

THE COSMIC ROSETTA STONE

Today the universe is characterized by a richness of complexity. Structure exists on scales from stars to superclusters of galaxies and beyond. Ordinary “baryonic” matter, in the form of protons, nuclei and their accompanying electrons, is found in stars, diffuse hot gas, cold gas and other forms; the admixture varies greatly with environment.

Most of the matter in the universe is simply dark. We know of its existence only because of its gravitational effects. Its composition is unknown, and most of it is probably not baryonic. It is hard to imagine that one could, from observations of the present universe alone, sort out how it all happened. During its earliest moments, however, the universe was much simpler—a smooth gas of photons, baryons and dark-matter particles.

The cosmic microwave background (CMB) radiation is a snapshot of the universe 300 000 years after the beginning, when these photons last scattered. At that time the opaque universal plasma had finally cooled down enough to become a transparent gas of neutral atoms. The CMB serves us as a cosmic Rosetta stone.

Like the Rosetta stone, which let 19th-century scholars decipher Egyptian hieroglyphics, the CMB was found by accident. The story¹ begins with theorist George Gamow and his colleagues Ralph Alpher and Robert Hermann, who saw the early universe as a nuclear oven in which the light elements of the periodic table were cooked. (See Hermann’s obituary in *PHYSICS TODAY*, August 1997, page 77.) They realized that the nuclear yields were functions of the present temperature of a residual cosmic background radiation. During the late 1940s and early 1950s, they made temperature predictions ranging from 5 to 50 kelvin for this putative relic radiation.

Not until 1964 did anyone actually go out and look for this radiation. Unaware of the earlier work by Gamow and company, and motivated by a more precise calculation of the temperature by their Princeton colleague P. J. E. Peebles, physicists Robert Dicke, David Wilkinson and Peter Roll were still setting up their experiment on the roof of the physics building to detect the microwave echo of the Big Bang when Arno Penzias and Robert Wilson at Bell Labs discovered an unexplained celestial microwave hiss. (See Dicke’s obituary in *PHYSICS TODAY*, September 1997, page 92.) Even before the Internet, physics gossip traveled at near the speed of light. The Princeton quartet

Microkelvin variations in the cosmic microwave background encode a wealth of information about the origin and composition of the universe.

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soon heard about the Penzias–Wilson hiss and quickly provided the Big-Bang interpretation.

Almost overnight, cosmology was transformed from the province of a handful of astronomers to a major field in its own right. Measurements made at electromagnetic wavelengths from

tens of centimeters down to less than a millimeter established the blackbody character of the CMB.² The hot-Big-Bang model was on its way to becoming the standard cosmology (see box 1).

As it turns out, only the lightest nuclei—H, D, ³He, ⁴He and ⁷Li—were made in the Big Bang; the rest came much later, made by nuclear reactions in stars and elsewhere. The agreement between measured and predicted abundances of the light elements is today one of the key tests of the standard cosmology.³ (See *PHYSICS TODAY*, August 1996, page 17.)

In 1989, after more than a decade of preparation (including a major redesign after the Challenger disaster), NASA launched the Cosmic Background Explorer (COBE), a satellite designed to study the microwave and infrared backgrounds. The results from COBE exceeded the hopes of even the most optimistic. COBE’s Far Infrared Absolute Spectrometer (FIRAS) determined the microwave background temperature T to four significant figures (2.728 ± 0.002 K) and showed⁴ that any spectral deviations from a Planck blackbody spectrum were less than 0.005%. The CMB is, in fact, the most precise black body known in nature. It could have arisen only from the very hot, dense conditions that existed in the early universe.

The search for spatial variations (anisotropy) in the intensity of the CMB across the sky began with Penzias and Wilson. They estimated the temperature to be isotropic within about 10%. In 1976, flying an instrument on a U2 spy plane, a group led by Berkeley physicists Richard Muller and George Smoot established a 3 mK dipolar temperature variation across the sky, arising from the motion of the Solar System with respect to the rest frame defined by the CMB. COBE greatly refined this measurement to yield a Solar System velocity of 370.6 ± 0.5 km/s in that frame, and it even detected the annual variation due to Earth’s motion around the Sun—the ultimate vindication of Copernicus.

On smaller angular scales, the anisotropy maps the distribution of matter in the early universe, because variations in the early matter density led to temperature fluctuations of similar size. It is generally assumed that the abundance of structure seen in the universe today—galaxies, clusters of galaxies, superclusters, voids and great walls—evolved by gravitational amplification from small, primeval density inhomogeneities.⁵ Theoretical expectations for the magnitude of the CMB fluctuations have decreased from the early 1% estimates to more precise estimates of around 0.001% calculated in recent years. For two decades, the instrument builders had to watch the goalposts recede

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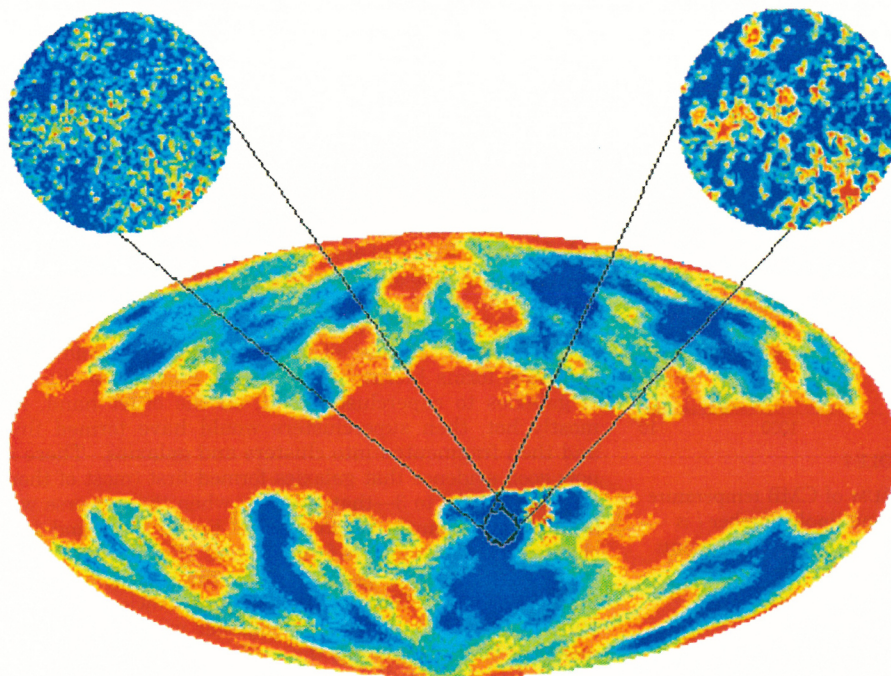


FIGURE 1. COBE DIFFERENTIAL MICROWAVE RADIOMETER 4-year full-sky temperature map of the cosmic microwave background, in Galactic coordinates. The dipole variation due to Solar System motion has been removed. The equatorial band is foreground Milky Way radiation. Elsewhere the colors indicate fluctuations of tens of microkelvin. The DMR's angular resolution is 7° . The blowups of a 7° circle indicate the finer detail that might be revealed by the next-generation MAP and Planck satellites: The left blowup simulates an open universe ($\Omega = 0.1$); the right blowup simulates the flat universe ($\Omega = 1$) preferred by inflationary theories.

faster than they could build more sensitive experiments.⁶

By 1992, small-scale anisotropy had still not been detected. Upper limits were already as stringent as $100 \mu\text{K}$ on angular scales ranging from tens of degrees down to fractions of a degree. It was not certain how much further the observers could push before foreground emissions from the Milky Way and extragalactic objects became insurmountable. Some even questioned the general idea that structure evolved primarily by the action of gravity. But then in April 1992, at the American Physical Society meeting in Washington, DC, the COBE Differential Microwave Radiometer (DMR) team announced evidence for temperature fluctuations of $30 \mu\text{K}$ on an angular scale of ten degrees.⁷ (See figure 1.)

The theorists had escaped disgrace, and cosmology was once again transformed overnight. With the COBE detection, the final piece of the standard cosmology was in place, and the testing of models for the formation of structure, most of them motivated by the physics of the early universe, could begin. The race to map the early universe by means of CMB anisotropy was on.

Anisotropy in the cosmic background

It is most useful to describe the CMB anisotropy on the celestial sphere by spherical-harmonic multipole moments,

$$\Delta T(\theta, \phi)/T = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi).$$

The multipole moments, which are determined by the underlying density perturbations, can only be predicted statistically. Averaged over all observers in the universe, they have zero mean; that is to say, $\langle a_{lm} \rangle = 0$. If the underlying density fluctuations are described by a gaussian random process, as inflationary cosmology predicts, the angular power spectrum, $C_l \equiv \langle |a_{lm}|^2 \rangle$, contains all possible information. (This is an average over all m for a given l , there being no preferred direction in the universe.) If the density fluctuations are nongaussian, as other models predict, then higher-order correlation functions contain additional information.

Temperature differences between points on the sky

separated by an angle θ are related to those multipoles with spherical-harmonic indices l near $100^\circ/\theta$. The rms fractional temperature fluctuation for a given angular separation is then

$$(\Delta T/T)_\theta \approx \sqrt{l(l+1)C_l/2\pi}.$$

The angle θ subtends a length on the surface of last scattering that would now, by the Hubble expansion of the universe, be about 200 megaparsecs per degree. (1 Mpc $\approx 3 \times 10^6$ light-years.) Therefore, the corresponding l th multipole is determined by density fluctuations on that wavelength scale. For example, the density fluctuations of wavelength around 2 Mpc, which seed galaxies, subtend an angle θ of about an arcminute; those of 20 Mpc, which seed clusters of galaxies, subtend about 10 arcminutes; and those of around 200 Mpc, which seed the largest structures we see today, subtend about 1 degree. (All these distances were a thousand times smaller at the time of last scattering, when the linear size of the universe was a thousand times smaller. But it is conventional to quote "comoving separations" as they would be now.)

The two competing models for the origin of the primeval density perturbations involve the physics of the early universe. The first holds that about 10^{-32} of a second after the Big Bang, a very short burst of tremendous expansion (called inflation) stretched quantum fluctuations on subatomic scales to astrophysical size, and that those fluctuations became density perturbations when the vacuum energy that drove inflation decayed into radiation and matter.⁸ According to this inflationary scenario, the density perturbations are almost scale-invariant: That is to say, fluctuations in the gravitational potential were of the same magnitude (a part in 10^5) on all length scales. Figure 2 shows the angular power spectrum predicted by inflation.

The competing theory holds that the density perturbations were seeded by topological defects formed even earlier (10^{-36} s), in a cosmological phase transition associated with spontaneous symmetry breaking in the theory that unifies the fundamental forces and particles. Depending upon how the symmetry is broken, these defects might be pointlike (global monopoles), one-dimensional (cosmic strings) or three-dimensional (spacetime textures).⁹

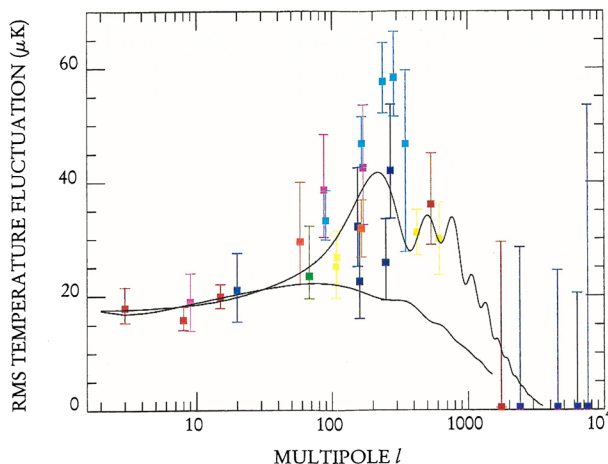


FIGURE 2. ANGULAR POWER SPECTRUM of CMB temperature fluctuations. The spherical-harmonic multipole number l is conjugate to the separation angle $\theta \approx 100^\circ/l$. The data points thus far favor the theoretical expectations for inflation + cold-dark matter (upper curve) over those for topological-defect theories (lower curve, provided by U. Seljak).

It is the gravitational effects of such defects that would induce perturbations thousand of years later in the matter distribution. Although these perturbations would also be approximately scale-invariant, the power spectrum of CMB anisotropy would be very different from what we expect from inflation, because the density perturbations would have originated so much later than in the inflationary scenario.¹⁰ The current anisotropy data appear to be consistent with inflation and inconsistent with the topological-defect scenario. (See figure 2.)

The inflation and defect models both require non-baryonic dark matter. So do the dynamical measurements of galaxies and clusters that tell us there is much more gravitating matter than can be accounted for by luminous

objects, or even by dark baryons. The notably successful theory of Big-Bang nucleosynthesis³ constrains the baryon density to be less than 10% of the “critical mass density” below which the Hubble expansion would eventually become a contraction. But the dynamical observations indicate that dark matter contributes at least 20% of this critical density, and inflation favors precisely the full critical density. The observed level of CMB anisotropy provides additional circumstantial evidence: If there were only baryons, the level of primeval inhomogeneity required to produce the observed structure would lead to an anisotropy ten times greater than we find. (See box 1.)

The nonbaryonic matter may be “cold” (slow moving) or “hot” (fast). If most of the dark matter is cold, then structure forms hierarchically—from galaxies to clusters of galaxies to superclusters. If, on the other hand, it’s mostly hot, then superclusters would have formed first and then fragmented into clusters and galaxies. There is now good evidence that galaxies formed first (most of them at redshifts of 2 to 3—that is to say, when the universe was a third, or a fourth, of its present linear size), and that clusters and superclusters formed later. That strongly favors the cold-dark-matter picture. (See the article by Henry Ferguson, Robert Williams and Lennox Cowie in *PHYSICS TODAY*, April 1997, page 24.) Together with the measurements of CMB anisotropy, the evidence of hierarchical formation has made “inflation + cold dark matter” the working hypothesis for how structure formed in the universe.¹¹

The precise shape of the angular power spectrum depends not only on the underlying inflation model, but also, in a well-understood way, on cosmological parameters such as the Hubble constant, the mass density and the composition of the dark matter. (See box 2.) Therefore, the 2500 or so independent multipoles that can be measured have enormous potential to determine cosmological parameters and test theories of the early universe.

Mapping to microkelvin precision

The key to realizing the full potential of the CMB is the ability to map its anisotropy with microkelvin precision. The accuracy of an experiment is limited by (1) instru-

Box 1. Big Bang Basics

The expansion of the universe is described by the cosmic linear-scale factor $R(t)$. The expansion rate $H \equiv (dR/dt)/R$ is gradually slowed down by gravitational attraction. H_0 denotes its present value. If the average mass density ρ is greater than the critical density ρ_c , the universe will eventually recollapse. (The density parameter $\Omega \equiv \rho/\rho_c$.) Otherwise the expansion continues forever. A critical universe ($\Omega = 1$) is spatially flat; a high-density universe ($\Omega > 1$) curves back on itself like the surface of a finite ball; a low-density universe ($\Omega < 1$), is negatively curved like a saddle.

As the universe expands, photons have their wavelengths stretched (redshifted) in proportion to $R(t)$. The measured redshift z of a photon of known wavelength at emission tells us that universe has expanded by a factor $z + 1$ since it was emitted, as well as the time t since the Big Bang:

$$t(z) \approx 13 \text{ Gyr} / (1 + z)^{3/2},$$

assuming a matter-dominated, flat universe with $H_0 = 50 \text{ km/s (Mpc)}$. The most distant object yet seen is a galaxy with a redshift of 4.92, which means the universe was 5.92 times smaller and about 0.9 Gyr old when the light we see was emitted.

The expanding universe cools adiabatically, with temperature falling like $1/R(t)$. At a temperature of around 3000 K (equivalent to 0.25 eV) the thermodynamic transition from

ionized matter to neutral matter occurred. This “recombination” drastically and suddenly reduced the Thomson-scattering opacity. That’s when the CMB photons experienced their last scattering. It was about 300 000 years after the Big Bang, and the cosmic photon background, now in the microwave regime, then had wavelengths in the visible.

When the universe was only 10 000 years old and the temperature was about 1 eV, the energy density in the thermal radiation was comparable to that of matter. Before that, density perturbations could not grow, because radiation dominated the energy density. During the time between matter-radiation equality and recombination, only perturbations in the nonbaryonic dark matter grow, because the baryons are supported against collapse by radiation pressure. (The putative nonbaryonic matter is presumed to be impervious to electromagnetic interactions.) But once the baryons are safely ensconced in neutral atoms, the photon background no longer keeps them from falling into the gravitational potential wells already formed by the dark matter.

This extra early growth of density perturbations in a universe with nonbaryonic dark matter means that less initial irregularity is needed to produce the structure seen today. That’s why one expects to see less CMB anisotropy if the bulk of the dark matter is nonbaryonic.

CMB ANISOTROPY EXPERIMENTS, current (above line) and future (below line). For each experiment, we list sensitivity range of microwave frequencies and multipole orders l , as well as a URL that offers further information.

Experiment	Frequency (GHz)	Scale (l)	Web page
COBE	30–90	2–30	www.gsfc.nasa.gov/astro/cobe/
FIRS	170–680	3–29	pupgg.princeton.edu/~cmb/welcome.html
Tenerife	10–33	13–30	www.jb.man.ac.uk/~sjm/cmb_teide.html
ACME	26–45	32–109	www.deepspace.ucsb.edu/research/Sphome.htm
Saskatoon	26–46	52–401	pupgg.princeton.edu/~cmb/welcome.html
Python	30–90	55–240	cmbr.phys.cmu.edu/pyth.html
BAM	110–250	30–100	cmbr.physics.ubc.ca/
ARGO	150–600	53–180	
HACME	39–45	10–180	www.deepspace.ucsb.edu/research/Sphome.htm
MAX	90–420	78–263	physics7.berkeley.edu/group/cmb/gen.html
IAB	130	60–205	
MSAM	150–650	69–362	cobi.gsfc.nasa.gov/msam-tophat.html
Q/DMAP	30–140	30–850	pupgg.princeton.edu/~cmb/
White Dish	90	381–851	cmbr.physics.ubc.ca/
CAT	13–17	339–722	www.mrao.cam.ac.uk/telescopes/cat/index.html
OVRO	20	1100–2750	www.ccc.caltech.edu/~emleitch/ovro/ovro_cmb.html
ATCA	9	3500–5780	www.nar.atnf.csiro.au/
SuZIE	150–350	1000–3700	astro.caltech.edu/~bjp/suzie/suz.html
Ryle	5, 15	4000–8000	www.mrao.cam.ac.uk/telescopes/ryle/index.html
VLA	5, 8, 15	5000–9000	www.nrao.edu/vla/html/VLAhome.shtml
MAXIMA	150–420	50–700	physics7.berkeley.edu/group/cmb/gen.html
Boomerang	90–420	10–700	astro.caltech.edu/mc/boom/boom.html
TopHat	150–720	10–700	cobi.gsfc.nasa.gov/msam-tophat.html
ACE/BEAST	25–90	10–800	www.deepspace.ucsb.edu/research/Sphome.htm
MAT	30–140	30–1100	dept.physics.upenn.edu/~www/astro-cosmo/devlin/project.html
VSA	26–36	130–1800	www.mrao.cam.ac.uk/telescopes/cat/vsa.html
DASI	26–36	125–700	astro.uchicago.edu/dasi/
CBI	26–36	630–3500	astro.uchicago.edu/dasi/
Viper	90	20–400	cmbr.phys.cmu.edu/vip.html
COBRA	100		astro.uchicago.edu/cara/science/#cobra
Jodrell Bank	5		www.jb.man.ac.uk/~sjm/cmb_top.html
POLAR	26–46	2–30	wisp5.physics.wisc.edu/ObsCosmology/
MAP	22–90	2–1000	map.gsfc.nasa.gov/
Planck	30–850	2–3000	astro.estec.esa.nl/SA-general/Projects/Cobras/cobras.html

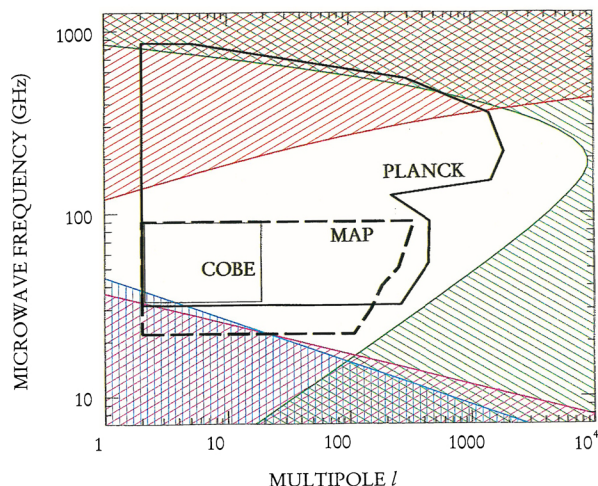
mental sensitivity; (2) systematics such as ambient temperature variations on the detectors, atmospheric emission and absorption, and nearby warm objects such as the Earth, Sun and Moon; (3) astrophysical foregrounds such as the Galaxy and extragalactic sources; and (4) sampling variance. This last uncertainty poses a fundamental limit: Because, for a given l , there are only $2l + 1$ multipole moments, C_l can be estimated to a precision no better than $C_l/\sqrt{l + 1/2}$. This is often called cosmic variance, because it is the variance in C_l that would be measured by an ensemble of observers studying different CMB skies.

In the three decades since the Penzias–Wilson discovery, there have been enormous technological advances in detectors. Two common means of detection are used nowadays: microwave amplifiers with high-electron-mobility transistors (HEMTs), and bolometers that measure the heating of a small amount of material by CMB photons. Historically, the HEMTs have been used at lower microwave frequencies and the bolometers have been used at the higher frequencies, but this distinction is no longer as strong as it once was. The improvement in detector sensitivity is remarkable: With today's state-of-the-art HEMTs, the sensitivity achieved by COBE's differential

microwave radiometer in four years could have been reached in ten days!

The first line of defense against systematic error is measuring differentially. Again fluctuation acts equally on both elements of the differential signal and cancels them out. COBE's DMR measured temperature differences between points on the sky separated by an angle of 60° . The matrix of these measured differences was inverted to obtain a true map of the CMB sky. Other techniques to minimize systematic errors include under-illumination of the optics to reduce off-axis signal pick-up from warm objects, and designs that are as symmetric as possible between the main and reference signal paths.

The microwave signal from the Milky Way is dominated by synchrotron and bremsstrahlung emission at low frequencies, and by dust emission at high frequencies. Happily, when one looks away from the Galactic plane, the CMB anisotropy dominates Galactic emission between about 30 and 120 GHz. Furthermore, the obscuring foregrounds fall off more rapidly than the CMB at high l . Extragalactic sources such as galaxies and quasars are only troublesome for experiments with angular resolution of much better than 1° . By observing at high Galactic



latitudes, where Milky Way emission is weakest, and by measuring at several different frequencies, the observer can separate the CMB anisotropy from the galactic foreground. (See figure 3.)

Cosmic anisotropy experiments have been carried out from the ground (including the South Pole and mountain tops), from balloon platforms and from two satellites in space: COBE and, back in 1983, the Soviet satellite Relict 1. The observer's choice involves trade-offs: Ground-based experiments allow easy access, but must deal with atmospheric emission and absorption; balloons can lift experiments above most of the atmosphere, but duration and flight opportunities are limited; satellites eliminate atmospheric problems and allow full-sky access, but opportunities are even more limited, and much more expensive.

As the table on page 35 illustrates, experimenters have taken up the challenge to map the CMB sky with microkelvin precision. A new generation of long-duration balloon experiments will map patches of the sky with subdegree angular resolution. Ground-based interferometers will make finer-resolution maps of smaller regions.

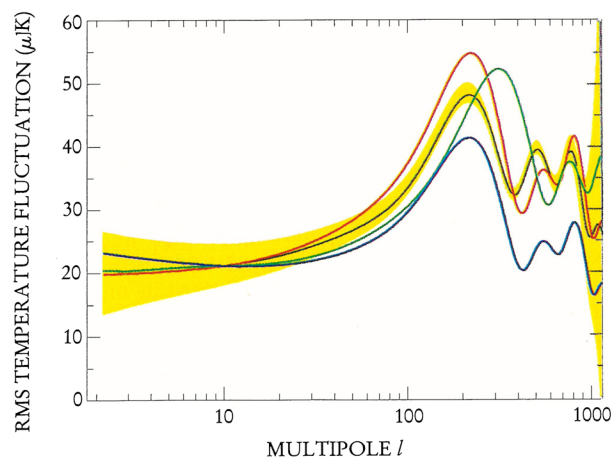


FIGURE 4. NASA's MAP SATELLITE, which will fly in the year 2000, should easily be able to discriminate between variants of cold-dark matter cosmology: The favored critical universe ($\Omega = 1$), to which baryons contribute 5% (black curve with yellow band) or 10% (red curve); an open universe with subcritical density $\Omega = 0.5$ (green); and a "tilted" fluctuation spectrum with $n = 0.8$ (purple). The yellow band around the "standard" $\Omega = 1$ model indicates MAP's expected rms error per multipole.

FIGURE 3. KNOWN FOREGROUNDS CONFRONTING COBE and its high-precision successors (MAP and Planck) seeking to measure CMB anisotropy, at different microwave frequencies and multipole orders l . The crosshatched regions indicate significant problems from the Milky Way and beyond: synchrotron emission (shown blue); bremsstrahlung (magenta); thermal dust emission (red); extragalactic point sources (green). The sensitivity regimes of the three experiments in the frequency-multipole plane are also outlined. (Adapted from a figure by G. Efstathiou and M. Tegmark.)

Two new space missions are now planned. NASA has approved the Microwave Anisotropy Probe (MAP), and the European Space Agency has approved Planck (formerly COBRAS/SAMBA). Both satellites will make full-sky maps with angular resolutions of 0.2° and 0.1° , respectively. That's more than 30 times better than the angular resolution of the COBE map. Both will use amplifiers with HEMTs for microwave frequencies between 20 and 100 GHz.

MAP, which is planned for launch in the year 2000, is a passively cooled differential radiometer like COBE, with back-to-back 1.4×1.6 m reflectors. Planck, scheduled for launch five years later, will, in addition to HEMT amplifiers, also have six higher-frequency channels (from 100 to 857 GHz) that use bolometers cooled by liquid helium. Both satellites will be placed in orbit at the remote, stable L2 Lagrange point, 1.5 million km antisunward from the Earth.

The scientific harvest

COBE's DMR detection of temperature fluctuations of amplitude $30 \mu\text{K}$ on the 10° angular scale gave us the first evidence for the density inhomogeneities that are believed to have seeded all the structure in the universe. For inflation or topological-defect theories, which specify the shape of the Fourier spectrum of density inhomogeneities but not its model-dependent amplitude, the accurate (10%) DMR measurement¹² fixes the spectrum on length scales of gigaparsecs and therefore permits extrapolation to the smaller scales relevant for the formation of galaxies, clusters of galaxies and other structures we see today. That immediately leads to more precise scenarios of the evolution of structure. Overnight, the term "COBE normalized" has become a part of the cosmological vernacular.

In the five years since the COBE detection, anisotropy on angular scales from 100° down to 0.1° has been detected by about twenty different experiments. Because these experiments have had to deal with the effect of the atmosphere, limited sky coverage and calibration difficulties, they have all been less precise than COBE. They have not resolved individual multipoles, yielding only broadband power determinations for bins of $\Delta l \approx l$. Nonetheless, they have added much to our understanding, and a picture is emerging: The anisotropy grows with increasing l on degree scales and then falls at smaller angles. (See figure 2.) Together with COBE, these experiments now cover almost three decades in angular scale; they are generally consistent with inflation, and they have eliminated all models of structure formation that do not incorporate nonbaryonic dark matter. They also disfavor topological-defect models.

Much will happen before MAP and Planck are launched. A new generation of instruments—flown on long-duration balloons or set on high, dry sites like the South Pole or the high desert of Chile—should begin to define the prominent "acoustic peaks" in the multipole spectrum (see box 2) by measuring power in $\Delta l \approx 30$ windows from $l = 200$ to 2500. (Because l and θ are Fourier conjugate variables, one sharpens the resolution in

Box 2. The Physics of CMB Anisotropy¹⁶

Temperature fluctuations in the CMB arise from the variations in the matter density.¹⁷ After last scattering, the photons stream freely to us and the temperature fluctuations are seen as CMB temperature differences across the sky. Anisotropy on a given angular scale is related to density perturbations with wavelengths corresponding to the length projected by that angle on the last-scattering surface. Until the ions and electrons “recombined” at last scattering, they were tightly coupled to the photons by Thomson scattering; together they behaved as a single fluid. The gravity-driven collapse of a baryon-density perturbation is resisted by the restoring pressure of the photons. Fourier mode k of the temperature fluctuation is governed by a harmonic-oscillator-like equation,

$$[m_{\text{eff}} \Delta T_k'] + \frac{k^2}{3} \Delta T_k = -F_k,$$

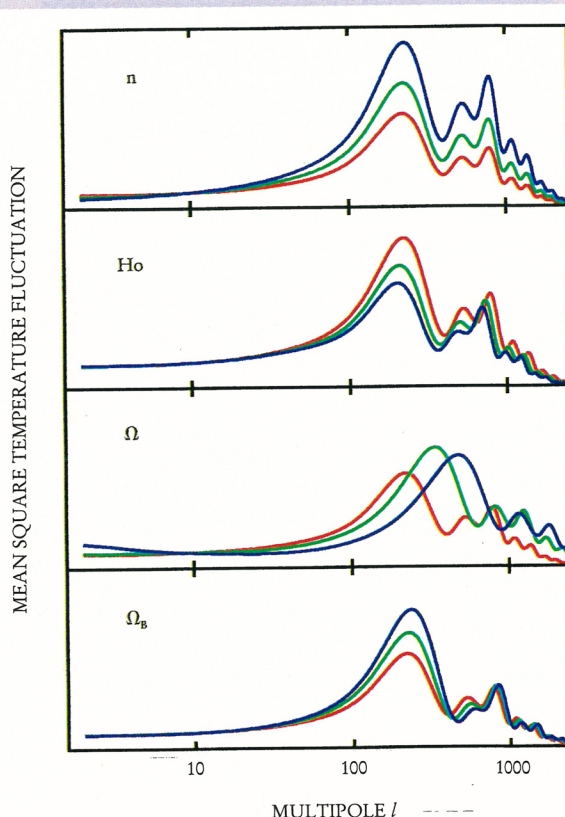
where F is the gravitational forcing term due to the dark matter, m_{eff} describes the inertia of the fluid and the primes denote derivatives with respect to (conformal) time. The solutions are acoustic waves.

The large-angular-scale (Sachs-Wolfe) plateau in the angular power spectrum below $l \approx 100$ (see figure at right) arises from perturbations with periods longer than the age of the universe at last scattering. CMB photons lose energy climbing out of the potential wells associated with these long-wavelength density perturbations, and the temperature differences seen on the sky reflect the gravitational potential differences on the last-scattering surface. If the density fluctuations are scale-invariant, the Sachs-Wolfe plateau is flat.

The baryon-photon fluctuations that produce anisotropy on subdegree angular scales ($10^2 < l < 10^3$) have time enough to oscillate. At maximum (minimum) compression, the CMB temperature is higher (lower) than average; neutral compression corresponds to maximum fluid velocity, which leads to a Doppler-shifted CMB temperature. Because last scattering is nearly instantaneous, the CMB provides a snapshot of these acoustic oscillations, with different wavelength modes caught in different phases. Because a given multipole l is dominated by the effects of a narrow band of Fourier modes ($k \approx H_0 l / 2$), this leads to peaks and valleys in the angular power spectrum. The peaks are modes that were maximally under- or overdense at last scattering, and the troughs are velocity maxima in between.

On the smallest scales ($l > 2500$), the spectrum is exponentially damped, due to the finite thickness of the last-scattering surface. Features on these angular scales are washed out because last scattering here is a montage of snapshots, which blurs the fine details.

The precise shape of the power spectrum depends on cosmological parameters as well as the underlying density perturbations. Thus, it encodes a wealth of information. (See the figure above.) The position of the first peak is sensitive to the



DEPENDENCE OF THE ANGULAR POWER SPECTRUM of CMB temperature fluctuations on cosmological and model parameters. From red to green to blue: (top panel) power-law index $n = 1, 1.1$ and 1.2 ; (2nd panel) Hubble constant $H_0 = 50, 60$ and 70 km/s (Mpc); (3rd panel) density parameter $\Omega = 1, 0.5$ and 0.3 ; (bottom panel) Ω_B (the baryon fraction of critical density) = $0.005, 0.0075$ and 0.01 .

total energy density, and it can be used to determine the geometry of the universe: $l_{\text{peak}} \approx 200/\sqrt{\Omega}$. It moves to smaller angles as Ω decreases because the distance to the last-scattering surface increases (the Hubble expansion decelerates less in a low-density universe) and geodesics diverge in negatively curved space, so that a given distance on the last-scattering surface subtends a smaller angle).

Other features encode other information. For example, the height of the first peak depends on the baryon and total matter densities (both of which both depend on H_0) and a possible “cosmological constant.” What if the spectrum of density perturbations is not scale-invariant? If, for example, there is more power on smaller scales ($n > 1$), the angular power spectrum rises with increasing l .

l by covering more sky.) By resolving the position of the first two or three acoustic peaks, these experiments should be able to pin down the mass-density parameter Ω to an accuracy of 20% and thus test the inflationary prediction of a flat universe ($\Omega = 1$). They should also begin to pin down other cosmological parameters, such as the baryon density and the Hubble constant, to a precision of 20% or so.

Using low-frequency receivers (22–90 GHz), MAP will determine the angular power spectrum out to $l \approx 1000$, to a precision close to the sampling-variance limit. Employ-

ing both high- and low-frequency detectors, Planck is expected to reach $l \approx 2500$ with similar precision. Between them, the two satellites should determine 2500 multipoles and come close to reaping almost all the information encoded in CMB temperature anisotropy.

Some of the cosmological parameters, including Ω , can be determined from the CMB without reference to a specific theory. However the full potential of the data is harvested by detailed modeling within a given theoretical framework. (See figure 4.) For a theory like inflation +

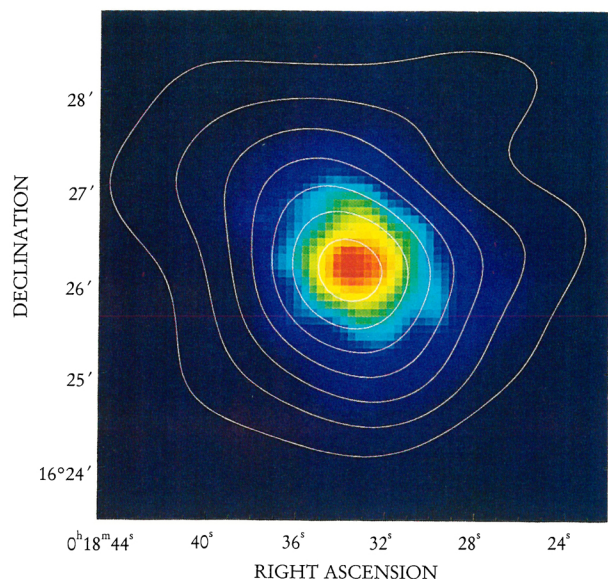


FIGURE 5. COMPARING MICROWAVE TOMOGRAPHY (contour lines) of a galaxy cluster (CL 0016+16) with an x-ray image of its hot intergalactic gas (false colors), provides a way of measuring the Hubble constant without standard candles. The tomography, which exploits the Sunyaev-Zel'dovich scattering of cosmic microwave background photons by the gas, was done with the BIMA and OVRO interferometric radio arrays. The x-ray image comes from the ROSAT satellite. (Figure courtesy of John Carlstrom and Marshall Joy.)

cold-dark matter, the theoretical angular power spectrum depends upon about ten parameters, including H_0 , Ω , the power-law index n that characterizes the spectrum of density perturbations ($n=1$ meaning scale invariance), the dark-matter composition and the amount of gravitational radiation produced during inflation. These parameters will be very overconstrained by the 2500 measured multipoles. Therefore the theory can be thoroughly tested. Furthermore H_0 , n , Ω and the baryon density will all be determined within a few percent.¹³

The CMB anisotropy should be polarized at the level of about 5 percent,¹⁴ and both MAP and Planck will have the capability of detecting it. The polarization arises because the radiation field was not isotropic before last-scattering and Thomson scattering produces partial polarization. This polarization, which has yet to be detected, provides a consistency check on the basic picture of anisotropy formation, and it can improve the accuracy with which cosmological parameters are determined.

There probably will still be much to learn from the CMB polarization after MAP and Planck. In particular, polarization may be very useful in separating out the contribution of inflation-produced gravity waves to the CMB anisotropy, because gravity waves and density perturbations differ in the polarization they engender. Determining the level of gravitational radiation fixes the energy scale of inflation.¹⁵ Polarization is also crucial for detecting the re-ionization of the neutral, transparent universe by the first generation of stars. The first stars, which are thought to have appeared at redshifts of 10 or 20, ended the "dark age" that began with the last scattering of the CMB photons.

Beyond its immense value as a cosmic Rosetta stone, the CMB is being exploited for other purposes. Perhaps the most exciting is "microwave tomography" of clusters of galaxies by means of the Sunyaev-Zel'dovich (S-Z)

effect. In 1972, Rashid Sunyaev and Yakov Zel'dovich pointed out that some of the CMB photons passing through the hot gas in clusters are scattered to higher energy by inverse Compton scattering. This effect produces a small spectral distortion in the CMB, whose amplitude depends on the temperature and density of the cluster gas, but is independent of redshift. The S-Z effect can be used to study the structure of clusters and also to search for high-redshift clusters whose constituent galaxies are too faint to be seen. Furthermore, by comparing S-Z maps with x-ray maps of clusters (see figure 5), one can measure the Hubble constant without recourse to the usual "standard candles." That's because the S-Z distortion is proportional to the line-of-sight integral of the electron density, whereas the x-ray intensity is proportional to the square of that integral. Thus, comparing the two yields a determination of the cluster's absolute size.

Since its discovery in 1965, the Cosmic Microwave Background has played a central role in cosmology. It is one of the cornerstones of the standard hot-Big-Bang theory. The study of CMB anisotropy with microkelvin precision and subdegree angular resolution is likely to have at least as much impact as the original Penzias-Wilson discovery. It will put to the test our most promising ideas about the earliest moments and it will determine for us the elusive fundamental parameters of cosmology.

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