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Can Doppler Peaks discriminate among Inflationary models and Topological Defect scenarios ?

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Abstract Doppler peaks in the cosmic microwave background may allow us to distinguish among the two classes of theories—inflationary models and topological defect scenarios—which attempt to explain the origin of structure formation in the universe. We consider density perturbations seeded by global textures in a universe dominated by cold dark matter. We calculate the height and the position of the primary peak and conclude a different signature than the one obtained if the initial perturbations were due to the amplification of quantum fluctuations of a scalar field during a generic inflationary era. We believe that our analysis holds for all kinds of global defects and general global scalar fields. We then question the validity of the temporal coherence of the sources, assumed in the texture models. We finally discuss the temporal coherence of cosmic string sources, through correlations of the energy and momentum in an evolving cosmic string network in Minkowski space.

One of the most important issues of modern cosmology is the origin of the large-scale structure. We believe that it was produced by gravitational instability from small primordial fluctuations in the energy density, generated in the early universe. Within this framework there are two classes of theories to explain the origin of the primordial density perturbations. They can be due to quantum fluctuations of a scalar field during an inflationary era, or they may be seeded by topological defects produced during a symmetry breaking phase transition. Inflationary fluctuations lead to an approximately scale-invariant (Harrison-Zel'dovich) spectrum of density perturbations, generated through a linear mechanism, with a Gaussian distribution of amplitudes on scales which are cosmological today. These are *passive coherent* fluctuations. Topological defect perturbations lead also to an approximately scale-invariant spectrum of density perturbations, however generated via a non-linear process, with constant amplitude on each scale at horizon crossing at all times. These are *active incoherent* fluctuations, for which causality requires the existence of a large-scale radiation white noise-spectrum. Either of these two classes of theories predicts precise fingerprints in the cosmic microwave background (CMB) anisotropies, which can be used to differentiate among them using a purely linear analysis.

The CMB fluctuation spectrum is usually parametrized in terms of multiple moments C_ℓ, defined as the coefficients in the expansion of the temperature autocorrelation function

$$\left\langle \frac{\delta T}{T}(\mathbf{n})\frac{\delta T}{T}(\mathbf{n}')\right\rangle\Bigg|_{(\mathbf{n}\cdot\mathbf{n}'=\cos\vartheta)} = \frac{1}{4\pi}\sum_\ell (2\ell+1)\, C_\ell P_\ell(\cos\vartheta)\ , \qquad (1)$$

which compares points in the sky separated by an angle ϑ. The main physical mechanisms which contribute to the redshift of photons propagating in a perturbed Friedmann geometry are: fluctuations in the gravitational potential on the last-scattering surface (*Sachs-Wolfe* effect), acting on large angular scales ($\ell \lesssim 50$) ; acoustic waves in the baryon-radiation fluid prior to recombination (*Doppler peaks*), acting on angular scales ($0.1^\circ \lesssim \theta \lesssim 2^\circ$); and suppression of CMB anisotropies due to the finite thickness of the recombination shell as well as to photon diffusion during recombination (*Silk damping*), acting on the smallest angular scales ($\ell \gtrsim 1000$). Both, generic inflationary models and topological defect scenarios predict an approximately scale-invariant spectrum of density perturbations on large angular scales. Thus CMB anisotropies on intermediate and small angular scales are very important. If the two families of models predict different characteristics for the Doppler peaks, one can discriminate among them. Inflationary perturbations predict coherent oscillations, with the primary Doppler peak at $\ell \sim 200$, having an amplitude $\sim$ 4–6 times the Sachs-Wolfe plateau, and the appearance of secondary oscillations [1].

To study the characteristics of the Doppler peaks in the CMB produced from textures, we will employ a gauge-invariant linear perturbation analysis. Neglecting the integrated Sachs-Wolfe (ISW) effect, the Silk damping and the contribution of neutrino fluctuations, the Doppler contribution to the CMB anisotropies is [2]

$$\left[\frac{\delta T}{T}(\mathbf{x},\mathbf{n})\right]^{\mathrm{Doppler}} \approx \frac{1}{4}D_r(\mathbf{x}_{\mathrm{rec}},\eta_{\mathrm{rec}}) + \mathbf{V}(\mathbf{x}_{\mathrm{rec}},\eta_{\mathrm{rec}})\cdot\mathbf{n}\ , \qquad (2)$$

where $\mathbf{V}$ is the peculiar velocity of the baryon fluid with respect to the overall Friedmann expansion, D_r is a gauge-invariant variable describing the density fluctuation in the coupled baryon radiation fluid and $\mathbf{x}_{\mathrm{rec}} = \mathbf{x} - \mathbf{n}\,\eta_0$ ($\mathbf{n}$ denotes a direction in the sky, η is conformal time, with η_0, η_{rec} the present time and the time of recombination respectively).

We study a two-component fluid system: baryons plus radiation, which prior to recombination are tightly coupled, and CDM. The evolution for the perturbation variables D (density perturbation) and V (velocity perturbation) in a flat background is given by

$$\mathcal{D}\begin{pmatrix} D_r \\ D_c \end{pmatrix} = S\ , \qquad (3)$$

where subscripts "r" and "c" denote the baryon-radiation plasma and CDM, respectively. In Eq. (3), $\mathcal{D}$ stands for a second order differential operator and S denotes the source term, in general given by $S = 4\pi G a^2(\rho + 3p)^{\rm seed}$; in our case, where the seed is described by a global scalar field ϕ, the source term is $S = 8\pi G(\phi')^2$. Numerical simulations show that the average of $|\phi'|^2$ over a shell of radius k can be modeled by [3]: $\langle|\phi'|^2\rangle(k,\eta) = 0.5A\tilde{\eta}^2\eta^{-1/2}[1+\alpha(k\eta)+\beta(k\eta)^2]^{-1}$, where $\tilde{\eta}$ is the symmetry breaking scale of the phase transition leading to texture formation; A, α, β are parameters of order 1. For a given scale k, we chose the initial time such that the perturbation is super-horizon and the universe is radiation dominated. With these initial conditions we solve the system of second order equations for the perturbation variables, obtaining $D_{\rm r}$ and $D'_{\rm r}$. The Doppler contribution to the CMB anisotropies is given by

$$C_\ell = \frac{2}{\pi}\int {\rm d}k \left[\frac{k^2}{16}\left|D_{\rm r}(k,\eta_{\rm rec})\right|^2 j_\ell^2(k\eta_0) + \frac{1}{(1+w)^2}\left|D'_{\rm r}(k,\eta_{\rm rec})\right|^2 (j'_\ell(k\eta_0))^2\right], \quad (4)$$

where $w = p_{\rm r}/\rho_{\rm r}$; j_ℓ is the spherical Bessel function of order ℓ, and j'_ℓ its first derivative. The angular power spectrum, shown in the figure, yields the Doppler peaks; we show separately the contribution of $D_{\rm r}$ (upper dotted line), $D'_{\rm r}$ (lower dotted line), as well as their sum (solid line).

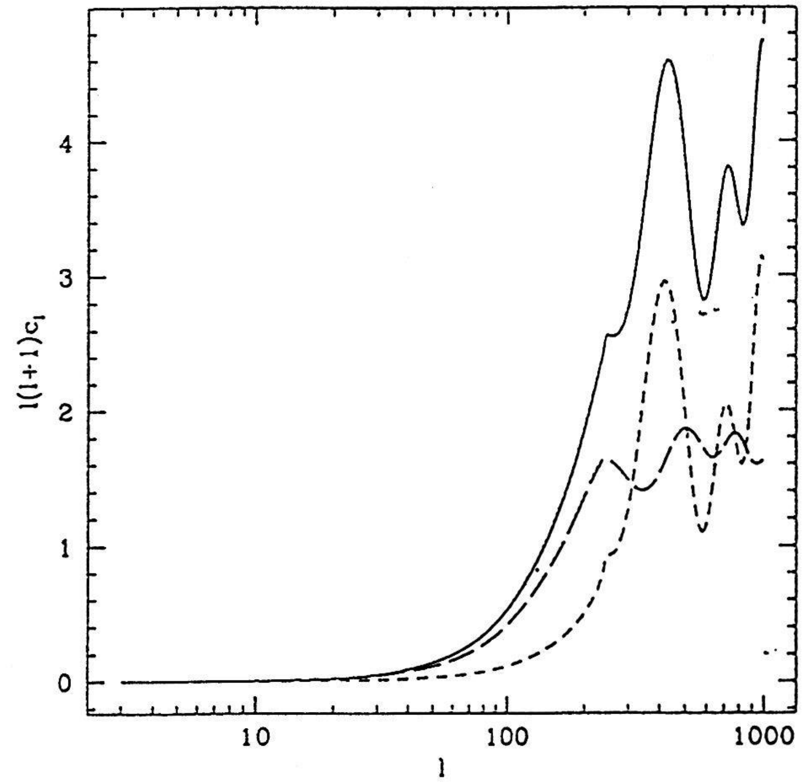

Fig. The angular power spectrum for the Doppler contribution to the CMB anisotropies is shown in units of ϵ. We choose the cosmological parameters $h = 1/2$, $\Omega_B = 0.05$ and $z_{rec} = 1100$.

The ISW effect will shift the position of the first peak to somewhat larger scales, lowering $\ell_{\rm peak}$ by (5–10)% and possibly increasing slightly its amplitude (by less than

30%). So the primary peak is displaced by $\Delta\ell \sim 150$ towards smaller angular scales than in standard inflationary models. Silk damping will decrease the relative amplitude of the third peak with respect to the second one; however it will not affect substantially the height of the first peak, which is $\ell(\ell+1)\,C_\ell|_{\rm Doppler} = (2-3)\;6C_2$ [2].

Here, as well as in [4], we assumed maximum coherence for the texture models and found that the peaks were preserved. As emphasised in [5], the distinctive appearance of Doppler peaks and troughs seen in inflationary calculations and texture models depend sensitively on the temporal coherence of the sources. Assuming little coherence the peaks are washed out, while an assumption of total coherence preserves them. An incoherent defect perturbation is effectively coherent and displays secondary oscillations, if the defect scaling coherence time is much bigger than $2\pi\eta/\xi_c$, where ξ_c is the defect coherence length [6]. Assumning effective coherence for textures means that the coherence function

$$\mathcal{C}_\Phi(k\eta, k\eta') \equiv \frac{<\Phi(k,\eta)\;\Phi(k,\eta')>}{\sigma(\Phi(k,\eta))\;\sigma(\Phi(k,\eta'))},$$

is equal to 1, where σ denotes the square root of the power spectrum. Checking numerically whether the unequal time corrrelator for $|\phi'|^2$ has an exponential decay on a timescale which will define the coherence time, we conclude [7] that even though effective coherence is not fully justified for textures, the characteristic features of the first Doppler peak found here, do indeed hold, while secondary oscillations should exist but be softened than the ones predicted according the coherent approximation.

We now question the validity of the coherence assumption for local gauge strings, since understanding the temporal coherence of string sources is very important when calculating their microwave background signals. The authors in [5] assumed that strings were effectively incoherent and obtained a rather featureless CMB power spectrum at large multipole ℓ. In [6] this assumption was justified by a numerical study of the two-time energy density correlator. The authors concluded the absence of secondary oscillations and the validity of the totally incoherent approximation. Performing numerical experiments, we investigate scaling properties of the power spectra and correlations of the energy and momentum in an evolving string network in Minkowski space [8] and measure the coherence time in the network. We expect a network of cosmic strings evolving in Minkowski space to have all the essential features of one in a Friedmann background, while the big advantage of Minkowski space is that the network evolution is very easy to simulate numerically. To a good approximation, the cosmic string network can be thought of as consisting of randomly placed segments of string, of length $\xi/\sqrt{1-\bar{v}^2}$ and number density ξ^{-3}, with random velocities; ξ denotes the energy density scale defined by $\xi^2 = \mu/\rho_{inf}$ (μ is the linear mass density and ρ_{inf} is the density of string with energy greater than ξ) and $\bar{v}$ is the r.m.s string velocity. The coherence time scale in a Fourier mode of wavenumber k is determined by the time segments take to travel a distance k^{-1} [8]. We find that the characteristic coherence time scale for a mode of spatial frequency k is $\eta_c \simeq 3/k$ [8]. Our numerical results indicate that at high k, η_c decreases faster than k^{-1}, but we believe that this behaviour is a lattice artifact. The implications of our simulations for the appearance of the Doppler peaks are not entirely clear cut. The coherence time is smaller than, but of the same order of magnitude as, the period of acoustic oscillations in the photon baryon fluid at decoupling, which is roughly $11/k$ [9]. This is in turn smaller than the time at which the power in the energy and velocity sources peak, approximately $20/k$ [8]. We believe that our string correlation functions can serve as realistic sources to answer the question of existence or absence of secondary peaks in the CMB angular power spectrum.

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