Observing the Cosmic Microwave Background at High Resolution Bolsters the Inflationary Big Bang Scenario

> The angular resolution of the new Cosmic Background Imager is fine enough to reveal, for the first time, the primordial seeds of galaxy clusters.

Sitting in the high Andean desert of northern Chile at an altitude of 5100 meters, the Cosmic Background Imager (CBI) has been scrutinizing the random microkelvin anisotropies of the cosmic microwave background (CMB) since the beginning of 2000. CBI is an interferometric microwave telescope operated by a collaboration of institutions in the US, Canada, and Chile, headed by Anthony Readhead and Stephen Padin at Caltech. The collaboration has now reported the results of its first full year of observing.[1]

The new microwave interferometer's special claim to fame is its ability to map fluctuations in the CMB with an unprecedented angular resolution of 4 arc minutes. The older microwave telescopes that have mapped the CMB in impressive detail in the last few years—Boomerang, Maxima, and DASI—were limited to resolutions coarser than 10 or 15 arc min (see PHYSICS TODAY, July 2001, page 16).

What's so important about high resolution? CBI is the first microwave telescope whose angular resolution is fine enough to discern the CMB hot spots that are presumed to be the seeds of the galaxy clusters we see today. Small point-to-point fluctuations of the microwave background's temperature on different angular scales can reveal different aspects of the early cosmos. And they provide independent probes whose consistency tests the underlying theory. Both in their new revelations and their confirmation of earlier findings, the CBI results lend strong support to the standard inflationary model of Big Bang cosmology.

Thermal wrinkles

The CMB is thought to be a largely undistorted snapshot of the cosmos at the time—some 400 000 years after the Big Bang—when the primordial plasma of hydrogen and helium finally became cool enough to permit the survival of neutral atoms. For the first time, photons could now travel large distances without scattering. Having been redshifted a thousandfold to microwave frequencies by about 14 billion years of cosmic expansion since that first moment of transparency, this relic radiation now surrounds us with a remarkably isotropic background with a blackbody temperature of 2.725 K.

But a perfectly isotropic CMB could not have evolved into the grossly nonuniform distribution of galaxies we see today. The observed patchwork of hot (and cold) spots in the CMB—microkelvin departures from perfect thermal isotropy—indicates random local regions with mass densities very slightly higher (or lower) than the average at the time of the snapshot. The standard cosmology assumes that these very shallow density fluctuations were the seeds, greatly amplified over eons by gravity, of all the large-scale filamentary and bubbly groupings of galaxies now seen by large-scale surveys. A CMB hot spot we see subtending an angle of 4 arc minutes would by now have been stretched by cosmic expansion to about 40 million light-years—the size of a large cluster of galaxies.

The ultimate source of these fluctuations is presumed to have been quantum fluctuations suddenly expanded to cosmological dimensions in less than 10^{-34} s by inflation, a burst of exponential cosmic expansion immediately following the Big Bang.

For cosmologists, the raw map of CMB hot and cold spots on the celestial sphere is less informative than is its spherical-harmonic decomposition—the power spectrum of these spatial temperature fluctuations. (See the article by Charles Bennett, Michael Turner, and Martin White in PHYSICS TODAY, November 1997, page 32.) If one decomposes the map of departures from the mean CMB temperature into spherical harmonics, the coefficient C_l of the lth multipole moment measures the mean-square temperature difference between points on the celestial sphere separated by angles of order $180°/l$.

Different cosmological models and parameters make different predictions for the CMB power spectrum—the plot of the mean-square fluctuations $l(l+1)C_l/2\pi$ versus l. And different microwave telescopes contribute significantly to different l ranges of the power spectrum—depending on the angular separations for which a particular telescope is optimized. The data from Boomerang, DASI, and Maxima, as shown in figure 1, provided a considerable triumph for the inflationary Big Bang scenario by confirming the first few "acoustic" peaks predicted by the theory.

The peaks in the power spectrum are called acoustic because they were expected to have arisen from compressional waves in the viscous elastic fluid of ions, electrons, and photons that characterized the plasma epoch. The harmonic spectrum of well-defined peaks, with more and more damping expected at higher harmonics, is attributed to the sharp temporal boundary conditions posited for the plasma epoch: its abrupt onset at the end of inflation, complete with a primordial spectrum of spatial fluctuations, and its rather less abrupt end when the ionized plasma finally became transparent.

The older microwave telescopes, with their limited angular resolutions, cannot measure the power spectrum above about $l = 1000$. And that's precisely where CBI

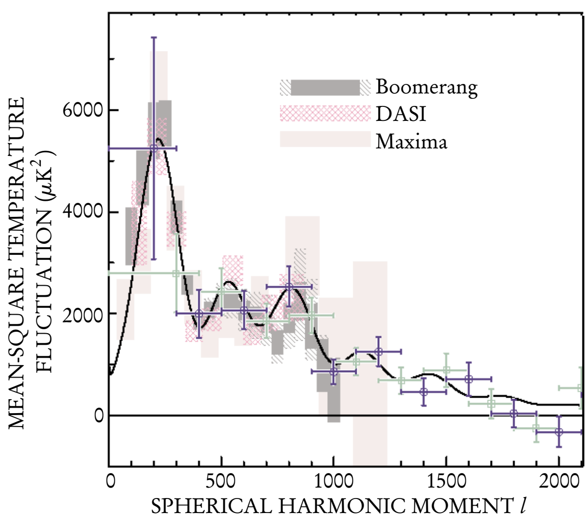

FIGURE 1. COSMIC MICROWAVE BACKGROUND fluctuation power spectrum from wide-field exposures by the Cosmic Background Imager is shown as crosses. The two different colored crosses represent different binning. The shaded bars show results from earlier microwave telescopes. The curve shows the best theoretical fit to all these data. (Adapted from ref. 1.)

CALTECH CBI TEAM

FIGURE 2. THE COSMIC BACKGROUND IMAGER, sitting on an arid plateau high in the Chilean Andes, is an interferometric array of 13 separate radio antennas mounted on a 6 m tracking platform. Each antenna is a 90-cm-wide parabolic reflector enclosed in an aluminum shield can with a teflon cover transparent to microwave radiation.

comes into its own. Complementing the older telescopes, it can measure the power spectrum out to $l = 3500$. Not even NASA's recently launched MAP (Microwave Anisotropy Probe) satellite,[2] which should measure the first three acoustic peaks in unprecedented detail, can see beyond $l = 1000$. There is, however, a tradeoff. CBI's capabilities are quite limited in the region below $l = 400$, where the prominent first peak was found.

Cosmic Background Imager

Like DASI, its smaller sister telescope sitting half a mile from the South Pole, CBI is an interferometric array of 13 individual microwave receivers mounted on a tracking platform. The two instruments have many features in common. But CBI, shown in figure 2, owes its finer angular resolution to its greater size. Each of its parabolic-reflector antennas is 90 cm in diameter, as compared with DASI's 20-cm reflectors. And the separations that provide the interferometric baselines between individual antennas are correspondingly larger. The biggest separation between any two CBI antennas is 5.5 m. An important feature of CBI is the very high sensitivity the receivers get from their indium phosphide HEMT (high-electron-mobility transistor) amplifiers, operating in the 26–36 GHz band.

The high, dry Andean site was chosen to minimize spurious signals from the thermal radiation of atmospheric moisture. "Even so, we were shut down by snow and clouds for a surprising number of nights in 2000," Readhead told us. In that respect, the South Pole might have been a better choice. "But configuring so large a telescope for operation at Antarctic winter temperatures would have been prohibitively expensive." Furthermore, CBI's fine angular resolution makes it essential to subtract foreground signals from radio galaxies. And the requisite catalog of radio galaxies is much less complete for the South-Polar sky than for more northern latitudes.

One might also imagine that the Chilean Andes are more accessible and hospitable than the South Pole. But working at an altitude of 5100 m—a thousand meters higher than the optical telescopes on Hawaii's Mauna Kea—the CBI staff were required to carry portable oxygen supplies when they were outside the specially oxygenated control room or laboratory.

The CBI collaboration took data in two distinct modes: To achieve the best possible angular resolution, and thus the highest values of l, the group took very long imaging exposures of six narrow fields, 45 arc min on a side. Each of these "deep" fields was observed for about 150 hours. Alternatively, to achieve greater sensitivity at low l and better Δl resolution on the power spectrum, the group covered six wider patches of sky, each about 155 arc min on a side, with shorter exposures. The crosses in figure 1 indicate the power spectrum, up to $l = 2000$, deduced from the wide-field exposures. The curve in the figure shows the best cosmological fit to all the CMB data from CBI *and* the older microwave telescopes.

The CBI data don't contribute much to the delineation of the first acoustic peak, which had already been clearly outlined by the other microwave telescopes. But CBI has given cosmologists a first look at the *terra incognita* beyond $l = 1000$. That first look confirms an essential prediction of the standard inflationary cosmology, namely, that the CMB power spectrum should fall off with increasing l in a so-called damping tail, with acoustic peaks of ever-diminishing amplitude. The prediction of the damping tail follows from the viscosity of the hot plasma fluid and from the finite duration (a few times 10^4 years) of the transition from opaque plasma to transparent neutral gas.

Cosmological parameters

The various cosmological density parameters deduced from the CMB power spectrum are most usefully quoted as fractions of the critical mass density (about half a dozen hydrogen atoms per cubic meter in the present epoch) above which the cosmos would eventually begin to contract—unless gravity is opposed by some sort of repulsive vacuum energy. Thus normalized, the cosmic densities of matter and vacuum energy are denoted, respectively, as Ω_m and Ω_Λ. The latter subscript reminds us that the simplest candidate for such a vacuum energy would be Einstein's cosmological constant Λ.

If there is indeed such a vacuum energy, the inflationary scenario requires that $\Omega_{total} \equiv \Omega_m + \Omega_\Lambda = 1$. That is to say, the cosmic geometry must be flat (Euclidean), any intrinsic curvature having been stretched out of existence by inflation.

The Boomerang, Maxima, and DASI fits to the CMB power spectrum appeared to confirm an astonishing finding of earlier supernova surveys (see PHYSICS TODAY, June 1998, page 17), namely, that Ω_Λ is about twice as big as Ω_m. In other words, mass plays second fiddle to a "dark" vacuum energy, with the result that the Hubble expansion is actually speeding up in the present epoch. The familiar world is further demeaned by the realization that Ω_b, the cosmic density of ordinary baryonic matter, constitutes only about 15% of Ω_m, the rest being some sort of exotic matter only slightly less mystifying than the dark energy.

For adherents of the inflationary Big Bang, the observation of the damping tail is very reassuring. And so is the good agreement between the cosmological parameters deduced from the high-angular-resolution CBI observations and the parameters deduced from the older CMB studies. This despite the fact that the two sets of observations yield the parameters from quite separate l ranges—the older telescopes derived the parameters mainly from the region of the first two acoustic peaks. The new CBI parameter fits, on the other hand, remain essentially unchanged when the collaboration ignores all of its data below $l = 600$. Yet CBI confirms precisely what the other groups had found at low l: Ω_{total} very close to 1, Ω_Λ about 0.7, and Ω_b about 0.05.

Beyond the cosmic density parameters, the CBI fits yield another important confirmation of the earlier results. The standard inflationary scenario specifies that the spatial density fluctuations seen in the CMB originated entirely from a scale-free spectrum of fluctuations already present at the end of inflation. Here, scale-free means, in essence, that the primordial fluctuation spectrum had the same power in all length scales. To test this key assumption, the fits to the CMB data include a free exponential parameter, n_s, that would, if it differs significantly from unity, indicate a departure from the scale-free primordial fluctuation spectrum suggested by inflation. But, much like the earlier fits, the CBI observations yield an n_s of 1.05 ± 0.09.

"Nature would have to be amazingly mischievous to fool us with the same wrong answers in two such different ranges of l," says Readhead.

"The confirmations provided by the CBI observations are particularly important," comments MIT theorist Alan Guth, who introduced the notion of inflation 20 years ago, "precisely because the now standard cosmology is so seemingly preposterous. We have absolutely no good physics reason for an Ω_Λ of order unity."

Secondary anisotropies

Above $l = 2000$, where the CBI collaboration relies primarily on the deep-field exposures, the data analysis finds that the amplitude of the power spectrum is actually three standard deviations too high to be attributed simply to the continuation of the CMB damping tail. But with the predicted damping tail so low at these high harmonic moments, one can expect to see secondary anisotropies due to foreground effects. One source of such foreground anisotropies is the Sunyaev–Zeldovich (SZ) effect, in which low-energy CMB photons are scattered to higher energies by hot electrons in the gas of foreground galaxy clusters.

The CBI group finds that the excess power seen above $l = 2000$ is consistent with the SZ effect. But a more definitive conclusion will probably require examining the CMB at higher frequencies, to look for the photons scattered to higher energies. One such undertaking, headed by William Holzapfel (University of California, Berkeley), is just getting under way at the South Pole, where the ACBAR bolometric detector mounted on the Viper telescope will be sensitive to microwave radiation up to 280 GHz.

Looking for the SZ effect is important for two reasons. Of course it will help cosmologists to distinguish between intrinsic properties of the CMB and secondary foreground effects. But it also promises to be a particularly sensitive way of studying the clustering of galaxies at a very early stage of cosmic evolution.

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1. CBI Collaboration, http://arXiv.org/abs/astro-ph/0205384 through 0205388.
2. See http://map.gsfc.nasa.gov.

Choreographing Wave Propagation in Excitable Media

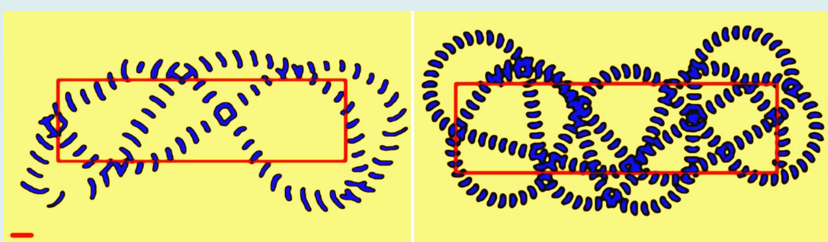
Excitable media can be coaxed into complex spatiotemporal patterns, including spiral waves and oscillating tiger stripes (see PHYSICS TODAY, July 2001, page 18). Like the antics of the Three Stooges, this captivating behavior often emerges in a state of near or actual chaos. But the excitable medium on display here has been so thoroughly tamed that its handlers, a team from West Virginia University in Morgantown, not only keep the onset of chaos at bay, they also direct the patterning at will and bestow on individual waves the kinetic behavior of a particle under the influence of a potential.

To develop their control techniques, the WVU team, led by Ken Showalter, worked on a Belouzhov–Zhabotinsky (BZ) system. In BZ systems, two or more reactions, mediated by a catalyst, consume and supply each other's intermediary species. The upshot of this chemical symbiosis is a zone of reacting species that travels through the medium like a tsunami in the open ocean.

In the WVU experiments, the chemical action takes place in a matchbox-sized tray. Covering the bottom of the tray is a thin layer of gel that contains a light-activated catalyst. Postdocs Tatsunari Sakurai and Eugene Mihailuk switch on the BZ reaction at a particular location in the tray by spotlighting the reactants and the catalyst beneath with visible light. The size of the spot controls medium's excitability and, with it, the size of the wave. Further, by increasing or decreasing the intensity of illumination at the edges of the wavefront, the WVU researchers can establish excitability gradients across the wavefront to control its direction of propagation.

The control method is reminiscent of the old-fashioned toy in which the player directs one or more tiny balls to locations in a small box by carefully tipping the box this way and that. The player has to react quickly to the ball's changing path, but the WVU researchers could prescribe the path of their wavefronts in advance.

Here's how. After setting a wave in motion, the researchers take an image of the tray with a video camera. The wave is brighter than its unexcited surroundings, and its size and location are easily measured. These measurements go into the feedback step: determining the pointing direction and brightness of the reaction-controlling spotlight. By comparing the current image with an image taken two seconds earlier,



the researchers can tell whether the wave needs a bigger or smaller dose of light to maintain its stability. By also applying a predetermined control algorithm, they know how much of a light gradient to apply across the wavefront to change its direction.

Conceivably, any algorithm can be used. The lefthand panel shows a sequence of snapshots tracking the course of a single wave. Under the algorithm's control, the wave is made to execute figure eights and, at certain times, to bounce off the notional boundary (red rectangle) as if undergoing a reflection. The righthand panel shows a similar course, but one simulated on a computer by Sakurai and Showalter's graduate student Florin Chirila.

What is the use of such a control mechanism? Showalter points out that wave behavior is ubiquitous in living systems and the excitable media in them are always adapting to various perturbations—even to the wave behavior itself. His team's method could provide a way to study those mechanisms.

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Reference

1. T. Sakurai, E. Mihaulik, F. Chirila, K. Showalter, *Science* **296**, 2009 (2002). ■