Cosmic microwave background radiation

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The cosmic microwave background radiation (CMBR) is widely interpreted as the thermal afterglow of a hot big bang. Measurements of the CMBR intensity as a function of frequency constrain the history of cosmic energetics. Measurements of the anisotropy in the CMBR temperature provide a snapshot of the distribution of fluctuations in the gravitational potential at the earliest stages of cosmic structure formation. The authors review the interpretation of the CMBR emphasizing the status of current observations and future observational prospects. Our knowledge of the CMBR will dramatically increase in the first decade of the twenty-first century. [S0034-6861(99)05202-2]

I. INTRODUCTION

Most astronomers and physicists now believe that we live in an expanding universe that evolved from an early state of extremely high density and temperature. Measurements of the spectrum and anisotropy of the cosmic microwave background radiation (CMBR) provide strong evidence supporting this picture. Today, the spectrum of the CMBR matches that of a 2.728 K blackbody to within 0.01%, and the radiation is highly isotropic on the sky. Both of these properties are expected of the thermal radiation remnant of a hot, dense early universe (Peebles, 1993).

The cartoon in Fig. 1 shows how the CMBR evolves as the universe expands and cools. Local thermal equilibrium is established in the radiation epoch by radiative scattering processes, bremsstrahlung and radiative Compton scattering. Thus the CMBR thermal spectrum was established when the temperature of the universe was $T_{CMBR}>10^7$ K, at an age $t<1a$ day after the beginning. The accurately measured thermal spectrum indicates that standard physics was at work during this radiation epoch. As the density and temperature continue to fall, the dominant source of energy density in the universe changes from radiation to matter. (In an expanding universe with scale factor a, $T_{CMBR}\propto a^{-1}$, $\rho_{rad}\propto a^{-4}$, and $\rho_{mat}\propto a^{-3}$.) At $T_{CMBR}\approx 4000$ K, neutral hydrogen forms for the first time. The scattering cross section for photons off matter drops dramatically, and they decouple. This decoupling epoch (age $t\approx 3\times 10^5$ years) is very important in the life of a typical CMBR photon. It scatters here for the last time (unless the universe reionizes soon after decoupling) and travels directly to us. However, slight perturbations in the matter density or motion impose a small temperature anisotropy on the scattered radiation. By measuring this tiny anisotropy (<100 μK) across the sky, we can learn about the density perturbations that seeded the formation of cosmic structure such as galaxies and clusters of galaxies. Accurate measurements of the angular power spectrum of the anisotropy at scales of a degree and smaller might tell us about the detailed physics of decoupling and determine long-sought parameters of the cosmological model (see Hu, Sugiyama, and Silk, 1997 for a conceptual view).

II. MEASUREMENTS OF THE CMBR

A. The spectrum

The temperature of the CMBR can be estimated by noting that a substantial fraction ($\approx$24%) of the matter in the universe is helium and assuming that it was made by nuclear reactions in the early universe. If so, at an age of $t\approx 100$ s, while neutrons were still around, a temperature of 10^9 K and a baryon density of 10^{27} m^{-3} would generate the observed He abundance. The mean baryon density today of about 1 m^{-3} gives an expansion factor of 10^9 and a temperature of 1 K. This rough estimate means that the CMBR is in the microwave band.

The essential ingredients of an experiment to measure the CMBR temperature at a given wavelength are (1) an antenna (usually a horn) with very low side-lobe response, (2) a cold emitter of known temperature (called the "cold load"), and (3) accurate knowledge of all sources of radio noise other than the CMBR. It is im-

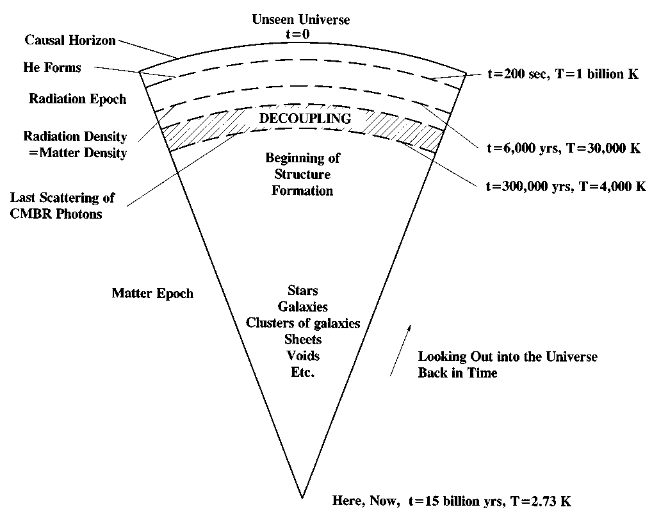

FIG. 1. Significant events for the CMBR in the standard cosmological model. We are at the vertex looking out at past epochs. The big bang happened here, and everywhere else, about 15 billion years ago. We see it now on our causal light horizon at a radius of about 15 billion light years. After matter and radiation decouple, gravity aggregates the now neutral matter, and the universe is transparent to CMBR photons. Their anisotropy carries information about physical conditions in the universe at decoupling and may provide a new way to measure cosmological parameters.

portant to reject radiation from the ground, the galactic plane, moon, etc., so usually beam sizes of a few degrees are used with careful attention to shielding. Ideally, the cold load can be connected to the horn antenna aperture without disturbing the radiometer. It establishes an output reading at a known temperature, a zero-point calibration. Most experimenters use a good microwave absorber connected to a bath of boiling liquid helium, a temperature conveniently close to T_{CMBR}. The gain (output units per Kelvin), is usually measured by making a known change in the cold-load temperature. Gain fluctuations are removed by periodically switching between the antenna signal and a known, stable, source (Dicke, 1946). The more troublesome noise sources are generated skyward of the Dicke switch. These include atmospheric emission, Galactic radiation, or emission from within the instrument, for example, radiation from the inner walls of the horn antenna. As in any experiment measuring an absolute number, all these must be accurately measured and subtracted from the total measured radiation temperature. In early experiments these extraneous sources were as large as several K. In a well-designed modern experiment they are the order of a few tens of mK.

Many measurements of the CMBR temperature have been made from the ground, balloons, high-flying aircraft, and a satellite. (For comprehensive reviews see Weiss, 1980, and Partridge, 1995.). From the ground one needs to measure and subtract emission from atmospheric oxygen and water vapor. This can be hundreds of Kelvin near emission lines or a few Kelvin in the atmosphere's microwave windows. Long-wavelength measurements ($\lambda > 20$ cm) are still made from the ground because appropriate antennas are large and cumbersome. At centimeter wavelengths, balloons offer a good way of reducing atmospheric emission to an effective temperature of a few mK. Balloon-based instruments have achieved $\leqslant 1\%$ accuracies at wavelengths between 1 cm and 3 cm.

However, the field was changed forever by a CMBR spectrum measurement from the Cosmic Background Explorer (COBE) satellite. The Far-Infrared Absolute Spectrophotometer (FIRAS) compared the spectrum of the sky with that of a very black cold load (emissivity >0.99997) whose temperature was accurately measured (Mather *et al.*, 1990). The instrument was a scanning Fourier-transform spectrometer with one input coupled to the sky through a tapered horn antenna with low sidelobe response. To minimize the effects of internal emission, the entire instrument was cooled to 1.5 K in a 500 liter dewar of liquid He. The entire satellite was oriented to always point away from the earth and sun. The crucial cold load could be moved into position over the FIRAS antenna, thus giving a blackbody reference source of accurately known temperature. Its temperature could be adjusted to closely match the signal from the sky, which gave a nearly zero output from the balanced spectrometer. The high accuracy of the measured CMBR spectrum is traceable to the differential nature of the instrument, and to the blackness and broad frequency range of the cold load.

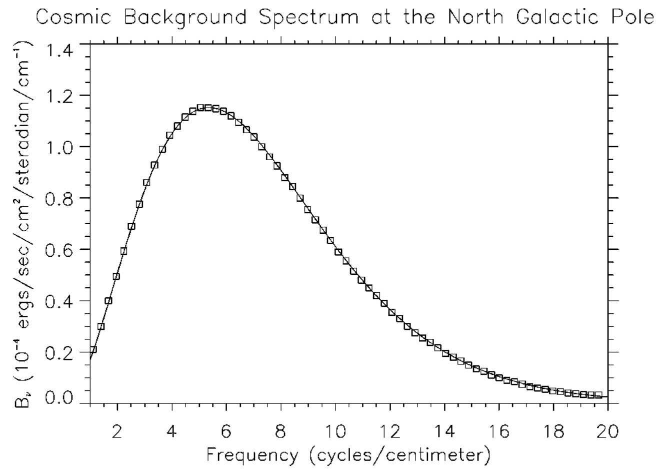

FIG. 2. The initial sky spectrum from the FIRAS instrument aboard the COBE satellite. The solid line is a 2.735 K blackbody and the squares are the FIRAS results. There can be no question that the universe is filled with thermal radiation as required by the hot-big-bang model. This preliminary spectrum was based on nine minutes of data. The horizontal axis is wave number (cm^{-1}); the vertical axis is sky brightness. (Figure courtesy Edward S. Cheng, NASA/GSFC.)

One version of the COBE/FIRAS spectrum is shown in Fig. 2. This is the first spectrum seen by the COBE team only a month after COBE's launch in November, 1989. When John Mather (COBE Project Scientist and FIRAS Principle Investigator) showed it to a packed session of the American Astronomical Society's January 1990 meeting, the audience stood and applauded. Subsequent careful analysis of the FIRAS data has greatly improved the accuracy of the results. The FIRAS team has shown that the sky spectrum fits a 2.728 ± 0.004 K blackbody spectrum to an accuracy of 0.01% at wavelengths between 5 mm and 0.5 mm (Fixsen *et al.*, 1996). A temperature measurement of this accuracy is not particularly useful in cosmology, but the spectral fit is very important. Only the hot-big-bang model predicts, or accounts for, such an accurate fit to a Planck spectrum.

Within two weeks of the announcement by the COBE/FIRAS team, a very similar result was reported by Gush, Halpern, and Wishnow (1990), who used a rocket-borne spectrometer. Their result would have predated the COBE/FIRAS result except that an erroneous setting in a vibration test damaged the instrument, postponing the successful rocket flight by about 5 months.

B. The anisotropy

Searches for anisotropy in the CMBR started soon after its discovery (Penzias and Wilson, 1965; Dicke *et al.*, 1965). Anisotropy experiments compare the CMBR temperatures at two or more points in the sky. Such relative measurements are intrinsically more accurate than the absolute temperature measurements. However, the expected CMBR anisotropy signals are small,

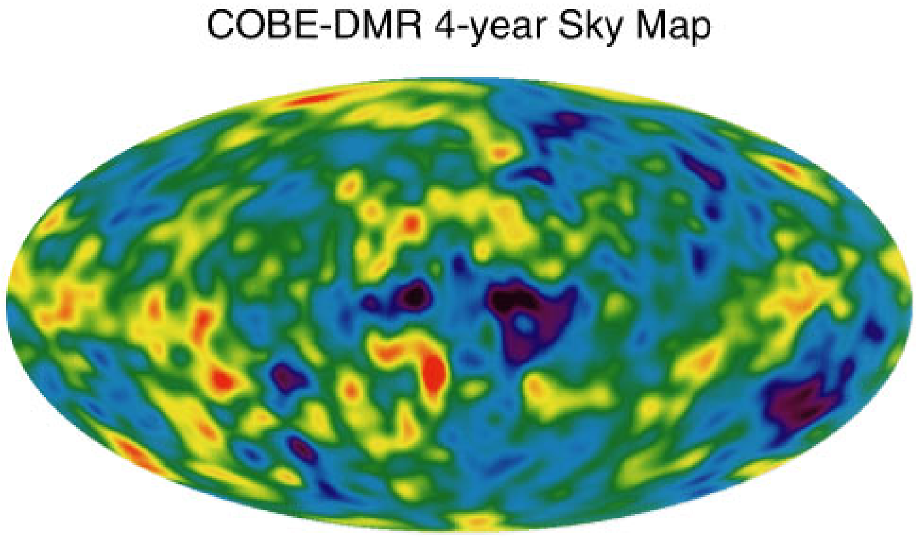

FIG. 3. (Color) The final four-year sky map (in galactic coordinates) produced by the DMR experiment aboard COBE. Some of the stronger features seen off the galactic plane are due to real CMBR anisotropy. The 2.73 K CMBR level, the 3.3 mK dipole, and most of the galactic emission have been subtracted to obtain this map. The temperature range is ± 150 μK. (Figure courtesy COBE Science Working Group, NASA/GSFC.)

<100 μK, so extraordinary detector sensitivity and stability are needed. Also, care must be taken to avoid changes in the signal from antenna side-lobes when moving the antenna beams, and the effects of atmospheric emission and galactic radiation must be minimized. Early experimenters spent many years developing receivers and techniques for observations from the ground, balloons, and aircraft. They successfully detected the dipole effect, a Doppler shift due to the sun's velocity with respect to the CMBR frame. The dipole amplitude is 3.3 mK, $\approx 10^{-3} T_{CMBR}$. However, the early experiments failed to separate the important intrinsic CMBR anisotropy from spurious effects.

By the late 1970s, the lessons learned from the early experiments led to the design of the COBE satellite's differential microwave radiometers (DMR) which conclusively detected the CMBR anisotropy after a year of orbital data had been analyzed (Smoot *et al.*, 1992). The COBE/DMR experiment used differential radiometers at 31, 53, and 90 GHz to map the sky with beams of 7° full width. The three frequencies were needed to separate the CMBR anisotropy from Galactic radio emission. These sources have different, but known, frequency dependence. The rms amplitude of the CMBR on angular scales $>7°$ was found to be 30 ± 5 μK. One sees why terrestrially based experiments had so much trouble separating the CMBR anisotropy from the effects of the 300 K background of the Earth's environment. After four years of data the signal-to-noise ratio in regions of the COBE/DMR map away from the galactic plane was about 2, so the CMBR anisotropy was clearly detected (Bennett *et al.*, 1996). Figure 3 shows a four-year COBE/DMR map in which the galactic signal has been subtracted using data from all three COBE/DMR frequencies. The subtraction is not complete near the galactic plane.

The COBE/DMR result was quickly confirmed using data from an earlier MIT balloon experiment, the Far Infrared Survey (FIRS). The measurement was made using bolometric detectors at 170 GHz and higher. On their own, the FIRS data were too noisy and contaminated by spurious effects to permit an unambiguous isolation of the CMBR anisotropy signal. However, cross correlation of the FIRS map with the COBE/DMR map showed a strong common signal. The much higher frequency of the FIRS data provided a measurement of the spectrum of the common signal; it matched that expected from a 2.73 K blackbody (Ganga *et al.*, 1993).

After COBE, interest in the CMBR anisotropy turned to measurements at smaller angular scales. Again, experimenters have used ground- and balloon-based instruments with coherent receivers, bolometric detectors, and interferometers (see Page, 1997, for a review). Since the COBE/DMR measured anisotropy only at angles $>7°$, it was natural for the experiments to move to smaller angular scales. Also, theorists had found that, during the decoupling process of the standard model, certain angular scales are enhanced, embedding measurable features in the angular power spectrum of the CMBR anisotropy (e.g., Bond and Efstathiou, 1987). These were predicted to appear at scales from about 1° to 0.1°. Experimental progress at these intermediate angular scales has been rapid, with all three detection techniques contributing to the current picture. Figure 4 shows a plot of the average of many measurements of CMBR anisotropy amplitude vs angular scale. (Angles are represented by the spherical-harmonic index ℓ, angle $\approx 180°/\ell$.) The solid line shows the prediction of a representative theoretical model. One is impressed that the measurements indicate increased fluctuations at about the angular scales predicted by the models. However, even after averaging over all measurements avail-

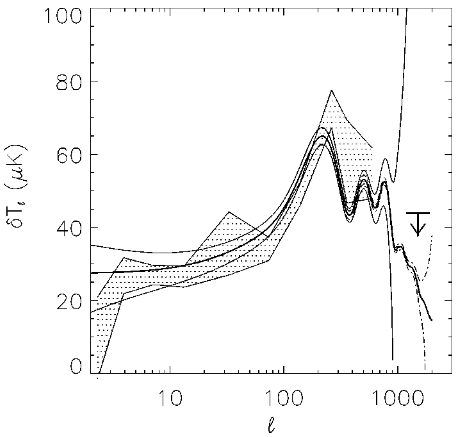

FIG. 4. Current results from CMBR anisotropy experiments averaged into ten bins in ℓ, the spherical-harmonic index. The point near $\ell = 1700$ (highlighted by an arrow) is an upper limit. δT_{ℓ} is the rms temperature fluctuation per logarithmic interval in ℓ. The COBE/DMR results appear at $\ell < 20$. Recent experiments are trying to test the prediction of some cosmological models that a series of peaks should appear at intermediate angular scales, $20 < \ell < 1000$. The thick curve is the prediction for "standard CDM" (cold dark matter) with $\Omega_{\text{baryon}} = 0.05$, $\Omega_{\text{CDM}} = 0.95$, and $H_0 = 50$ km/sec/Mpc. The solid lines on either side of the model are an estimate of the noise per ℓ for the MAP satellite. At low ℓ, cosmic variance dominates; at high ℓ one is limited by MAP's angular resolution. The dot-dash line is a similar estimate for the Planck Surveyor.

able at this time, the accuracy is not yet sufficient to confirm a specific model or to reliably fit for parameters.

At large ℓ, radio telescopes and close-packed radio interferometers are needed to get the small beam sizes and sensitivity needed for CMBR anisotropy measurements. The measured upper limits at $\ell \approx 1700$ in Fig. 4 seem to show a falling spectrum. The effect is due to photon diffusion out of small regions and to multiple scattering of photons during the finite decoupling epoch, $\Delta z \approx 75$ at $z = 1400$.

III. WHAT WE'VE LEARNED FROM THE CMBR MEASUREMENTS

Before discussing the near-term prospects for CMBR anisotropy research, we review briefly what the CMBR measurements have taught us to date. The accurate fit of the CMBR spectrum to that of a blackbody shows that the universe went through an epoch of local thermal equilibrium when radiative processes thermalized the energies in radiation and matter. It also places limits on the amount of energy that could have been injected into the early universe, for example by decaying particles. Future experiments at $\lambda > 5$ mm will continue to search for distortions in the CMBR spectrum.

The isotropy of the CMBR created a causality problem for the original big-bang cosmological model. How did the different parts of the currently visible universe manage to come to the same temperature when they were not in causal contact at earlier times? The idea of inflation, an enormous expansion in the very early universe (Turner and Tyson, 1999, this volume), currently provides the best solution to this puzzle. One pictures our visible universe as a causally connected sphere (radius ≈ 15 billion light years) inside a much larger, inflated, region. The observed isotropy of the CMBR temperature supports the inflation hypothesis, since no other explanation exists.

Causality has an interesting implication for the CMBR anisotropy measurements. The angular scales of the anisotropy measured by COBE/DMR ($>7°$) are larger than a causally connected patch on the decoupling surface. That is, at the time of decoupling a photon has a causal horizon, and any physical process that generates anisotropy at that time must lie within that horizon. Today, the angular size of those causal patches on the decoupling surface is about 1°, much smaller than angular size of anisotropy observed by the COBE/DMR. One explanation is that the large scale anisotropy was produced by quantum fluctuations in the preinflation epoch. Inflation can then produce anisotropy patches larger than the causal size at the decoupling epoch. The quantum fluctuation idea also predicts the slope of the angular spectrum for the anisotropy measured at large scales. The COBE/DMR measurements are in agreement with this prediction, lending further support to the inflation hypothesis.

From measurements of the anisotropy of the CMBR we also learn that the gravitational scenario for cosmic structure formation is plausible. The amplitude of the CMBR anisotropy corresponds to density fluctuations at decoupling, which are about the amplitude needed to seed gravitational growth of the cosmic structures seen today. It was by no means obvious that this would be the case. Indeed, the great notoriety that accompanied the announcement of the COBE/DMR detection of CMBR anisotropy was, in part, an expression of relief by cosmologists that the standard model was still alive.

IV. INTERPRETATION OF MORE ACCURATE CMBR MEASUREMENTS

The origin of the peaks in the theoretical angular spectrum of CMBR anisotropy (Fig. 4) offers some physical insight into how more accurate measurements might be used. The basic physics of peak generation is straightforward (Hu, Sugiyama, and Silk, 1997). During the epoch of decoupling, the baryons and photons are coupled by the baryon-electron Coulomb force and Compton scattering. To illustrate the peak-generation process, we use the cold dark matter (CDM) model, even though it is inconsistent with some modern observations. In this model, density fluctuations in the dominant dark matter provide gravitational potential wells into which baryons fall, compressing and raising the temperature of the photons. However, the collapsing baryon-photon fluid will bounce due to the increasing pressure of the photons. These acoustic oscillations continue until the matter is neutral and decoupling is complete. The sound-horizon size in the photon-baryon fluid at that time establishes a maximum physical scale size for a causally connected region, which corresponds to the angular scale of the first peak in the anisotropy spectrum. The peaks at smaller angular scales correspond to higher-frequency modes of the acoustic oscillations. Of course, the details of the spectrum generation at decoupling are more complicated. For example, the density and temperature of the compressed or rarefied fluid at last scattering is only one effect on the photon temperature. Two others are the gravitational redshift as the photons climb out of the potential wells and the Doppler shift due to the fluid motion at last scattering.

This simplified picture of peak generation gives some insight into how careful measurements of the anisotropy spectrum give values for cosmological constants. Space curvature is measured because one knows a physical scale size at an early epoch in the universe and measures the apparent angular size now. In a positively curved universe (closed), the angle will be larger than in a flat universe; the angle will be smaller in an open universe. So the angle corresponding to the first peak in the anisotropy spectrum should indicate the curvature of space over a distance nearly equal to our horizon size. Likewise, the amplitude of the peaks is sensitive to the baryon density in the universe. In the CDM model, the additional mass of the baryons in the potential wells increases the compression of the oscillating fluids and the amplitude of the peaks.

Polarization of the CMBR has not yet been observed. However, theoretical studies predict linear polarization at about 1 part in 10^6, a few μK. Only recently have detector technology and experimental technique reached levels where detection of such a small polarization might be possible. Polarization of the CMBR is generated when last scattering of photons occurs from a region bathed in a local quadrupole temperature anisotropy (Rees, 1968). Models predict an angular spectrum with many peaks for the CMBR polarization across the sky, and most models predict correlations between the patterns of polarization and temperature anisotropy. Polarization sky maps contain information complementary to that derived from temperature anisotropy maps, so much can be learned from accurate sky maps of the CMBR polarization.

A particularly attractive feature of probing cosmology with CMBR anisotropy and polarization is that the physics is relatively simple. Linear processes dominate and the time dependence is straightforward. So for a given set of model parameters, accurate calculations are possible.

V. FUTURE EXPERIMENTS

Currently, the primary needs in CMBR research are: (1) more accurate anisotropy spectra at scales smaller than 10°, and (2) the detection and mapping of CMBR polarization. Theoretical studies of physical processes during and after decoupling are producing detailed predictions of the spectral and statistical properties of the CMBR anisotropy and polarization. The predictions are highly dependent on choices of the cosmological model, the composition of dark matter, and the nature of the fluctuations. Thus accurate measurements of the anisotropy may determine cosmological parameters and allow us to study the detailed physics of decoupling and post-decoupling processes (Jungman *et al.*, 1995). It remains to be seen whether the measured anisotropy spectrum will show complex features, and how many models can be made to fit them accurately.

Modern experiments aim to measure the angular spectrum of the CMBR to a percent, map the polarization of the radiation and correlate it with the temperature fluctuations, measure the frequency spectrum of the anisotropy, determine the statistics of the fluctuations, and measure the distortion of the anisotropy due to gravitational lensing of the photons on their way to our detectors. The future of experimentation on the CMBR lies primarily in the control and identification of instrumental systematic effects and in an increased understanding of contamination by the astrophysical foreground emission and by the atmosphere. While an increase in detector sensitivity is always beneficial for identifying the tiny signals, the trend in current experimental design is to sacrifice sensitivity for control over potential systematic error.

We look forward to the launch of two satellite missions in the first decade of the new millennium. The primary goal of both NASA's MAP[1] and ESA's Planck Surveyor,[2] is to make multifrequency, high-fidelity, polarization-sensitive maps of the CMBR anisotropy over the entire sky. These maps will be sensitive to angular scales ranging from the dipole (180°) to the instrument resolution (≈0.2° for MAP, smaller for Planck Surveyor) and will be calibrated to better than 1% accuracy. Both missions will observe from L2, the earth-sun Lagrange point. In addition, there will be a number of multielement ground-based and balloon experiments, to corroborate and extend the satellite results.

The statistical nature of the anisotropy is of fundamental importance and will not be well constrained without unbiased full-sky maps. In the basic inflationary model, the production of the anisotropy by fluctuations in a primordial quantum field results in a normal distribution of temperatures. Other models make different predictions. Should the measured temperatures follow a normal distribution, then the anisotropy is completely specified by the angular power spectrum, as shown in Fig. 4. In this case, we may determine the variance of the source of the fluctuations only to order $\sqrt{2/N_d}$, where N_d is the number of degrees of freedom in the spherical harmonic, 5 for the quadrupole, 10^3 for $\ell=500$. This is called the cosmic variance limit. MAP will be "cosmic variance" limited up to $\ell \approx 700$ and Planck to $\ell \approx 1700$.

[1]MAP, http://map.gsfc.nasa.gov, scheduled launch is late 2000.

[2]PLANCK, http://astro.estec.esa.nl/SA.general/Projects/Planck, expected launch is 2007.

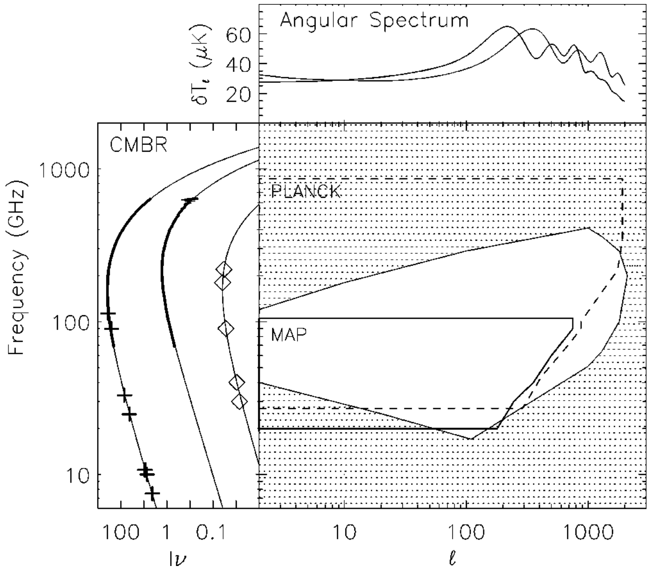

FIG. 5. The frequency and ℓ-space coverage of the upcoming satellite missions. In the shaded region, foreground emission from our galaxy and distant galaxies is expected to dominate the anisotropy in the CMBR. The top panel shows two models of the anisotropy, the one peaking at smaller ℓ is "standard CDM," as in Fig. 4; the other is an open model with $\Omega_0 = 0.4$. Notice how the peak moves to smaller angular scales. The left panel shows the surface brightness spectrum of the CMBR in units of 10^{-26} W/m^2/Hz/sr vs frequency. Representative measurements are shown. The thickened lines are from the COBE satellite. The dipole is shown at $10^{-3}T_{CMBR}$ and the anisotropy is shown at $10^{-5}T_{CMBR}$.

The other natural limit is set by the contamination of the anisotropy maps by emission from our galaxy and emission from distant galaxies, as shown in Fig. 5. Our knowledge of these sources is incomplete. Fortunately, over much of the angular spectrum, these contributions are small, ~3 μK, and add in quadrature to the primary anisotropy. In addition, the contaminants can be identified by their frequency spectra. MAP is expected to be able to extract the CMBR anisotropy to the 1% level with its frequency coverage of 20 to 100 GHz; measuring the CMBR anisotropy to greater accuracy will await the 30 to 850 GHz coverage of the Planck Surveyor.

It has become clear from years of experimentation that it is not possible to make full-sky maps suitable for detailed anisotropy analysis from balloons or the ground. This is primarily due to thermal variations in the radiometers, the anisotropy in the observing environment, and varying thermal gradients in the atmosphere. However, patches of order 10° can be mapped with precision. While various radiometric and beam-switching techniques continue to be productive, interferometers offer a proven method for minimizing atmospheric effects. Vigorous experimental efforts are underway to build arrays of bolometers at frequencies between 90 and 300 GHz and interferometers between 30 and 200 GHz.

If the pattern in the observed anisotropy should match one of the theoretical models, then the predicted polarization level and correlation between the polarization and temperature provide a built-in cross check. A number of groups are building radiometers and small arrays designed specifically to measure the linear polarization of the CMBR as a function of angular position. Because one measures the difference between orthogonal polarizations in a single beam, the receiver systems are intrinsically more immune to systematic error than traditional beam-switching experiments.

In addition to its intrinsic properties, the CMBR may be thought of as a distant light source that illuminates younger objects. Hot electrons in distant clusters of galaxies scatter low-frequency photons, for example at 30 GHz, to higher frequencies, for example at 240 GHz. This is known as the Sunyaev-Zel'dovich effect (Sunyaev and Zel'dovich, 1972). When viewed at 30 GHz and high resolution, the CMBR appears cold at the positions of galaxy clusters containing large amounts of ionized gas. This effect has been used to study distant clusters of galaxies. In the future, it may reveal their motions and, with a large number of clusters, it offers another way to ascertain the cosmological parameters.

In the beginning of the century, we learned of the existence of other galaxies. We are now probing the anisotropy of the oldest photons in the universe to a part in a million to discover how those galaxies came to be. The interlocking web of theory and constraints from observations of the distributions and velocities of galaxies, the abundances of the light elements, and the CMBR may single out a cosmological model. Should the evidence admit, it will perhaps be as convincing as the "standard model" of particle physics.

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