LOOKING FOR LUMPS

Seeking the seeds of structure in the early universe

First in a two-part series

By RON COWEN

With an earsplitting rush, gas from a truckload of helium cylinders breathes life into a giant, deflated balloon. Billowing to more than 10 stories high and endowed with 10,000 pounds of lift, this lighter-than-air craft will carry a special payload: a high-tech collage of instruments that will listen to the faint, primordial whisper of radiation that bathes the cosmos.

A technician releases a weight and the balloon begins to rise, tugging on its payload. But the payload hangs back, temporarily tethered to the crane of a vehicle, 100 yards behind, that resembles a humongous dune buggy. On cue, the buggy's driver floors the accelerator and heads toward the balloon. Just as the payload hangs directly beneath the ascending craft, someone removes the pin holding the payload to the crane. Several nervous researchers hold their breath. If the payload crashes, it will shatter instruments that took five years to design and build.

But the positioning is perfect and the balloon with its detectors intact ascends above the flat, East Texas countryside. Princeton University astronomer Lyman A. Page and his colleagues sigh with relief.

Known as the Far Infrared Survey, this experiment is one of many designed to detect tiny temperature deviations — a few ten millionths of a kelvin — in the microwave afterglow left over from the explosive birth of the universe. Such fluctuations may indicate how the universe evolved from its suspected smooth beginning to its present state — a lumpy collection of clusters of galaxies separated by vast regions of empty space.

"It's ironic," notes David T. Wilkinson of Princeton University, "but we think we know something about how the universe began — the first 300,000 years or so. And we know what the universe looks like at present. But what happened in between these times? Right now, that's the biggest mystery in the universe."

According to the simplest version of the Big Bang theory, the universe began as a fireball. A smooth mixture of radiation, ions, and electrons filled the cosmos. After about 300,000 years, however, the universe had cooled and expanded sufficiently for ions and electrons to combine into atoms. Atoms don't scatter and redirect radiation as strongly as ions do. Thus, the cooling enabled radiation from that early period of the cosmos to reach our corner of the universe, some 15 billion years later, relatively unimpeded by the matter it encountered along the way.

This radiation, now observable as a microwave background that fills the entire cosmos, behaves as if it were a nearly ideal heat source — a blackbody — apparently glowing with the same intensity everywhere. Until recently, scientists thought the radiation had a uniform temperature of 2.73 kelvins (SN: 1/20/90, p.36).

But the present universe isn't uniform. Instead, it's a collection of galaxy clusters separated by huge voids. Theorists had predicted that the "seeds" of these lumps ought to be present in the cosmic microwave background. In other words, the microwave background shouldn't have exactly the same temperature everywhere.

In some regions, the background radiation should glow ever so slightly warmer than 2.73 kelvins, while in other regions it should glow ever so slightly colder. These temperature fluctuations could signify wiggles or bumps in the fabric of space — a slight overdensity or underdensity of matter — that with the help of gravity might eventually have given rise to the clumps of matter that became galaxies and galaxy clusters.

In April 1992, researchers announced that a careful analysis of the first year's worth of data gathered by the Cosmic Background Explorer (COBE) satellite showed that the cosmic radiation indeed fluctuates by a tiny but significant 10 parts per million throughout the sky (SN: 5/2/92, p.292). (Two years earlier COBE beautifully confirmed the blackbody nature of the background radiation.) And last December, researchers reported that a 1989 flight of the balloon-borne Far Infrared Survey, which uses an entirely different set of detectors tuned to a different set of microwave frequencies, helped confirm the COBE findings (SN: 12/19&26/92, p.420).

But both COBE and the Far Infrared Survey have their limitations. They can only gauge how the temperature of the cosmic microwave background varies from one relatively large patch of sky to the next. COBE, for instance, can only examine temperature variations on an angular scale greater than about 7° — roughly the area of sky blocked by two fists extended at arm's length. The Survey experiment can do a little better, detecting temperature fluctuations over patches of sky half that size. But temperature variations over such large regions of sky correspond to "lumps" about 10 times bigger than the largest structures — superclusters of galaxies measuring about 300 million light-years across — ever observed in the universe.

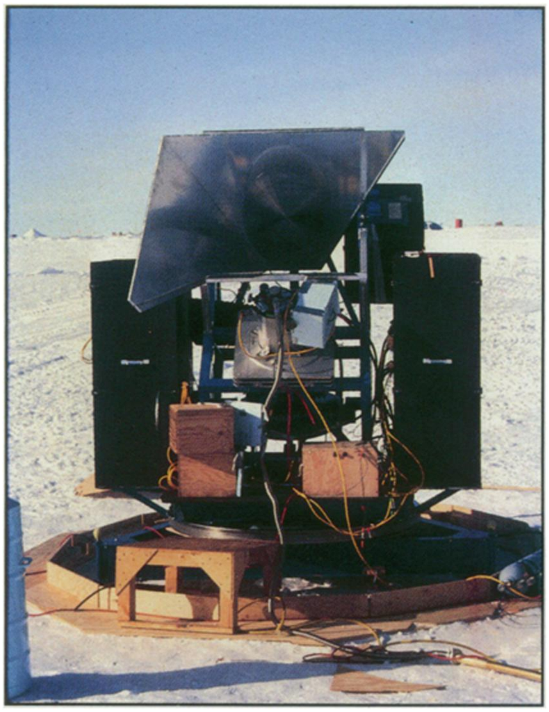
"In effect, COBE has terrible eyesight; it can't see any [small-scale] bumps or wiggles," says P.J.E. Peebles of Princeton University.

To examine the smaller angular-scale variations associated with the evolution of galaxy superclusters, clusters, or individual galaxies, researchers turn to larger antennas, which can resolve fluctuations on a finer spatial scale. Searching smaller patches of sky, however, doesn't eliminate a major technological challenge. Because the hot and cold spots in the microwave background differ by only a few ten millionths of a kelvin, spurious fluctuations from the atmosphere and our galaxy can confound results, making it appear as if different parts of the sky are colder or hotter than they really are. Random electronic noise from the radio-wave detectors themselves, analogous to the static on a radio channel or "snow" on a television screen, can also confound observations.

Thus, researchers must somehow separate fluctuations in microwave radiation emitted by material in our own galaxy from the true primordial fluctuations in the cosmic background. While investigators in both Europe and the United States have searched for small angular-scale fluctuations since the 1970s, the development of more sensitive instruments is now yielding several intriguing results.

Consider an experiment with the acronym ACME-HEMT, which currently holds the record for the most sensitive medium-angle measurements yet performed. (ACME stands for Advanced Cosmic Microwave Experiment, HEMT for the type of solid-state detector used.) Like several other surveys, this one operates on the thick ice sheet at the South Pole, a locale that minimizes microwave noise from an irksome and nearly ubiquitous source of contamination – water vapor in Earth's atmosphere. The pole's frigid, dry climate, equivalent to conditions at an elevation of 11,000 feet, freezes out water vapor from the atmosphere, reducing the problem. In addition, radiowave detectors mounted at the pole can scan the sky with a minimum of motion, reducing the errors associated with a moving instrument.

Looking for temperature fluctuations on an angular scale of 1.2°, ACME-HEMT has made the most sensitive measurements to date of any instrument trying to find hot and cold spots in the microwave background. In 1991, this ground-based experiment, conducted by Philip M. Lubin of the University of California, Santa Barbara, and his co-workers, recorded temperature variations of 16 parts per million that may or may not represent true fluctuations in the microwave background.


Steve Platt


Ed Wollack

Above: Python, a radio telescope at the South Pole, searches for temperature fluctuations in the microwave background on the angular scale of 2.8°. Left: At Saskatoon, Saskatchewan, an instrument called BigPlate looks for hot and cold spots in the microwave background at an angular scale of 2°. Below: A balloon experiment, the Microwave Anisotropy Experiment, searches for temperature fluctuations on the 0.5° scale – roughly the width of the full moon as it appears on the sky.

Lange, Lubin, et al.

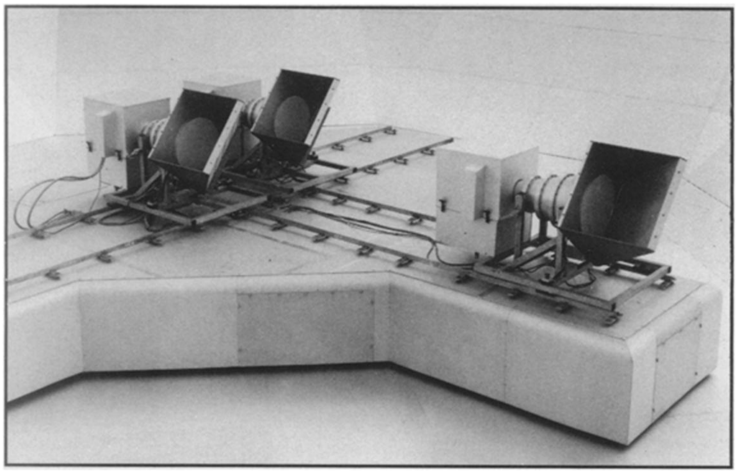
For example, the team hasn't ruled out the possibility that the signals in the experiment may stem from radio-wave-emitting electrons in the Milky Way. But if the hot and cold spots are truly cosmological, then over a patch of sky measuring 1.2° across, the cosmic microwave background varies by no more than 16 parts per million. The researchers reported the work last December in Berkeley, Calif., at a workshop on the cosmic microwave background.

ACME-HEMT uses a funnel-shaped horn to gather microwave radiation from a chosen spot on the sky. A waveguide channels the radiation through a series of filters that select particular wavelengths to analyze. The experiment relies on several solid-state devices known as high electron mobility transistors (HEMTs) to detect the microwave background. A HEMT acts as a radio receiver, amplifying faint incoming signals. In contrast, the bolometer, another type of device used to detect cosmic microwave emissions, acts as a thermometer. Incoming radio waves are absorbed by a thin metal film, raising its temperature; the heat generated is recorded and then amplified to measure the intensity of the microwave radiation in that part of the sky.

Bolometers, which are currently more sensitive than HEMTs, require cooling to a fraction of a kelvin – nearly absolute zero – and give best results when detecting radiation at wavelengths shorter than 3 millimeters. HEMTs, which don't require such drastic cooling, are most sensitive when detecting radiation at wavelengths longer than 3 millimeters.

This wavelength represents a dividing line for detection of the microwave background. For wavelengths longer than 3 millimeters, microwave emissions from electrons in the galaxy – synchrotron radiation from electrons spiraling around magnetic fields and bremsstrahlung radiation, created when electrons collide with atomic nuclei – are the major foreground contaminants. Shorter than 3 millimeters, microwave emissions from warm dust are the primary contaminant. Thus, bolometer experiments must contend with confounding radiation primarily emitted by galactic dust, while ACME-HEMT and other HEMT surveys are more sensitive to the spurious microwave radiation emitted by electrons in the Milky Way speeding up, slowing down, or changing direction.

A South Pole experiment known as Python takes advantage of the 3-millimeter dividing line. Operating at exactly 3 millimeters – the wavelength at which total galactic noise is at a minimum – Python may soon rival ACME-HEMT as the most sensitive medium-angle experiment so far conducted, says co-investigator Mark Dragovan of Princeton University. Python records variations in the microwave background at 2.8°, a larger angular scale than ACME. Dragovan and John Ruhl of Princeton will report the first results from Python next month in Berkeley at a meeting of the American Astronomical Society.



Duffett-Smith et al.

The Cosmic Anisotropy Telescope, one of the first radio interferometers devoted to studying temperature fluctuations in the cosmic microwave background, began operation last month in Cambridge, England.

Another experiment that has recently received attention looks for hot and cold spots on the 0.5° angular scale – the width of the full moon as seen on the sky. Such fluctuations may correspond to structures in the universe roughly midway between galaxy clusters and superclusters. Known as MAX (Microwave Anisotropy Experiment), this balloon-borne sky survey uses the same telescope as the ACME experiments but relies on bolometers rather than HEMTs to detect the microwave background. It was last flown in 1991 over Texas. Preliminary results from this flight seem to pose a puzzle, says Andrew E. Lange of the University of California, Berkeley. He and his colleagues, which include Lubin and Paul Richards of Berkeley, report that MAX recorded temperature fluctuations that varied in magnitude dramatically according to the region of sky studied.

In 1991, MAX examined two small strips of sky. In one region, near the star Mu Pegasi, foreground emissions from our own galaxy have a relatively high intensity and dominated the signal measured by the instrument. Doing their best to account for temperature fluctuations that stem from emissions in our own galaxy, Lange and his co-workers estimate that the microwave background temperature near Mu Pegasi varies by no more than 24 parts per million.

MAX also studied another region of sky, near the star Gamma Ursa Minoris, where emissions from our galaxy are far fainter. If the signal recorded by MAX in this region is a true indicator of fluctuations in the microwave background there, then this radiation varies in temperature by 45 parts per million – about twice the upper limit estimated for microwave fluctuations detected near Mu Pegasi. (A MAX flight in 1990 detected a similar variation in microwave temperature near this star.) The team will report its findings in upcoming issues of ASTROPHYSICAL JOURNAL LETTERS.

The MAX findings may contradict a popular model for the evolution of the universe known as cold dark matter. That theory holds that variations in the microwave background are the same in all parts of the sky. Other theories, which require the presence in the early universe of unusual structures, called cosmic strings or textures, predict just the opposite. To check their findings, Lange and his colleagues have scheduled a return engagement. MAX will fly again later this month. Lange cautions that the MAX team hasn't ruled out the possibility that instrument noise could have created the apparent discrepancy in temperature fluctuations between the two regions.

So when is a fluctuation truly from the microwave background and when is it just noise?

One problem with the various ground-based and balloon measurements is that "bolometers see a different kind of galactic confusion than HEMTs," notes Lange.

"There is no experiment yet that is exploring the same region of sky at wavelengths that span the range from below 3 millimeters [where bolometers operate] to above 3 millimeters [where HEMTs operate]. My own feeling is that you need to have both types of detectors exploring the same part of the sky, then have each of these experiments subtract their different sources of [galactic] confusion.

"If, at the end of that process, you get the same underlying pattern for fluctuations in the cosmic background radiation, then that would be a convincing result."

A few radio surveys search for temperature variations in the microwave background over much smaller patches of sky, a fraction of a degree in angular scale. Such fluctuations may correspond to clumps of matter in the early universe that were the precursors of clusters of galaxies. Since 1984, astronomers including Charles R. Lawrence and Anthony C.S. Readhead of the California Institute of Technology in Pasadena have surveyed small patches of sky to look for hot and cold spots in the microwave background on an angular scale ranging from one-thirtieth to one-third of a degree. Their weapon of choice has been the 40-meter radio telescope at the Owens Valley Radio Observatory near Bishop, Calif. Last year, the researchers began a second survey with a 5.5-meter radio telescope at Owens Valley. So far, the team has found no hard evidence for small angular-scale fluctuations.

Meanwhile, a fleet of other experiments are joining the search for microwave variations on the medium angular scale. In March, Lyman Page, graduate student Ed Wollack, and their Princeton collaborators traveled to Saskatoon, Saskatchewan, to inaugurate a ground-based instrument called BigPlate. Designed to search for variations in the microwave background on an angular scale of 2°, BigPlate uses HEMT detectors that comb small strips of sky at several wavelengths. The detectors search for fluctuations by recording the difference in temperature between a succession of three points on the sky a fixed distance apart.

Recently, Stephan S. Meyer of the Massachusetts Institute of Technology and his collaborators at NASA's Goddard Space Flight Center in Greenbelt, Md., replaced the mirror of their large angular-scale experiment, the Far Infrared Survey, with a radio-wave reflector 10 times as big. The larger reflector enables the survey's detectors to search for fluctuations on an angular scale of 0.5°. The team first flew their modified balloon experiment, known as the Medium-Scale Anisotropy Experiment, last year and plan to fly it again in August.

Next spring, Mark Halpern and his colleagues at the University of British Columbia in Vancouver plan to fly a different type of instrument to measure temperature fluctuations in the microwave background. Known as the Balloon Anisotropy Measurement, this survey employs a spectrometer, a device normally used to study how closely the intensity of the microwave background at different wavelengths matches a perfect blackbody spectrum. Indeed, the research team previously used the same spectrometer for just that purpose.

Now, the scientists plan to point the spectrometer at several different patches of sky to record variations in temperature. Fluctuations in microwave emissions from Earth's atmosphere or dust in our galaxy have a spectrum markedly different from that produced by the actual microwave background. Thus, Halpern and his collaborators hope their spectrometer can easily identify and reject spurious microwave "noise" and home in on the true signal associated with the formation of large-scale structure in the universe.

"If [the fluctuations] we see are from the atmosphere, or dust in our galaxy, these will look really different to us than the cosmic microwave background," says Halpern. "We can identify the source in a very clean way."

The spectrometer, he notes, is equivalent to having 10 detectors, each tuned to a different microwave frequency band. One problem plaguing most other experiments that search for temperature variations in the microwave background, explains Halpern, is that they lack the frequency range to easily distinguish noise from a true cosmic signal.

At the University of Cambridge last month, Anthony N. Lasenby, Peter J. Duffett-Smith, and their colleagues began operating one of the first radio interferometers – a multidish instrument that mimics a larger single dish – built solely for studying the microwave background.

Other interferometers, notes Duffett-Smith, are designed to look at radio sources much brighter than the microwave background and consist of individual telescopes spaced too far apart to rapidly detect the cosmic emission. In addition, conventional interferometers don't completely screen out microwave emissions from the ground, which pose no threat for observing the typical astronomical radio source but can confound attempts to detect hot and cold spots in the microwave background.

Known as the Cosmic Anisotropy Telescope, the instrument searches for temperature variations in the microwave background on the angular scale of 0.5°. Working in concert, the interferometer's three conical antennas, each 1.2 meters in diameter, act as a three-element radio telescope. Placed in an aluminum-lined pit to reduce spurious radio emissions from the ground and from the radio telescope itself, the entire device rotates on a turntable to scan different parts of the sky. The interferometer eliminates most atmospheric noise, since such random fluctuations are washed out when the signals from the three antennas are combined, Duffett-Smith says.

The newest instruments may probe medium-scale fluctuations in the microwave background with greater sensitivity than existing instruments. Ultimately, however, the definitive measurements may require a satellite akin to COBE, but which can detect hot and cold spots on a 0.5° angular scale, Wilkinson says. "There's no question that a satellite is eventually needed," he asserts. Balloons, Wilkinson notes, don't allow sufficient measuring time, and ground-based experiments are hampered by unpredictable fluctuations in the atmosphere.

He calculates that a satellite designed to measure medium-scale fluctuations might cost $40 million, about one-fifth NASA's estimated price tag for COBE. U.S. researchers, including Michael A. Janssen of the Jet Propulsion Lab in Pasadena, are studying the possibility of building such a satellite. A group of European and U.S. scientists has submitted to the European Space Agency a proposal to build a similar satellite.

This kind of an instrument, if it ever received funding, probably wouldn't be launched until the turn of the century. It would also require a new generation of sensitive HEMTs that can operate above 3 millimeters. And even then, the finer-scale measurements taken by that satellite would mean it could cover only part of the sky in a few years' time.

But, Wilkinson says, when it comes to solving "the biggest mystery in the universe" – understanding how and when large-scale structure arose in the cosmos – such a project could be worth the wait. □

Next: Combining experiment and theory (May 22 issue)