

SEARCH AND DISCOVERY

Cosmic Microwave Observations Yield More Evidence of Primordial Inflation

Last year, two balloon-borne bolometric telescopes—Boomerang and Maxima—spectacularly confirmed the large-scale Euclidean flatness of the universe by measuring the first “acoustic peak” of the fluctuation power spectrum of the cosmic microwave background (CMB). (See PHYSICS TODAY, July 2000, page 17.) Now the other shoe has dropped.

A compact microwave interferometer called DASI (Degree Angular Scale Interferometer), installed at the South Pole last year, has recorded a clear second acoustic peak and enticing evidence of a third.¹ (See figures 1 and 2.) That’s what cosmologists had been waiting for with eagerness and some trepidation. Flat cosmic geometry is just one of the central predictions of the widely accepted inflationary version of Big Bang cosmology. The inflationary scenario also requires a harmonic sequence of lesser acoustic peaks corresponding to CMB fluctuations on ever-smaller angular scales. (See the article by Charles Bennett, Michael Turner, and Martin White in PHYSICS TODAY, November 1997, page 32.)

The peaks are called acoustic because they’re thought to be manifestations of soundlike compressional waves in the plasma epoch that began a few minutes after the Big Bang and its inflationary encore. The microwave telescopes make sensitive CMB temperature maps of patches of sky, which are then fitted by a spherical-harmonic series. The power spectrum is essentially a plot of the spherical-harmonic coefficients squared, displayed as a function of l , the multipole order. The square of the l th coefficient measures the mean square spatial temperature fluctuation (or variance) at angular separations near $180^\circ/l$.

Last year’s Boomerang and Maxima results had shown hints of a second peak. But it seemed to be lower than the theoretical expectation—if it was there at all. A lower-than-expected second acoustic peak implied one of two possibilities, both quite unpalat-

Whether you look at relics from three minutes after the Big Bang or from 400 000 years later, you find the same meager value for the cosmic abundance of ordinary matter.

able to inflation theorists: Either the primordial spectrum of density fluctuations just before inflation was far from being scale invariant; or the abundance of baryons (protons and neutrons) just after inflation was significantly greater than the theory of primordial nucleosynthesis predicts.

Another triumph for inflation

Now the inflationists are relieved. At the April meeting of the American Physical Society in Washington, DC, John Carlstrom (University of Chicago), leader of the DASI team, reported that the height of the second peak yielded a cosmic baryon density in

excellent agreement with the theory of primordial nucleosynthesis. At the same session, the Boomerang group reported that an expanded analysis of the data from its 1998 flight produced essentially the same baryon-density result.²

Furthermore, both the expanded Boomerang analysis and a high-resolution reanalysis of the data from the 1998 Maxima flight³ strengthened the case for the second and third acoustic peaks. All three groups reported at the Washington meeting that the theoretical fits to their data yielded a primordial spectrum of adiabatic quantum fluctuations that had essentially no dependence on length scale. Adiabatic, in this context, means that all forms of energy and matter were perturbed to the same extent. Inflation implies a nearly scale-free spectrum of adiabatic primordial fluctuations.

The microwave background comes to us directly from the moment, some 400 000 years after the Big Bang, when the cosmos first became cool enough to be transparent. So why is the size distribution of its measly parts-per-million random departures from perfect isotropy so potentially informative about the first few minutes after the Big Bang?

Growing fluctuations

The inflationary scenario begins with microscopic quantum fluctuations in the energy distribution that are suddenly inflated to astronomical size at about 10^{-35} s after the Big Bang. In the next three minutes, as the cosmos cools, the lightest nuclear species—mostly hydrogen and helium—condense out of the primordial soup of quarks, photons, and leptons. The ordinary nuclear matter is presumed to be overwhelmed by about seven times as much nonbaryonic “dark matter” of a kind we don’t know about. Nonetheless, the baryonic matter plays a central role in the fully ionized hot plasma that renders the cosmos opaque for the next 400 000 years.

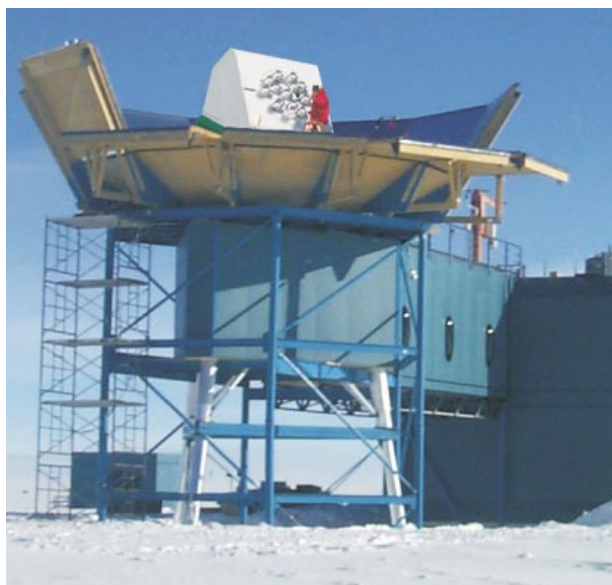


FIGURE 1. THE COMPACT DASI microwave interferometer, half a mile from the South Pole, measures the fluctuation spectrum of the cosmic microwave background. Its circular faceplate, next to the redcoated scientist, has 13 individual microwave detectors. Pairing them provides 78 different interferometric baselines. DASI can point continually to the same patch of sky by rotating diurnally around its vertical axis.

Around the random local islands of atypically high mass density, gravity tends to accumulate still more matter. But as the local density increases, the gravitational attraction is increasingly opposed by repulsive radiation pressure. This interplay of attractive and repulsive stresses generates compressional acoustic waves in the plasma, with “sound” velocity somewhat less than $c/\sqrt{3}$. Because the nonbaryonic matter is impervious to radiation pressure, the sound-wave amplitudes depend sensitively on the baryon density.

The CMB photons we now observe have been redshifted a thousandfold in the cosmic expansion since the end of the plasma epoch. But they have not suffered any significant scattering since the plasma gave way to transparent neutral gas. So they still carry the imprint of the density fluctuations as they were at the abrupt end of the plasma epoch.

Higher harmonics

The growth of a coherent region of high density (or temperature) is limited by the velocity of the compression waves. So the largest hot spots at the end of the plasma epoch were about 200 000 light-years across. That’s roughly the sound velocity times the duration of the plasma epoch. The largest accumulations of minimum density (or temperature) were about half that size, because, in the time available before the plasma cleared, an acoustic wave would have traversed such a region *twice*, propagating first compression and then rarefaction. Similarly, a region reaching maximum compression a second time at the end of the epoch would have been traversed three times, and thus would be limited to $1/3$ the diameter of the largest hot spots. So we end up, roughly speaking, with a harmonic sequence ($1, 1/2, 1/3, 1/4 \dots$) of characteristic sizes for alternating regions of maximal compression and rarefaction that manifest themselves as small temperature fluctuations in the CMB.

These very faint spatial fluctuations about the CMB’s spectacularly uniform blackbody temperature of 2.725 K are measured in microkelvins. If one maps the CMB temperature of a patch of sky with sufficient sensitivity and angular resolution, the spherical-harmonic power spectrum should exhibit the first few acoustic peaks (see figure 2). One important condition for the appearance of distinct peaks in the fluctuation power spec-

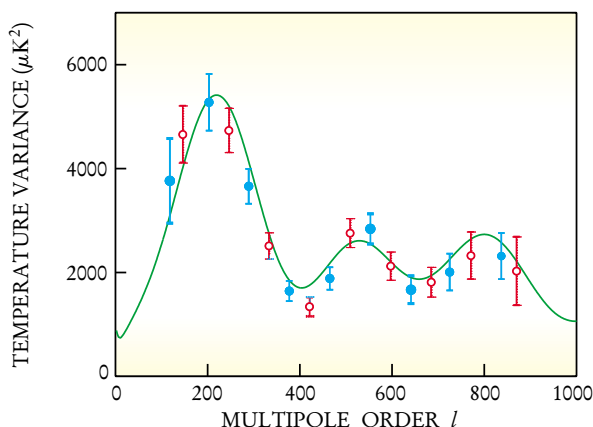


FIGURE 2. POWER SPECTRUM of the cosmic microwave background’s spatial fluctuations, as measured by DASI.¹ The two sets of data points involve different binning. The curve is the theoretical spectrum for $\Omega_b = 0.042$, $\Omega_T = 1.04$, and the other cosmological parameters yielded by fits to the DASI data.

trum is the crisp, well-defined starting time inflation imposes on the plasma epoch. The oscillations all begin almost simultaneously.

The position of the first peak tells us that the biggest CMB hot spots subtend an angle of about 1° on the sky. That’s what one would expect at the end of the plasma epoch, *if* the subsequent 10^{10} -year journey of the CMB photons was not distorted by large-scale cosmic curvature. In other words, the geometry of the universe is, as far as we can tell, quite flat.

But that was last year’s news. This time, the second peak has center stage. Its height, relative to the first peak, is a sensitive measure of the baryon density in the plasma. The second peak, and in fact all the cold-spot peaks (4th, 6th, $\dots$), should become higher, relative to the hot-spot peaks, with *decreasing* baryon density. The best fits to the DASI and Boomerang power spectra both yield $\Omega_b = 0.042 \pm 0.008$, where Ω_b is the cosmic baryon mass density expressed as a fraction of the total “critical density” of mass and energy required to make the cosmic geometry flat. (The error quoted here ignores the uncertainty in our knowledge of the Hubble constant.)

That’s in very good agreement with the Ω_b one gets by applying the theoretical details of primordial nucleosynthesis to the most recent observations of the cosmic abundance of deuterium.⁴ It is assumed that all deuterium in the cosmos was created in the first three minutes, and the theory predicts a steep dependence of the

deuterium abundance on the overall baryon density (see PHYSICS TODAY, August 1996, page 17). So here we have reassuring observational concord between the predictions of the inflationary scenario for three minutes and 400 000 years after the Big Bang.

For Ω_m , the overall (normalized) cosmic mass density for baryonic and nonbaryonic matter, a variety of different sorts of observations are convincingly converging on a value of about 0.35. In other words, the ordinary matter we know about accounts for little more than 10% of all matter. This affront to our material dignity is compounded by the growing evidence that matter as a whole plays second fiddle to some sort of dark energy ($\Omega_\Lambda \approx 0.65$). (See PHYSICS TODAY, June 2001, page 17.) The flat cosmic geometry demanded by inflation requires that $\Omega_T \equiv \Omega_m + \Omega_\Lambda = 1$. The CMB observations are particularly sensitive to this sum. The best fits to the DASI and Boomerang power spectra yield $\Omega_T = 1.04 \pm 0.06$ and 1.02 ± 0.06 , respectively.

At the South Pole

Unlike Boomerang and Maxima, which are imaging telescopes, DASI is an interferometer that measures spherical-harmonic (or Fourier) components of the CMB directly, without having to rely on spatial images. This obviates a number of calibration problems that burden the analysis of the imaging-telescope data. The DASI design owes much to decades of successful interferometric radio astronomy. But the radio telescopes need very long baselines to achieve subarcsecond angular resolution. DASI, by contrast, can make do with baselines on the order of a meter to achieve the modest 0.2° resolution needed to measure the CMB power spectrum out to $l = 900$.

As shown in figure 1, DASI’s faceplate sports 13 microwave detectors, each with a 20-cm aperture. Pairing these detectors provides 78 interferometric baselines of 26 different lengths. Being just half a mile from the South Pole, DASI can fix its gaze continually on a patch of sky simply by rotating diurnally about its vertical axis. As Carlstrom puts it, “The Earth rotates, but we don’t.”

In recent weeks, galaxy redshift survey teams have reported hints of the CMB acoustic peaks in the cosmic distribution of galaxies.⁵ That’s not surprising if one assumes, as cosmologists

do, that the parts-per-million CMB fluctuations in the incredibly homogeneous plasma epoch were the seeds of today's highly structured universe.

As of this writing, NASA's MAP (Microwave Anisotropy Probe) satellite was scheduled for launch at the end of June. From its quasi-stable

perch at the Lagrange point L2, a million miles antisunward from Earth, MAP should be able to measure the CMB power spectrum with unprecedented sensitivity and precision.

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Feedback Tames Chaotic Surface Chemistry

Chaotic systems typically lurch from one point in phase space to another, usually wildly different one. Yet amid the seemingly random flailings, episodes of near periodic behavior appear, then disappear, like spells of sunny weather in storm-battered Shetland.

In their ability to quickly change states, chaotic systems can outmaneuver their incrementally changing linear cousins. But if their nimbleness is to be exploited, chaotic systems must be harnessed and controlled. Paths must be found to the desirable, well-behaved states.

In the early 1990s, the University of Maryland's Edward Ott, Celso Grebogi, and James Yorke proved theoretically that a chaotic system can indeed be controlled.¹ Now known as OGY, their method is to apply judiciously chosen perturbations to an available system parameter. (For more on controlling chaos, see Ott and Mark Spano's article in *PHYSICS TODAY*, May 1995, page 34.)

Since that pioneering effort, which was first brought to bear on a wobbling magnetoelastic ribbon,² various chaotic systems have been tamed—among them, oscillatory chemical reactions. In these bizarre systems, two or more reactions wax and wane in turn as each inhibits and promotes the other. With the right mix of conditions, the concentrations of species in chemical oscillators can be induced to exhibit temporal chaos or, in some cases, spatiotemporal chaos.

The first chemical oscillator to be controlled was the classic Belousov-Zhabotinsky (BZ) system of reactions. Discovered 50 years ago, the BZ system involves a somewhat complex mix of reactants, but it boils down to a simple plan. A slow reaction consumes a species that stifles a second, faster reaction that can be switched on autocatalytically.

As it proceeds, the fast reaction triggers the production of the species that inhibits it, and the cycle begins again. With the right mix of concentrations, the BZ system oscillates chaotically.

With a single parameter as a tiller, surface scientists can steer a model catalyst away from chaos toward regimes of regular, repeating behavior.

The state of the BZ system can be monitored by dipping an electrode into the vat of reactants and measuring the reactions' ionic fluctuations. In 1993, Kenneth Showalter's group at West Virginia University used a perturbation method akin to OGY to successfully control temporal chaos in a BZ system.³

Now, from Harm Hinrich Rotermond's group at Berlin's Fritz Haber Institute (FHI), comes an experiment that extends the control of chemical chaos in a significant and new direction.⁴ Working with a simple catalytic system, the FHI team created chaotic spatiotemporal patterns of surface reactants and then, by using a simple feedback mechanism, pushed the system into one of several well-behaved, nonchaotic spatiotemporal regimes.

"It's a major advance in understanding and controlling complex spatiotemporal behavior," says Showal-

ter. What's more, the chemical system that the FHI group studied—the oxidation of carbon monoxide on platinum—is an idealized version of what goes on in the catalytic converters of cars and trucks. It's closer, therefore, to practical applications than the rather academic BZ system.

Lifted reconstruction

In their experiments, the FHI researchers waft CO and O₂ in a vacuum over the (110) surface of a single Pt crystal. When O₂ molecules hit the surface, they dissociate into two O atoms that stick firmly to the surface. CO molecules also stick to the surface, but, being more loosely bound, diffuse about.

When a CO molecule encounters an O atom, the two combine to make a carbon dioxide molecule, which promptly leaves the surface. In a car's catalytic converter, this reaction converts the poisonous CO to the less malign CO₂.

Two key phenomena cause the CO-O-Pt system to oscillate: asymmetric inhibition and lifted reconstruction. Asymmetric inhibition occurs because CO needs just one adsorption site, whereas the dissociating O₂ needs two adjacent sites. If too much CO covers the Pt surface, oxidation can't occur. At that point, the catalyst is, as chemists say, "poisoned."

Reconstruction is the rearrangement of surface atoms with respect to the bulk. It occurs no matter how the surface is created. In the case of Pt(110), surface atoms rearrange themselves in such a way that every second row is missing.

When CO coverage reaches about half a monolayer—the point at which poisoning occurs—CO removes (or "lifts," as surface scientists say) the reconstruction, restoring the bulk configuration to the surface. This is significant because oxygen's sticking probability is 50% higher for the bulk configuration.

Asymmetric inhibition and lifted reconstruction work together to produce an oscillation as follows. Start off

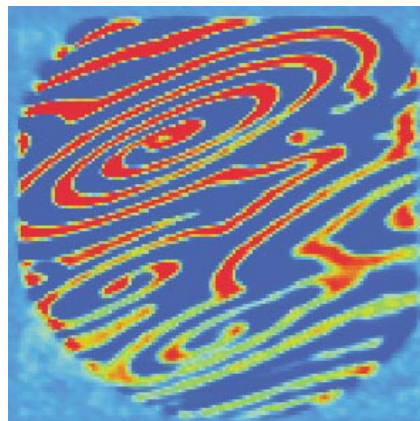


FIGURE 1. CHAOTIC SPIRALING patterns of carbon dioxide and oxygen can form on a platinum surface. In this snapshot from a photoemission electron microscope (PEEM), red represents the areas of the Pt surface covered in carbon monoxide; areas covered by atomic oxygen are shown in blue. The field of view is 500 μm across. (Adapted from ref. 4.)