THE COSMIC MICROWAVE BACKGROUND: BEYOND THE POWER SPECTRUM

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ABSTRACT. Much recent work on the cosmic microwave background (CMB) has focussed on the angular power spectrum of temperature anisotropies and particularly on the recovery of cosmological parameters from acoustic peaks in the power spectrum. However, there is more that can conceivably be done with CMB measurements. Here I briefly survey a few such ideas: cross-correlation with other cosmic backgrounds as a probe of the density of the Universe; CMB polarization as a gravitational-wave detector; secondary anisotropies and the ionization history of the Universe; tests of alternative-gravity theories; polarization, the Sunyaev-Zeldovich effect, and cosmic variance; and tests for a neutrino mass.

1 Introduction

Extraordinary results from COBE and balloon-borne and ground-based experiments, a recent healthy interplay between theorists and experimentalists, and the vision of MAP and Planck on the horizon have focussed a considerable amount of attention on the cosmic microwave background (CMB). The primary aim of these experiments is recovery of the angular power spectrum of the temperature anisotropy, and from this, we hope to determine cosmological parameters and test structure-formation theories. However, there is conceivably much more that can be learned from the CMB. Here I review briefly (and by no means exhaustively!) a few such ideas. Although the title suggests otherwise, some of the ideas discussed do involve the power spectrum.

2 Cross-Correlation with Other Backgrounds

If the Universe has a critical density, then temperature fluctuations are produced by density perturbations at or near the surface of last scatter at a redshift \( z \approx 1100 \), well beyond the reach of even the deepest galaxy surveys. However, if the Universe has less than the critical density, either in a flat cosmological-constant or open Universe, then additional anisotropies are produced by the red- and blue-shifting of photons as they pass in and out of gravitational potential wells along the line of sight at redshifts \( z < \Omega_0^{-1} - 1 \). Therefore, if \( \Omega_0 < 1 \), then there should be some cross-correlation between the CMB temperature in a given direction and some tracer of the mass distribution along that same line of sight (Crittenden & Turok 1996), such as the extragalactic x-ray background.

Fig. 1 shows predictions for the cross-correlation amplitude in flat cosmological-constant and open models as a function of \( \Omega_0 \), as well as experimental upper limits. The results seem to indicate that an open universe must have \( \Omega_0 \gtrsim 0.7 \), and that \( \Omega_0 \approx 0.3 \) is ruled out. However, the theoretical predictions assume that all of the XRB fluctuation is due to density perturbations; this implies an x-ray bias \( b_x \approx 3 \). However, some of the XRB fluctuation may simply be due to Poisson fluctuations in the number of x-ray sources. If so, the inferred x-ray bias is lowered accordingly, and the predicted cross-correlation is also decreased by the same factor. Since the scaled cross-correlation amplitude is \( \approx 0.13 \) at \( \Omega_0 \approx 0.3 \), and the 95% CL upper limit is \( \approx 0.6 \), it suggests that an open-CDM Universe is viable only if the x-ray bias is \( b_x \lesssim 1.5 \), significantly smaller than biases of other high-redshift populations.
Figure 1. \( C_{\text{CMB/XRB}}(0) / \sigma_T \sigma_X \) vs. \( \Omega_0 \)

3 Reionization and Secondary Anisotropies

Although most of the matter in CDM models does not undergo gravitational collapse until relatively late in the history of the Universe, some small fraction of the mass is expected to collapse at early times. Ionizing radiation released by this early generation of star and/or galaxy formation will partially reionize the Universe, and these ionized electrons will re-scatter at least some cosmic microwave background (CMB) photons after recombination at a redshift of \( z \approx 1100 \). Theoretical uncertainties in the process of star formation and the resulting ionization make precise predictions of the ionization history difficult. Constraints to the shape of the CMB blackbody spectrum and detection of CMB anisotropy at degree angular scales suggest that if reionization occurred, the fraction of CMB photons that re-scattered is small. Still, estimates show that even if small, at least some reionization is expected in CDM models: for example, the most careful recent calculations suggest a fraction \( \tau_r \sim 0.1 \) of CMB photons were re-scattered (Haiman & Loeb 1997).

Scattering of CMB photons from ionized clouds will lead to anisotropies at arcminute separations below the Silk-damping scale (the Ostriker-Vishniac effect) (Ostriker & Vishniac 1985; Vishniac 1987; Jaffe & Kamionkowski 1998). These anisotropies arise at higher order in perturbation theory and are therefore not included in the usual Boltzmann calculations of CMB anisotropy spectra. The level of anisotropy is expected to be small and it has so far eluded detection. However, these anisotropies may be observable with forthcoming CMB interferometry experiments.
that probe the CMB power spectrum at arcminute scales.

Fig. 3 shows the predicted temperature-anisotropy spectrum from the Ostriker-Vishniac effect for a number of ionization histories. The ionization histories are parameterized by an ionization fraction \( x_e \) and a redshift \( z_r \) at which the Universe becomes reionized. The optical depth \( \tau \) to the standard-recombination surface of last scatter can be obtained from these two parameters.

Reionization damps the acoustic peaks in the primary-anisotropy spectrum by \( e^{-2\tau} \), as shown in Fig. 3, but this damping is essentially independent of the details of the ionization history. That is, any combination of \( x_e \) and \( z_r \) that gives the same \( \tau \) has the same effect on the primary anisotropies. So although MAP and Planck will be able to determine \( \tau \) from this damping, they will not constrain the epoch of reionization. On the other hand, the secondary anisotropies (the Ostriker-Vishniac anisotropies) produced at smaller angular scales in reionized models do depend on the ionization history. For example, although the top and bottom dashed curves in Fig. 3 both have the same optical depth, they have different reionization redshifts (\( z_r = 20 \) and \( z_r = 57 \)). Therefore, if MAP and Planck determine \( \tau \), the amplitude of the Ostriker-Vishniac anisotropy determines the reionization epoch.

In a flat Universe, CDM models normalized to cluster abundances produce rms temperature anisotropies of 0.8-2.4 \( \mu K \) on arcminute angular scales for a constant ionization fraction of unity, whereas an ionization fraction of 0.2 yields rms anisotropies of 0.3-0.8 \( \mu K \). In an open and/or high-baryon-density Universe, the level of anisotropy is somewhat higher. The signal in some of these models may be detectable with planned interferometry experiments.

### 4 Polarization and Gravitational Waves

Although a CMB temperature map cannot unambiguously distinguish between the density-perturbation and gravitational-wave contributions to the large-angle CMB anisotropy, the two can be decomposed in a model-independent fashion with a map of the CMB polarization (Kamionkowski, Kosowsky & Stebbins 1997a, 1997b; Seljak & Zaldarriaga 1997; Zaldarriaga & Seljak 1997). Suppose we measure the linear-polarization “vector” \( \vec{P}(\hat{n}) \) at every point \( \hat{n} \) on the sky. Such a vector field can be written as the gradient of a scalar function \( A \) plus the curl of a vector field \( \vec{B} \),

\[
\vec{P}(\hat{n}) = \vec{\nabla}A + \vec{\nabla} \times \vec{B}.
\]

The gradient (i.e., curl-free) and curl components can be decomposed by taking the divergence or curl of \( \vec{P}(\hat{n}) \) respectively. Density perturbations are scalar metric perturbations, so they have no handedness. They can therefore produce no curl. On the other hand, gravitational waves do have a handedness so they can (and we have shown that they do) produce a curl. This therefore provides a way to detect the inflationary stochastic gravity-wave background and thereby test the relations between the inflationary observables. It should also allow one to determine (or at least constrain in the case of a nondetection) the height of the inflaton potential.

The sensitivity of a polarization map to gravity waves will be determined by the instrumental noise and fraction of sky covered, and by the angular resolution. Suppose the detector sensitivity is \( s \) and the experiment lasts for \( t_{yr} \) years with an angular resolution better than \( 1^\circ \). Suppose further that we consider only the curl component of the polarization in our analysis. Then the smallest tensor amplitude \( T_{\min} \) to which the experiment will be sensitive at \( 1\sigma \), in units of the measured COBE temperature quadrupole moment \( C_2^{TT} \), is (Kamionkowski & Kosowsky 1998)

\[
\frac{T_{\min}}{6C_2^{TT}} \simeq 5 \times 10^{-4} \left( \frac{s}{\mu K \sqrt{yr}} \right)^2 t_{yr}^{-1}.
\]
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Figure 2. Multipole moments for the Ostriker-Vishniac effect for the C OBE-normalized canonical standard-CDM model ($\Omega = 1$, $h = 0.5$, $n = 1$, $\Omega_b h^2 = 0.0125$), for a variety of ionization histories as listed. We also show predictions for several open high-baryon-density models with the same $x_e$ and $\tau_r$, normalized to the cluster abundance, with dashed curves. The dotted curves show the primary anisotropy for this model for $\tau_r = 0.0, 0.1, 0.5, 1,$ and 2, from top to bottom. [From Jaffe & Kamionkowski (1998).]

5 \times 10^{-15} \xi_3^{-1} (s/\mu K \sqrt{\text{sec}})^2. Improvement on current constraints with only the curl polarization component requires a detector sensitivity $s \lesssim 40 t_{1/2}^{1/2} \mu K \sqrt{\text{sec}}$. For comparison, the detector sensitivity of MAP will be $s = O(100 \mu K \sqrt{\text{sec}})$. However, Planck may conceivably get sensitivities around $s = 25 \mu K \sqrt{\text{sec}}$.

A more complete analysis of the data will improve the sensitivity relative to the simple estimate given here. Furthermore, even a small amount of reionization will actually increase the large-angle polarization (Zaldarriaga 1997) and thus also improve the detectability.

5 New Particle and Gravitational Physics

The CMB may be used as a probe of new particle physics in yet another way: One of the primary goals of experimental particle physics these days is pursuit of a nonzero neutrino mass. Some recent (still controversial) experimental results suggest that one of the neutrinos may have a mass of $O(5 \text{ eV})$ (Athanassopoulos et al. 1995), and there have been some (again, still controversial) arguments that such a neutrino mass is just what is required to explain some apparent discrepancies between large-scale-structure observations and the simplest inflation-inspired standard-CDM model (e.g., Primack et al. 1995).

If the neutrino does indeed have a mass of $O(5 \text{ eV})$, then roughly 30% of the mass in the Universe will be in the form of light neutrinos. These neutrinos will affect the growth of gravitational-potential wells near the epoch of last scatter, and they will thus leave an imprint on the CMB.
angular power spectrum (Dodelson, Gates & Stebbins 1996). The effect of a light neutrino on the power spectrum is small, so other cosmological parameters that might affect the shape of the power spectrum at larger \( l \)'s must be known well. Still, Hu, Eisenstein & Tegmark (1998) argue that by combining measurements of the CMB power spectrum with those of the mass power spectrum measured by, e.g., the Sloan Digital Sky Survey, a neutrino mass of \( \mathcal{O}(5 \text{ eV}) \) can be determined.

The CMB may also conceivably be used to test alternative gravity theories (Liddle, Mazumdar & Barrow 1998; Chen & Kamionkowski 1998) such as Jordan-Brans-Dicke or more general scalar-tensor theories. The idea here is that in such a theory, the expansion rate at the epoch of last scatter will be different, and this will provide a unique signature in the CMB power spectrum.

6 Polarization in the SZ Effect

Finally, there is a tremendous amount which can be learned from scattering of CMB photons from the hot gas in x-ray clusters both about cosmology and about cluster physics, much of which has recently been reviewed by Birkinshaw (1998). Most work on the SZ effect to date has focussed on the temperature perturbation produced. However, several mechanisms may cause these scattered photons to be polarized. In particular, if the radiation incident on a given cluster is anisotropic, the scattered light will be polarized in proportion to the quadrupole moment incident on this cluster. In this way, measurement of the SZ polarization may some day tell us about the quadrupole anisotropy of the CMB as viewed by an observer in a distant cluster, and this could, in some sense, help reduce the cosmic variance in the CMB determination of the large-scale fluctuation amplitude (Kamionkowski & Loeb 1997).

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