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GRAND UNIFICATION, THE NEUTRON ELECTRIC DIPOLE MOMENT
AND GALAXY FORMATION

John Ellis
CERN - Geneva

Mary K. Gaillard
LAPP, Annecy-le-Vieux, France

and

D.V. Nanopoulos and Serge Rudaz
CERN - Geneva

A B S T R A C T

It has been argued that in a Robertson-Walker-Friedmann Universe grand unified theories (GUTs) only generate adiabatic perturbations, while galaxies probably evolved from isothermal perturbations. These may have arisen from inhomogeneous shear in an anisotropic early Universe. We strengthen a recent lower bound on the neutron electric dipole moment d_n in terms of the of the baryon asymmetry generated by GUTs, and argue that in many models d_n should be within one order of magnitude of the present experimental upper limit. Large shear dissipated after baryon generation would increase d_n above this lower limit, and the present experimental upper bound on d_n strongly constrains the permissible amount of this shear without jeopardizing the isothermal perturbations desirable for galaxy formation. The dipole moment serves as a cosmological seismometer.

Grand Unified Theories (GUTs) provide a possible solution to the long-standing cosmological problem of the apparent asymmetry between matter and antimatter ¹⁾. The mechanism for baryon generation that they propose leads ²⁾ to adiabatic perturbations ($\delta T/T \approx \frac{1}{3}(\delta \rho/\rho)$) in a Robertson-Walker-Friedmann (RWF) Universe. However, astrophysical observations tend to favour isothermal perturbations as the origin of galaxies and other large-scale structures in the Universe ³⁾. A particularly severe problem is the apparent quadrupole anisotropy recently discovered ⁴⁾ in the microwave background radiation, which in an adiabatic model would probably imply ⁵⁾ dipole anisotropy in excess of observation ⁶⁾, though this discrepancy might be reduced ⁵⁾ if there were massive neutrinos. Although adiabatic perturbations are probably not yet excluded as the origin of galaxies, it becomes very important to understand whether isothermal perturbations are compatible with the GUT mechanism for baryon generation.

Several scenarios have been proposed ⁷⁾⁻⁹⁾ for creating isothermal perturbations by deviating from a strict RWF cosmology. These include the explosions of primordial black holes (PBHs) which themselves originate from adiabatic perturbations ^{7),8)} and inhomogeneities in curvature, vorticity, the cosmological constant or shear ^{8),9)}. Alternatively, isothermal fluctuations could arise in an RWF model when CP is violated ⁸⁾ softly at a GUT phase transition preceded by an inflationary de Sitter epoch ¹⁰⁾.

It has been argued that the isothermal modes generated by PBH explosions would be overwhelmed by the growing adiabatic modes associated with the formation and explosion of the holes. Curvature fluctuations would have to be uselessly small ⁹⁾ in order to avoid the domination of the present Hubble expansion by scalar curvature, and they would in any case give rise to growing adiabatic perturbations which would overwhelm the isothermal perturbations ⁸⁾. Fluctuations in the cosmological constant could occur during a phase transition in the early Universe, but they would presumably be restricted to the size of the horizon at that time, and hence much smaller than the scale of a galaxy ⁹⁾. Perhaps fluctuations could be generated on a larger scale if the causally connected domains were blown up by a period of de Sitter expansion during a first order GUT phase transition. It is difficult to follow up this possibility in the absence ¹⁰⁾ of a convincing mechanism for terminating the transition. The soft CP violation proposal ⁸⁾ relies on a similar idea of expanding exponentially a small sub-horizon region to become a large region which then breaks CP spontaneously in a correlated way. Quite apart from the problem of boundaries between domains where CP is violated differently, we object to this proposal because in a model of spontaneous CP violation one cannot know during the symmetric phase how CP will be violated

subsequently. Some as yet unknown mechanism has to be invented for "encoding" the instructions for the mode of breakdown before the de Sitter phase starts, storing the information during the inflationary period, and then "decoding" the message in parallel in a myriad of separated domains. The same hurdle has to be crossed ¹¹⁾ if one is to suppress monopole production in an inflationary Universe ¹⁰⁾.

In view of these considerations, we concentrate in what follows on inhomogeneous shear ^{8),9)} as a possible source of isothermal fluctuations. This may be the most natural and attractive possibility, since there is no direct evidence that the RWF metric is applicable in the very early Universe. One is naturally led to consider more general anisotropic models like the simple Bianchi type I cosmologies in which there is primordial shear. Since the local expansion rate depends on the amount of shear $\Sigma \equiv (\sigma^2/8\pi G_N \rho)$, and the baryon asymmetry generated depends in turn on the rate of expansion, so

$$\delta(n_B/n_\gamma) [n_B/n_\gamma]^{-1} \sim \delta\Sigma/\Sigma$$

for large shear Σ , and $\sim \delta\Sigma$ for small shear Σ . One might question whether a large enough shear could exist during the period of baryon number generation when the temperature $T \sim 10^{15}$ GeV. In addition to the normal diminution of shear: $\Sigma(T) \sim T^2$, dissipative processes due to the grand unified viscosity ¹²⁾ associated with the long mean free paths of elementary particles at temperatures $\gtrsim 10^{15}$ GeV might wash out some of the shear before the baryon number was generated, or might dilute the baryon-to-entropy ratio by creating more entropy after the baryon asymmetry was established. Preliminary estimates ¹²⁾ of the grand unified viscosity are roughly confirmed by more careful calculations ⁹⁾ which indicate that all the shear is not dissipated before baryon generation, but that an extra entropy factor

$$E \simeq \left[\Sigma(m_X) \Delta \overline{(a_0/a)^2} \right]^{3/4} \quad (1)$$

can be created after baryon generation. In formula (1), $\overline{(a_0/a)^2}$ is a ratio of scale sizes $\gtrsim 10^{-2}$ while Δ is rather slippery to estimate ⁹⁾: for illustrative purposes we take it to be $\Delta \cong 10^{-3} \Sigma(m_X)^{-1/2}$. The present non-zero $n_B/n_\gamma \gtrsim 2 \times 10^{-10}$ [?Ref. 13] means that the factor E , and hence the shear $\Sigma(m_X)$ cannot be too large ⁹⁾. Since the original CP violating baryon asymmetry must be $\lesssim O(\alpha/\pi)$, one can deduce from (1) that $\Sigma(m_X) \lesssim O(10^{29})$. This limit on shear is already many orders of magnitude better than the present best limit from nucleosynthesis ^{14),15)} which leads to $\Sigma(m_X) \lesssim O(10^{36} \text{ to } 10^{42})$. However, it is possible to do rather better than this limit, as we will now see.

In a recent paper ¹⁶⁾ we have argued that in a class of GUTs, diagrams analogous to those giving (n_B/n_Y) also contribute to renormalization of the QCD θ parameter and hence indirectly to the neutron electric dipole moment d_n , giving an order of magnitude lower bound

$$d_n \gtrsim O(2.5 \times 10^{-18}) \times E \times \left(\frac{n_B}{n_Y} \right) \text{ e-cm} \quad (2)$$

where E is now the total unexpected entropy generated by hiccups in the expanding Universe at $T < m_X \simeq 10^{15}$ GeV. Setting ¹³⁾ $(n_B/n_Y) \gtrsim 2 \times 10^{-10}$ and using the latest experimental upper bound ¹⁷⁾ on d_n of 6×10^{-25} e-cm, we find from (2) that

$$E \lesssim 1.2 \times 10^3, \quad \Sigma(m_X) \lesssim O(10^{16}) \quad (3)$$

This bound on $\Sigma(m_X)$ is similar to that quoted by Bond, Kolb and Silk ⁹⁾, but does not depend on a guess at the primordial CP violating parameter responsible for baryon generation.

Our bound is actually rather conservative, since d_n is considerably larger than the lower bound (2) in all the GUTs we have studied. For example, in an $SU(5)$ model with just one $\underline{5}$ representation of Higgs fields, d_n is larger ¹⁸⁾ by a factor of $O((\alpha_H/\pi)^{-2}) \equiv O((\alpha m_q^2/\pi^2 m_W^2)^{-2})$ than the lower bound (2). However, this model has difficulties in getting a large enough (n_B/n_Y) . The conventional three-generation model certainly gives too small a ratio ¹⁹⁾, while going to four generations may appear to give a large enough CP violation if one neglects ²⁰⁾ the evolution of quark mass parameters between present energies and 10^{15} GeV. However, one expects ²¹⁾ the effective quark masses to diminish by a factor of 3 in this energy range, thus diminishing the attainable CP violation by a factor of $3^6 \simeq O(10^3)$, while the masses of the fourth generation fermions are restricted by the stability of the Higgs potential ²²⁾. In any case the phenomenological ratio of the b quark and τ lepton masses argues against ²¹⁾ increasing the number of generations beyond 3. In an $SU(5)$ model with two $\underline{5}$ representations of Higgs fields ²³⁾, the leading contribution to d_n is expected to be $O((\alpha_H/\pi)^{-1}) = O((\alpha m_q^2/\pi^2 m_W^2)^{-1})$ larger than the bound (2), and comes via renormalization of the QCD θ vacuum parameter due to the diagrams in the figure. However, it is possible neither to make a quantitative estimate nor to exclude a cancellation in this order because of the arbitrariness of the Yukawa coupling parameters. In an $SU(5)$ model with a $\underline{5}$ and a $\underline{45}$ of Higgs fields ²⁴⁾ the leading contribution to d_n is $O((\alpha/\pi)^{-1})$ larger than the bound (2), provided one takes the plausible point of view that most of the baryon asymmetry is generated by Higgs boson

decay. In fact the observed m_b/m_τ ratio suggests that the masses of these heavy fermions do not get a substantial contribution from a $\frac{45}{24}$ of Higgs, though there may be a rôle for it in lighter fermion masses ²⁴⁾. Both these SU(5) models with two Higgs representations contributing masses to fermions suggest $\theta \sim (\alpha/\pi)m_q^2/m_W^2$ and hence values for d_n very close to the experimental upper limit. Thus we see that the need to complicate GUTs to get a large enough baryon asymmetry may have other observable consequences.

On the basis of the three models discussed in the preceding paragraph, we are tempted to strengthen our previous ¹⁶⁾ bound (2) to

$$d_n \gtrsim O\left(\left(\frac{\alpha}{\pi}\right)^{-1} \times 2.5 \times 10^{-18}\right) \times E \times \left(\frac{n_B}{n_\gamma}\right) \gtrsim O(6 \times 10^{-26}) E e^{-am} \quad (4)$$

so that the entropy factor $1 \lesssim E \lesssim O(10)$ and $\Sigma(m_X) \lesssim O(10^{12})$, but this may be premature until we know which is the right GUT. Even if we did know our GUT, the calculational uncertainties are unlikely ever to exclude a factor of 10 extra entropy generation, and so $O(10^{12})$ is likely to be the best bound on primordial shear that one could ever obtain in this way. Since the minimal shear inhomogeneity $\delta\Sigma(m_X)$ that one needs is $O(10^{-3})$, this line of argument is never likely to exclude the reconciliation of GUTs and galaxy formation from isothermal perturbations ⁹⁾. On the other hand, if a neutron electric dipole moment d_n were to show up at a level appreciably higher than that expected if $E=O(1)$, it would suggest that the Universe may have had an irregular expansion subsequent to baryon generation. In our previous paper ¹⁶⁾ we pointed out that this argument raised a problem for the idea of breaking the Weinberg-Salam SU(2) symmetry by radiative corrections, because of the excess entropy ²⁵⁾ this would generate when $T \sim 1$ GeV. In this paper we have pointed out that d_n tells us something significant about primordial shear. The neutron electric dipole moment is a sensitive cosmological seismometer.

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FIGURE CAPTION

Third order renormalizations of the Higgs-fermion-fermion vertex which change θ in an $SU(5)$ model with two $\underline{5}$ representations of Higgs fields. The dashed lines are Higgses, the solid lines $\underline{10}$ fermions and the zigzags are $\underline{5}$ fermions.