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.

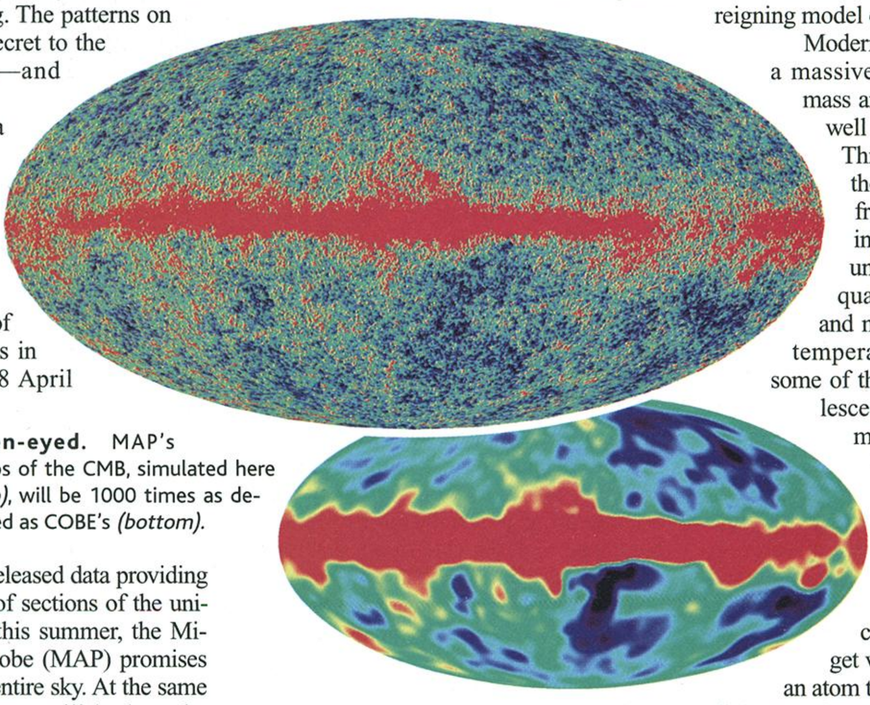
–ROBERT IRION

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

CREDIT: GSFC/NASA

gamma rays stretched into x-rays, visible light, and now, 15 billion years after recombination, microwaves. The scream of light has become a mere whisper, a faint glow with a temperature 2.7 degrees above absolute zero. This is the CMB.

Theoretical explosion

Once physicists knew the CMB existed, they set to work figuring out its attributes. They concluded that the background radiation had to look like a "blackbody" spectrum—the sort of light that an object radiates because of its thermal energy. Furthermore, its spectrum must bear the stamp of the tiny mass fluctuations that eventually developed into galaxies and galaxy clusters.

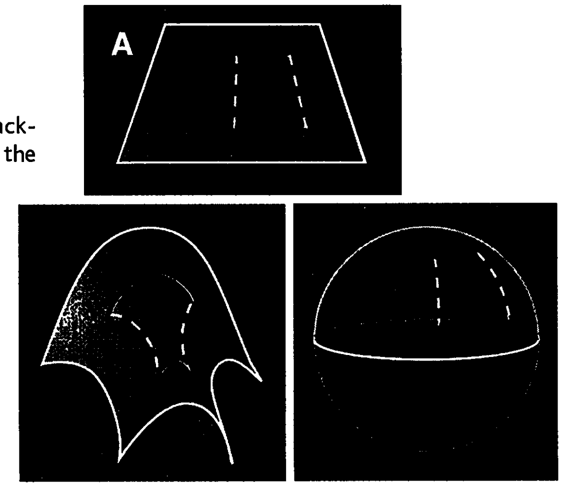
By the early 1970s, the Russian physicist Iakov Zel'dovich realized that these fluctuations would have a subtle signature. The light and matter in the pre-recombination universe would have been ringing like a bell. Alternately pulled together by gravity and blown apart by intense scattered light, lumps of matter oscillated, compressing and expanding, from the moments after the big bang until recombination finally set the light free. Zel'dovich and others, such as Princeton physicist Jim Peebles, showed that these "acoustic oscillations" should have stamped the CMB with a measurable imprint: a "fundamental" of hot spots each about 1 degree across, sprinkled with "overtones" of smaller hot and cold spots. The only problem was that nobody had any way of measuring such tiny features. In 1990, the Cosmic Background Explorer (COBE) satellite and an unnamed rocket-borne experiment confirmed that the cosmic background spectrum was indeed blackbody radiation. However, even COBE's vision was too blurry to see features smaller than several degrees. Astronomers had to wait another decade to see the acoustic oscillations.

That wait just ended. Last year, the BOOMERANG balloon experiment saw the 1-degree hot spots, which showed up as a peak in a graph. From the size of the spots, theorists concluded that the universe is "flat" in a four-dimensional sense, rather than curved (see sidebar). More data from BOOMERANG and other experiments—the Cosmic Background Imager, MAXIMA, and the Degree Angular Scale Interferometer (DASI)—found evidence of the second peak and hints of a third (*Science*, 4 May, p. 823). These peaks not only confirmed the acoustic-oscillation model of the early universe but are also revealing the contents of the cosmos. For several decades, astrophysicists have postulated the existence of dark matter—objects that have mass but don't interact with light very well. By skewing the tug-of-war between light and gravity in the early universe, dark

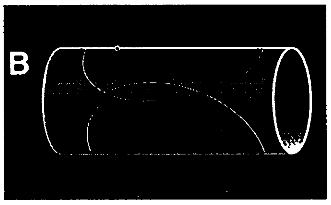
ILLUSTRATIONS: A. STONEBRAKER

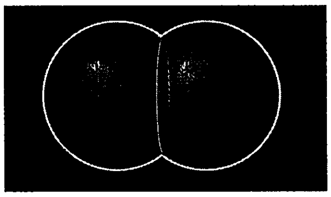
Shaping a Universe

What links the cosmic microwave background (CMB) to the grand structure of the universe is the fabric of space-time. But just what is that fabric, and what can CMB measurements tell us about it?



In Einstein's general theory of relativity, space and time are knit together in a stretchy "manifold"—a mathematical object, every small patch of which looks roughly like a four-dimensional rubber sheet. Light rays follow contours of the manifold, called geodesics. On a flat plane, parallel rays from a distant object will stay the same distance apart as they approach an observer. But on a surface with "positive" curvature, like a sphere, approaching rays will move farther apart, making distant objects look bigger than normal. And on a surface with "negative" curvature, like a saddle, parallel beams will get closer together, making the object look smaller (see figures A).



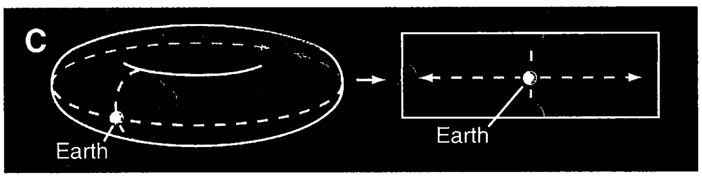


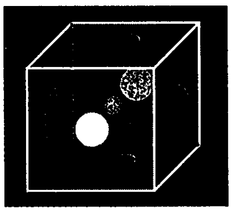
Because curved manifolds distort light differently from flat ones, they should also give rise to different sorts of CMB. The 1-degree-wide ripples that BOOMERANG observed were precisely what theory predicted for a flat universe—a conclusion that most physicists fully expect the Microwave Anisotropy Probe's (MAP's) maps to bear out.

Some researchers hope that MAP will give more specific information about the size and shape of the universe. "When we look at the microwave background, we're basically looking out to the surface of a sphere," explains David Spergel, an astrophysicist at Princeton University and a member of MAP's science team. If the universe is infinite, that "surface of last scattering" will give few clues about its shape. But if the universe is finite, then space-time—and the scattering surface nestled within it—must bend back on itself. A large enough sphere would then intersect itself in at least one circle, just as a disk wrapped around a dowel overlaps itself at the ends (see figures B).

In fact, Spergel says, because light can take more than one path through curved space-time, astronomers would see each intersection not once but twice—as paired circles tracing out identical patterns of hot and cold spots in different parts of the sky. Spergel's group in the United States and a group headed by Jean-Pierre Luminet at the Paris Observatory are developing algorithms to look for such signatures in MAP's data.

Meanwhile, mathematician Jeff Weeks, a freelance geometer based in Canton, New York, has written a computer algorithm that turns paired circles into model universes. Easiest to visualize, Weeks says, is a "toroidal" universe slightly smaller than the surface of last scattering. In a 2D universe wrapped around a torus, he points out, astronomers would seem to see identical points on opposite walls of an imaginary box of space (see figures C). Similarly, astronomers in a 3D toroidal universe would see three pairs of circles in opposite directions.



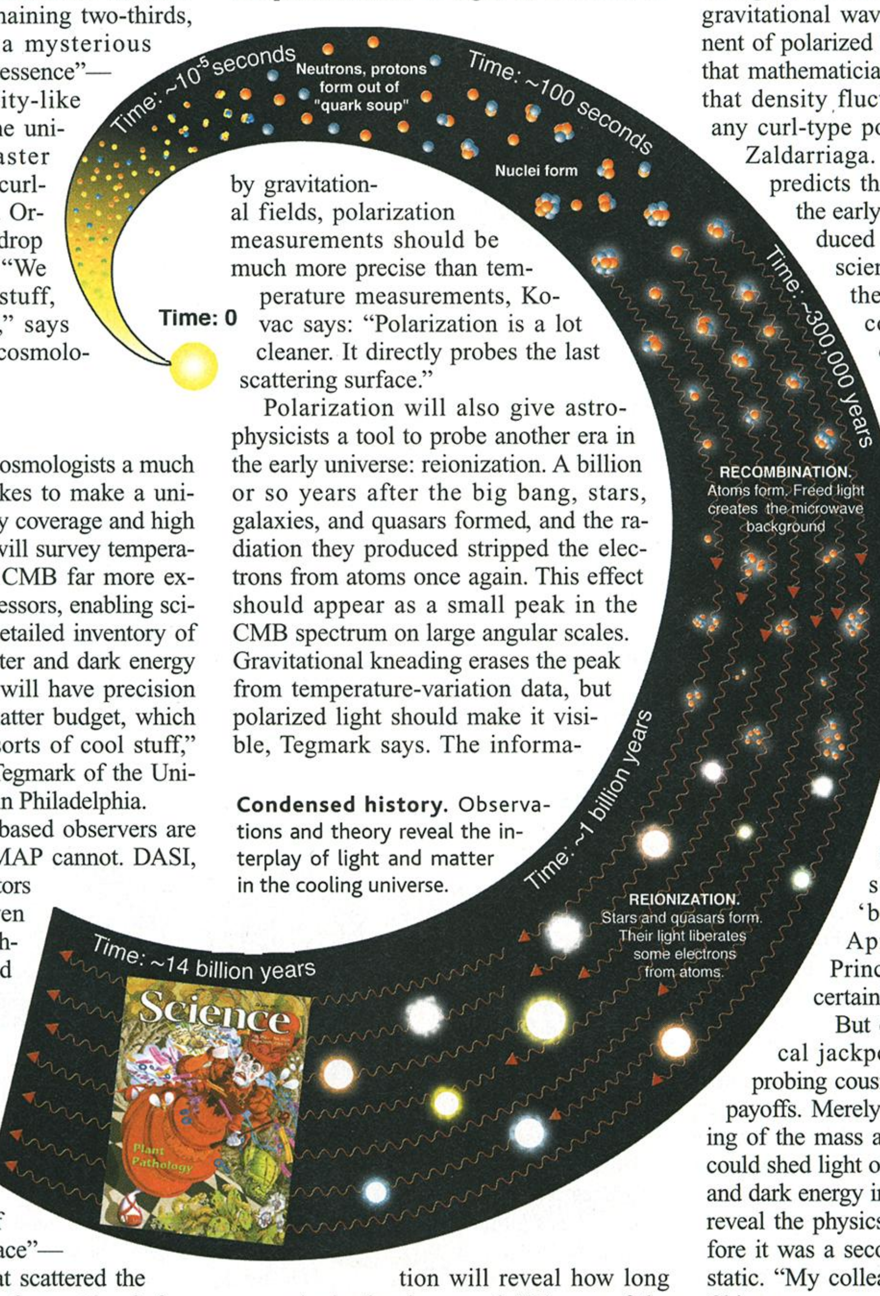


Toroidality is just the simplest of 10 different topologies for a "flat" finite universe. If the universe turns out to be curved—which is currently thought not to be the case—then there will be infinitely many more possibilities for Weeks's algorithm to sort through. "We'll start taking a look as soon as any sort of data is available," Weeks says. If the cosmos cooperates, they may not have long to wait, Spergel says: "In 2 years, we could know that we live in a finite universe."

–BARRY CIPRA

matter would have subtly altered the oscillations in the plasma in much the same way that tightening a guitar string alters its pitch. By measuring the relative sizes of the first and second peak, scientists have calculated that baryonic, ordinary matter—the stuff of stars and of people—makes up just over 4% of the energy and matter in the universe.

What about the rest? Combined with observations from galaxy surveys and other sources, the CMB measurements give some rather troubling numbers. They show that about 30% of the stuff in the universe is dark matter. The remaining two-thirds, theorists believe, is a mysterious "dark energy" or "quintessence"—a large-scale antigravity-like effect that is making the universe expand ever faster while keeping it from curling into a saddle shape. Ordinary matter is just a drop in the cosmic bucket. "We may be made of star stuff, but the universe ain't," says University of Chicago cosmologist Mike Turner.



Condensed history. Observations and theory reveal the interplay of light and matter in the cooling universe.

Map of the future

MAP promises to give cosmologists a much better fix on what it takes to make a universe. With its whole-sky coverage and high resolution, the satellite will survey temperature fluctuations in the CMB far more extensively than its predecessors, enabling scientists to take a more detailed inventory of the amount of dark matter and dark energy in the universe. "They will have precision measurements of the matter budget, which enables you to do all sorts of cool stuff," says cosmologist Max Tegmark of the University of Pennsylvania in Philadelphia.

Meanwhile, ground-based observers are now doing what even MAP cannot. DASI, PIQUE, and other detectors are searching for an even fainter signal nestled within the cosmic background radiation: polarization.

When electrons recombined with nuclei, the photons stopped scattering and escaped from their cage of plasma. The cosmic background radiation is an image of the "last scattering surface"—the cloud of plasma that scattered the light for the last time before setting it free. The problem with studying temperature variations in the light coming from that surface is that the photons get stretched and kneaded by their trip across the universe. "The photons climb in and out of dimples in space-time" caused by massive bodies, says John Kovac, a physicist at the University of Chicago, and the passage through those "gravitational potential wells" masks some temperature fluctuations.

But as the last scattering surface bounced photons into space, it also polarized them. By studying the angles of the polarization of the CMB, scientists can calculate where the light was bouncing from, information that reveals how matter was distributed in the early universe. And because the polarization of light is unaffected by gravitational fields, polarization measurements should be much more precise than temperature measurements, Kovac says: "Polarization is a lot cleaner. It directly probes the last scattering surface."

Polarization will also give astrophysicists a tool to probe another era in the early universe: reionization. A billion or so years after the big bang, stars, galaxies, and quasars formed, and the radiation they produced stripped the electrons from atoms once again. This effect should appear as a small peak in the CMB spectrum on large angular scales. Gravitational kneading erases the peak from temperature-variation data, but polarized light should make it visible, Tegmark says. The information will reveal how long ago reionization happened. "It's one of the most exciting numbers that we have no clue about right now, and there's no way we can do that with current measurements," Tegmark says.

But scientists are hot on the trail of CMB polarization. Initial results just released by the PIQUE experiment, whose hot tub–sized detector sits atop the roof of the physics building at Princeton University, show that that instrument is slightly too insensitive to see the expected polarization. But PIQUE's successor, CAPMAP, is beginning construction, BOOMERANG is being upgraded, and DASI is already taking data. "It's a very exciting race," says Tegmark. "It's hard to say who the winner will be."

CMB polarization might even help cosmologists close in on a long-sought quarry, gravitational waves. The key is a component of polarized light with a spiral quality that mathematicians call curl. "It turns out that density fluctuations cannot produce any curl-type polarization," says NYU's Zaldarriaga. But inflationary theory predicts that gravitational waves in the early universe would have produced a curl-type component. If scientists studying light from the CMB see a clean curl-containing component—one uncontaminated with false signals from, say, polarized light from galaxies—it will be "a smoking gun for gravitational waves," Tegmark says. Unfortunately, the curl-type component is extremely weak, so astronomers don't expect to see it for the next few years. But observations, if they come, could make or break inflation theory. "Gravitational waves might tell whether inflation is right, or if something else, like the 'big splat' [*Science*, 13 April, p. 189] is," says Princeton's Peebles. "We can certainly hope so."

But even absent such theoretical jackpots, MAP and its CMB-probing cousins seem sure to yield rich payoffs. Merely giving a precise accounting of the mass and energy of the universe could shed light on the nature of dark matter and dark energy in ways that, with luck, will reveal the physics of the universe from before it was a second old. Physicists are ecstatic. "My colleagues at the University of Chicago accuse me of wandering around the halls saying 'We're in a golden age of cosmology, we're in a golden age of cosmology,' " says Turner. "Well, I'm proudly saying that we're in a golden age of cosmology."

–CHARLES SEIFE

ILLUSTRATION: C. SLAYDEN