ABSTRACT

Topological defect theories lead to non-Gaussian features on maps of fluctuations of the cosmic microwave background radiation (CMBR), which enable us to distinguish them from maps predicted by standard inflationary models. We have recently presented a maximum entropy method (MEM) which simultaneously deconvolves interferometer maps of CMBR fluctuations, and separates out foreground contaminants. By applying this method to simulated observations using a realistic ground-based interferometer, we demonstrate that it is possible to recover the prominent hotspots in the CMBR maps which delineate individual defects, even in the presence of a significant Galactic foreground.

Key words: methods: data analysis – techniques: image processing – cosmic microwave background.

1 INTRODUCTION

In recent years, two competing theoretical paradigms have been proposed for the origin of structure in the Universe. The first was the standard inflationary/cold dark matter (CDM) model, but, more recently, defect cosmologies have been investigated. In these theories symmetry breaking in unified field theories, which occurs as the Universe cools through a phase-transition, leads to spatial gradients in the value of the field which cannot be eliminated. These field defects contain energy concentrations that can gravitationally perturb the surrounding matter and thus induce structure formation. Depending on the properties of the field involved, the most common defects are strings, monopoles and textures.

The effects of defects on the cosmic microwave background radiation (CMBR) are not yet fully understood, but the study of defect cosmologies has recently begun to progress significantly. The overall shape of the power spectrum of CMBR fluctuations produced by defects has been calculated (Crittenden & Turok 1995; Albrecht et al. 1996; Magueijo et al. 1996), and differences in the position of its peak relative to that predicted by standard inflation/CDM discussed. Alternatively, the presence (or otherwise) of secondary Doppler peaks in the power spectrum may enable a distinction between inflationary models and defect models to be made (Hobson & Magueijo 1996).

More recently, simulated maps of subdegree-scale CMBR fluctuations due to defects have been produced (Turok 1996). These calculations indicate that CMBR maps due to defects (in particular monopoles and textures) are characterized by steep temperature gradients and by well-defined non-Gaussian ‘hotspots’ of emission, which correspond to 5σ or greater variations in the CMBR. The identification of such features on CMBR maps would therefore provide a very direct method of distinguishing defect and inflationary cosmologies.

The next generation of CMBR interferometers, such as the Very Small Array (Jones 1997), are ideally placed to observe such features, since they are designed to be sensitive to the range of angular scales on which we expect to detect signatures of non-Gaussianity. The maps produced by such an instrument will, however, contain contributions from foreground emission. In the frequency range 20–40 GHz, this is mainly due to extragalactic point sources, and diffuse free–free and synchrotron emission from the Galaxy. Most point sources may be identified with higher resolution observations and subtracted from the maps (O’Sullivan et al. 1995). For sources that are time-variable, however, the subtraction can be inaccurate and pixel removal may be a safer option in this case. Diffuse emission must be removed using multifrequency observations, and using their spectral differences to distinguish between the various components.

In all CMBR work, efforts will have to be made to remove the effects of the sampling strategy (single dish, switched beam or interferometer) and to remove the effects of foreground contamination, principally from our own Galaxy. In addition to linear techniques such as Wiener filtering (e.g. Tegmark & Efstathiou 1996), non-linear maximum entropy method (MEM) algorithms provide an alternative means of performing foreground separation and CMBR map reconstruction, and we have a continuing programme of work to assess their viability in future experiments, as well as apply them to current data (Maisinger, Hobson & Lasenby 1997; Jones et al. 1998; Hobson et al., in preparation). As discussed in Zaroubi et al. (1995), both Wiener filtering and MEM can be considered in the context of Bayes theorem, and both produce reconstructions that maximize the a posteriori probability distribution, but each assumes a different form for the prior probability. The Wiener filter assumes the prior to be Gaussian, corresponding to some assumed power spectra for the CMBR and foreground components, whereas MEM adopts a prior based on
information-theoretic considerations alone (Skilling 1989). In particular, it is believed that the quality of MEM reconstructions is not sensitive to the Gaussian/non-Gaussian nature of the input statistics, although to our knowledge this has not been specifically tested so far. This is a key question in the context of the alternative theories of structure formation, and here we carry out a specific test of this matter.

We perform simulated observations of CMBR maps due to textures and monopoles, which are contaminated by Galactic emission in the form of a Gaussian random field with a given power spectrum. We then use the method described by Maisinger et al. (1997) to perform a simultaneous deconvolution of the interferometer maps, and a separation of the CMBR and Galactic components. We show that the extremely non-Gaussian features in the original CMBR maps are faithfully reproduced.

2 THE SIMULATED OBSERVATIONS

As mentioned above, Turok (1996) has recently created simulated maps of intrinsic CMBR anisotropies according to different topological defect theories. These maps show a clear excess of extreme hot peaks compared with what would be expected from a Gaussian theory. Although the maps do not include contributions to the anisotropy produced after the recombination process (in particular the Sachs–Wolfe effect, which dominates on larger angular scales, is neglected), their most striking features occur on smaller scales, and so should be accurately represented.

In order to test how well interferometers can recover these non-Gaussian features in the CMBR, and separate them from foreground contaminations, we perform simulated observations with a model interferometer with realistic capabilities, based on the next generation of CMBR experiments. In particular, we assume an array with 15 horn-reflector antennas, which have symmetric-Gaussian envelope beams of 4° FWHM at 30 GHz, scaling with frequency as $n^{-1}$. The assumed observing bandwidth is 2 GHz, and the system temperature 30 K. Observations are made at 28 and 38 GHz in order to perform the spectral separation.

The arrangement of the antennas is designed to give as close to uniform coverage as possible in the Fourier plane (or $uv$ plane), between an inner and outer radius. The particular arrangement used here measures Fourier modes between about $|u| \approx 20$ and $|u| \approx 150$ wavelengths, which corresponds to the multipole range $\ell = 150–950$. The physical antenna separations then lie between 25 cm and 1.60 m. The baselines are appropriately rescaled for different frequencies to ensure equal coverage of the $uv$ plane at each frequency.

In addition to the CMBR fluctuations, we assume a Galactic component described by a single effective power law $\Delta T(\ell) = \ell^2$, with $\beta = -0.7$. The simulated Galactic fluctuations are drawn from a random Gaussian field described by a Gaussian autocorrelation function (GACF) $C(x) = C_0 \exp(-|x|^2/2\theta_c^2)$. In these simulations, we choose an intrinsic rms of the fluctuations of $\sqrt{C_0} = 60\,\mu K$ and a coherence angle $\theta_c = 10$ arcmin. This level of Galactic fluctuations is much higher than would be expected from Galactic surveys, and thus provides a severe test of the separation algorithm.

Our simulated data consist of two $30 \times 12$-h observations, one at
28 GHz and the other at 38 GHz, of a patch of sky at a declination of 70°. The corresponding rms noise on a single frequency map is about 25 μK at 28 GHz and 15 μK at 38 GHz. In each simulation, the Fourier modes are reconstructed at 30 GHz on a 128 × 128 grid, with a cell size in the Fourier domain of Δμ = 5 wavelengths (or Δℓ = 30). The corresponding cell size in the map plane is ≈5 arcmin. A map made from the raw simulated data at 28 GHz is shown in Fig. 1.

The algorithm used to reconstruct the CMBR fluctuations is that presented by Maisinger et al. (1997), which performs a simultaneous MEM spectral separation and deconvolution of the synthesized beam. For details of the method and a discussion of realistic levels of Galactic emission, see this reference.

### 3 RESULTS

Fig. 2 compares a reconstructed texture map with the original input map on the same grid. Neither of the maps has been reconvolved with a synthesized beam. The FWHM of the primary beam of the interferometer is indicated on the plots as a white circle. The prominent hotspot on the original map is a 5σ peak, and indeed the spot on the reconstructed map also has a maximum of close to 5σ as compared with the rms within the primary beam FWHM. A comparison with the map for the Galactic component in Fig. 3 shows that the separation algorithm did not attribute any significant part of the CMBR hotspot to the Galactic component. In Fig. 4 we compare a horizontal cut taken through the centre of the hotspot on the original CMBR maps with the mean of cuts taken at the same position through each of 100 reconstructed maps, as obtained from Monte Carlo simulations with different noise realizations on each map. Monte Carlo simulations provide a comparatively simple way to estimate the errors on the reconstruction, since the MEM is a non-linear algorithm, which makes it difficult to quantify errors in a straightforward manner. Both reconstructions and original maps have been convolved with the synthesized beam.
and only those multipoles that lie within the $\ell$-range sampled by the telescopes have been used to make the maps. The cut demonstrates that the peak has indeed been properly recovered, except perhaps for the topmost pixel.

In order to provide a different illustration of the significance of the CMBR hotspot, in Fig. 5 we have plotted a three-dimensional surface relief of the the central $4^\circ \times 4^\circ$ patch of the convolved reconstruction from Fig. 2.

The texture reconstruction presented here serves just as an example to illustrate the viability of the method. We have performed a set of analogous simulations with different map realizations and other defects, such as monopoles and strings, and have obtained similar results. Cosmic monopoles, for instance, also leave non-Gaussian imprints on the CMBR. Fig. 6 shows the reconstruction of a map produced by monopoles. There are several hotspots of more than $4\sigma$ on the map, each of which has been recovered in the reconstruction. The cut through the map plane in Fig. 7 demonstrates that the heights of the peaks relative to the surrounding emission have been preserved in the reconstruction.

Assuming a $4^\circ \times 4^\circ$ field size, Turok’s calculations show that we can expect one $5\sigma$ event per 4 monopole maps or one per 18 texture maps. One $4\sigma$ event might be observable per 1.4 monopole maps or per 3 texture maps. Each of the reconstructions performed in our simulations assumes a total observing time of 2 months. Since fields of $4^\circ \times 4^\circ$ are subject to a significant sample variance, multiple observations of different fields of the sky have to be performed. These observations can then also be used to search for defects, and the abundances presented above indicate that we can indeed hope to discover defects on the maps within a reasonable observing time of less than a year.

4 CONCLUSIONS

We have performed simulated observations of CMBR temperature fluctuations due to textures and monopoles (separately), using a model ground-based interferometer with realistic capabilities observing for 1 month each at 28 and 38 GHz. In addition to the CMBR fluctuations the simulations contain a Gaussian Galactic component.

Using a maximum entropy method (Maisinger et al. 1997) on multifrequency data, we have performed a separation of the CMBR and Galactic components, based on their spectral differences. We have found that non-Gaussian hotspots in the CMBR map, which delineate individual textures, are faithfully recovered by the algorithm. We therefore conclude that ground-based interferometers are indeed capable of observing such features. Therefore, in addition to determining the overall shape of the CMBR power spectrum, measuring the abundance of hotspots on CMBR maps provides a viable test for a discrimination between defect and inflationary cosmologies.

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REFERENCES

The observability of topological defects


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