PRIMORDIAL MAGNETIC FIELDS AND SYMMETRY RESTORATION

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Abstract. In the standard cosmological model symmetry breaking in grand unified theories will occur at times $\sim 10^{-39}$ s after the initial singularity when the Universe has cooled to a temperature $\sim 10^{16}$ GeV. We investigate here whether it is possible for a uniform, large-scale, magnetic field present in the early universe to delay significantly the time at which symmetry breaking occurs. Given the present magnitude of the intergalactic B-field ($\lesssim 10^{-11}-10^{-9}$ G) it is found that no significant effects are introduced.

1. Introduction

In the past few years much progress has been made in describing the strong, weak, and electromagnetic interactions between the fundamental particles. With the recent experimental observations of the $W^\pm$ and $Z^0$ bosons predicted by the SU(2) x U(1) electroweak theory of Glashow, Weinberg, and Salam, theorists have begun to speculate on the possibility of unifying all three fundamental forces under one gauge group. Such grand unified theories (GUT's) predict the symmetry breaking that separates the strong and electroweak forces will occur at energies of order $10^{15}-10^{16}$ GeV. Such energies are clearly beyond the realm of terrestrial experimentation and almost by default the early universe is probably the only testing ground we have where such energies should have existed.

The standard big-bang scenario envisages the Universe to be infinitely hot and dense at the initial singularity, cooling to temperatures of order $10^{16}$ GeV after some $10^{-39}$ s—GUT symmetry breaking should generally occur around this time. The SU(2) x U(1) gauge group undergoes symmetry breaking at much lower energies $\sim 100$ GeV which corresponds to a time some $10^{-11}$ s after the singularity.

Large-scale magnetic fields can be incorporated in the standard big bang model under certain conditions (Zeldovich, 1965, 1970), they are generally ignored under most conditions. However, it is our purpose in this paper to investigate the consequence of a homogeneous magnetic field present in the early universe paying particular attention to the effects it might have at the time of GUT symmetry breaking.

2. A Magnetic Universe?

Astronomical systems supporting magnetic fields have been observed on all scale lengths up to and including galactic dimensions. The maintenance of these fields is in most cases unclear but the origins can possibly be described by hierarchical arguments, that is, assuming flux conservation we can construct stellar B-fields from interstellar

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magnetic fields which are in turn derived from an overall galactic field. Enhanced magnetic fields in stellar objects such as magnetic Ap stars \( (B \lesssim 10^4 \text{ G}) \) and RSCVn binaries are then further explained on the basis of magnetic dynamos where surface convection and rotation have conspired to enhance the surface field (Mestel, 1981). In the limit of this hierarchical argument of obvious importance is the origin of the galactic field \( (B_g \approx 10^{-6} \text{ G}, \text{Heiles, 1976}) \): is it derived from a ‘primeval’ B-field as first suggested by Hoyle (1958), or is it the result of large-scale dynamo action in the interstellar medium as proposed by Parker (1971, 1975). At the present time we defer the arguments for and against such models (see Beech, 1985) and throughout this paper we consider the galactic field to be the fossil remnant of a primeval intergalactic magnetic field formed with the matter in the initial big bang (Piddington, 1974, 1981; and Wasserman, 1978).

3. The Intergalactic Magnetic Field

The presence of an intergalactinetic field can be inferred directly from observations of Faraday rotation in extra galactic radio sources. This method was first applied by Sofue et al. (1968) and more recently by Vallee (1983). An indication of how difficult it is to interpret such observations is exemplified by the two orders of magnitude difference in the results. Sofue et al. (1968) found \( B_{IG} \sim 10^{-9} \text{ G} \) while Vallee (1983) finds \( B_{IG} \lesssim 10^{-11} \text{ G} \). Kawabata et al. (1969) used an alternative method to constrain the upper limit of the present day intergalactic B-field by utilizing measurements of the radio and X-ray background radiation (the former being due to synchrotron radiation from the relativistic electrons responsible for the X-ray background radiation produced via Compton scattering with microwave background photons). An upper limit of \( G_{IG} \lesssim 10^{-8} \text{ G} \) was found. This increases the observational discrepancy to three orders of magnitude! Although many estimates of the possible intergalactic field strength have been made (see Beech, 1985) it seems prudent at this stage to parameterize its value between the limits \( 10^{-11} \) to \( 10^{-7} \text{ G} \); noting, however, that the more recent data suggests the smaller upper limit is more probably (Vallee, 1983).

3. Anisotropic Cosmoiogies

Under the working hypothesis of a primeval origin for the intergalactic field we now have to consider the effects such a magnetic field might have on the early universe.

The standard big bang model is based on the cosmological principle which requires the Universe to be isotropic and homogeneous at all times. The best evidence for the validity of this principle is provided by observations of galaxy distributions and the microwave background. The distribution of galaxies across the sky is isotropic to about 30\% (McCullum, 1979) and has been investigated out to a distance of \( \sim 2000 \text{ Mpc} (H_0, \text{the present value of Hubble's constant is taken as } 50 \text{ km s}^{-1} \text{ Mpc}^{-1}) \). Clustering of galaxies occurs on a scale-length \( \sim 10 \text{ Mpc} \) with superclustering on scales \( \sim 100 \text{ Mpc} \) (Oort, 1983). Over the largest observable dimensions \( \lesssim 6000 \text{ Mpc} \) the Universe is highly isotropic (Barrow, 1982) with variations in the microwave background of order