

## Polarization of the Microwave Background in Defect Models

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We compute the polarization power spectra for global strings, monopoles, textures, and nontopological textures, and compare them to inflationary models. We find that topological defect models predict a significant ( $\sim 1 \mu\text{K}$ ) contribution to magnetic type polarization on degree angular scales, which is produced by the large vector component of the defect source. We also investigate the effect of decoherence on polarization. It leads to a smoothing of acoustic oscillations both in temperature and polarization power spectra and strongly suppresses the cross correlation between temperature and polarization relative to inflationary models. Both effects should be testable with the next generation of CMB satellites. [S0031-9007(97)03907-0]

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Fluctuations in the cosmic microwave background (CMB) have the promise to become the most powerful testing ground of cosmological models today. Their main advantage is that they test the universe in its early stages of evolution, when it was much simpler than it is today. The physics that determines the fluctuations is well understood and the small amplitude of perturbations allows one to use linear perturbation theory to perform the calculations to almost arbitrary accuracy. Moreover, theoretical predictions are very sensitive to various cosmological parameters, holding the promise of their determination to a high precision. It has long been recognized [1] that polarization in the microwave background shares these same advantages, but is sensitive to somewhat different physical processes and as such would provide a valuable complementary information to the temperature measurements. Although the amplitude of polarization is typically less than 10% of temperature and has not yet been observed so far, the sensitivity of future experiments such as MAP and Planck satellites should allow one to map polarization with a high accuracy over a large fraction of the sky. In particular, the temperature-polarization cross correlation offers particular promise as a clean observational signature well within reach of the next generation of CMB satellite measurements [2,3]. In addition, it was recently shown that polarization Stokes parameters  $Q$  and  $U$  can be decomposed into electric ( $E$ ) and magnetic ( $B$ ) components [4,5], which have opposite parities allowing one to make a model independent identification of nonscalar (i.e., vector or tensor) perturbations.

Most previous work on polarization has concerned the predictions of inflationary models, where power spectra are easy to compute with a high accuracy, allowing one to propose several high precision tests of cosmological models. In contrast, the competing theories of cosmic structure formation, based on symmetry breaking and phase ordering, have been plagued by calculational difficulties

preventing firm conclusions from being drawn. These theories involve a stiff causal source comprising the ordering fields and/or defects, which continually perturb the Universe on ever larger scales. Both the nonlinear evolution of the source and a full linear response theory for the linearized Einstein/fluid/Boltzmann equations are required to compute power spectra in such models. Recently, the first accurate calculations of power spectra in global defect models covering all observational scales of interest have been presented [6], employing a new two-stage calculational method. First, an accurate numerical code for field evolution is used to measure the unequal time correlator of the defect source stress energy tensor  $\Theta_{\mu\nu}$ . This quantity uses all the information present in the simulations, incorporates the powerful property of scaling evolution, and preserves enough information needed to compute all power spectra of interest. In the second part of the calculation, the unequal time correlator is decomposed into a sum of coherent sources, each of which can be fed into the linearized Einstein/fluid/Boltzmann equations, which are evolved using a modified CMBFAST code [7] from the early epoch until today. Contributions from individual coherent sources are then added together incoherently to obtain the total power spectrum of interest. Several independent tests all give consistent results to within about 10%.

The results of this calculation indicate that in symmetry breaking theories a significant component of CMB anisotropies on large scales is contributed by vector and, to a lesser extent, tensor modes, in addition to the usual scalar modes. The shallow peak in the power spectrum, typically around  $l \sim 100$ , is determined by the vector modes that are only weakly dependent on cosmological parameters. In addition, the defect stress-energy tensor, whose evolution is nonlinear, is continuously sourcing the metric perturbations, which in turn are sourcing the fluids. This leads to a decoherence: even though fluids are

oscillating in different regions of the universe, these oscillations may be out of phase with each other and do not show up when averaged over the whole sky. Calculations indicate that decoherence leads to a partial or complete destruction of acoustic oscillations. As a consequence of these two features, varying cosmological parameters has a smaller effect on the temperature spectrum than in inflationary models.

The significant amount of power seen in degree scale experiments compared to COBE already poses problems for this class of models [6], although given the difficulty of these measurements one would require further confirmation with the future observations before completely ruling them out. Moreover, it is possible that a modified version of symmetry-breaking models that satisfies the current observational constraints will be found, and so it is important to investigate other properties of this class of models. In this Letter we concentrate on polarization of CMB and show that it has several characteristic properties that enable one to distinguish the defect models from inflationary models.

*Electric and magnetic polarization.*—Polarization in the microwave background is created by Thomson scattering of photons on electrons. However, if the photon distribution function has zero quadrupole moment in the electron rest frame, then no polarization can be generated. Before electron-proton recombination the photon mean free path is very short and the system forms a perfect fluid, whose phase space density has only monopole and dipole moments nonzero. After recombination the photons start to free stream, which generates the quadrupole and higher moments of the distribution function. At the same time the probability for Thomson scattering rapidly decreases, so polarization can only be generated during recombination. Its amplitude will in general be smaller than the amplitude of temperature fluctuations. These processes are generic, and one expects some amount of polarization to be present irrespective of the specific cosmological model. However, symmetry-breaking models differ from inflationary models in several aspects, of which the two most important are the relative contributions from scalar, vector, and tensor modes and decoherence. We will show below that both lead to a very distinctive signature in polarization.

Temperature and polarization spectra for various symmetry breaking models are shown in Fig. 1. Both electric ( $E$ ) and magnetic ( $B$ ) components of polarization are shown. We also plot for comparison the corresponding spectra in a typical inflationary model, which we have taken to be the standard cold dark matter (CDM) model ( $h = 0.5$ ,  $\Omega = 1$ ,  $\Omega_b = 0.05$ ) with equal amount of scalars and tensors ( $T/S = 1$ )—the latter model has about as large a  $B$  component as is possible in inflationary models. In all the models we assumed no reionization. The most interesting feature of the symmetry-breaking models is the large magnetic mode ( $B$ ) polarization, with

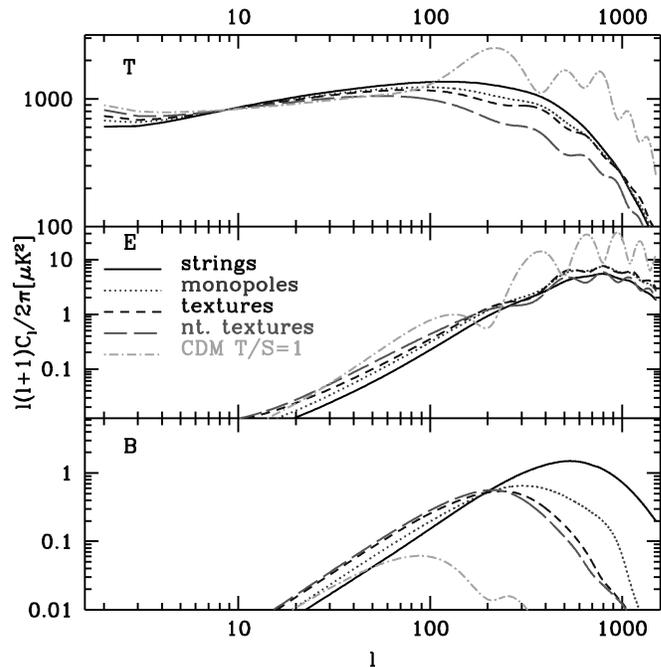


FIG. 1. Power spectra of temperature ( $T$ ), electric type polarization ( $E$ ), and magnetic type polarization ( $B$ ) for global strings, monopoles, textures, and nontopological textures. For comparison we also show the corresponding spectra in a standard CDM model with  $T/S = 1$  (which maximizes the  $B$  component present). Defect models all predict a much larger component of  $B$  polarization on small angular scales.

a typical amplitude of  $1 \mu\text{K}$  on degree scales. For multipoles below  $l \sim 100$ , the contributions from  $E$  and  $B$  are roughly equal. This differs strongly from the inflationary model predictions, where  $B$  is much smaller than  $E$  on these scales even for the extreme case of  $T/S \sim 1$ . The reason for this difference is a combination of different relative contributions from scalar, vector, and tensor modes in the two classes of models and their corresponding contributions to electric and magnetic types of polarization. Relative contributions from each type of perturbations to  $T$ ,  $E$  and  $B$  are shown explicitly in Fig. 2 for the global string model. Inflationary models generate only scalar and tensor modes, while symmetry-breaking models also have a significant contribution from vector modes. Scalar modes only generate  $E$ , vector modes predominantly generate  $B$ , while for tensor modes  $E$  and  $B$  are comparable with  $B$  being somewhat smaller [4,8]. Together this implies that  $B$  can be significantly larger in symmetry-breaking models than in inflationary models.

The amplitudes of  $E$  and  $B$  polarization as a function of scale can be understood qualitatively from the evolution of scalar, vector, and tensor modes. The latter two decay away on subhorizon scales, so on small angular scales only scalar modes are important, hence only  $E$  will contribute there in inflationary models. In such models  $B$  is typically much smaller than  $E$  on degree scales, with the total amplitude less than  $0.3 \mu\text{K}$  in the absence of reionization

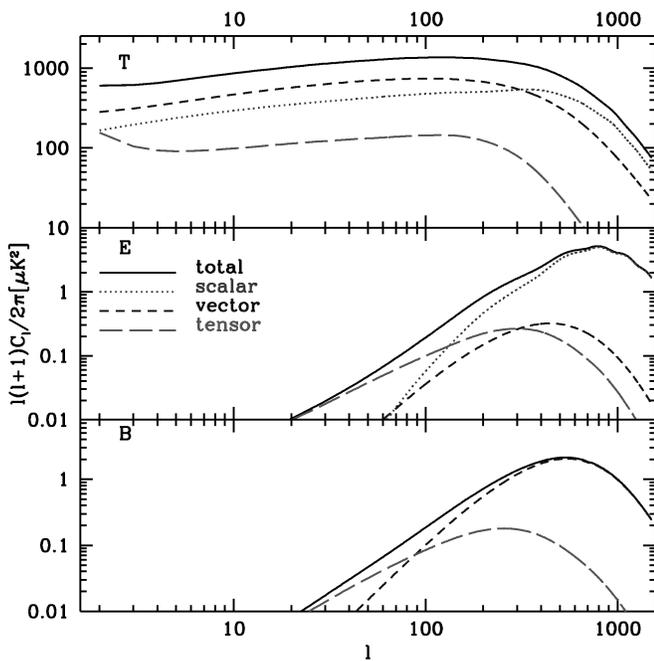


FIG. 2. The breakdown of the contributions to the total power by the scalar, vector, and tensor components for a global string model. Scalars and vectors dominate  $E$  and  $B$  polarization, respectively. Other defect models give qualitatively similar results.

[9], while the amplitude of  $E$  can be several  $\mu\text{K}$  on subdegree angular scales. In symmetry-breaking models most of the  $E$  component is still generated by scalar modes. However, now  $B$  will not be negligible compared to  $E$ , because it is dominated by vectors, which are an important component in the defect source, but do not contribute significantly to  $E$ . Moreover, defects are sourcing fluid perturbations even after horizon crossing, so vectors and tensors are important also on subdegree scales.

*Decoherence.*—Another interesting question is how coherent are polarization spectra in symmetry-breaking models relative to their inflationary counterparts or to the temperature spectra. In general, one expects some degree of decoherence in any symmetry-breaking model [6,10] and this leads to a smearing of characteristic acoustic peaks in the spectrum. Appearance of such peaks is the key requirement for the accurate determination of cosmological parameters, because their amplitude and position depend sensitively on parameters such as baryon and matter density, Hubble constant, curvature, etc. Temperature spectra in the symmetry-breaking model show little or no evidence of acoustic oscillations (Fig. 1 and Ref. [6]). Both velocity and density contribute to temperature and are out of phase in the tightly coupled regime [11], which leads to partial cancellation of the peaks even before decoherence. On the other hand, polarization receives contribution only from velocity of photon-baryon plasma during recombination [11], so for a coherent source the peaks in polarization will be narrower than in tempera-

ture. Note that acoustic oscillations are expected only for scalar modes and hence for  $E$  polarization. The spectra in Fig. 1 confirm this expectation, and acoustic peaks are indeed somewhat more visible in  $E$  polarization than in temperature spectra. However, decoherence still plays an important role, leading to a suppression of peaks, being progressively more important for lower  $N$  (where  $N$  is the dimension of the field). In the case of strings (Fig. 2), acoustic oscillations are completely washed out in temperature and almost nearly so in polarization power spectra.

Decoherence has an even more dramatic effect on the cross correlation between temperature and  $E$  polarization. Here the spectrum can be either positive or negative, so decoherence may actually destroy the cross correlation [12]. In addition, causality requires the correlation to vanish on scales larger than the horizon in defect models [13]. Figure 3(a) shows the cross-correlation power spectra for the defect models studied here, together with the CDM model for comparison. As expected, cross correlation is strongly suppressed in the defect models relative to the inflationary model, having 5–10 times less power. Part of this suppression is simply due to a smaller amplitude of both temperature and polarization in symmetry-breaking models. To correct for that we show in Fig. 3(b) the correlation coefficient  $\text{Corr}_l = C_{Cl}/(C_{Tl}C_{El})^{1/2}$ . On intermediate scales ( $l < 400$ ) cross correlation in coherent models oscillates roughly around zero. Here decoherence can destroy any correlations; in

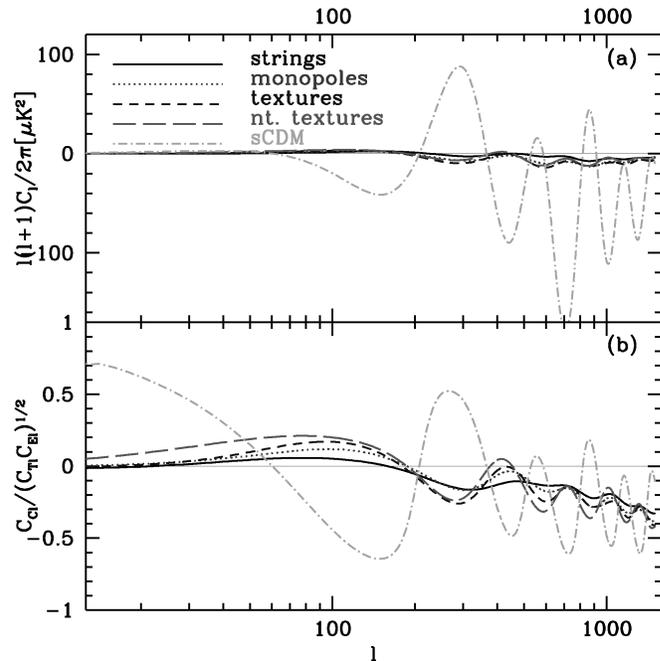


FIG. 3. The cross-correlation power spectrum (a) and the correlation coefficient (b) for the same defect models as in Fig. 1, as well as for the standard CDM model. Defect models predict significantly less power in cross correlation than inflationary models.

practice decoherence is not perfect and some correlations remain, but the correlation coefficient is very small compared to inflationary models. On smaller scales the cross correlation becomes predominantly negative with the more incoherent model (strings) tracing the broadband average of the more coherent ones. The cross correlation in the defect theories is phase shifted by  $\sim 180^\circ$  relative to that in the inflationary model, a result of the well known  $\sim 90^\circ$  phase shift in isocurvature perturbation modes relative to adiabatic ones. Note also the sign of the cross correlation at small  $l$ : positive for scalar and vector perturbations and negative for tensors [8,14].

To address the question of whether the polarization signal discussed in this Letter is detectable with the future CMB missions we will use a simple signal to noise estimator [15]

$$S/N = \sum_l \frac{(2l+1)f_{\text{sky}}C_l^2}{2[C_l + w^{-1}e^{l(l+1)\sigma_b^2}]}, \quad (1)$$

where  $f_{\text{sky}}$  is the sky coverage,  $\sigma_b$  is the Gaussian beam size of the instrument in question, and the instrument noise is characterized with  $w^{-1} = 4\pi\sigma^2/N$ . Here  $N$  is the number of pixels and  $\sigma$  is the receiver noise in each pixel. Typical values for MAP are  $(0.1 \mu\text{K})^2$  and  $(0.15 \mu\text{K})^2$  for temperature and polarization, respectively, while for Planck they are a factor of  $\sim 100$  smaller. The expression above includes both noise and cosmic variance and is valid for  $T$ ,  $E$ , and  $B$  power spectra, while it is somewhat more complicated for the cross correlation [4,5]. Using the typical numbers for MAP we find that it will reach  $S/N$  of order unity on both  $E$  and  $B$  polarization in symmetry-breaking models. For an unambiguous detection of polarization, one would therefore require either several years of MAP observations or the Planck mission. In the latter case  $S/N$  will be above 20 in all the models, making possible a clear detection of magnetic polarization. In contrast, in inflationary models  $S/N \sim 3$  in  $B$  polarization even if  $T/S = 1$ .

The prospects of detecting cross correlation between temperature and polarization are even better. The amplitude of cross correlation in inflationary models is quite large and should be detected by the MAP satellite over a range of scales up to  $l \sim 500$  [3]. Even for symmetry-breaking models the detection of cross correlation should be marginally achievable at the MAP sensitivity levels, with typical  $S/N \sim 5$ . This would therefore allow a detailed comparison between the model predictions in the two competing theories. As discussed above, MAP detection of a large signal in cross correlation would not favor the symmetry-breaking models such as the ones studied here.

In conclusion, symmetry-breaking models predict a large magnetic type polarization on small angular scales

and a small cross correlation between temperature and polarization relative to inflationary models. These predictions are quite robust: detection of magnetic polarization on subdegree scales would demonstrate a presence of nonscalar perturbations, which should be negligible in inflationary models, while absence of significant cross correlation on degree scales would indicate causality and decoherence. Both predictions should be accessible to experimental verification in the near future.

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