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Abstract:

We suggest that grand unified field theories with spontaneous symmetry breaking in the very early big-bang can lead more naturally to a baryon symmetric cosmology with a domain structure than to a totally baryon asymmetric cosmology. The symmetry is broken in a randomized manner in causally independent domains, favoring neither a baryon nor an antibaryon excess on a universal scale. Arguments in favor of this cosmology and observational tests are discussed.

Two basic schemes for baryon-symmetric big-bang cosmologies have been suggested. One scheme has it that regions containing excess baryons existed apart from regions containing excess antibaryons as an initial condition of the big-bang.[1] The other, more ambitious picture is that of an initially globally (universally) symmetric big-bang where a small scale dynamical separation of matter and antimatter follows. Like regions then coalesce into astronomically large domains.[2] A review of these symmetric cosmologies and their consequences together with a large list of references may be found in Ref. 3, but we should mention that one of the long-standing attractive features of such theories is the explanation of the origin and spectrum of the observed cosmic background γ-radiation.

In spite of the pleasing initial and overall symmetry of the above schemes, the case against antimatter existing anywhere on a large scale in the universe has been made and has a pervasive influence in present thinking about cosmology.[4] If this alternative view is correct, we seem to be up against the baryon excess as an initial condition, ex nihilo. However, advocates of this alternative can, on the face of it, be heartened by recent developments in elementary particle theory involving baryon-non-conserving forces in grand unified field theories. Perhaps an initial, aesthetic baryon symmetry is broken in an early stage of the universe by leptoquark interactions.[5-10] (Even if there was an initial baryon excess, leptoquark interactions would first restore and then break the overall baryon symmetry as the universe cools). Such interactions will also provide for proton decay with a lifetime $\leqslant 10^{32}$ years or so,[11] a prediction which is the basis of some new experimental proposals[12,13] and may soon be tested. It is even said that the matter-antimatter asymmetry is the first good thing about proton instability, the latter being hard to avoid in grand unified theories.[14]

Thus a popular scenario is that the universe has the observed baryon number to photon number ratio of about 10^{-9} throughout as the result of baryon nonconservation. A universal symmetry has evolved to a universal asymmetry. We believe, on the other hand, that the assumption of a universal asymmetry may not be justified. We argue in this paper that in fact the microscopic physics involved may very well maintain an overall, universal symmetry in the present epoch through a network of random domains of varying degrees of baryon excess, positive and negative.

There are three important considerations:

(1) Owing to the finite age of the universe, t_u, regions separated by distances greater than the event horizon ct_u are not and never were in causal contact.(15)

(2) The symmetries of the particle interactions involved in obtaining theoretical estimates of the baryon excess change as the universe cools. In those theories where at least part of the CP (charge conjugation X parity) violation arises from spontaneous symmetry breaking, we need thermal disequilibrium, baryon non-conservation, C and CP violation for a net effect. We start with CP symmetry at high temperatures (energies) and achieve a "soft" CP asymmetry at low temperatures. (There may be additional "hard" CP violation throughout the temperature range.)

(3) There is no way of determining a priori which way such CP breaking will occur. From the continuous set of vacuum states admitted by the Lagrangian with which we begin, the resulting degree of CP violation from spontaneous symmetry breaking may be fixed at random. Indeed, the choice of sign in the existing calculations has never been questioned. (Never mind the fact that one could change the definition of which field represents the quark or the antiquark.)

Thus, if there is additional CP symmetry breaking at time t^*, it should be broken in such a way that regions separated by distances greater than ct^* will have <u>independent phases</u> in the symmetry breaking parameters. Whatever the possible subsequent evolution of these domains[16-17] and coalescence processes occurring in the quark or baryon interactions which follow[18-21], it appears that causality does not permit the generation of a universal asymmetry from the spontaneous symmetry breaking process. Rather, one might expect a domain structure not unlike the domain structure generated when a piece of ferromagnetic material cools without the presence of an external magnetic field. In that case, spin-spin interactions produce a phase transition to a state where the directional symmetry of the Lagrangian becomes hidden on a small scale owing to a spontaneous symmetry breaking into a mosaic of independent domains, each of which contains atoms having their magnetic moments aligned in a given direction. On the average, there will be no preferred direction on a global scale. Analogously, one may expect that spontaneous symmetry breaking processes in the early big-bang will most likely break baryon symmetry in localized regions of the universe, but will preserve the overall global matter-antimatter symmetry of the initial state. Thus, present ideas of unified gauge theories with spontaneous symmetry breaking can lead more naturally to a baryon-symmetric cosmology[3], as opposed to the totally asymmetric cosmology implicit in the work of previous authors.[5-10]

We now focus on the relationship between fundamental parameters in the symmetry breaking and the astrophysical baryon asymmetry. In general the asymmetry is proportional to a parameter ξ which characterizes CP violation.[5-10] Let us introduce the CP phase parameter δ where

$$\xi \propto \sin \delta \qquad (1)$$

If δ takes on random values in different domains, we cannot achieve a uniform baryon excess throughout the universe. That δ is randomized follows if it is an appropriate linear combination of vacuum-expectation-value phases α_i, e.g.,

$$\delta = \sum_i N_i \alpha_i \tag{2}$$

where N_i is an integer. More complicated, and perhaps more realistic, relations $\delta(\alpha_i)$ may have the same effect.

Although there has been a good deal of interest in understanding CP non-invariance through spontaneous symmetry breaking[22], the specific gauge model relationships giving $\delta(\alpha_i)$ have received little attention. Thus, an example may be helpful. The general idea is that the Yukawa terms give rise to a fermion mass matrix after the scalar fields are translated. For a four-quark left-right symmetric model with two Higgs doublets, patterned after that of Ref. 23, a mass matrix of the form

$$M = \begin{pmatrix} ae^{i\alpha_1} & ce^{-i\alpha_2} \\ ce^{-i\alpha_2} & be^{i\alpha_1} \end{pmatrix} \tag{3}$$

holds for quark pairs of a given charge. This symmetric matrix can be diagonalized by a biunitary transformation $U_L M U_R^{-1}$, where

$$U_L = U_R^{\star} = \begin{pmatrix} \cos\theta & e^{i(\delta/2)}\sin\theta \\ -e^{i(\delta/2)}\sin\theta & \cos\theta \end{pmatrix} e^{i\varphi}. \tag{4}$$

Neglecting the masses of the first generation quarks, i.e. m_u, $m_d \ll m_s$, m_c, we obtain the relation $\delta = 2(\alpha_1 + \alpha_2)$ for this model.

As one goes about calculating $\delta(\alpha_i)$ for the various grand unified theories, there are two extremes to keep in mind. On the one hand, we must consider a sufficiently rich Higgs sector such that the phases α_i could not all be simply redefined into the fermion fields. On the other hand, variations in α_i may change more than δ. In general, different breaking directions may lead to quite different physics for a given model. However, the breakdown of SU(5) to

SU(3)⊗SU(2)⊗U(1) can be independent of the phases if the Higgs potential parameters are so restricted.[24,25]

In the light of the above discussion, we suggest that the initial domains formed at a time when the temperature of the universe was comparable to the masses of the superheavy gauge or Higgs bosons involved in the symmetry breaking. The initial domains could then have acted as nuclei for triggering growth to much larger sized regions. Although an examination of possible growth mechanisms is beyond the scope of this paper, several possibilities come to mind. One is domain growth through CP-violating instanton transitions.[26] Another relevant scheme involves not the Higgs fields, but the quarks. In this regard, possible mechanisms involving quark-gluon Leidenfrost effects and quark clustering remain to be explored.

At lower temperatures, nuclear effects and Leidenfrost effects have been suggested[2] and studied up to the stage of galaxy formation as mechanisms for increasing the size of domains to encompass masses on the scale of galaxy clusters.[3] Such explorations have shown that globally baryon symmetric cosmology can lead more readily to galaxy formation than can the standard totally asymmetric cosmology.[18,20] It is important to note in this context that among cosmological models involving spontaneous symmetry breaking in grand unified theories, the standard asymmetric model requires an even stronger domain growth so that the whole universe becomes the final domain! The only other alternative is to put in an ad hoc hard CP violation without knowing over what size scale it applies. However, it is not clear that such a gauge theory with an external CP-violating piece in the Lagrangian would preserve the attractive aspects of the spontaneous-symmetry-breaking models for CP violation, such as renormalizability.

While we cannot claim that the arguments presented above constitute a proof for the baryon-symmetric domain-type cosmology, there are recent astrophysical data which tend to support this point-of-view. In addition to the data on the cosmic γ-ray background mentioned previously, two other pieces of evidence have presented themselves.

The first additional piece of evidence comes from new and striking results on the distribution of galaxies in the universe. Not only do galaxies form clusters, but also these clusters of galaxies are not uniformly distributed; they cluster into superclusters. Between the superclusters are large voids - regions with a very low (possibly zero) space density of galaxies.[27-29] The existence of these holes, which is difficult to understand in the context of standard big-bang cosmology, is the kind of structure which can arise from a domain-type universally symmetric cosmology. The cosmic background γ-radiation originating from supercluster boundary annihilations[3] should exhibit angular fluctuations which can best be studied with a high-resolution detector[30] such as the 100 MeV spark chamber detector proposed for a future satellite "Gamma Ray Observatory".

The astronomical observations of the non-uniform "cell structure" distribution of galaxies also gains credence with the third piece of evidence of nonuniformity, which comes from studies of the origin and propagation of ultrahigh energy cosmic rays (UHCR). It was pointed out some time ago, when the microwave background radiation was discovered, that the lifetime of UHCRs should be cut short by their interaction with the background radiation.[31,32] The result should be a high-energy cutoff in their energy spectrum which is not in accord with observation. Various hypothesis have been proposed to account for the lack of a cutoff and detailed calculations have been made. After careful consideration of all the evidence it appears that the explanation lies in a true non-uniformity of the sources of these particles with the observed

UHCRs coming mainly from within the local supercluster of which our galaxy is a member.(33,34) The obvious inference is that immediately beyond the region of the local supercluster is a dearth of UHCR sources. Making the logical assumption that UHCRs are produced in galaxies or radio sources, we would then infer a real dearth of galaxies between the superclusters, supporting the domain structure viewpoint.

The bedrock of this viewpoint has been spontaneous symmetry breaking in the early big-bang. This may solve the strong CP problem and keep renormalizability. We are thus led to the seeds whose growth may give cluster or supercluster domains-cells of matter and antimatter. In this framework, there must be constraints on gauge theory model building and symmetry breaking, depending on the nature of the physics implied for different domains. (Of course, CP violation changes from domain to domain.) Quantities such as fermion mass ratios, P violation parameters, and gauge group breakdown patterns can depend upon the vacuum-expectation-value phases so that the models must be constrained by the tests of observational cosmology. It is both interesting and important to note that such observations are of limited scope and that many high-energy laboratory observables (e.g., heavy quark masses) cannot readily be determined for other parts of the universe. However, the proton-electron mass ratio is an example of a quantity which cannot be violently tampered with, since it affects the frequency of observable line spectra. But even in this case, a <u>small</u> effect can be blurred by the cosmological redshift. The scenario presented here thus poses a challenge for both the gauge theory model builder and the observational astronomer.

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