The Future of Microwave Background Physics

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Abstract. The cosmic microwave background is now fulfilling its promise of determining the basic cosmological parameters describing our Universe. Future study of the microwave background will mostly be directed towards two basic questions: a complete characterization of the initial perturbations, and probes of the nonlinear evolution of structure in the Universe. The basic scientific issues in both of these areas are reviewed here, along with possibilities for addressing them with further microwave background measurements at higher sensitivities and smaller angular scales. The proposed ACT experiment, which will map 200 square degrees of sky at arcminute resolution and micro-Kelvin sensitivity in three microwave frequency bands, is briefly described as an example of rapidly advancing experimental technique.

WHERE WE ARE NOW

The cosmic microwave background is one of the best-studied sources of cosmological information (see [1, 2, 3] for reviews). It is nearly isotropic on the sky, with small temperature fluctuations at the level of one part in $10^5$. These fluctuations arise from several basic physical mechanisms in the early Universe at a redshift $z \approx 1100$: gravitational redshift, temperature fluctuations at the last scattering surface, Doppler shifts from peculiar velocities at the last scattering surface, and diffusion damping through the thickness of the last scattering surface [4, 5]. In addition, further temperature fluctuations and spectral distortions arise from gravitational and scattering effects at comparatively recent epochs, with $z < 3$. Simple arguments show that the microwave background should also have small polarization fluctuations, roughly an order of magnitude smaller than the temperature fluctuations [6].

Power Spectra

The temperature fluctuations have been measured and studied in detail for the past decade, beginning with the watershed COBE detection [7], while the first measurement of polarization fluctuations by Kovac and collaborators has been discussed at this conference. So far, on angular scales down to about a degree, the temperature fluctuations appear to possess a Gaussian random distribution [8, 9]. To the extent that the fluctuations are Gaussian, they are described completely by their power spectra. A parity-invariant distribution of primordial fluctuations will result in four non-zero power spectra: temperature $C_l^T$, two polarization $C_l^E$ and $C_l^B$, and the cross-correlation $C_l^{TE}$ [10, 11, 12] (where $l$ is the multipole moment, inversely proportional to angular scale with $l = 200$ cor-
responding to one degree). These are the observables we will primarily consider here, although additional non-Gaussian temperature structure in the maps will also be very interesting to probe.

Theoretically, we can model how well a given measurement will probe the power spectrum, given its sky coverage, angular resolution, and sensitivity [13, 10, 11]. Experimentally, the MAP satellite will map the full sky with an angular resolution of around 12 arcminutes and an effective sensitivity of around 25 µK, in five frequency bands ranging from 30 GHz to 150 GHz. A few ground-based experiments have displayed higher angular resolution and sensitivity over far smaller regions of the sky; see Max Tegmark’s contribution to these proceedings for a current compilation of power spectrum measurements.

Cosmological Parameters

The intense interest in microwave background temperature fluctuations has been fueled largely by the realization that the power spectrum contains much information about cosmological parameters which describe the fundamental properties of the Universe [14, 15, 16]: the Hubble parameter $h$; the densities of baryons $\Omega_b$, dark matter $\Omega_{cdm}$, and “dark energy” $\Omega_\Lambda$; the primordial power spectrum of scalar perturbations parameterized by an amplitude $A_s$ and power law index $n_s$; the same for tensor fluctuations $A_t$ and $n_t$; and the optical depth to the surface of last scattering $\tau$.

The ability of the microwave background to constrain these parameters hinges on the existence of acoustic oscillations of the primordial plasma at the last scattering surface. These oscillations are phase-coherent in simple cosmological models, since each $k$-mode has a characteristic cosmological time at which it enters the horizon, and result in the well-known series of “acoustic peaks” in the power spectrum. The amplitudes and angular scales of these peaks in turn depend on the entire set of cosmological parameters. Precision measurements of the power spectrum constrain the parameters, with only one essential degeneracy. The microwave background provides, by far, the single most powerful set of constraints on the basic properties of the Universe, and indeed is on the verge of giving definitive answers to most of the historically most important and vexing questions of classical observational cosmology.

Parameter Constraints

Extracting parameter constraints from microwave background power spectrum measurements is conceptually simple, but somewhat difficult in practice. Finding the best-fit cosmological model for a given power spectrum is not hard, but evaluating an error region requires looking around in a multi-dimensional parameter space. Approximations based on linear extrapolations of the likelihood in the above parameters give the right qualitative answer [14], but are inadequate to support the currently available data. Brute-force analyses on parameter space grids have been performed [17], but are not in general sufficiently accurate or flexible for upcoming data.
Monte Carlo techniques are much better, provided that the power spectra for a given cosmological model can be evaluated efficiently enough [18, 19, 20]. To this end, it is convenient to use a different set of cosmological parameters which better reflect the physical effects determining the acoustic peak structure in the power spectra. The following set of physical parameters has several advantages, including being largely uncorrelated and having nearly linear power spectrum dependence [21]:

- $\mathcal{A} \equiv r_s(a_*)/D_A(a_*)$, where $r_s(a_*)$ is the sound horizon at the time of last scattering, and $D_A(a_*)$ is the angular diameter distance to the surface of last scattering. This parameter determines the angular scale of the acoustic peaks.
- $\mathcal{B} \equiv \Omega_b h^2$, the baryon density.
- $\mathcal{V} \equiv \Omega_\Lambda h^2$, the vacuum energy density.
- $\mathcal{R} \equiv a_\* \Omega_{\text{mat}}/\Omega_{\text{rad}}$, the ratio of matter to radiation energy density at last scattering.
- $\mathcal{M} \equiv (\Omega_{\text{mat}}^2 + a^{-2} \Omega_{\text{rad}}^2)^{1/2} h^2$, which is approximately a degenerate direction in the space of physical parameters. It is fixed if the number of neutrino species is assumed known.
- $\mathcal{Z} \equiv e^{-2\tau}$, which parameterizes the effect of reionization.
- $n$, the primordial scalar perturbation power spectrum index.

These parameters allow an extremely efficient evaluation of the power spectrum for a given set of cosmological parameters over a large region of parameter space via simple functional approximations; they make Monte Carlo evaluations of parameter space error regions far less demanding computationally [21]. Also, the parameters give insight into the fundamental physical effects the cosmological parameters have on the power spectrum. Some conclusions are immediate; for example, with these parameters, it is clear that power spectrum measurements at angular scales $l > 1000$ will give very little additional constraint on any physical parameters besides $n$ and $\mathcal{A}$, because the change in the power spectrum for $l > 1000$ when the other parameters are varied is negligible. A full sky map with MAP’s angular resolution and sensitivity will provide 1-σ constraints of approximately 0.5% for $\mathcal{A}$, 2% for $\mathcal{A}$, 3% to 5% for $\mathcal{B}$, $\mathcal{R}$, and $\mathcal{N}$, 30% for $\mathcal{M}$; $\mathcal{V}$ is essentially undetermined by the CMB alone [21].

**THE MICROWAVE BACKGROUND AND FUNDAMENTAL PHYSICS**

Beyond simple cosmological parameter estimation, the microwave background can provide other data with potential impact on fundamental physics.
Primordial Power Spectrum

Generally, the primordial power spectra of scalar and tensor perturbations have been parameterized as power laws. This approximation appears to be fairly good in the case of scalar perturbations, and slow-roll models of inflation predict power law spectra. However, more complicated inflation models generically predict departures from exact power laws [22], and the microwave background fluctuations have considerable power to measure the primordial power spectrum without prior assumptions about its shape.

The angular scales between $l = 1000$ and $l = 3500$ are largely unaffected by variations in the physical parameters in the previous section, and thus reflect the primordial power spectrum directly. However, this is only a factor of 3 in angular scale. To constrain the primordial perturbations over a significantly wider range of scales, the region between $l = 2$ and $l = 1000$ must be probed, but here the microwave background fluctuations vary greatly with the other cosmological parameters. The temperature fluctuations alone exhibit a virtual degeneracy between the primordial power spectrum and the effect of the other cosmological parameters on this range of scales [23]. The power spectrum in this range cannot be probed effectively by temperature fluctuations alone, without further assumptions or other measurements of the cosmological parameters. However, the acoustic peaks in the polarization power spectrum are generally out of phase with those in the temperature power spectrum, which breaks this degeneracy to a large extent. Accurate measurement of both the temperature and polarization power spectrum between $l = 2$ and $l = 3500$ has the potential to measure directly the primordial power spectrum of scalar perturbations over a significant range in wavenumber [24].

Initial Conditions

Usually, “adiabatic” initial conditions are assumed, which means that the fractional density fluctuations in each particle species are identical. Again, this is the natural prediction of the simplest inflationary models, but in general other fluctuations are possible. Efforts have been made to classify all such “isocurvature” fluctuations [25], although no mathematically rigorous classification has yet been obtained. Arbitrary initial conditions greatly expand the parameter space of possible models and reduce the ability to determine the cosmological parameters [26, 27]. The current CMB measurements show that the primordial perturbations are not far from adiabatic; power spectrum measurements of both temperature and polarization have the potential to put fairly sharp limits on the contributions from any other isocurvature components, which in turn could constrain the number of dynamical fields in inflation and their couplings to each other.

Gaussianity

The statistical distribution of the temperature fluctuations on the sky, and not just their power spectrum, is another way to probe the characteristics of the primordial perturbation. Simple inflation models predict the primordial perturbations should be Gaussian
random distributed; departures from this prediction would signify a more complicated inflation mechanism or other new physics \cite{28}. Gaussianity is a highly special case of all possible fluctuation patterns; no single definitive test for non-Gaussianity exists. Various techniques have been developed in the context of the microwave background (e.g. \cite{29, 30, 31}), but so far all measurements of the temperature fluctuations down to sub-degree angular scales show no statistically significant departure from Gaussianity \cite{8, 9, 32}.

### Gravitational Waves

Inflation generically predicts primordial tensor perturbations, or gravitational waves, with an amplitude proportional to the energy scale of inflation. Tensor perturbations can be cleanly separated from scalar perturbations by observing a B-polarization signal, which is produced by tensor but not by scalar perturbations \cite{33, 34, 11}. Current measurements of the temperature power spectrum limit the amplitude of tensor perturbations to be no larger than around 20\% of the scalar perturbation amplitude. Recently, Knox and collaborators have shown that the B-polarization induced by gravitational lensing provides a lower limit to the amplitude of tensor perturbations which can be detected via microwave background polarization, corresponding to an inflation energy scale of around $3 \times 10^{15}$ GeV \cite{35}. If inflation occurred at energy scales higher than this, we can eventually expect direct confirmation of the inflationary scenario via detection of the microwave background polarization signal produced by the inevitable inflationary gravitational waves. Note this energy scale is generally below the coupling-constant unification scale in GUT models of particle physics.

### Topology

A novel application of full-sky microwave background maps is a strong test for non-trivial large-scale topology of the Universe. While the assumption of local homogeneity and isotropy determines the Friedmann equation governing the expansion of the Universe, it says nothing about large-scale topology (see \cite{36} for a review). Cornish, Spergel, and Starkman \cite{37} have proposed an elegant topological test using the cosmic microwave background. They noticed that since the last scattering surface is a sphere, any non-trivial topology, which translates into intersecting the last scattering surface with multiple copies of itself, will lead to circles on the sky with identical temperature patterns. (This is actually only approximately true, because part of the observed temperature fluctuation comes from Doppler shifts at the last scattering surface instead of temperature fluctuations.) The number of these circles and their relative directions and orientations can be used to reconstruct the topology of the Universe \cite{38}. Only a small number of topologies are possible in Universes with positive or zero spatial curvature, but negatively curved ones can support a rich variety of topologies, including some relatively small compared to the curvature scale \cite{39}. The MAP satellite has sufficient resolution to perform this test. Related ideas have also been studied \cite{40, 41}; see \cite{42}.
What Cosmology Offers High-Energy Theorists

Here is a brief list of cosmological information that is relevant to fundamental physics, probed mostly by the microwave background:

- The primordial power spectrum of fluctuations over three decades in wavelength.
- Limits on or characterization of non-Gaussianity in the primordial fluctuations.
- Limits on or characterization of any isocurvature components in the primordial fluctuations.
- Detection of primordial gravitational waves, or a limit on their amplitude.
- Limits on or detection of global topology.
- Expansion rate of the Universe at the epoch of nucleosynthesis [43].
- Expansion rate of the Universe at recent epochs, either from direct observation of standard candles like SNIa [44, 45] or from nonlinear fluctuations in the microwave background (see below).
- Constraints on dark matter properties. These come from galaxies and clusters, but are less clean than microwave background conclusions, and are currently in an unsettled state (see, e.g., [46]).
- Direct detection of gravitational radiation from the early Universe. This is the other potential direct source of information about the early Universe besides the microwave background, and could potentially probe the electroweak phase transition and similar epochs [47, 48].

This is the ground on which high-energy theorists must meet cosmologists. A general and largely unaddressed question is in what ways these sources of information can constrain fundamental theories of matter and its interactions. Optimistically, eventually we will have a candidate “theory of everything” with unavoidable cosmological predictions, and the above data sources will serve as a strong test of any such theory.

SMALL-SCALE NONLINEAR FLUCTUATIONS

At small angular scales, $l > 3500$, the power spectrum of microwave background fluctuations becomes dominated by secondary effects from nonlinear structures at recent epochs, not by the primary fluctuations from linear perturbations in the early Universe. MAP will produce the definitive measurement of microwave background temperature fluctuations out to $l = 800$, and the upcoming Planck satellite will measure the temperature (and polarization) fluctuations out to $l = 3000$ in many frequency bands before the end of this decade. At that point, observations of the primary temperature anisotropies will largely be exhausted. Presently, attention is shifting to the small-scale, non-linear fluctuations, and particularly the fluctuations induced by clusters of galaxies, the largest gravitationally bound objects in the Universe. Clusters are potentially powerful tracers
Thermal Sunyaev-Zeldovich Effect

The largest non-linear signal is that of the thermal Sunyaev-Zeldovich effect [49, 50], the spectral distortion that occurs when microwave background photons, with an initially blackbody spectrum, are Compton scattered by hot electrons, generally in clusters of galaxies. Lower energy photons are boosted to higher energies; the spectrum amplitude at the “null” of the effect, around 218 GHz (depending slightly on the density and temperature of the electrons), remains constant. In the direction of galaxy clusters, therefore, the microwave radiation appears cooler for frequencies below the null, hotter for frequencies above. The amplitude of this effect can be as large as 1 mK for large clusters of galaxies, much larger than the primary temperature fluctuations. The total spectral distortion is proportional to the product of the electron density and the electron temperature, integrated along the line of sight.

The thermal SZ effect has now been detected for numerous clusters of galaxies, at roughly arcminute angular resolution (e.g. [51, 52]). Besides providing direct information about the density and temperature of the gas in galaxy clusters, the great utility of the SZ effect is its independence of cluster redshift: since the induced spectral distortion remains as the microwave background radiation propagates, a given galaxy cluster will produce the same observed SZ distortion independent of its distance from the observer. This is in marked contrast to other methods of observing clusters from their direct emission of radiation. SZ observations hold the promise of cluster catalogs with relatively simple and complete selection functions, which in turn are necessary for any use of galaxy clusters as precision cosmological probes.

Kinematic Sunyaev-Zeldovich Effect

A related but smaller nonlinear effect results from the Doppler shift experienced by photons scattering from electrons moving with a coherent peculiar velocity. This bulk velocity induces a blackbody temperature shift of the microwave photons proportional to the radial component of the electrons’ peculiar velocity. (In the mildly nonlinear regime of structure, this effect is known as the Ostriker-Vishniac effect [53].) In galaxy clusters, the typical amplitude of this temperature shift is a few µK, much smaller than the thermal effect. The two can be separated by their spectral dependences, in principle. Even though galaxy clusters are highly dynamic objects with significant internal bulk flows due to mergers, the average kinematic SZ signal provides a largely unbiased measure of the cluster’s peculiar radial velocity [54]. If the kinematic SZ distortion can be extracted reliably for individual galaxy clusters, then galaxy clusters can be used as tracers of the growth of cosmic structure, and thus have the potential for further probes of the fundamental properties of the Universe, though these conclusions will necessarily be accompanied by more severe systematic challenges than for probes based on the primary, linear CMB fluctuations. Below, several interesting aspects of nonlinear CMB fluctuations are sketched.
cosmic peculiar velocity field out to redshifts beyond $z = 1$. Current peculiar velocity surveys extract velocities by estimating the distance to galaxies and then subtracting the inferred Hubble velocity from the observed redshift velocity to obtain a peculiar velocity. Such a procedure quickly becomes dominated by systematic errors at cosmologically modest distances due to the difficulty of accurate distance estimation. The great advantage of the kinematic SZ effect, in comparison, is that it provides a direct peculiar velocity estimate without requiring a distance determination. A peculiar velocity map over a substantial portion of the observable Universe will provide a sharp test of the gravitational instability paradigm of structure growth and a strong consistency check with surveys of the cosmic density field.

Weak Gravitational Lensing

As the microwave background radiation propagates from the last scattering surface to the observer, its geodesics will be altered by the presence of intervening matter inhomogeneities. This gravitational lensing has only small effects on the power spectrum of the microwave background fluctuations, but does change the pattern of the radiation, inducing a specific form of non-Gaussianity. Lensing creates a correlation between two-point correlations on degree scales and four-point correlations on smaller scales. Recently, algorithms have been developed to reconstruct the lensing mass distribution given a lensed temperature map. Temperature information alone can give the correct qualitative structure, while a high-sensitivity polarization map on scales of a few arcminutes can determine the projected lensing mass distribution to good accuracy on sub-degree scales. The lensing mass distribution can also be determined from shear measurements of background galaxies on comparable angular scales, providing a valuable cross-check. Microwave background lensing has the advantage of a well-defined source redshift, along with completely different systematic errors for these challenging observations.

Strong Gravitational Lensing

In the sky regions of galaxy clusters, the large mass concentration significantly distorts the microwave background temperature pattern. This strong gravitational lensing signal has several distinct features. Most notably, it produces a double-lobe distortion aligned with the temperature gradient of the background fluctuations. This distortion can be used to reconstruct the cluster mass profile, in principle: while observations of background galaxy shapes yield only information about the relative shear field of the mass distribution, lensing of the microwave background provides direct information about the displacement field induced by the mass distribution. The characteristic angular scale of the strong lensing distortion is an arcminute; on this scale, the primary CMB fluctuations have essentially no power. Thus, in certain regions of the sky where the primary fluctuations are especially regular, the lensing displacement field from a cluster can likely be modelled with good precision and used to estimate cluster masses. Since
the displacement is estimated directly, this method has no mass sheet degeneracy, like optical galaxy lensing estimates of cluster masses, and has no uncertainties related to the background source redshift. Ultimately, the accuracy of this cluster mass determination method will depend on how well the background microwave temperature distribution can be modelled, and on how well the blackbody lensing distortion can be separated from the blackbody kinematic SZ distortion. Accurate cluster mass determination is crucial for directly measuring \( N(M, z) \), the number density of clusters at a given mass and redshift. This function is a highly sensitive probe of the recent growth of structure and constrains the cosmological constant or other “dark energy” contributions, as well as small neutrino masses.

**FUTURE EXPERIMENTAL PROSPECTS: ACT**

Experimental techniques for measuring the microwave background radiation are, remarkably, advancing at an accelerating pace. The various kinds of observations outlined in the previous section require, roughly, arcminute resolution maps with micro-Kelvin temperature sensitivity. Such measurements are on the menu for the coming half-decade. As an example, I provide a brief overview of the Atacama Cosmology Telescope (ACT), an experimental collaboration between Princeton, U. Pennsylvania, Rutgers, NASA Goddard, NIST, and several other smaller partners. This collaboration exhibits many technological and organizational characteristics which we anticipate will come to dominate the microwave background field over the coming decade. Experiments of comparable scope and ambition are also being planned by other groups.

The ACT collaboration plans to construct a custom-designed 6-meter off-axis telescope which is optimized to minimize the systematic errors which can easily dominate any precision measurement of the microwave background radiation. It will scan the sky at fixed elevation by rotating on a turntable; the entire telescope, including ground screens, will rotate as a unit to eliminate any change in side lobes. Constant-elevation scans greatly aid in controlling systematic errors, since the atmospheric emission changes by many hundreds of \( \mu \)K for elevation changes smaller than a degree. A similar design philosophy was used successfully in the Saskatoon \[63\] and MAT \[64\] experiments. The telescope will be cited on Cerro Toco in the Atacama Desert of the Chilean Andes, near the site for the ALMA interferometer. Site studies show that the atmospheric signal at microwave frequencies will generally be smaller than our detector noise for all scales \( l > 100 \). At this latitude, scans at a constant 45° elevation with an amplitude of \( \pm 1.5° \) can be combined over 24 hours to produce a map of an annular region of sky approximately 2° wide by 120° degrees around. About half the scan will cover the galactic plane and will be useful for galactic astronomy; the other half will be of cosmological quality.

ACT’s novel detector technology will enable it to produce maps of unprecedented sensitivity and angular resolution. We plan to build a “camera” composed of bolometer arrays at three different frequencies, each array containing 1024 square-millimeter transition edge sensor detectors \[65, 66\]. These bolometers are very fast, enabling rapid scanning of the sky. Each individual bolometer’s sensitivity is within a factor of two of
the bolometers planned for the Planck satellite; packing them into a large array gives ACT the raw detector sensitivity required for achieving a nominal angular resolution of 1.7' (at 150 GHz) with a nominal sensitivity per pixel of near 1 $\mu$K for a three-month observing campaign. The largest technological challenge of the experiment is fabricating the detector arrays with their associated SQUID multiplexors \cite{67} and other back-end electronics. Current state-of-the-art bolidum arrays employ tens of bolometers; we aim to increase this by a factor of a hundred. The anticipated time scale for building the experiment and observing for two seasons is five years.

The microwave observations from ACT will be combined with an integrated optical and X-ray observing campaign aimed at the galaxy clusters discovered via their SZ signals. Optical observations with the Southern African Large Telescope (currently under construction) and other large telescopes will provide redshifts and galaxy velocity dispersions for hundreds of clusters out to redshift unity, while X-ray observations will give information about gas temperature and density. Through this combination of observations, we aim to construct the most complete and useful cosmological cluster sample to date. We will begin to probe all of the small-scale signals outlined in the previous section.

As spectacular as the advances in microwave background physics have been over the past decade, we can reasonably expect another decade of comparable discovery, with remarkable implications for cosmology, fundamental physics, and astrophysics.

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