The Microwave Anisotropy Probe heralds a new era of sensing the remnant heat from the big bang

Precision Cosmology Takes Flight

When navigating the side streets of a big city, it helps to have an accurate map. And when it comes to charting the fine details of the big bang, there's nothing like an accurate MAP: the Microwave Anisotropy Probe. The $95 million satellite, scheduled for launch on 30 June from Cape Canaveral, Florida, has cosmologists aglow about measurements that should confirm—or refute—their dearest models of the first incandescent moments of the universe.

MAP LAUNCH

In this special focus on the cosmic microwave background, *Science* looks at current and upcoming experiments and describes how theorists read the history and fate of the universe in the reverberations of the explosion that created it.

► **MANY EYES ON THE SKY**

THE BIG PICTURE

MAP will pick up where its orbiting predecessor, the Cosmic Background Explorer (COBE), left off a decade ago. COBE made a big splash in 1992, when it exposed subtle ripples in the faint bath of microwave radiation that fills the sky. This heat, which registers a mere 2.725 kelvin, is literally the dying ember of the once-hot cosmos. Its fluctuations encode a wealth of information about the birth and evolution of the universe and the types of matter it contains (see p. 2236). However, COBE saw those ripples with a blurry eye: Its sharpest focus spanned a patch of sky nearly 15 times the width of the full moon.

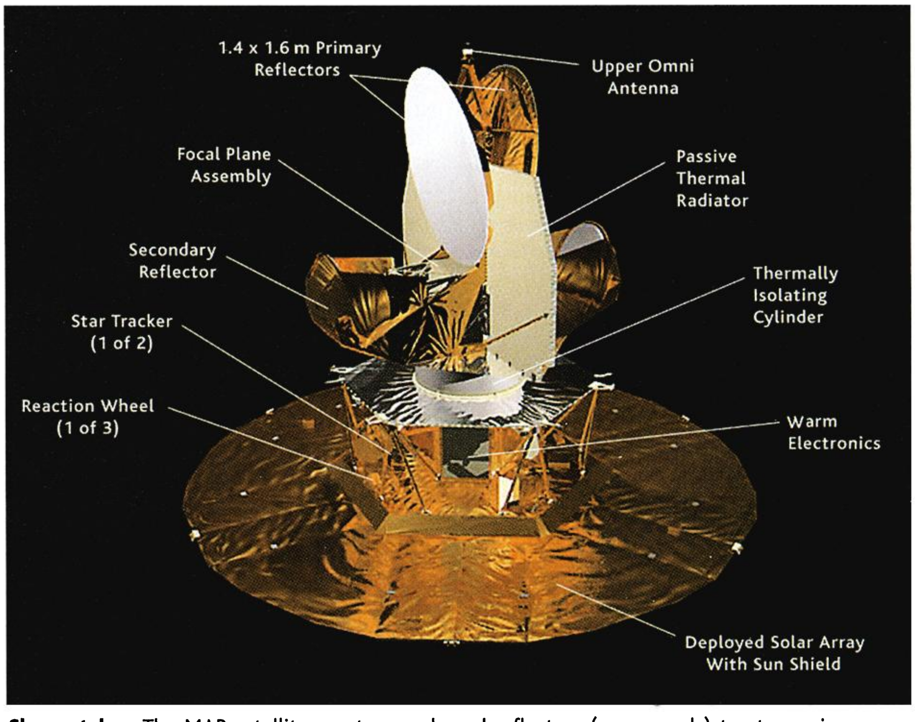
Since then, microwave-sensitive telescopes on high-altitude balloons and perched at high, dry spots on the ground have picked and prodded at the fabric of the cosmic background. The latest analyses from a few such experiments yielded strikingly similar numbers for the basic parameters of matter and energy in the cosmos (*Science*, 4 May, p. 823).

Still, microwave observers face uncertainties that limit the accuracy of their data. For instance, it's hard to reconstruct precisely where a telescope is pointing when it's dangling from a balloon 37 kilometers high. Ground-based instruments have to peer through the atmosphere and sit on a planet hundreds of degrees warmer than the 0.0001-kelvin fluctuations they are trying to detect. Such limitations have made it hard for cosmologists to constrain all but the broadest details of their models.

MAP should erase those doubts. "It's a pivotal moment in cosmology," says astrophysicist David Spergel of Princeton University, a member of MAP's science team. "We'll find ourselves either converging on a standard model, or things aren't going to fit." Adds Lyman Page, Spergel's colleague at Princeton who is also on the MAP team: "The jump from where we are now to MAP's map of the sky is a giant leap. It's going from indications to certainty."

MAP's main advantage will be its isolation from the heat and din of our planet. After MAP's launch on a Delta 2 rocket, a series of cigar-shaped loops around Earth will position the 800-kilogram satellite to whip past the moon. That gravitational assist will deliver MAP to prime real estate: the L2 Lagrange point, a spot in space 1.5 million kilometers from Earth in a straight line away from the sun. There, the combined gravitational pulls of Earth and the sun equal the centripetal force required to revolve in tandem with Earth. That allows the spacecraft to wander lazily around L2 like a tiny asteroid, with little need for fuel during its 2-year mission. MAP will be the first probe to occupy this choice spot. A solar shield will block Earth, the sun, and the moon. Further, the angle between the satellite and the sun—and therefore the amount of heat influencing the satellite—will never change. "It's hard to imagine a better environment" for MAP, says theorist Max Tegmark of the University of Pennsylvania in Philadelphia. "It will just stare into dark, pristine space."

Equally critical to MAP's mission is its goal to chart the entire sky, not just the small patches probed from the ground and from balloons. COBE did the same thing,



Sky watcher. The MAP satellite sports egg-shaped reflectors (upper ovals) to steer microwaves into amplifiers beneath. A 5-meter shield will block radiation from the sun and Earth.

CREDITS: GSFC/NASA

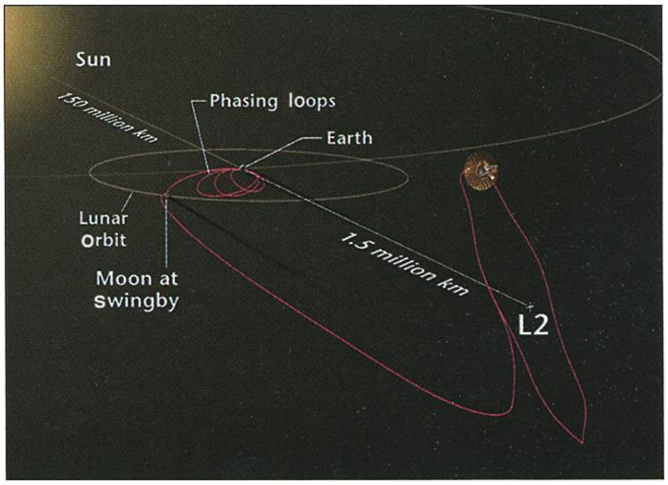
but with a coarse resolution of 7 angular degrees; MAP will resolve details less than one-quarter of an angular degree across. Millions of measurements will lead to a full-sky map of the microwave background during each 6-month orbit around L2. To create that atlas, MAP will sweep the sky as the satellite spins once every 2.2 minutes and precesses on its axis like a top once per hour. The resulting pattern covers about 30% of the sky each hour in an interlaced web, like a Spirograph drawing. Two pairs of reflectors will funnel microwaves into a series of amplifiers from two directions on the sky at the same time. The detectors will measure the difference in the temperature readings but not their absolute values. This "differential" approach, also employed by a COBE instrument, is like putting two kilometer-long rods alongside each other to ascertain that one rod is a few millimeters longer rather than trying to measure each one from end to end.

Another challenge for MAP scientists is to account for microwaves from our Milky Way galaxy. Those emissions—streaming from electrons spiraling in magnetic fields, warm gas, and dust—make it harder to determine which microwaves truly journeyed from the early universe. To sort the various kinds, MAP's readings will span five frequencies of radiation, from 22 to 90 gigahertz (wavelengths between 3 and 13 millimeters). Subtle distinctions among the channels should expose the galaxy's contributions. A final strength of MAP will be its ability to yield what Page calls a "true map of the sky." The observation design leads to an atlas in which each pixel has its own set of readings, uncorrelated with those around it or elsewhere on the sky. That's not the case with other cosmic background experiments, in which the statistical noise at any one pixel must be correlated with many thousands of other pixels. That linkage makes the data cumbersome to analyze.

These careful plans should lead to the new benchmark in the field: microwave charts with uncertainties perhaps 100 times lower than those produced by any previous project. "MAP's map will be a joy to work with," says principal investigator Charles Bennett of NASA's Goddard Space Flight Center in Greenbelt, Maryland. "It will really nail the cosmological models. ... There won't be a lot of wiggle room left." If all goes well, Bennett adds, MAP may gain an additional 2 years of observing time to clamp down on those wiggles even further.

For all its prowess, MAP won't monopolize the microwave measurements. Balloon-borne and ground-based instruments will continue to play vital roles in two other areas.

The first is to probe the microwave signature on ever-smaller angular scales. By focusing on narrow strips of sky, cosmologists intend to tease out the tiny heat fluctuations that reflect the minutiae of physical processes during the big bang and as the universe evolved. For example, the photons we see in the cosmic background were deflected slightly on their way to Earth as they passed by galaxy clusters and other masses. This gravitational lensing averages about 1/60th of an angular degree for each photon, says theorist Wayne Hu of the University of Chicago. Research teams are devising plans for large ground-based reflectors—at least 6 meters across—to home in on that scale, which is about 15 times finer than MAP can resolve. That could provide the most powerful probe of how matter was distributed throughout the history of the universe.



Distant vision. MAP will follow a loopy 3-month path to the L2 Lagrange point, where the satellite will need little fuel.

CREDIT: GSFC/NASA

A second enticing frontier is the suspected polarization of the microwave background. Models predict that about 5% to 10% of the microwaves became polarized, largely by scattering off electrons in the young universe. Some of this occurred when the first stars and galaxies lit up, bombarding the surrounding gas with radiation and stripping electrons from hydrogen atoms. By detecting polarized microwaves, researchers might be able to pin down when that happened and what those first luminous objects were like. Another target is the polarization from density ripples in the primordial plasma that produced the microwave background itself. That's likely to be the first type spotted.

However, no one yet knows whether such studies are feasible. "Polarization is a new game," says physicist John Ruhl of the University of California, Santa Barbara. "For starters, the signals probably are only a tenth as strong as the already faint temperature signals. "It's that much harder to see it and to convince yourself that you're measuring the cosmos, not some instrumental effect," Ruhl says. Further, polarized microwaves from the Milky Way may shroud the background patterns.

An answer is likely to come within a year. Although MAP will not detect the polarization of any one point on the sky, it should be able to draw a statistical correlation between the temperature map it sees and the expected patterns of polarization over the whole sky. "We'll use the temperature fluctuations as a template to ask where we should see more polarization, and where we should see less," Bennett says. That would help tell ground- and balloon-based detectors where best to look.

But other experiments may get there first. The Degree Angular Scale Interferometer, a network of 13 microwave collectors run by the University of Chicago at the South Pole, is now collecting data with polarization-sensitive detectors in an attempt to see polarized microwaves directly. In December, Ruhl and an international team will travel to Antarctica to launch BOOMERANG 2001, a follow-on to the most successful balloon-borne mapping mission to date. The new mission, which will stay aloft for at least 10 days, will include polarization detectors. "If the models are correct, we should see it with good signal to noise," Ruhl says.

Polarization of the microwave background will drive the field once MAP nails down the temperature fluctuations, says theorist Marc Kamionkowski of the California Institute of Technology in Pasadena. The real push, several years from now, will be to detect a faint but distinctive spiral pattern of polarization in the microwaves imprinted by gravitational waves in the early universe. Those waves, says Kamionkowski, were spawned by the violent expansion of the cosmos in its first fraction of a second—the scenario called inflation.

The mission with the best chance to see such curlicues is Planck, a satellite slated for launch in 2007 by the European Space Agency (ESA). Planck, which also will orbit around the L2 point, will carry delicate polarization detectors that just might see the inflationary signature. Kamionkowski puts those odds at 50–50—and he hopes that Planck won't be the end of the line. "Before Planck flies, we'll begin serious development of a post-Planck polarization experiment," he says. "Detecting the gravitational-wave polarization with confidence would be something spectacular. Physicists would leave their particle accelerators to go after that."

However, Planck's designers note that its primary purpose is to serve as a much more sophisticated temperature probe than MAP. It will have twice the angular resolution of MAP and about 10 times the sensitivity to temperature fluctuations. "As you go into the kind of precision that Planck will provide, you will achieve a much greater ability to discriminate between cosmological models," says Planck project scientist Jan Tauber, an ESA radio astronomer in Noordwijk, the Netherlands.

For now, though, all eyes are turning to see what MAP will reveal about the oldest light in the cosmos. "In some fields of physics, the style of work is one of ultimate precision craftsmanship," says astrophysicist Craig Hogan of the University of Washington, Seattle. "We're seeing that in cosmology now, and it's very different from the raucous cavalry style of the last few decades." Still, there's a chance that MAP or its Earth-bound brethren will find something out of kilter in the patterns of the microwaves—forcing cosmologists back on their horses to round up new explanations for our wild universe.

–ROBERT IRION

MAP LAUNCH

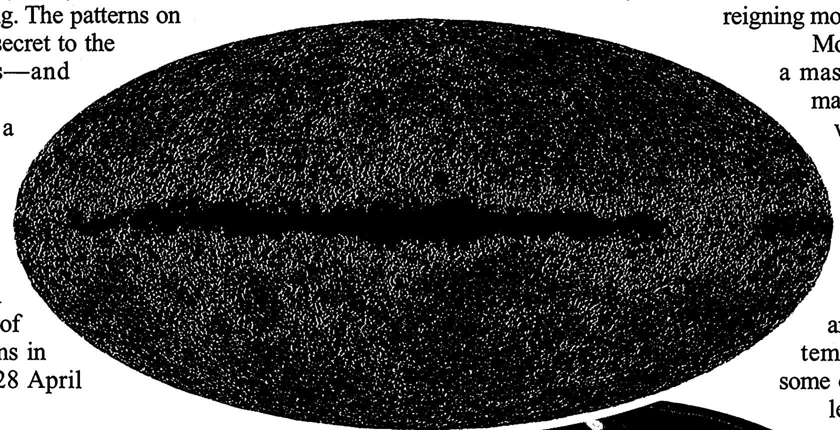
THE BIG PICTURE

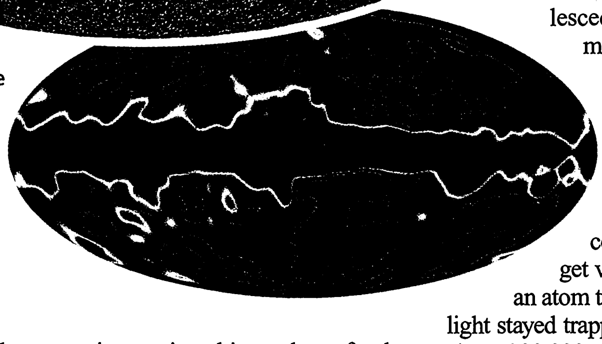
Peering Backward to the Cosmos's Fiery Birth

A generation after the cosmic microwave background sold physicists on the big bang, ever-sharper views of it are filling in the theoretical details

The universe has walls of fire. No matter where astronomers point their telescopes, they see a distant sheet of light surrounding us. Beyond that enormous shell of radiation, astronomers can see nothing. We are caged in by this surface: the cosmic microwave background (CMB), the faint afterglow of the big bang. The patterns on this surface hold the secret to the birth of the cosmos—and they foretell its death.

Last spring a balloon-borne experiment called BOOMERANG began to decipher the writing on those walls when it returned the first detailed map of the small-scale patterns in the CMB (*Science*, 28 April 2000, p. 595). Since then, the discoveries have been coming faster and faster. This April, three teams simultaneously released data providing the finest picture ever of sections of the universe's edge. Starting this summer, the Microwave Anisotropy Probe (MAP) promises to do the same for the entire sky. At the same time, new measurements will look at the CMB with polarized glasses, revealing how space-time creaked and groaned under its enormous load of matter and energy.





Keen-eyed. MAP's maps of the CMB, simulated here *(top)*, will be 1000 times as detailed as COBE's *(bottom)*.

As they wait for the floodgates to open, cosmologists agree that by the end of the decade, theorists may be well on the way to answering some of their deepest questions about what the universe is made of and how it evolved. "There are a lot of weird things in the standard model—dark matter and dark energy, for one thing," says Matias Zaldarriaga, an astrophysicist at New York University (NYU), who hopes CMB measurements will soon clear up some of the mystery. "If the model hangs together, then we might be able to say interesting things about fundamental physics."

Echoes of the big bang

The discovery of the cosmic microwave background in the mid-1960s gave scientists their first view of the origin of the cosmos. Until then, cosmologists were split between two vastly different models: the "big bang," which proposed that the universe had exploded into being and then evolved into its present form, and "steady state" cosmology, which held that the universe is continuously under construction, new matter coalescing to fill the voids as galaxies fly apart. Starting in the 1940s, different groups of physicists realized that if the big bang had taken place, microwave radiation left over from the explosion should still be detectable. In 1965, two engineers at Bell Telephone Laboratories, Arno Penzias and Robert Wilson, concluded that stubborn static in their microwave antenna was the afterglow of the big bang. The discovery netted them the Nobel Prize and enshrined the big bang as the reigning model of cosmology.

Modern big bang theory states that a massive explosion created all the mass and energy in the universe, as well as the fabric of space-time. This fabric inflated rapidly after the cataclysm, but within a tiny fraction of a second, the rapid inflation slowed down and the universe cooled. Free-roaming quarks began to form protons and neutrons. Within minutes, the temperature dropped enough that some of the protons and neutrons coalesced into nuclei of simple elements. The universe was filled with a plasma of atomic nuclei and electrons—and with light. Whenever an electron tried to combine with a nucleus, a hurtling photon would strip it away; conversely, a photon couldn't get very far before it scattered off an atom trying to coalesce. As a result, light stayed trapped in a cage of plasma until about 300,000 years after the big bang. Then the expansion of space-time cooled everything to the point that the electrons combined with their nuclei. This "recombination" freed light from its confines; the entire universe glowed. (See figure, p. 2238.)

The light from recombination still rattles around the cosmos. As the fabric of space-time expanded, the original ultrahigh-energy

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