmetry in the laws of physics at the microscopic level is strongly violated in macroscopic situations. For example, Maxwell's equations are time symmetric but the interesting physical solutions are the outgoing spherical waves and not incoming spherical waves or a 50-50 mixture of the two. Similarly, at the microscopic level, parity violation is an extremely small effect, but we need only glance around to find evidence that real, macroscopic physical systems strongly violate mirror symmetry. These examples and many similar ones suggest that it may be necessary to strongly violate the symmetries of the micro-physics in order to achieve 'interesting' macroscopic physical systems. If this suggestion is valid, then perhaps the symmetry between particles and antiparticles must be broken on the large scale in order to have an 'interesting' universe. When we consider the symmetric, hot big-bang model, we will find some support for this hypothesis.

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In the example of Maxwell's equations, the breaking of the time symmetry is achieved by the appropriate choice of boundary conditions. In cosmology, boundary conditions may play a crucial role in determining the content (i.e.: baryon number, lepton number, etc.) of the Universe. Perhaps all boundary conditions are possible, but 'interesting' universes only develop if the baryon number is non-zero. We return to this possibility later.

There is a further reason to expect that exact particle-antiparticle symmetry may be violated in astrophysical systems. The point is the following. General Relativity, as well as most other theories of relativistic gravity, predicts the existence of collapsed bodies in the Universe: Black Holes (and, possibly, their time reversed counterparts: White Holes). The probability that such objects do exist seems large and perhaps such objects have already been discovered. Because of the long range of the gravitational and electromagnetic interactions, the gravitational mass and the electric charge (as well as the angular momentum) of such a collapsed body can be measured by an external observer. However, because of the short range of the strong and weak interactions, it is impossible to determine the baryon number or the lepton number of a Black Hole. As a result, we may throw baryons down a Black Hole and watch them disappear in apparent violation of the law of conservation of baryon number which requires that particles and antiparticles only be created or destroyed in pairs. Similarly, if we stumble upon a White Hole, we may find the material issuing forth to have non-zero baryon number. Again, an apparent contradiction with the law, requiring that baryon number be exactly and locally conserved.

The previous examples suggest that the answer to the question, 'Must the Universe be symmetric?' may be: not necessarily. However we may answer the above question, it is crucial that we consider the second question, 'Is the Universe symmetric?' Here is where the confrontation of cosmological theories with observational data lies.

The evidence relating to the possible existence of astrophysically interesting amounts of antimatter in the Universe has been reviewed quite recently [1, 2, 3]. I shall therefore present in the following sections a summary of that evidence and refer the interested reader to the above references for more detailed discussions and references to earlier work.

2. Direct Evidence

The detection of antimatter is quite straightforward and extremely simple. Take your detector – the most rudimentary device will do – to where you suspect a concentration of antimatter, place it down and wait. If your detector starts disappearing, get out fast – you've discovered antimatter. Seriously, such experiments have in fact been performed within the solar system via the manned lunar flights and the unmanned Venus probes. In fact, even before interplanetary (and lunar) space travel, we had similar information from the solar wind which acts as a probe just as our hypothetical detector would. As we suspected with very good reason, the solar system is made of ordinary matter.

We are, of course, severely limited in our ability to carry out the above sort of experiment outside of the solar system. It is fortunate indeed, therefore, that we receive from outside the solar system a flux of particles whose composition we can study: the cosmic rays.

The cosmic rays are something of a mixed blessing. It is relatively easy to identify an antinucleus in the cosmic rays but, since the cosmic rays are tied to the magnetic field and don't travel in straight lines (except, of course, for the very high energy cosmic rays whose composition we are unable to determine) we don't know where they are coming from. The composition of the cosmic rays is very well known but very little is known of the region of space they permit us to sample.

Despite intensive searches, no antinucleus has ever been found in the cosmic rays. The results of these searches are summarized in Table I where the 95% confidence level limits to the fraction of antinuclei ($\bar{N}/N$) are presented.

TABLE I

95% Confidence level limits to antinuclei in the cosmic rays

Nuclear charge	Rigidity[a] (GV)	$\bar{N}/N$	Reference
1	<0.6	8×10^{-4}	4
	<1.4	3×10^{-3}	5
	1–6	1×10^{-2}	6
	$\sim10^3$	5×10^{-2}	7
2	<1.4	6×10^{-3}	5
	1–10	1×10^{-3}	8
	10–25	8×10^{-2}	8
$\geqslant2$	<5	9×10^{-3}	9
	14–100	3×10^{-2}	10
$\geqslant3$	<3	3×10^{-3}	11
	4–125	5×10^{-3}	12
	<33	2×10^{-4}	13
	33–100	2×10^{-2}	13
$\geqslant6$	<1.4	1×10^{-2}	5
	10–18	8×10^{-2}	14

[a] Rigidity is the momentum per unit charge and for relativistic particles is proportional to the kinetic energy per nucleon.

It should be noted that cosmic rays passing through a few grams per cm^2 of interstellar gas will produce antiprotons as secondaries. As a result we expect to find antiprotons in the cosmic rays at a level of about 1 part in 10^4 ($N_{\bar{p}}/N_p \sim 10^{-4}$) [15]. Hence, antiprotons are not as useful a probe for antimatter as, for example, antihelium or heavier antinuclei whose production as secondaries is entirely negligible. For this reason, the results of Evenson [8] and of Buffington *et al.* [13] provide us with the most significant upper limits to antimatter in the cosmic rays.

As was already emphasized, we can't be sure whence the cosmic rays have come and of what region of space they are providing us a sample. Since the observed cosmic rays only pass through a few grams per cm^2 of interstellar material, they must be able to travel far enough to escape from the disk of the Galaxy. Thus, the cosmic rays we sample probably originate in a volume whose typical dimension is at least a few hundred parsecs. In fact, they probably come from a considerably larger volume. Indeed, the isotropy of the cosmic rays, the relative constancy of their flux at Earth over periods up to 4.5 b.y. and the smoothness of the distribution of galactic, non-thermal radio emission all indicate that the observed cosmic rays find their origin in a volume comparable in size to and perhaps even greater than that of our Galaxy. The lack of antimatter in the cosmic rays supplies good evidence that every second star in our Galaxy is not made of antimatter. In fact, the limits on antinuclei are so low that if even a small fraction ($\sim 10^{-4}$–10^{-3}) of the cosmic rays had an extragalactic origin, then we would already have learned that very few, if any, extragalactic systems could be made of antimatter.

To summarize we note that the discovery of an antihelium nucleus (or, better still, an anticarbon or anti-iron nucleus) in the cosmic rays would supply convincing evidence for the presence of large amounts of antimatter. However, no antinucleus has ever been found in the cosmic rays. The very low limits which have been set indicate the absence of antimatter from a large part if not all of our own Galaxy. If, as some suggest [16], a non-negligible fraction of the observed cosmic rays are extragalactic in origin, then we may already have learned that the Universe is not symmetric.

3. Indirect Evidence

Since we are unable to travel around the Universe in search of antimatter and, since the cosmic rays probably provide a sample of the material only within our own Galaxy, we must rely on indirect evidence which may indicate the presence of antimatter.

Faraday rotation supplies indirect evidence for the absence of antimatter within the Galaxy. Since the sense of rotation is opposite for electrons and positrons, if typical lines of sight contained equal numbers of each no net Faraday rotation should be observed. However, observations of Faraday rotation coupled with pulsar dispersion measures (which are proportional to the *sum* of the line of sight column densities of electrons and positrons) as well as independent determinations of the strength of the magnetic field yield a consistent picture indicating that typical lines of sight in the Galaxy do not contain equally many positrons and electrons. This evidence of course is consistent with that obtained from the cosmic rays: The Galaxy has no (astrophysically interesting amounts of) antimatter. Of especial interest would be conclusive evidence for the existence of an extragalactic component of the Faraday rotation. Such evidence would indicate the absence of extragalactic antimatter. What observations exist are far from being conclusive and it is hoped the observational situation will improve in the near future.

If matter and antimatter meet and annihilate, the annihilation products carry indirect evidence of the presence of antimatter. We may search for antimatter by searching for the annihilation products. The end products of a typical annihilation are high energy electron-positron pairs, γ-rays and neutrinos [1]. The electron-positron pairs will not travel far from where they are created because they will be tied to magnetic fields and will lose energy rapidly via synchrotron radiation or by scattering on any photons present (starlight, infra-red, black-body, etc.). Since we have already seen that it is unlikely that there is any galactic antimatter and since, in any case we know of mechanisms for accelerating electrons and positrons to high energy (pulsars), the electron-positron component is not likely to provide unambiguous evidence for the presence of antimatter.

The annihilation neutrinos are very difficult to detect. Only if a major fraction of the matter in the Universe were annihilating would a detectable flux of neutrinos be produced [2]. It is therefore unlikely that such annihilation neutrinos can provide significant information relating to the presence of antimatter.

The annihilation γ-rays provide the best means for searching for the presence of large scale amounts of antimatter in the Universe. Annihilations produce a spectrum of γ-rays extending from several tens of MeV to several hundred MeV. On average, 3–4 γ are produced per annihilation, most with energy $\gtrsim 70$ MeV. Hence, observations of ~ 100 MeV γ-rays enable limits to be set on the amount of contemporaneous annihilation. Only limits can be set since there are other mechanisms for producing such energetic γ-rays.

The OSO-3 observations [17] indicate the presence of a γ-ray ($E \gtrsim 70$ MeV) background with three distinct components. There is an isotropic component which presumably is extragalactic and probably universal in origin (e.g.: from an intergalactic gas or from clusters of galaxies, etc.). In addition, there is a galactic component which correlates well with the distribution of hydrogen in the Galaxy. Finally, there is a galactic center component which may or may not be due to the integrated effect of individual sources. From the observed flux, limits may be set on the annihilation rate and thereby to the amount of mixed matter and antimatter. We may express the results [1, 3] in terms of f, the antimatter fraction (alternately, if equal amounts of matter and antimatter are assumed, then f is the mixed fraction). The limits are summarized in Table II and discussed below.

If, as has been suggested ([18] and G. Field this symposium), there exists a hot ($T \approx 3 \times 10^8$ K) intergalactic gas at the critical density, then less than one part in 10^8 could be antimatter if the gas is fully mixed. On the other hand, if we assume that such an intergalactic gas is symmetric, then it must be divided into regions of matter and antimatter. If L is the typical size of such regions and d is the typical extent of the overlap between adjacent regions then: $f \approx d/L \lesssim 10^{-8}$. If L is cluster size ($L \approx 10$ Mpc) then, $d \lesssim 10^{-1}$ pc. It should be noted that in the absence of the constraining influence of magnetic fields, a thermal particle ($T \approx 3 \times 10^8$ K) will travel ≈ 30 Mpc in 10^{10} yr. A hot, symmetric intergalactic gas at the critical density must conspire to get and remain very well separated lest the limits set by the γ-ray observations be violated.

While on the subject of a possibly symmetric intergalactic gas, it is worth calling

TABLE II

γ-ray limits to matter-antimatter annihilation

γ-ray component	Possible source	Comments
Isotropic	Cool, neutral intergalactic gas	If $f=1$, then $n \lesssim 10^{-11}$ cm^{-3}
	Hot, ionized intergalactic gas	If $f=1$, then $n \lesssim 10^{-9}$ cm^{-3}. Or, if $n=n_c^*$, then $f \lesssim 10^{-8}$
Galactic	Cool, interstellar clouds	$f \lesssim 10^{-16}$
	Hot, intercloud medium	$f \lesssim 10^{-12}$

* n_c is the 'critical' density which would just close the Universe.

attention to the observations [19] which have shown several clusters of galaxies to be sources of extended X-ray emission. If, for example, the emission from Coma is interpreted as due to a hot intracluster gas, then if that gas were symmetric Coma would be a bright γ-ray source: $\mathfrak{F}_\gamma \approx 10^{-1}$ γ's cm^{-2} s^{-1}. But no extragalactic gamma ray source is known at a level $\mathfrak{F}_\gamma \gtrsim 10^{-5}$ γ's cm^{-2} s^{-1}.

The galactic γ-ray observations fully confirm the previously reached conclusion that the Galaxy contains no antimatter. Indeed, an antiparticle will only survive for $\sim$30 yr in an interstellar cloud and $\sim$300000 yr in the intercloud medium before annihilating.

Finally, what of the possibility that strong extragalactic systems (e.g.: QSOs, Seyfert nuclei, Radio galaxies, etc.) derive their energy from annihilation? If that were the case, then these objects should be detectable γ-ray sources. Since none has ever been found to be a γ-ray emitter, either annihilation has nothing to do with these sources, or the γ-rays have been absorbed. The effect of the absorbed γ-rays on the source (recall that in a typical annihilation twice as much energy is released in γ-rays than in electron-positron pairs) must be considered. It appears difficult to construct an annihilation model which is still consistent with all observations.

4. Symmetric Cosmological Models

From the preceding consideration of the relevant observations it emerges that there is no evidence in support of the hypothesis that the Universe contains equal amounts of matter and antimatter. However, a symmetric universe in which matter and antimatter are very well separated on a large scale may still be consistent with the observational constraints. It is therefore of interest to consider the evolution of symmetric cosmological models to determine how likely it is that matter and antimatter be separated and remain separated. Unfortunately, such an investigation is not likely to lead to firm conclusions. For example, it will emerge that all symmetric models thus far proposed suffer from serious difficulties which go a long way towards eliminating them from consideration. That may either be yet another indication that our Universe is not symmetric or, it may only mean we have not yet been clever enough to discover the 'correct' cosmological model.

The status of three symmetric cosmological models will be briefly reviewed. For a more detailed discussion of the issues involved see references [1] and [20] and further references cited therein.

5. Symmetric, Hot, Big-Bang Model

The cosmological model which has met with the most observational success is the standard (unsymmetric) hot, big-bang model. It is therefore natural that we first consider the evolution of this model modified only to the extent that it now be symmetric.

At early times ($t \lesssim 10^{-4}$ s) when the temperature is very high ($kT \gtrsim 100$ MeV) nucleon pairs will be copiously produced and will be as numerous as photons. As the temperature drops, the production of nucleon pairs is supressed (exponentially) and the pairs annihilate. Hence, for $kT \lesssim Mc^2$ the nucleon-photon ratio decreases rapidly. When $kT \approx 30$ MeV the ratio is $\approx 10^{-9}$ and when $kT \approx 20$ MeV the ratio is $\approx 10^{-18}$ and there are so few nucleon pairs that annihilation effectively ceases. Thus, a co-moving volume will contain more than 10^{18} photons per nucleon. Observations show there are roughly 10^9 photons per nucleon and so theory and experiment differ by nine orders of magnitude – the model permits too much annihilation. To prevent this annihilation, it is clear that matter and antimatter must be separated before the temperature drops to $kT \approx 30$ MeV. Statistical fluctuations are entirely inadequate and it is clear that at such high temperatures (and densities) the strong interaction holds the only possibility for such a separation. Indeed Omnes [21–23] has suggested that the strong interaction causes a phase transition in which nucleons are separated from antinucleons (see also Puget, this volume). Since the strong interaction is so imperfectly understood and since the calculations in support of this phase transition do not satisfy detailed balance, it is not at all certain that such a phase transition is inevitable. Even if such a separation occurs, it is necessary to follow the subsequent re-mixing of the gas in detail. For $kT \gtrsim 1$ MeV, the re-mixing (and, hence, annihilation) is determined by neutron diffusion [20] (since the nucleon spends half its life as a neutron and the neutron diffuses much further than the proton) the re-mixing is so efficient [20] that virtually all the pairs still annihilate and for $kT \lesssim 1$ MeV, the nucleon to photon ratio is $\ll 10^{-9}$. Observations seem to eliminate the symmetric, hot, big-bang model (see also the comments after Puget's paper).

6. Symmetric, Steady-State Model

In the steady-state or continuous creation model [24] it is assumed that newly created matter compensates for the dilution due to the expansion of the Universe. If it is further assumed that the matter is created as particle-antiparticle pairs, then the Universe should be symmetric. For creation which is uniform in space and time, there will exist a symmetric, fully mixed intergalactic gas at the critical density. The flux of annihilation γ-rays from such a gas would be seven orders of magnitude higher than the observed flux. Indeed, the flux of muon-neutrinos from this gas would be two orders of magnitude higher than observational limits [2]. Clearly, such a gas does not exist and, hence, uniform (in space and time) creation of particle-antiparticle pairs has not occurred. Hoyle [25] has suggested that creation may occur nonuniformly, in active regions such as galactic nuclei, QSOs, Seyfert nuclei, etc. In such regions, the annihilation γ-rays may be absorbed and thus will not be observed. However, pairs produced in such dense regions will annihilate very rapidly (more rapidly than in a dilute, intergalactic gas). Limits to the muon neutrino flux [2] rule out this possibility. A symmetric, steady-state model is inconsistent with observations.

7. Alfvén-Klein Model *

This model [26, 27] differs radically from the cosmological models usually discussed. The observed universe is taken to be a finite system (called the Metagalaxy) consisting of equal amounts of matter and antimatter. Initially, the Metagalaxy is a dilute gas undergoing gravitational collapse. As the density increases so does the annihilation rate. The idea is that the annihilation products may exert a pressure on the infalling gas sufficient to halt the collapse and produce the observed expansion. The model faces a large number of serious problems.

One serious quantitative difficulty is that the Metagalaxy is always optically thin to the annihilation products. How, then, can these annihilation products be effective in halting the collapse? Indeed, since the annihilation cross sections far exceed the cross sections for the scattering of the annihilation products, the gas will annihilate too soon for the annihilation products to have any effect on the collapse. Computations by Laurent and Söderholm [28] confirm this. Despite underestimating the annihilation cross sections and overestimating the cross sections for the scattering of the annihilation radiation, they find the maximum possible mass of the Metagalaxy to be at least one order of magnitude smaller than the observed mass in galaxies. Furthermore, they find the maximum redshift to be ≈ 0.4.

Many other difficulties with this model could be cited (see reference [1] and other work cited therein). However, observations provide the most damaging testimony against the model. The Metagalaxy is optically thin to X-ray radiation as well as the 3 K microwave radiation. These background radiations are observed to be highly isotropic which would require us to be very precisely at the center of the Metagalaxy. At a symposium devoted to observations and held to honor the contribution of Copernicus this must surely eliminate the Alfvén-Klein model (or any variants of it) from serious consideration.

* At this symposium, Dr Elvius has presented a new variant of this model. The conclusions reached in this section apply to this modified model as well.

8. Conclusions

Earlier we posed two questions: Must the Universe be symmetric? and, Is the Universe symmetric? We have briefly argued that the Universe need not necessarily be symmetric. Interesting though such arguments may be, they can never be decisive. The second question we have attempted to answer by considering the observations. We have found no evidence for any antimatter in the Universe. Indeed, if antimatter is present, it must be very well separated from matter on scales comparable to or greater than clusters of galaxies. Of course, the most straightforward conclusion is that there is no antimatter in the Universe. Finally, we have confronted several symmetric, cosmological models with observations. All models are in conflict with the observational data.

Taken together, the evidence seems to suggest overwhelmingly our Universe is not symmetric. In conclusion we offer a speculation on why this may be the case. Consider an ensemble of very many possible universes. Most of them may have exactly equal numbers of particles and antiparticles. In such universes there will be an annihilation catastrophe. With such little remaining matter, it is unlikely that such universes will become interesting in the sense that probably neither galaxies, nor stars, nor planets will form. On the other hand, a small number of universes in our ensemble may have a slight excess of particles over antiparticles (or vice-versa). A small excess ($\Delta B/B \approx 10^{-9}$) ensures that such a universe avoids an annihilation catastrophe. These may become 'interesting' universes. We speculate that, to become 'interesting' a universe must have non-zero baryon number.

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