The microwave background anisotropies: Observations

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ABSTRACT Most cosmologists now believe that we live in an evolving universe that has been expanding and cooling since its origin about 15 billion years ago. Strong evidence for this standard cosmological model comes from studies of the cosmic microwave background radiation (CMBR), the remnant heat from the initial fireball. The CMBR spectrum is blackbody, as predicted from the hot Big Bang model before the discovery of the remnant radiation in 1964. In 1992 the cosmic background explorer (COBE) satellite finally detected the anisotropy of the radiation—fingerprints left by tiny temperature fluctuations in the initial bang. Careful design of the COBE satellite, and a bit of luck, allowed the 30 μK fluctuations in the CMBR temperature (2.73 K) to be pulled out of instrument noise and spurious foreground emissions. Further advances in detector technology and experiment design are allowing current CMBR experiments to search for predicted features in the anisotropy power spectrum at angular scales of 1° and smaller. If they exist, these features were formed at an important epoch in the evolution of the universe—the decoupling of matter and radiation at a temperature of about 4,000 K and a time about 300,000 years after the bang. CMBR anisotropy measurements probe directly some detailed physics of the early universe. Also, parameters of the cosmological model can be measured because the anisotropy power spectrum depends on constituent densities and the horizon scale at a known cosmological epoch. As sophisticated experiments on the ground and on balloons pursue these measurements, two CMBR anisotropy satellite missions are being prepared for launch early in the next century.

In the standard hot Big Bang cosmological model, cosmic microwave background radiation (CMBR) is the remnant thermal radiation which dominated the development of the very early universe. Its currently observed properties give us an important means of testing the standard model and of studying physical processes in the universe beyond the reach of our most powerful optical telescopes. Measurements by the cosmic background explorer (COBE) satellite show that the CMBR spectrum between wavelengths of 5 mm and 0.5 mm is the same as that of a blackbody emitter with an accuracy of ±0.01% (1), in surprisingly good agreement with predictions based on the hot Big Bang model. Of secondary interest to cosmology, the CMBR temperature is measured as 2.728 ± 0.004 K. The absence of spectral distortions in the CMBR imposes limits on energy-producing processes in the universe from an age of \( t \approx 1 \) year to an age of \( t \approx 10^9 \) years. Another critical test of the standard model is to measure and characterize the CMBR anisotropies expected from density perturbations at \( t \approx 3 \times 10^9 \) years, when the matter becomes neutral and decouples from the thermal radiation for the first time. Theorists predicted CMBR anisotropies of about 1 part in \( 10^9 \) (\( 67 \approx 30 \mu K \)), corresponding to the mass density perturbations needed to seed the mass structure seen in the universe today. In 1992 the COBE science team announced a detection of CMBR anisotropy (2, 3) close to the predicted amplitude at angular scales larger than 10°. Regions of this size were not yet connected by light speed at the time of decoupling, so these perturbations must have been imbedded in the original bang. The physical mechanism for generating the density perturbations may be quantum fluctuations in the very early universe, but this has not yet been verified.

Currently most CBMR observations are designed to measure the angular power spectrum of anisotropies with scales of a few degrees and smaller. The standard model predicts a complex series of peaks caused by acoustic oscillations of the recombining plasma during the decoupling process. The measurements will test the model’s ability to describe detailed physics of this critical epoch in cosmic evolution. Also, because the oscillations depend on the density and horizon size at the decoupling epoch, a careful tracing of the power spectrum of the anisotropies might measure several important cosmological parameters.

Anisotropies at Angles Larger than 10°: The COBE Measurements

One of the three experiments aboard the COBE satellite, the differential microwave radiometers (DMR), was designed specifically to look for large-scale anisotropy in the CMBR. Six radiometers at 31, 52, and 90 GHz measured the CMBR temperature difference between 7° (full width at half maximum) spots 60° apart in the sky. Spacecraft rotation and orbital motion caused the radiometers to scan about half of the sky per orbit. However, although launched in November 1989, the COBE/DMR radiometers were vintage 1975. A year of observation was required before their sensitivity was sufficient to distinguish 30 μK CMBR anisotropy from instrument noise. Even then the detection was a statistical result, because the signal to noise ratio in the map pixels was only about 1:1. Three more years of data were required to reach 5/N = 2, where some real CMBR features can be distinguished in the COBE/DMR sky map. The 4-year map is shown in Fig. 1.

It is not well known how close the COBE/DMR came to not detecting the CMBR anisotropy. As one might expect, at the 30 μK level there were several systematic effects competing with the CMBR signal. These effects had to be removed or understood before a CMBR anisotropy detection could be assured. This took about 6 months from the time that the COBE science team first suspected that a CMBR signal was present in the data. The largest systematic effect was due to the...

Abbreviations: CMBR, cosmic microwave background radiation; DMR, differential microwave radiometers; MAP, microwave anisotropy probe; CDM, cold dark matter; HEMT, high electron mobility transistor amplifier; COBE, cosmic background explorer; SIS, superconductor-insulator-superconductor.
regions of space that were connected by light speed (causal) at that time. In the standard cosmological model causal events at decoupling are separated by less than about 1° as seen now. Numerical integration of the behavior of matter and radiation through the decoupling epoch have long shown (8) that structure should be expected in the angular power spectrum of anisotropies at scales below a few degrees (9). Recent analytic work on the decoupling process (10) has shown that most of the CMBR anisotropy is caused by acoustic oscillations in the ionized fluid as the universe expands and cools. The scale of the oscillating regions is determined by the speed of sound which in turn is set by the density and composition of the fluid. This is the idea behind using medium-scale anisotropy measurements to test the detailed physics of the cosmological model and, if a model fits the data, to measure the values of some cosmological parameters.

The physics is deceptively simple. During decoupling, as the fluid is still partially ionized, radiation and matter are still coupled, but the coupling is growing weaker as the matter recombines. The acoustical oscillations are caused by mass falling into relatively over-dense regions [caused by clumped dark matter in cold dark matter (CDM) models]. The radiation is compressed like a spring, eventually causing the fluid to rebound and expand. Meanwhile the optical depth of the fluid is decreasing and more and more photons are scattering for the last time. The phase of the fluid oscillation when photons are scattered for the last time determines whether their temperatures will be slightly above or below the mean CMBR temperature. There are several effects that shift the photon frequency, and hence the CMBR temperature. If the photons are scattered for the last time from a compressed region, adiabatic fluctuations imply a higher temperature, but gravitational redshift will cool the CMBR photons as they climb out of the potential wells. If, however, the region is expanding at that time the scattered photons will be blue shifted by the Doppler effect. The gravitational and Doppler effects are 90° out of phase, so they may tend to reinforce or cancel one another. The angular scale of the oscillations that cause CMBR anisotropy is determined by the sound horizon of the fluid at the decoupling epoch. The phase of an oscillation at last scattering is set by its period and the time between when a scale enters the horizon and when the CMBR photon last scatters. Some acoustical oscillation scales release the photons when they are near the extremes of compression or expansion causing these scales to have a larger rms 8T than others. Therefore, a measurement of the rms 8T vs. angular size—the anisotropy power spectrum—is expected to have peaks from about 1° to 10°.

The detailed shape of the medium-scale anisotropy power spectrum depends on the cosmological model, the constants of that model, and the detailed physics of decoupling. Some predicted peaks are shown in Fig. 2 for various cosmological models of current interest. Accurate measurements of the angular power spectrum can be used to determine the important cosmological parameters of the model (11, 12). For example, the baryon density and Hubble constant, ΩB and H0, largely determine the height of the first peak and the ratio between peak heights. The total mass density, Ω0, and H0, largely determine the angles at which the peaks occur. Is there, after all, a significant cosmological constant, Λ, in our universe today? Fig. 2 shows that such a model is easily detectable by a well-measured anisotropy power spectrum. A major issue in cosmology research is the whether the universe is open (ΩTOTAL < 1) or closed, perhaps with a large density of unidentified CDM. Finally, what is the nature of those initial perturbations? Are they adiabatic or isocurvature? Again Fig. 2 indicates that accurate measurements of the anisotropy power spectrum can distinguish between these various models. Theoretical cosmologists continue to work out the possible consequences of accurate measurements of the anisotropy...
techniques being used to observe CMBR anisotropies: cohering strategies. Currently, there are three types of detection to develop more sensitive detectors and sophisticated observers built larger telescopes to get smaller beams and continued

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Anisotropies at Angular Scales Smaller than 10°: Current Measurements

After the COBE/DMR detection of large-scale CMBR anisotropy the focus of the field shifted to smaller angular scales. Theoretical work intensified as it became clear that the decoupling epoch could be studied in detail and some important cosmological constants might be measured. Experimenters built larger telescopes to get smaller beams and continued to develop more sensitive detectors and sophisticated observing strategies. Currently, there are three types of detection techniques being used to observe CMBR anisotropies: coherent microwave receivers, low temperature bolometers, and radio interferometers. Detectors are sufficiently difficult to develop that most groups specialize on one or two types. The detector type usually drives the choice of observing frequency, angular scale, and observing platform. Currently, all anisotropy observations are being made from the ground or from balloons; planned observations from satellites will be described in the next section.

Low-temperature bolometers are the most sensitive detectors currently available. Optical techniques can be used to obtain sensitivity to wide frequency bands and many propagating modes, so more energy can be collected from the extended, broadband CMBR source. The disadvantages of bolometric detectors are their need for relatively complicated cryogenic techniques \( (T \leq 300 \text{ mK}) \) and the high frequency range needed for best sensitivity, \( v \geq 90 \text{ GHz} \). Atmospheric emission is a problem at these frequencies, so observations must be made from the South Pole or mountain tops \((14-17)\) or from balloons \((18-22)\). Foreground emission from Galactic dust competes with the CMBR anisotropy at frequencies \( >150 \text{ GHz} \), so most experimenters use several frequency bands to measure and remove the dust signal. Coherent microwave receiver techniques use high electron mobility transistor amplifiers \((\text{HEMTs})\) or SIS \((\text{superconductor-insulator-superconductor})\) junction mixers to achieve low instrument noise. HEMT-based receivers are currently limited to frequencies \(<100 \text{ GHz} \) and they have lower sensitivity than bolometers. However, they do not require complex cryogenic systems to give adequate noise performance; they work well at 10 K, which is easily reached by standard mechanical refrigerators. Because the atmosphere is relatively quiet in some bands \(<90 \text{ GHz} \), HEMT receivers can make good measurements of the CMBR anisotropy from ground-based sites under cold, dry atmosphere \((23-25)\). SIS mixers go higher in frequency, and wide bandwidths can be achieved. They require cooling below 1 K, usually obtained with pumped liquid helium.

Problems due to fluctuations in atmospheric emission can be minimized by making observations from balloons, but observing time is currently limited to about 10 hr per flight. Several groups are working to relax this restriction by developing long duration ballooning techniques—perhaps circumpolar flights of 2 weeks or more. Other groups observe from high altitude sites with particularly dry atmosphere, such as the South Pole, Mauna Kea, or northern Chile. As the accuracy of CMBR anisotropy measurements increases, foreground emission from our Galaxy becomes a more important issue. Measurements at a wide range of frequencies are needed to separate CMBR anisotropies from Galactic radio and dust emission. Because radio emission decreases with frequency, and dust emission increases, there is a minimum in the temperature of foreground emission. The minimum is somewhere between 70 and 90 GHz.

Another way to reduce the effects of atmospheric emission is to use radio interferometer techniques. Interferometers can also achieve higher angular resolution at some sacrifice of sensitivity. The National Radio Astronomy Observatory’s Very Large Array, and the Mullard Observatory’s Cosmic Anisotropy Telescope have already been used to make sensitive measurements of CMBR small-scale anisotropy \((26, 27)\). Because the separate antennas of the array look through different atmospheric paths, most of the atmospheric signal is uncorrelated, whereas the CMBR signal is correlated in all antennas. Currently, observing frequencies are quite low \((\approx 20 \text{ GHz})\) and bandwidths are limited by correlator technology and cost. Of course, the main advantage of interferometer arrays is their capability to measure small-scale anisotropy without having to build a large, expensive mm-wave antenna. Mapping capability is intrinsic to interferometers.

Several dozen measurements of the medium- and small-scale CMBR anisotropy have been made and more are un-
underway in this very active field. Page (28) has compiled a list of properties for recent, current, and planned experiments; a version of that list is shown here in Table 1. As an illustration of the results from a typical experiment, the results from the Saskatoon experiments are shown in Fig. 2. The measured rms anisotropy, $\delta T_0$, is plotted against angular scale as represented by the spherical harmonic index, $l$. A range of angular scales can be studied in these experiments by scanning the beam back and forth across the sky and then doing Fourier analysis of the data. The high $l$ end of the measured spectrum is set by the beam size, and the low $l$ end is set by the length of the scan. Predictions of some cosmological models are also shown in Fig. 2. The re-ionization model seems to be ruled out, but one should treat the results of any single anisotropy experiment with caution. Signals are very weak compared with instrument noise, so the evaluation of systematic effects is difficult. Multiple experiments with different technologies, frequencies, screening, and scanning techniques are needed to assure that it is the true CMBR anisotropy that is being measured.

Fig. 3 shows an attempt by Page (28) to make an objective summary plot of CMBR anisotropy results as of June 1996. He used the compilation of experimental results of Ratra et al. (ref. 29; and B. Ratra, personal communication) and averaged the data into logarithmically spaced angle bins, four per decade. The error bars on $\delta T_0$ in each band are derived from the error bars reported by each experimental group. There is a strong indication that the CMBR anisotropy is larger at medium angular scales (100 < $l$ < 500) than at large scales where the COBE/DMR results anchor the anisotropy at about 30 $\mu$K. At small scales upper limits have been set (asterisks in Fig. 3) by interferometer and large single-dish experiments. These indicate a decrease in the small-scale anisotropy spectrum compared with the measurements at medium scales. Perhaps we are seeing the decay of anisotropy expected from multiple scattering of photons at decoupling. However, most experimenters urge caution in the interpretation of current anisotropy results. Only a few measurements have been confirmed by a second group observing the same region of sky (Far Infrared Survey confirms COBE/DMR, see ref. 30; and Saskatoon confirms Medium-scale Anisotropy Measurement, see ref. 31). Calibration and systematic errors are known to be present. Ground- and balloon-based experiments will continue.

Table 1. Recently completed, current, and planned anisotropy experiments

<table>
<thead>
<tr>
<th>Experiment*</th>
<th>Resolution, °</th>
<th>Frequency, GHz</th>
<th>Detector</th>
<th>Type†</th>
<th>Group‡</th>
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<tbody>
<tr>
<td>ACE(c)</td>
<td>0.2</td>
<td>25–100</td>
<td>HEMT</td>
<td>R/B</td>
<td>UCSB</td>
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<tr>
<td>APACHE(c)</td>
<td>0.33</td>
<td>90–400</td>
<td>Bol</td>
<td>R/G</td>
<td>Bologna, Bartol Rome III</td>
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<tr>
<td>ARGO(f)</td>
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<td>140–3,000</td>
<td>Bol</td>
<td>R/B</td>
<td>Rome I</td>
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<tr>
<td>ATCA</td>
<td>0.03</td>
<td>8.7</td>
<td>HEMT</td>
<td>I/G</td>
<td>CSIRO</td>
</tr>
<tr>
<td>BAM(c)</td>
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<td>90–300</td>
<td>Bol</td>
<td>R/B</td>
<td>UBC, CIA</td>
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<td>Bartol(c)</td>
<td>2.4</td>
<td>90–270</td>
<td>Bol</td>
<td>R/G</td>
<td>Bartol</td>
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<tr>
<td>BEAST(p)</td>
<td>0.2</td>
<td>25–100</td>
<td>HEMT</td>
<td>R/B</td>
<td>UCSB</td>
</tr>
<tr>
<td>BOOMERanG(p)</td>
<td>0.2</td>
<td>90–400</td>
<td>Bol</td>
<td>R/G</td>
<td>Rome I, Caltech UCB, UCSB</td>
</tr>
<tr>
<td>CAT(c)</td>
<td>0.17</td>
<td>15</td>
<td>HEMT</td>
<td>I/G</td>
<td>Cambridge</td>
</tr>
<tr>
<td>CBI(p)</td>
<td>0.0833</td>
<td>26–36</td>
<td>HEMT</td>
<td>I/G</td>
<td>Caltech, Penn.</td>
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<tr>
<td>FIRS(f)</td>
<td>3.8</td>
<td>170–680</td>
<td>Bol</td>
<td>R/B</td>
<td>Chicago, MIT, Princeton, NASA/GSFC</td>
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<tr>
<td>HACME/SP(f)</td>
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<td>30</td>
<td>HEMT</td>
<td>R/G</td>
<td>UCSB</td>
</tr>
<tr>
<td>IAB(f)</td>
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<td>150</td>
<td>Bol</td>
<td>R/G</td>
<td>Bartol</td>
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<tr>
<td>MAT(p)</td>
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<td>30–150</td>
<td>HEMT/SIS</td>
<td>R/G</td>
<td>Penn, Princeton</td>
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<tr>
<td>MAX(f)</td>
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<td>90–420</td>
<td>Bol</td>
<td>R/B</td>
<td>UCB, UCSB</td>
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<tr>
<td>MAXIMA(p)</td>
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<td>90–420</td>
<td>Bol</td>
<td>R/B</td>
<td>Caltech</td>
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<tr>
<td>MSAM(c)</td>
<td>0.4</td>
<td>40–680</td>
<td>Bol</td>
<td>R/B</td>
<td>Chicago, Brown, Princeton, NASA/GSFC</td>
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<tr>
<td>OVRO 40/5(c)</td>
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<td>15–35</td>
<td>HEMT</td>
<td>R/G</td>
<td>Caltech, Penn</td>
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<tr>
<td>PYTHON(c)</td>
<td>0.75</td>
<td>35–90</td>
<td>Bol/HEMT</td>
<td>R/G</td>
<td>Carnegie Mellon, Chicago, UCSB</td>
</tr>
<tr>
<td>QMAP(f)</td>
<td>0.2</td>
<td>20–150</td>
<td>HEMT/SIS</td>
<td>R/B</td>
<td>Princeton, Penn</td>
</tr>
<tr>
<td>SASK(f)</td>
<td>0.5</td>
<td>20–45</td>
<td>HEMT</td>
<td>R/G</td>
<td>Princeton</td>
</tr>
<tr>
<td>SuZIE(c)</td>
<td>0.017</td>
<td>150–300</td>
<td>Bol</td>
<td>R/G</td>
<td>Caltech</td>
</tr>
<tr>
<td>TopHat(p)</td>
<td>0.33</td>
<td>150–700</td>
<td>Bol</td>
<td>R/B</td>
<td>Bartol, Wisconsin, DSRI, Chicago, NASA/GSFC</td>
</tr>
<tr>
<td>Tenerife(c)</td>
<td>6.0</td>
<td>10–33</td>
<td>HEMT</td>
<td>R/G</td>
<td>NRAL, MRAO, IAC</td>
</tr>
<tr>
<td>VCA(p)</td>
<td>0.33</td>
<td>30</td>
<td>HEMT</td>
<td>I/G</td>
<td>Chicago</td>
</tr>
<tr>
<td>VLA(c)</td>
<td>0.0028</td>
<td>8.4</td>
<td>HEMT</td>
<td>I/G</td>
<td>Haverford, NRAO</td>
</tr>
<tr>
<td>VSA(p)</td>
<td>—</td>
<td>30</td>
<td>HEMT</td>
<td>I/G</td>
<td>Cambridge</td>
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<tr>
<td>White Dish(f)</td>
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<td>90</td>
<td>HEMT</td>
<td>R/G</td>
<td>Carnegie Mellon</td>
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†For “Type” the first letter distinguishes between radiometer or interferometer, the second between ground or balloon.

‡The groups are as follows: UCSB, University of California, Santa Barbara; CSIRO, Commonwealth Scientific and Industrial Research Organization; UCB, University of California, Berkeley; Caltech, California Institute of Technology; Penn., University of Pennsylvania; MIT, Massachusetts Institute of Technology; NASA, National Aeronautics and Space Administration; GSFC, Goddard Space Flight Center; DSRI, Danish Space Research Institute; NRAL, Nuffield Radio Astronomy Laboratory; NRAO, National Radio Astronomy Observatory; IAC, Instituto de Astrofisica de Canarias; MRAO, Mullard Radio Astronomy Observatory.
Anisotropies at Angular Scales Smaller than 10°: Future Prospects

There are two promising innovations underway in this field. Prospects are good for a detection of CMBR polarization, and space missions promise sensitive full-sky measurements of the medium-scale anisotropy. Thirty years ago Rees (32) predicted that the CMBR would be polarized at a level of about 10% of the expected temperature anisotropy—i.e., a polarization signal of a few µK. The polarization is produced at the time of last scattering of CMBR photons. If the scattering electron is bathed by an anisotropic flux of photons in the plane perpendicular to our line of sight, the scattered CMBR that we measure will be polarized. However, because the effect is expected to be much weaker than the temperature anisotropy, instrument sensitivity and systematic errors have so far precluded measurements from reaching the expected levels of a polarization signal. Radiometer sensitivity has now improved to the point where experiments can be designed with an expectation of seeing the CMBR signal (polarization experiment) in the near future. To avoid the Earth’s environment, which contaminates the COBE/DMR anisotropy signal, MAP will be placed at the Earth-sun Lagrange point, L2, 1.5 × 10^6 km outside of the Earth’s orbit. This appears to be an excellent location for high sensitivity astronomical observations.

A simulation of the expected sky map from 2 years of MAP data is shown in Fig. 5. This can be compared with Fig. 1, which

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**Fig. 3.** A graphical summary of experimental attempts (up to June 1996) to measure the medium-scale CMBR anisotropy. Points for \( l \leq 17 \) are from the COBE/DMR experiment; \( 20 < l < 800 \) are the combined (28) measurements of many groups; the asterisks are upper limits from small-scale measurements. The upper and lower curves are estimated one standard deviation error bars for the combined data.

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**Fig. 4.** A sketch of the MAP satellite. The upper half of the spacecraft is cooled by passive radiation to space to get lower noise performance from the optics and the radiometers. Two back-to-back 1.5 m telescopes receive CMBR radiation from spots 141° apart on the sky. Each telescope illuminates 10 horn antennas in its focal plane. The radiometers measure the difference in the powers from pairs of horns on opposite sides of the spacecraft. Twenty radiometer channels capture both polarization modes in each of 5 microwave bands between 20 and 106 GHz. The solar panels (shown deployed) also serve as shields to minimize emission from the sun, Earth, and moon, which are behind the spacecraft at all times. The hexagonal box contains the spacecraft support electronics and the momentum wheels used for attitude control. Data will be sent by telemetry to Earth once a day.
is the real map from the COBE/DMR instrument. MAP’s 30 times greater resolution is due to the larger apertures of its back-to-back telescopes (see Fig. 4), and its HEMT amplifier technology developed at the National Radio Astronomy Observatory (35) is 50 times more sensitivity than the mixer-based radiometers used in the COBE/DMR. MAP measures the CMBR anisotropy in 5 frequency bands from 20 to 106 GHz to separate foreground microwave sources from the spectrally unique CMBR anisotropy. Because of its differential design and beam size, MAP’s angular power spectrum will cover the range $2 \leq l \leq 800$. The COBE/DMR measurement will be repeated to establish the large-scale baseline, and at least two of the predicted peaks of the angular power spectrum will be measured, if they exist. PLANCK, scheduled to launch 5 years after MAP, will be able to resolve more peaks and get better data on the expected damping at small angles. Hu and White (36; also see the Hu Web site, http://www.sns.ias.edu/~whu/physics/physics.html) show simulated power spectrum results for both satellites, and several theoretical groups have estimated the accuracy to which successful MAP and PLANCK missions can measure important cosmological parameters (11, 12). However, these should be regarded as a rough indication of the potential of these satellites. Much will depend on whether the underlying cosmological model can be independently established from the CMBR anisotropy data or from other methods. Parameter values will depend strongly on the model used, and accuracy of the parameter estimates will depend on the parameter correlations within that model.

Current active development of close-packed interferometers is directed at measuring small-scale CMBR anisotropy (interferometers are being developed at the Mullard Radio Observatory, the California Institute of Technology, and the University of Chicago). The resolution of these instruments will overlap the angular scales measured by the satellites, and they will extend the angular power spectrum down to a few arcminutes. Small-scale anisotropy measurements will be contaminated by emission from point sources, so interferometers are needed to identify those sources and remove them. Thus, the entire range of angular scales where CMBR anisotropy is expected will be examined with high sensitivity in the next decade.

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