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F. W. Stecker

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Goddard Space Flight Center
Greenbelt, Maryland 20771

BARYON SYMMETRIC BIG-BANG COSMOLOGY

F. W. Stecker
Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, MD 20771 U.S.A.

Abstract: *The framework of baryon-symmetric big-bang (BSBB) cosmology offers our greatest potential for deducing the evolution of the universe as a consequence of physical laws and processes with the minimum number of arbitrary assumptions as to initial conditions in the big-bang. In addition, it offers the possibility of explaining the photon-baryon ratio in the universe and how galaxies and galaxy clusters are formed. BSBB cosmology also provides the only acceptable explanation at present for the origin of the cosmic γ-ray background radiation.*

1. Reconciling Physics and Cosmology

The combined principles of quantum theory and special relativity, two cornerstones of modern physics, imply that the creation of matter must occur simultaneously with the creation of antimatter. This is true in the same way that the construction of a closed curve divides a simply connected surface into an inside and an outside. As is the case generally in astrophysics, it is both natural and logical to extend this principle of theoretical and laboratory physics by extrapolating its validity to all other parts of the Universe in order to construct a coherent and rational picture of the Universe and its development. This motivation, among others, leads to the consideration of the matter-antimatter symmetric (or baryon symmetric) cosmologies which we will discuss here.

On the other hand, there is no *direct* evidence for the existence of antimatter on a cosmic scale. (Possible indirect evidence exists which we will discuss later.) Except for the possible detection of one candidate antinucleus in the cosmic radiation[1], only upper limits exist from experiments to detect the existence of antimatter in the cosmic radiation. These upper limits appear to rule out the existence of large-scale amounts of antimatter at least within about 10^3 to 10^4 light-years of the sun's position in the Galaxy, given the evidence that the overwhelming bulk of the cosmic-radiation is galactic in origin[2-4]. They are also consistent with a possible small extragalactic flux of cosmic-rays[5] which may have a substantial antimatter component. Observations of the amount of cosmic galactic and background γ-radiation[4,6] as compared with expected fluxes from the annihilation of matter and antimatter indicate that matter and antimatter, if they exist in equal amounts on a universal scale, are most probably separated into domains of the scale of clusters of galaxies. The generation and evolution of such a domain structure thus becomes an important aspect of a baryon-symmetric cosmology[7,9,10].

We thus come to one of the key questions of cosmology, i.e., how do we reconcile the symmetry of the matter-antimatter creation process with the apparent lack of evidence for antimatter on a large scale, at least in our corner of the Universe? Possible indirect evidence for the existence of antimatter on a cosmic scale must also be considered in this context as well as other aspects of baryon symmetric cosmology.[11,12]

2. Universal Versus Local Matter-Antimatter Asymmetry: Domain Structure

There are basically three scenarios for reconciling the physics of symmetric particle production processes with the lack of matter-antimatter symmetry on a local astronomical scale.

I. One may postulate that there was initially, at the beginning of the big bang, a global or universal matter antimatter asymmetry. This imbalance amounted initially to a excess of matter over antimatter by a very small, but nonvanishing amount of roughly one part in 10^9. Then, in the early, dense stages of the big-bang, all the matter and antimatter annihilated with the exception of the matter excess which became the present matter content of the universe. The radiation resulting from the annihilation was cooled as the universe expanded and is now observed as the 3K microwave blackbody radiation. This scenario, which I will refer to as the partially symmetric big-bang (PSBB) is the view most widely held at present. It relegates all symmetry problems to a postulated initial condition outside the context of everyday physics. (This may be analogous, in the metaphor of a curve dividing a surface, to a curve on the surface of a torus which can be constructed so that there is no inside and outside, this because of the global properties of the system.)

II. There existed, as an initial condition, localized regions or domains in which there was an initial excess of matter over antimatter and other domains in which there was an excess of antimatter over matter.[9] These domains would have to have been too large to have been produced by statistical fluctuations or else total annihilation would have subsequently occurred as the universe evolved.[13,14]

III. The universe started out in an extremely dense, very high temperature state in a homogeneous condition with zero net baryon number (matter-antimatter symmetry). Such a state would be naturally arrived at, e.g., in theoretical models where matter is created in particle-antiparticle pairs from fluctuations in the space-time metric of the universe when it was in this compact state (See, e.g., refs. 15 and 16 and refs. therein). One then examines and attempts to describe processes in which the universe evolves in a way which is consistent with and indeed dictated by the laws of physics at extreme energies (i.e. temperatures) and densities followed by further evolution at lower temperatures and densities until a global or domain structure is arrived at which is in accord with observational cosmology.

The construction of Scenario III is a prodigious task, indeed one which would probably of necessity require many small steps by many workers. However, this is the most philosophically satisfactory scenario to follow since it is the only one which offers the potential for new cosmological discoveries employing recent advances in particle physics. It offers the hope of maximizing our understanding of the evolution of the universe as a consequence of natural processes, recognizing that such an evolution is a complex process as indicated by the large amount of structure existing in the universe (galaxies, clusters of galaxies, etc.). It is within the spirit and faith of Einstein regarding natural laws, that Nature is subtle but not malicously capricious or esoteric, "*Raffiniert ist der Herrgott, aber boshaft ist er nicht*".

Also, in the context of this scenario other important cosmological problems may be resolved. Given a universe with postulated or arbitrary boundary conditions, it is difficult to understand why the 3K microwave background appears to be so uniform over a large scale. As we look out over the sky in different directions with our radio telescopes, we are looking at parts of the universe which were not in causal contact with each other when the interactions which thermalized this radiation ceased. Indeed, they were not in contact up to that time since they were separated by distances such that the light travel time between them was greater than the age of the universe during those epochs. The isotropy of the background radiation then becomes enigmatic unless that background was generated by natural physical processes which follow the same evolutionary track starting from an initially simple state without arbitrary initial conditions, as in Scenario III.

Another important problem concerns the evolution of structure in the universe. Such evolution can be more easily understood in the context of a matter-antimatter domain structure evolving out of a phase transition from a homogeneous state in the early universe[7,10,17].

3. Other Suggestions for Baryon-Symmetric Cosmologies

The types of cosmological evolutionary models which conform to the program outlined in Scenario III we will refer to as baryon symmetric big-bang (BSBB) cosmologies as opposed to the standard PSBB cosmology. Other types of initially baryon symmetric cosmologies have been suggested, those being unsatisfactory in one way or another. We mention them here briefly before going on to a more extensive discussion of BSBB cosmologies.

The first suggestion was made by Goldhaber[18]. He suggested that initially the universe consisted of a single particle, the "universon" which then split into a "cosmon" and an "anticosmon". Aside from not accounting for the 3K radiation (which was unknown at the time) and the lack of a basis for such a process in particle theory, this suggestion is really tantamount to assuming an initial condition of all baryons in the universe, since the "anticosmon" universe has no observable consequences.

Variants of the steady state cosmology[19], which have the general drawbacks of steady state cosmology (e.g., cannot account for the 3K background), also have other unsatisfactory aspects. Either only matter is created or matter and antimatter are created separately in widely separated regions (violation of conservation of baryon number, i.e., asymmetry in the creation process) or matter and antimatter are created together in regions of high density such as galaxy nuclei. In the later case, the amount of annihilation γ-radiation expected would far exceed that observed unless the regions where creation occurs are opaque to γ-radiation[20]. In this case, however, it is difficult to see how matter and antimatter ever underwent a large-scale separation in the first place in order to form the galactic nuclei in which continuous creation is postulated to be occurring.

We next come to the cosmology of Alfven and Klein[21]. In the Alfven-Klein cosmology, the observable universe began as a diffuse "metagalaxy" consisting of equal amounts of matter and antimatter in an "ambiplasma" whose ingredients are then separated by the combined effects of gravitation and gradients in electromagnetic fields. There are many problems with this general picture. The picture requires that the metagalaxy gravitationally collapses until it reaches a critical density where the radiation pressure from annihilation causes it to bounce and expand in accord with the Hubble law. However, detailed dynamical calculations showed that for the estimated total observable mass in the universe, gravitational forces will overwhelm annihilation pressure and this "bounce" will never occur.[22] Other problems with Alfven-Klein cosmology are, again, the lack of explanation for the 3K background and also insufficient separation of matter and antimatter at present. In the Alfven-Klein scenario, half of our Galaxy would be antimatter and a much higher than observed γ-ray background would be produced by annihilation.

Within the context of big-bang cosmology, various asymmetric processes of particle production and decay or destruction have been suggested as a way of producing a present global baryon asymmetry. It has been argued[15] that asymmetries in possible production processes[23,24] will not necessarily lead to a global baryon asymmetry since, in thermal equilibrium in a dense high temperature initial state, the inverse processes having the opposite asymmetry will occur with equal frequency. It has been speculated that CP-violating weak decays of certain types of particles, if such postulated particles played a prominent role in the initial stage of the big-bang, might produce an asymmetry of the order of magnitude

(10^{-9}) needed in the PSBB cosmology[24].

Various people have suggested that since baryon number is not necessarily conserved when matter falls down a black hole, such processes could account for a universal baryon asymmetry. However, black holes are not selective and they will ingest matter and antimatter with equal voracity in a universe which is initially baryon symmetric!

4. Particle Physics, Phase Transitions and Domain Structure in BSBB Cosmology

The evolutionary program which the Universe should follow according to Scenario III, in order to arrive at a permanent matter-antimatter domain structure consistent with observational data, was first outlined by Omnes (Ref 10 and references therein). According to this scheme, when the Universe was above a critical temperature and when its density was above a critical value, a phase transition occurred, creating a structure in which there are domains containing mostly matter (positive baryon number) and domains having negative net baryon number (mostly antimatter). Subsequent, annihilation pressure tended to coalesce regions of like baryon number by pushing apart regions of unlike baryon number. This process is similar to the Leidenfrost effect as first discussed in the context of the Alfven-Klein cosmology.[21] One of the important questions in BSBB cosmology can then be stated as follows: What kind of phase transition can occur at the highest temperatures and densities as implied by present (and future) high energy physics?

Omnes' approach has been to use theoretical and experimental information about nucleon-antinucleon scattering properties to derive a relation giving the free energy for a system of nucleons and antinucleons interacting with each other in thermal equilibrium at a given temperature and density. The relation for the free energy as a function of net baryon number is obtained using a formula derived by Dashen, Ma and Bernstein[25] who generalized the formalism originally given by Beth and Uhlenbeck[26] to express the free energy of a system of strongly interacting particles in terms of observed scattering phase shifts. The treatment of Omnes then indicated that the free energy of a gas of strongly interacting nucleons and anti-nucleons is minimized above a certain critical density when a phase separation occurs. These calculations were also supported in other independent work.[27,28] A key concept of the Omnes model is that the bound states of the nucleon-antinucleon system behave like mesons with the appropriate quantum numbers. In this "lattice gas" type model, a nucleon and an antinucleon at high enough densities such that they are both placed within a cell of size $\sim$ 1 fermi, look like a meson. However, the number density of mesons is determined by statistical equilibrium at temperature T so that there is a statistical exclusion principle acting to keep nucleons and antinucleons from occupying the same cell. No such principle applies to like species of baryons. The result is an effective repulsion for nucleons and antinucleons. In that situation, it has been shown that a phase separation should occur.[29,30] Furthermore, the free energy of the system per unit volume is proportional to the ratio of surface area to volume of the domains so that the domains tend to grow to minimize this ratio. The effect is similar to the coalescence of soap bubbles.[31] The most extensive work to date on the "Leidenfrost" coalescence process is that of Aldrovandi et al. and[32] Aly et al.[33] Electromagnetic and gravitational coalescence processes[21,34] may, of course, combine with the Leidenfrost process to provide a substantially more efficient coalescence as the universe evolves. This may be particularly important in reconciling some aspects of BSBB with observational data, as will be discussed. In the Omnes model[10], the observed ratio is derived from the physical processes involved.

Other types of baryon-antibaryon phase transitions in the early big-bang have been suggested[35,36]. In particular, Etim et al.[36] have applied the methods used by Omnes to show that a phase transition can exist in the early universe using the "statistical bootstrap model" of Hagedorn[37-39] where the number of hadrons increases exponentially with mass and there exists a maximum temperature. In the work of Etim et al., this maximum temperature coincides with the critical temperature.

The development of a phase transition stemming from physical processes at high temperatures and densities, i.e., the spontaneous breaking of charge conjugation symmetry in the early universe, is an area which may be a fertile one for future theoretical investigation using such newly developed concepts as unified gauge theories, "instantons", "supergravity" and quantum chromodynamics. Certainly, the full range of modern particle physics will come into play in the early universe.

5. Galaxy Formation in BSBB Cosmology

Various workers have tried to trace the growth of the domains of matter and antimatter from the era of phase separation to the era marking the decoupling of the matter and antimatter from the blackbody radiation field.[7,10,17,31-34] This takes us to a time of the order of 10^6-10^7 years after the big-bang when the cosmic plasma was almost cool enough to combine into neutral atoms. Starting at this point in the evolution of the BSBB, the question of structure and galaxy formation arises. Models of galaxy formation from "primordial turbulence" have always been attractive as a way of accounting for galaxy formation as well as for observed parameters such as the angular momenta and spatial distribution of galaxies.[40-49] However, in this work, turbulence was introduced in an *ad hoc* manner and, furthermore, such turbulence is strongly damped out in the cosmic plasma because of the very high viscosity of the blackbody radiation field which remains coupled to the cosmic plasma until the neutralization ("recombination") epoch. Several years ago, Stecker and Puget[7] proposed a model for galaxy formation within the context of BSBB cosmology. In this model, dissipation is constantly fought by continuing radiation pressure from annihilation on the boundaries of domains which regenerates the turbulence. Radiation pressure from the annihilation, being directed generally away from the boundary regions, can drive mass fluid motions of the domains as well as causing further coalescence until the domains reach the size of galaxy clusters.

At the recombination epoch, two important changes were caused in the cosmic fluid motions. The viscosity dropped drastically and the turbulent fluid motions became supersonic. This occurred because the sound speed dropped sharply from its value in the cosmic plasma of $3^{-1/2}c$ (because the momentum was transferred by radiation) to the thermal velocity of the neutral gas. Thus, whereas the cosmic plasma behaved as a viscous incompressible fluid, both "small-scale" turbulence and density fluctuations could start to build up in the decoupled atomic fluid and later contract to form galaxies. The Stecker-Puget model thus resembles proposals on galaxy formation dating back to von Weiszäcker[40] and Gamow[41] with the significant difference that in the BSBB scenario annihilation pressure can provide a continuous source of generating turbulence. The basic results and concepts of the Stecker-Puget model have found support in later work by Dallaporta et al.[17]

6. Observational Consequences of BSBB Cosmology

One of the most significant consequences of BSBB cosmology lies in the production of an observable cosmic background of γ-radiation from the decay of π°-mesons produced in nucleon-antinucleon annihilations throughout the history of the universe. This is also perhaps at present the most encouraging aspect of BSBB cosmology since it satisfactorily explains the observed energy spectrum of the cosmic background γ-radiation as no other proposed mechanism does[12,50-55].

Figure 1 shows the observational data on the γ-ray background spectrum as compiled in Refs. 11 and 52 as well as that recently given by Fichtel et al.[54] and Trombka et al.[56] Data of Makino[57] are not shown but are in agreement with other data. The dashed line marked X is an extrapolation of the data from the x-ray range[56,58]. The theoretical curve marked "annihilation" is the annihilation spectrum calculated using the method of Stecker et al., but adopting a mean present universal gas density of $3\times10^{-7}cm^{-3}$ (Ref. 53) and a Hubble constant $H_o = 50$km/s/Mpc. This corresponds to a value of $\Omega \simeq 0.1$ where Ω is the ratio of the mass of the universe to that needed to gravitationally close the universe. The density adopted here fits the more recent revised Apollo data[56] better than the value of $10^{-5}cm^{-3}$ originally used by Stecker et al. It is interesting to note that the values of H_o and Ω used in Ref. 53 are more in line with present observational evidence regarding these parameters. Gott and Turner[59] estimate that the mass in galaxies gives $\Omega_G = 0.08$ and that although $\Omega \geq \Omega_G$, $\Omega \simeq \Omega_G$.

Other recent attempts to account for the γ-ray background radiation above 100 MeV energy[60-62] give spectra which are in one way or another inconsistent with the observations, generally by being too flat[12,54,55]. Previous attempts to account for this radiation also have been found wanting.[50-52]

Neutrinos are another annihilation product. The neutrino background spectrum in the energy range 1-50MeV should be similar in shape and intensity to that of the background γ-radiation. However, because of the small interaction cross section of these neutrinos, their detection at present is not feasible.

Similar detection problems face the proposal of Cramer and Braithwaite[63], who pointed out that radiation from antimatter supernovae may show some circular polarization opposite to that of matter supernovae.

If the detection of an antinucleus in the cosmic radiation, as has been suggested[1], could be confirmed in the future, it would probably establish BSBB cosmology.

Another observational consequence of BSBB cosmology is the expected distortion of the 3K microwave blackbody radiation (e.g., Ref. 64 and references therein). An analysis of the observations of the 3K background by Field and Perrenod[65] indicates that there is a distortion at the 90% confidence level. This will be discussed further in the next section.

7. Problems Concerning BSBB Cosmology

Two areas of particular concern have been discussed concerning BSBB cosmology, *viz* , distortion of the 3K background radiation and nucleosynthesis of helium. Two types of distortion of the 3K background are expected to occur: (1) distortion owing to bremsstrahlung radiation of suprathermal electrons which affects the Rayleigh-Jeans part of the 3K spectrum and (2) distortion from Thomson scattering after the decoupling epoch which affects the Wien part of the spectrum. The Rayleigh-Jeans part of the spectrum is affected by annihilation taking place when most of the energy density in the universe was in the form of radiation, long before neutralization of the cosmic plasma and galaxy formation, and it is difficult to determine the precise amount of annihilation to expect at this remote epoch; it depends on the details of the coalescence process. Extrapolation of the γ-ray background data would indicate that possibly as much as 99.999% of the annihilation may have taken place before the Rayleigh-Jeans distortion epoch whereas calculations[66] would put a lower limit of 96.5-99% on this value. Thus, there is no critical conflict between model and observation on this point, although Ramani and Puget[67] have concluded that for the specific coalescence model of Aldrovandi et al.[32] taken alone, there may be a conflict unless $\Omega \leqslant 0.01$.

The Wien (or high frequency) distortion from electron-photon scattering, sometimes referred to as comptonization, has been treated in various papers[67-70]. Refs. 68 and 69 conclude that the high frequency distortion predicted by the Stecker-Puget model is not in conflict with the observations. The calculations of Ramani and Puget[67], when combined with the analysis of Field and Perrenod[65], imply consistency only for $\Omega \leqslant 0.22$ (Ref. 12), consistent with the value of 0.1 used to fit the γ-ray background observations. The work of Jones and Steigman[70] indicates that there is no conflict between the coalescence model of Aldrovandi et al.[32] and the analysis of Field and Perrenod[65], however, these authors conclude that the Stecker-Puget turbulence model leads to distortions in conflict with observation. Further analysis of subtleties not taken account of in the original work of Stecker and Puget may help resolve some of the difficulties. For one thing, in the annihilation process, photons are created and not just scattered so that at least partial thermalization may result. This is not taken account of in the work of Jones and Steigman. There is also the question of what percentage of annihilation energy is "fossilized" in mass motion versus that dissipated. On the other hand, the original Stecker-Puget model may have overestimated the role of annihilation generated turbulence in the galaxy formation process. Although the mechanism may provide a key trigger, mass perturbations and the effects of subsequent gravitational and magnetic fields, not fully considered in the original model, may well play a priminent role. However, the overall scale of structure as given by the Stecker-Puget model, seems to be supported by a recent analysis of the spatial distribution of galaxies.[71]

We next come to the nucleosynthesis problem. It has been concluded that within the context of the Omnes coalescence model, nucleosynthesis cannot take place in the BSBB.[72,73] This is because at the time nucleosynthesis would occur, the mean size of coalesced domains would be smaller than the neutron diffusion length for escape from the domains. Thus, the neutrons would be annihilated before they can participate in the nucleosynthesis process. There are two ways around this apparent difficulty: (1) If the coalescence process is more efficient than the initial work indicated (see section 4), the size of the resulting domains could be larger than the neutron diffusion length. Combes et al.[73] find that for this to be so, the domain sizes should be $\gtrsim 1.5\times10^{8}$ cm during the nucleosynthesis epoch. (2) Nucleosynthesis may not have taken place in the big bang, but rather may have taken place in "little bangs" early in the life of galaxies.[74] There is some support for this point of view in optical observations of a galaxy-to-galaxy variation of helium abundance[75] which would not be expected if the helium was produced uniformly in the big-bang.

As was stated in section 1, the upper limits which exist on anti-nuclei in the cosmic radiation (see summary of Ivanova et al.[76]) do not conflict with the existence of antimatter in other galaxies in accord with BSBB cosmology.

8. Conclusion

Both the encouraging aspects and the problems of BSBB cosmology should serve as an impetus for future work. Particularly significant areas for research are (1) the implications of recent advances in particle physics for the phase transition epoch, (2) a more complete treatment of the coalescence process, and (3) a more complete treatment of the galaxy formation process. In this short conceptual review, it has only been possible to touch briefly and qualitatively on these areas. However, it is hoped that the reader will now have some better feeling for this presently unorthodox but exciting and potentially vastly rewarding field of modern astrophysical cosmology.

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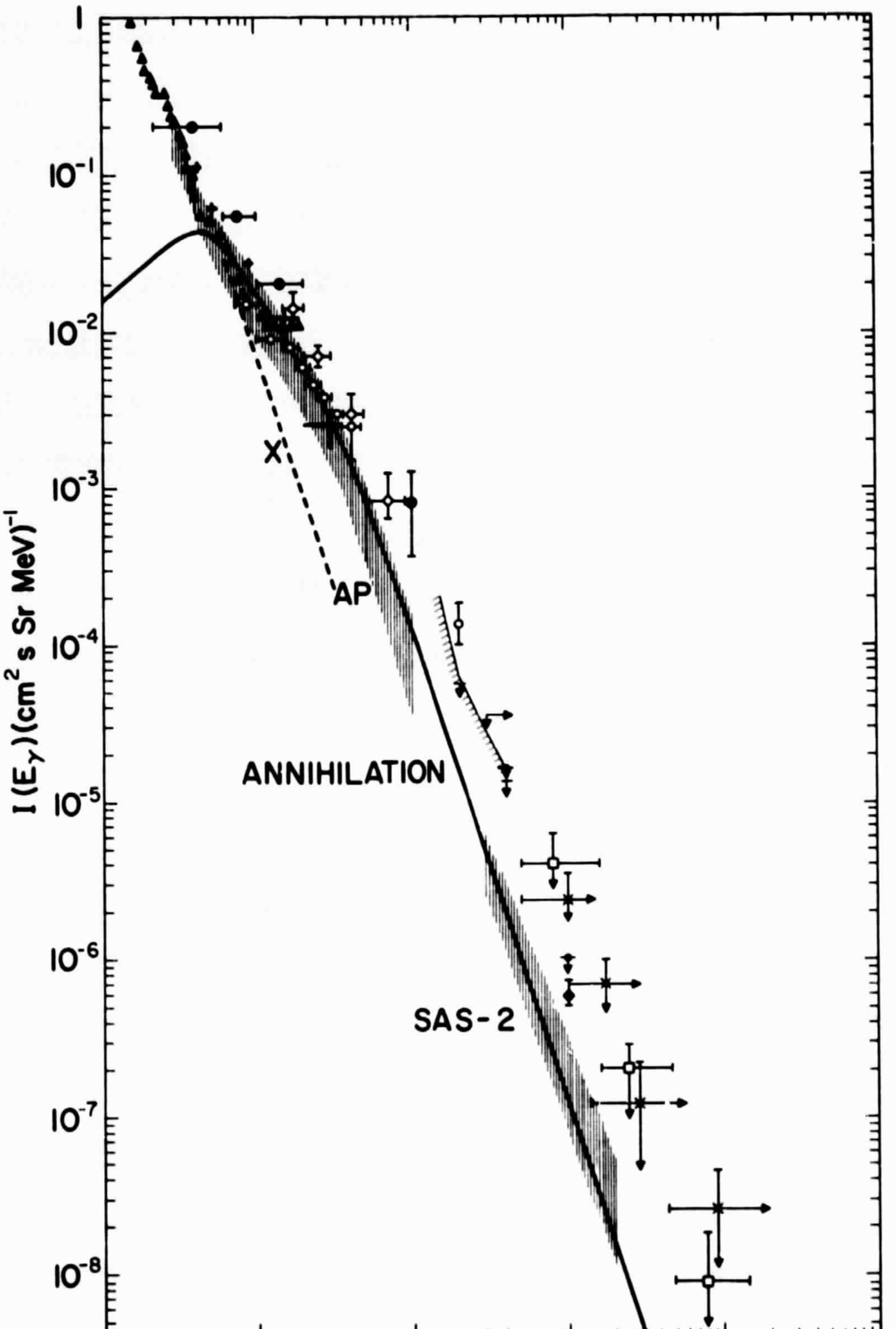
Fig. 1 Theoretical matter-antimatter annihilation spectrum and observational data on the cosmic background γ-radiation. Points with arrows show upper limits from balloon data. The black diamond, representing the OSO-3 satellite data[6] contains a probable contribution of high latitude galactic γ-rays[54]. Data from the Apollo flights[56] and the SAS-2 satellite[54] are shown as shaded areas.



1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$I(E_\gamma)(cm^2\ s\ Sr\ MeV)^{-1}$
X
AP
ANNIHILATION
SAS-2
0.1
1
10
10^2
10^3
10^4
E_γ (MeV)

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16. Abstract

The framework of baryon-symmetric big-bang (BSBB) cosmology offers our greatest potential for deducing the evolution of the universe as a consequence of physical laws and processes with the minimum number of arbitrary assumptions as to initial conditions in the big-bang. In addition, it offers the possibility of explaining the photon-baryon ratio in the universe and how galaxies and galaxy clusters are formed. BSBB cosmology also provides the only acceptable explanation at present for the origin of the cosmic γ-ray background radiation.

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