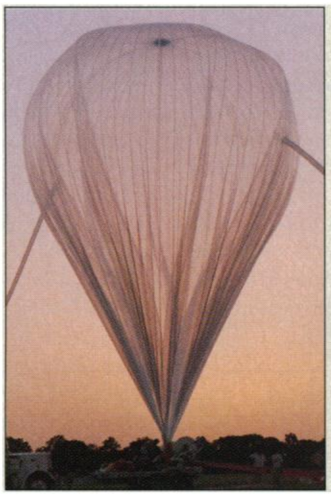
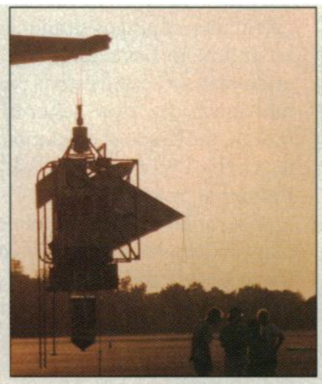
Microwave Mappers Sweat Details

The story of how cosmic structures formed is written in the microwave background left by the Big Bang. But observers mapping its details are finding that it's a confusing text

Welcome to what George Smoot, a University of California, Berkeley, cosmologist, cheerfully calls the "confusion phase." Smoot is referring to the state of knowledge about the cosmic microwave background, the cool bath of microwaves left over from the Big Bang. Two years ago, Smoot and a team of investigators finally learned from the Cosmic Background Explorer Satellite (COBE) that, as theory predicted, this ubiquitous background glow isn't completely smooth. It has hotter and cooler spots reflecting subtle fluctuations in the density of the early universe. Now, at least half a dozen teams of experimenters are delving deeper into the nature of these fluctuations by mapping the details of the glow. But like early cartographers, they're far from agreed about what they're seeing.





LAWRENCE BERKELEY

Going up for a look. The Berkeley/Santa Barbara Millimeter Wave Anisotropy Experiment is readied for takeoff.

That's not surprising, considering that the investigators have to detect variations in the temperature of the radiation on the order of one part in 100,000 while coping with an atmosphere that shines 10 times brighter at those wavelengths than the microwave background itself. To see anything at all, the detectors generally have to be cooled to within an iota of absolute zero and flown at the outer edge of the atmosphere or mounted in high, dry locales like the South Pole. Even so, the results to date barely stand out above the noise, and they can't be cross-checked because they come from different parts of the sky.

But what is at stake in the details of the cosmic background is nothing less than the story of how primordial matter became clumped into galaxies, clusters of galaxies, and even larger structures (see story on p. 1684). As a result, theorists haven't been able to resist interpreting these statistically suspect results. It's an activity that Neil Turok of Princeton University (himself a theorist) describes as "ambulance chasing—running after these experiments hoping one of them will disprove some theory."

If the results are accepted as accurate, the theory that fares best so far is one that traces large-scale structures to "defects" that formed as the universe cooled during the first fraction of a second after the primordial fireball. But the measurements also reveal other things, including bright point sources of microwaves, that theorists can't even begin to explain. As David Schramm, a cosmologist at the University of Chicago, puts it, either half the experiments are wrong—as he and most other cosmologists are betting—or the universe is a much more interesting place than they ever imagined.

The new round of experiments is an effort to bring the microwave background back home. Left over from when the universe was young—only several million years old—and consisted of a 3000 degree plasma of hydrogen and helium, the background radiation, says Paul Richards of Berkeley, provides "the initial conditions for astronomy." Cosmic expansion has Doppler-shifted the original radiation into the microwave band, and it now has the spectrum given off by an object at 2.7 degrees above absolute zero.

As the COBE results showed, this cold primordial glow isn't all of a piece: Fluctuations in the temperature of the microwaves reveal the density variations that, reinforced by gravity, gave rise to the large-scale structures visible today. "If you want to know why there are big superclusters," says Richards, "why a great wall, why the deepest surveys show these gigantic structures," the answer lies in the details of the background radiation. And the shape of those variations can be a clue to the processes that produced them in the first place. Some questions are well beyond the scope of the maps so far (see box). But one key issue seems tantalizingly accessible.

If the variations originated as "defects" in the cooling universe—threadlike imperfections known as strings or more complex ones called textures—they should be large and "have lots of interesting structures," says Turok. "For instance with strings you would see lines in the sky. With textures you would get hot and cold spots." An alternative scenario called inflation predicts a less dramatic and varied pattern. Inflation holds that the universe underwent a surge of expansion in the first instants of the Big Bang that would probably have swept any defects out of the visible universe. The only source of density variations would have been random fluctuations in the primordial plasma.

Telling details

COBE couldn't distinguish these two possibilities because its instruments were incapable of resolving temperature differences between two points in the universe less than 7 degrees apart. A separation of 7 degrees in the infant universe translates, after 15 billion years of cosmic expansion, to a scale considerably larger than any structures ever observed. To understand the birth of the structures familiar to astronomers and test theories of their formation, observers have to map variations in the microwave background on a scale of 2 degrees or less. As a result, after the flurry of excitement brought by the COBE announcement, says Schramm, "the action moved down to the 1 to 2 degree scale."

Making these finer scale measurements was beyond the abilities of COBE, because it requires a larger telescope than that satellite could carry. At the same time, it doesn't require the full-sky view available only by going into orbit, so the new generation of microwave mappers have been able to work from balloons and the ground. Even so, creating an apparatus that can detect deviations of one part in 100,000 in the 2.7 degree background radiation is anything but easy. As Richards puts it, "Lots of things in the sky are lumpy. It's a major, major issue to know what it is you're seeing when you see something."

The first step toward making trustworthy measurements is to choose an observing site that minimizes interference from the atmosphere, which contains water vapor and oxygen that both happen to glow at the frequencies best suited for microwave background watching. The solution is to do the experiments either from high-altitude balloons or from the ground at sites with extremely cold, dry climates, such as the high plains outside

Putting Questions to the Cosmic Background

The flurry of efforts to map the details of the cosmic background radiation deliver an ambiguous answer to even the biggest question about structure in the universe: whether it originated as "defects" in the fabric of spacetime or as tiny, random density variations generated during an early burst of "inflation" (see main story). But even after that question is answered, cosmologists will be ready with at least two other pressing questions.

■ What is the nature of dark matter? Candidate dark matter particles, believed to make up most of the mass in the universe, fall into two categories: hot and cold. Particles that move at close to the speed of light—low mass neutrinos, for example—qualify as hot. Slow-moving particles—hypothetical massive particles such as the photino—are cold. Either way, the unseen matter would have clumped around the initial variations in the fabric of the universe and helped draw visible matter into galaxies and galaxy clusters. Because it travels so fast, hot dark matter would wipe out any density perturbations on small scales—less than the scale of galaxy clusters—while cold dark matter would form clumps on smaller scales. As a result, optimists like Berkeley cosmologist George Smoot argue, it might be possible to probe the nature of the dark matter by finding the angular scale at which the bumps in the microwave background are most pronounced. A "cold dark matter" universe should be bumpier on smaller scales than a "hot dark matter" universe.

■ Did the Big Bang produce gravity waves? In some scenarios of inflation, ripples in spacetime known as gravity waves would have been generated during the universe's first fraction of a second. The gravity waves, moving at the speed of light, would spread out too rapidly in the infant universe to provide the seeds of later structure, but they might account for some of the temperature differences seen in the microwave background at angular scales above about 3 degrees, and Smoot and his colleague Paul Steinhardt of the University of Pennsylvania have a way to tell. Once again, the trick is to compare the lumpiness of the universe at different angular scales, says Smoot. The telltale feature would be a drop-off in the bumpiness between angular scales of one degree—where matter was clumping around cosmic density fluctuations and accentuating them—and three degrees, where gravity waves would show themselves.

Cosmologists aren't counting on a quick resolution to either question, no matter how refined the maps of the microwave background become. Princeton theorist Neil Turok, for example, argues that dark matter speculations are so ad hoc that the microwave background may not clarify them. Smoot agrees that cosmological theories can be tough to pin down. "The more the noose tightens around the theorists, the more they'll wiggle to get out of it. It's an uncertainty principle for theorists."

–G.T.

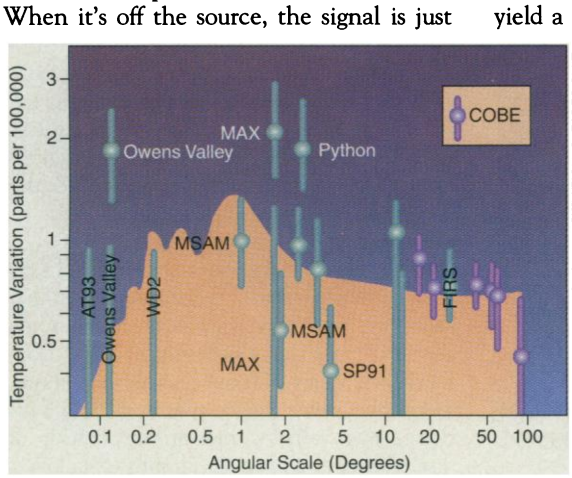
Saskatoon, where one Princeton group observes, or the South Pole, where a Princeton-Carnegie Mellon collaboration and another group from the University of California, Santa Barbara, have set up shop.

Step two is to remove whatever atmospheric signal is left. That's accomplished through a scheme conceived by Princeton physicist Robert Dicke, now called Dicke switching. "Suppose you have a very weak source up in the sky," says David Wilkinson of Princeton, "and it's thousands of times weaker than the noise in your instrument. You just point the telescope off and on the source. When it's on the source, the signal is a lot of noise plus a little from the source. When it's off the source, the signal is just noise, and so you just rock back and forth and measure the small change in the signal. If you're willing to do that long enough you can get high accuracy."

Even then, observers still face the question of whether their signal comes from the microwave background or something nearer and younger in the cosmos—such as emission from dust grains in the Milky Way or radiation from charged particles. But here, too, the observers have developed various tricks for distinguishing the faint signal they're interested in from the various interlopers.

All over the map

The initial efforts to overcome these hurdles yield a tantalizing, contradictory picture of the infant universe that seems to offer something for everyone. On the one hand are results like those of a balloon experiment called MSAM, for Medium Scale Anisotropy Measurement, built by Stephan Meyer of the University of Chicago and collaborators at NASA's Goddard Space Flight Center and Princeton, and flown from the National Scientific Ballooning Facility in Palestine, Texas. MSAM has reported anisotropy, or deviations in the microwave temperature, of 1.1 to 2.5 parts per hundred thousand over angles of half a degree, about what is predicted by the inflationary universe scenarios. Another balloon experiment called MAX (Millimeter-wave Anisotropy Experiment), flown from Palestine and Ft. Sumner, New Mexico, by a group out of Berkeley and Santa Barbara, detected anisotropy of about the same magnitude—1.4×10^{-5}—in one observing run, as did a detector mounted at the South Pole by Santa Barbara cosmologist Phil Lubin and an experiment on the Canadian prairie by Wilkinson. Wilkinson's result, an anisotropy of 1.3×10^{-5}, was "right on what the simple [inflation] theory would have predicted," says Schramm.



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Blowing hot and cold. Measurements of the cosmic background don't agree with one another, let alone with predictions of a "cold dark matter" theory *(line)*.

On the other hand are measurements that seem to show much more pronounced bumpiness. Examining a different patch of sky, MAX revealed bumps four times as pronounced as those in the first data set. Similar evidence comes from Python, a ground-based experiment run at the South Pole by Princeton's Mark Dragovan and Jeff Peterson of Carnegie Mellon, which has seen anisotropy of 3.1×10^{-5} and 3.8×10^{-5}. Examining the universe on very small angular scales of arc-minutes, a Caltech collaboration using the Owens Valley Radio Observatory found anisotropy of 3.5×10^{-5}. But several other fine-scale measurements—including a different measurement by the Caltech group—saw no anisotropy at all.

"Maybe half the experiments are wrong," says Peterson. "These experiments are so hard we shouldn't be cavalier about that possibility. But it's also possible that some fields of sky contain cosmic background structure and others don't." If the fluctuations of the cosmic background really do vary drastically from place to place, then the universe is a very lumpy place at this angular scale, more consistent with the defect models then with the inflationary scenarios.

But then there are clues that don't fit either of the two main models—in particular, a report by the MSAM collaboration that they observed two point-like hot spots in the cosmic background. "We expected to see a random pattern of variations," says Meyer, "but in fact we saw in two regions what appeared to be point-like sources. They're reasonably bright, and they are consistent with a thermal fluctuation in the cosmic background radiation." Meyer and his collaborators believe they can rule out galactic dust as the culprit, and the emissions don't seem to come from any known distant galaxies. "We still could be seeing something garbagey, but we haven't thought of what it might be," says Meyer. This May, Meyer and his colleagues will go back to Palestine to search the same positions for the point sources.

That sort of replication, everyone agrees, is exactly what's needed for even the less startling measurements. Cambridge University's Anisotropy Telescope has already provided the first such replication by confirming that three of the MAX results couldn't be due to interference from galactic radiation. In the coming year, Princeton's Saskatoon experiment will be looking at the same patch of sky as MSAM, and the Santa Barbara South Pole experiment will try to replicate observations by Python. To improve its data, Python will also make observations throughout the winter, stretching its observing time by a factor of 10. The downside is the need for someone to go out every day in temperatures of -60° C to tend the instrument. "The guy who's going to do it is really tough," says Dragovan.

Balloon-borne measurements—now limited to flights of 10 hours or so—will also get longer. A collaboration from the University of Chicago, MIT, and NASA Goddard is planning to build a balloon experiment called TopHAT, in which the telescope will sit on top of the balloon—"one of the big problems with ballooning," says Meyer, "is you always have this crazy balloon above you." By flying the balloon in the vortex of winds swirling around the South Pole, the investigators hope to keep it aloft for as long as 2 weeks. Teams at Berkeley and Santa Barbara are developing similar projects.

And if winterlong vigils and long balloon flights don't start to produce consistent maps of the bumps in the cosmic background, says Smoot, salvation may come from a satellite called COBRA, for Cosmic Background Radiation Anisotropy. The object of the satellite, which has been proposed to the European Space Agency, would be to "get an angular resolution of half a degree or better and map a large area or all of the sky."

COBRA wouldn't fly until the turn of the century, but the cosmic background mappers aren't put off. "This is a long haul," says Wilkinson, "I've been at it for 30 years, and it's not an easy experiment. There are lots and lots of ways to go wrong when you're trying to measure signals of 30 microkelvin. It's just going to be a while before the experiments become absolutely convincing, and everybody's working to do that."

–**Gary Taubes**

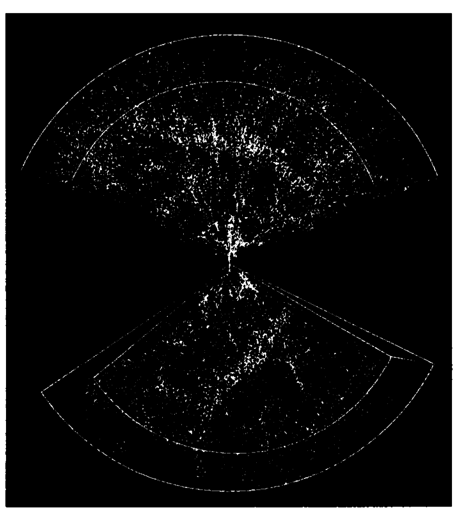
ASTRONOMY

Cosmic Structures Fill Southern Sky

In the mid-1980s, working together at the Harvard-Smithsonian Center for Astrophysics, Margaret Geller and John Huchra shook the astronomical community when they discovered gigantic curving sheets of galaxies, voids hundreds of millions of light-years across, and other large-scale structures filling the sky over the Northern Hemisphere. Conventional models of the cosmos, which had predicted a much more homogeneous universe, could not explain these surprising conglomerations. Perhaps, theorists suggested, the two astronomers had surveyed an unusual part of the sky, and matter in the rest of the universe was more evenly distributed.

No such luck. As part of an international collaboration led by Luis Nicolaci da Costa of the Brazilian National Observatory, Geller and Huchra have now taken their brand of cosmic cartography to the southern sky. And their latest map of galaxy distribution, reported in the 20 March *Astrophysical Journal (Letters)*, looks just like the one in the north: There are lengthy arcs of galaxies, puzzling voids, even a southern counterpart to the "Great Wall"—a continuous stretch of galaxies that had covered the field of view in their northern survey. "Every measure we can find shows they're similar, remarkably so," notes Geller.

After this latest survey, such features can no longer be viewed as cosmic rarities, says da Costa. Just as important, he adds, researchers are beginning to get a handle on the typical sizes of these large-scale structures. The voids, for example, tend to run 150 light-years in diameter. Faced with such data, cosmologists must now develop models of the universe that can yield structures of that size. "There are certainly important constraints coming from these galaxy maps," says



M. GELLER / J. HUCHRA

Structured sky. A new map of the southern sky *(bottom)* shows large clumps of galaxies, as does its northern counterpart *(top)*.

Princeton theorist James Peebles, who has wrestled with the thorny problems of large-scale structures for years.

To construct their southern chart, astronomers selected an area of sky, and then located the position of every galaxy, up to a specified level of brightness, within it. To add depth to the picture, they estimated each galaxy's distance by observing its "red shift," the adjustment of its emitted light toward longer (redder) wavelengths. The redder a galaxy, the farther away it is. For this latest chart, which took more than 3 years and observations from telescopes on three continents to complete, the cosmic cartographers recorded positions and red shifts for more than 3600 galaxies. Combined with the northern map, that totals some 14,000 galaxies and covers one-third of the nearby universe.

The structures revealed by this celestial coverage are certainly sowing confusion. "We see these large-scale features and we don't know how to make them. We don't know how to make the structure of the universe," says Geller. For instance, minor energy fluctuations that cosmologists argue existed in the early universe appear to be insufficient seeds to give rise to such prodigious clusters of galaxies. "Gravity can't, over the age of the universe, amplify these irregularities enough," Geller explains.

The puzzle of large-scale structure is likely to get even tougher in the future. A number of still more ambitious red shift surveys, some that will peer out much farther away from Earth and chart perhaps a million galaxies, are either under way or planned. And with them, says Geller, comes an expectation of discovering even greater clumps of galaxies. And those larger structures should give theorists even bigger headaches.

–**John Travis**