Balloon Measurements of the Cosmic Microwave Background Strongly Favor a Flat Cosmos

In 1998 two related but independent groups sent balloon-borne microwave telescopes aloft to study fluctuations in the cosmic microwave background (CMB) at fine angular resolution. In August of that year, the Maxima telescope spent one night at 40 km above Texas. And at the end of the year, its "sister" telescope, called Boomerang, took advantage of the steady circumpolar winds of the austral summer to complete a 10-day stratospheric circumnavigation of Antarctica.

Now we have the first reports of their analyses.[1,2] Although both analyses have thus far processed only a fraction of the data taken during the two balloon flights, they already provide us with the best observational evidence yet that the large-scale geometry of the cosmos is flat.

General relativity allows for a flat, Euclidean universe or, alternatively, for a universe with overall spatial curvature—either positive, like a hypersphere, or negative, like a saddle point. But the very appealing "inflationary" version of Big Bang cosmology appears to dictate that any initial cosmic curvature would have been stretched to absolute flatness by a great inflationary spurt of expansion that ended before the universe was 10^{-32} seconds old.

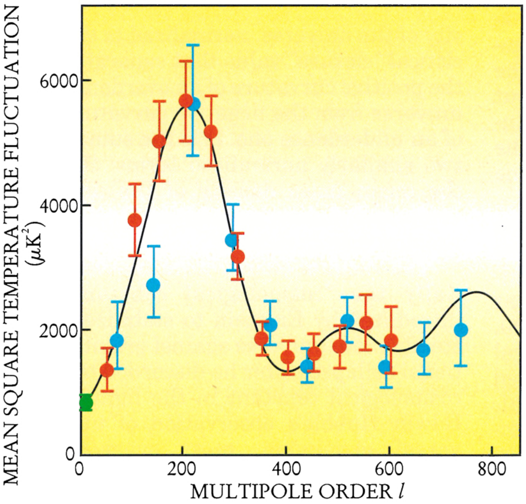
The nonuniformity of the CMB, especially on angular scales of about 1°, turns out to be a superb probe of cosmic curvature. (See PHYSICS TODAY, November 1997, page 32.) In 1989 the Cosmic Background Explorer (COBE) satellite revealed that the microwave background sky—after corrections for foreground sources and our own motion—has an astonishingly uniform blackbody temperature of 2.725 K. In fact, it took another three years for COBE's differential microwave radiometer to uncover the tiny spatial fluctuations in the CMB temperature—a few parts in 10^5—required by the inflationary scenario.

First light

The CMB is thought to be the vestigial light from the first moments of clarity when the cosmos had finally cooled down enough, some half a million years after the Big Bang, for the opaque universal plasma of ions and electrons to coalesce into a transparent gas of neutral hydrogen and helium. For the 10 or 20 billion years since then, these first "free" photons have been traveling, largely unscattered, and stretching in wavelength—from microns to millimeters—in concert with the thousandfold linear expansion of the cosmos during their journey.

> The power spectrum of the microwave background's tiny point-to-point temperature fluctuations is a superb probe of cosmic curvature.

The temperature fluctuations of the CMB are imprints of the point-to-point density fluctuations of the cosmos at the "moment of last scattering." Hotter than average points on the CMB signify regions of above-average mass density. Happily, cosmologists can estimate, with considerable confidence, the size spectrum of typical regions of unusually high and low mass density at the end of the era of primordial plasma opacity. Comparing these expectations with the angular size distribution of hot and cold spots on the CMB, as we see them now, tells us about the optical properties, and thus the intrinsic geometry, of the intervening cosmic space.



POWER SPECTRUM of spatial temperature fluctuations of the cosmic microwave background, as determined by Maxima (red dots), Boomerang (blue dots), and COBE (green point) from spherical-harmonic fits to their CMB maps. The spherical-harmonic order index l pertains to temperature differences at angular separations of roughly $180°/l$. The curve is the best fit with $\Omega = 1$, as required by inflation. It yields an unsurprising $\Omega_\Lambda = 0.7$. But the fit's baryon density, though still dwarfed by cold dark matter, nonetheless exceeds standard expectations by about 50%. (Courtesy of A. Lange and P. Richards.)

The task is made easier by the "acoustic" properties of the plasma, which create standing waves and thus impose a distinctive structure of acoustic peaks on the expected power spectrum of the CMB's spatial temperature fluctuations. (See figure at left.) With photons and charged matter strongly coupled in the plasma epoch, the competition between gravity and radiation pressure produced regions of slow oscillatory contraction and expansion.

The maximum size of an overdense region that could have shrunk coherently by self gravitation in the half million years before the plasma cleared was limited by the propagation speed of sound—which, in such a radiation-dominated plasma, would be $c/\sqrt{3}$. Large regions began collapsing later than small ones. The largest scale size for CMB hot spots, corresponding to the first acoustic peak, is set by the biggest region that would have reached maximum oscillatory compression *for the first time* just at the moment of last scattering. The sequence of other acoustic peaks, at increasingly smaller scale sizes, manifests regions that have undergone repeated cycles of compression and dilation.

This sequence of CMB granularity scales depends somewhat on the details of the plasma. But the position of the first acoustic peak—the angular size at which the biggest CMB hot spots should appear at a remove of some 14 billion years—turns out to depend principally on the presence or absence of distorting cosmic curvature between us and the horizon of last scattering. In the absence of any such large-scale optical distortion, calculations of the primordial plasma predict that the largest angular scale for CMB thermal fluctuations should be about 1°. That would have been an overdense region roughly 300 thousand light years across.

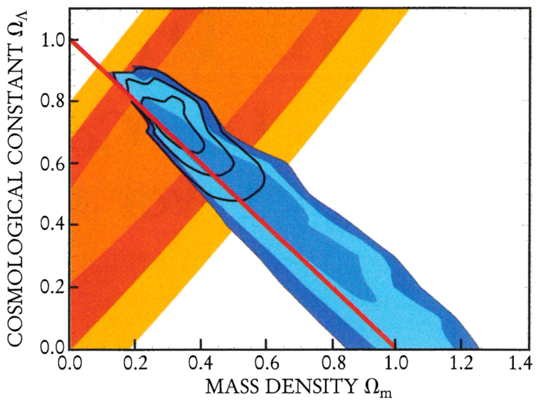
After the subsequent thousandfold Hubble expansion, this density fluctuation would now extend over about 300 million light years, as big as the largest concentrations of galaxies we know about. That's no surprise, because the very shallow density fluctuations at the end of the plasma epoch are presumed to be the gravitational seeds of today's galaxies and clusters of galaxies.

Fluctuation power spectrum

To extract cosmological details from the observations, one calculates the power spectrum of the thermal fluctuations by fitting the CMB temperature map to a spherical-harmonic series. Then the absolute square of the fitted amplitude for the lth-order spherical-harmonic component is essentially the mean-square point-to-point temperature fluctuation of the CMB on an angular scale of about $180°/l$. The finer the angular resolution of the microwave telescope, the higher is the order l out to which one can measure the power spectrum.

The figure on page 17 shows the CMB fluctuation power spectrum as measured by Boomerang and Maxima. Both experiments show a clear first acoustic peak, near $l = 200$. That's very close to the theoretical expectation (shown by the fitted curve), *if* the cosmic geometry is flat. Boomerang and Maxima, with angular resolutions on the order of 10 arcminutes, have given us the first CMB maps fine-grained enough to yield at least one acoustic peak that can confront the theory in some detail. Earlier indications of this first peak had been found by ground-based instruments in the Andes and at the South Pole.

If the cosmos had a positive curvature, parallel light beams would converge over sufficiently long distances, making the CMB hot spots appear larger (as if seen through a convex lens), thus moving the acoustic peaks to lower values of l. Similarly, negative curvature would move the peaks to higher l. The cosmological parameter that determines the large-scale curvature is Ω, the total energy den-



COSMIC MICROWAVE BACKGROUND observations constrain the cosmological parameters Ω_m and Ω_Λ to lie close to the (red) diagonal $\Omega_m + \Omega_\Lambda = 1$ required by inflation. The blue area represents the Boomerang and Maxima data. The orange and yellow area shows the roughly orthogonal constraint imposed by high-redshift supernova observations. Shaded contours mark confidence levels of 68, 95 and 99%, as do the black contour loops, which indicate confidence levels from a joint fit to the CMB and supernova data. (Courtesy of A. Lange and P. Richards.)

sity of the universe, normalized to the critical "closure" value that separates the positive curvature of an overdense universe from the negative curvature of an underdense one. It is the sum of two similarly normalized terms: Ω_m, the mean mass density of the universe, and a more speculative Ω_Λ, the vacuum energy density.

The vacuum-energy term is essentially the "cosmological constant" introduced by Einstein to stabilize a steady-state universe against gravitational collapse. After he discarded the cosmological constant in the light of Edwin Hubble's observation of universal expansion, most everyone assumed it to be zero. But in 1998, Ω_Λ was revived to explain the startling observation—by two groups looking at very distant supernovae—that the Hubble expansion appears to be speeding up. (See PHYSICS TODAY, June 1998, page 17.)

That discovery came just in time to save inflationary cosmology from a growing embarrassment. In the absence of a cosmological constant, the flat geometry required by inflation dictates that $\Omega_m = 1$. But a great variety of searches for the gravitational effects of "dark matter" were beginning to converge on a skimpy Ω_m of about 0.3 or 0.4. If one allows for a cosmological constant, however, inflation requires only that $\Omega_m + \Omega_\Lambda = 1$.

The supernova data leave this issue in limbo. They tell us that the *difference* $\Omega_\Lambda - \Omega_m$ is something like 0.3, but they are rather insensitive to the *sum* Ω. That's why the CMB fluctuation data have been so eagerly awaited. Because the magnifying (or demagnifying) effect of cosmic curvature depends only on the total Ω, the precise position of the first acoustic peak is a particularly sensitive measure of $\Omega_m + \Omega_\Lambda$, and hence of the inflationary hypothesis. (See figure at left.)

"Inflation has passed its first real test," said University of Chicago theorist Michael Turner in response to Boomerang's April announcement that $\Omega = 1.06 \pm 0.06$. "The first acoustic peak fits inflation like a glove." Two weeks later, Maxima reported its confirmatory finding: $\Omega = 0.90 \pm 0.07$.

The inflationary scenario presumes that density fluctuations of the plasma epoch originated in microscopic primordial quantum fluctuations that were suddenly stretched to astronomical size by inflation. Rival schemes that attribute the origin of the CMB density fluctuations to topological defects in the fabric of spacetime seem now to be ruled out by the great height of the spectral peak at $l = 200$.

But if the balloon experiments have seen any evidence of the smaller second acoustic peak predicted at around $l = 500$, it turns out to be even smaller than the theorists expected. That might just be the bad luck of limited statistics at this early stage. Or it might be a suggestion that the spectrum of primordial quantum fluctuations, generally presumed to have been "scale-free," was, perhaps, slightly tilted in favor of spatially larger fluctuations.

Or the data may be telling us that the density of ordinary baryonic matter (a small fraction of the presumed dark-matter density) is somewhat higher than the standard theory of Big Bang nucleosynthesis would seem to allow. (See PHYSICS TODAY, August 1996, page17.) Fitting the curve in the figure to the data near $l = 500$ did, in fact, require this higher baryon density. The second peak represents the largest dilated cold spots at the end of the plasma epoch. Its height is particularly sensitive to the density of the ordinary matter that interacts with radiation.

Over glaciers and dogwoods

The name Boomerang is a tedious acronym (which we spare the reader), but also an apt metaphor: When the balloon had completed its 10.5-day circumpolar ride on the south-polar stratospheric vortex, the instrument was parachuted back to Earth only 30 miles from its McMurdo launch site. Boomerang is a large international collaboration headed by Paulo de Bernardis (University of Rome) and Andrew Lange (Caltech).

Maxima (Millimeter Anisotropy Experiment) was launched on its one-night flight from the National Scientific Balloon Facility in Palestine, Texas. The group's leader is Paul Richards (Berkeley). The two experiments, with very similar instruments and considerable personnel overlap, have their common origin in 1992, when Lange, Richards' former student, was still at Berkeley. The idea was to build a balloon-borne microwave telescope with sufficient angular resolution and dynamic sensitivity to resolve the fluctuation spectrum of the CMB.

THE BOOMERANG BALLOON, minutes before launch in December 1998 from the US Antarctic base at McMurdo. By the time it reaches its 40 km cruising altitude, the balloon will have expanded a hundredfold. In the background is the active Mt. Erebus volcano.

As the project evolved and the number of players grew, it diverged into two distinct experiments, with somewhat different strategies. Both are microwave telescopes that scan the sky and focus the radiation onto an array of bolometers sensitive to different frequency bands. The resultant heating of these very sensitive "spider web" bolometers, all built at Caltech's Jet Propulsion Laboratory, measures the incident intensity. Mapping the sky at different frequencies—from 100 to 400 GHz—helps the observers distinguish the true cosmic microwave background from extraneous foreground sources.

The Boomerang group undertook to brave the rigors of the Antarctic primarily to gain the advantage of longer flight time and thus greater sky coverage. Their 1998 flight mapped about 3% of the full sky. The Maxima collaboration, taking advantage of its more convenient launch site festooned with dogwoods, chose to incorporate elaborate cryogenics to enhance the sensitivity of the bolometers. Furthermore, Maxima carried star-tracking instruments to facilitate its pointing precision. It's hard to track stars when the sun is shining 24 hours a day in the antarctic summer.

The two balloon instruments will fly again. And both groups still have lots of data yet unanalyzed from their 1998 fights, which should let them determine the power spectrum out to $l = 1000$. With the launch of NASA's MAP satellite next spring, we should have year-round full-sky coverage of the CMB from this very sophisticated instrument's unobstructed perch at the Lagrange point L2, a million miles antisunward from Earth.

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References

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2. Maxima collaboration: S. Hanay *et al.*, http://xxx.lanl.gov/astro-ph/0005123, and A. Balbi *et al.*, http://xxx.lanl.gov/astro-ph/0005124.

An Atom Is Trapped by the Field of Just One Photon

The field of a single photon can not only trap atoms but also signal its position.

Researchers have been pushing atoms around with laser beams for many years, cooling them to record low temperatures and capturing them in confined spaces. Most such efforts require many photons. The field of a single photon is not generally strong enough to corral an atom—unless, that is, the light field is enhanced by confinement within a tiny cavity and the atom enters at a crawl. Then the coupling energy of the atom to the field can exceed the atom's kinetic energy, and the atom can become ensnared. A group from Caltech and the University of Auckland,[1] and also a group at the Max Planck Institute for Quantum Optics in Garching, Germany,[2] recently created the required conditions by combining cavity quantum electrodynamics with laser trapping and cooling; both groups succeeded in confining single atoms within optical cavities with an average of one photon in the cavity.

The photons in these experiments played a double role, not only trapping the atom but giving information about its position. By monitoring the rate of transmission of photons through the cavity, the Caltech–Auckland experimenters could infer the atom's orbit-like motion within the cavity. Getting this result required the Caltech team to build an exceptionally small cavity that is strongly coupled to the atom. (In earlier work, Caltech researchers had tracked, but not trapped, single photons as they passed through a cavity.[3]) Team leader Jeffrey Kimble said that he and his colleagues are now working to add feedback to control the motion and extend the atom's lifetime in the cavity.

The top figure on page 20 is an artist's rendering of the experiment: The cavity consists of parallel half-silvered mirrors. Laser light (red beam) traveling along the cavity axis sets up a standing wave within the cavity. Atoms (green) released from a magneto-optical trap fall through the cavity region and become trapped. Yellow path indicates the trajectory reconstructed from the passage of an atom through the cavity.

The figure shows a continuous laser beam shining through the cavity rather than a single photon bounding around inside of it. That's because the lifetime of a photon in the cavity