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

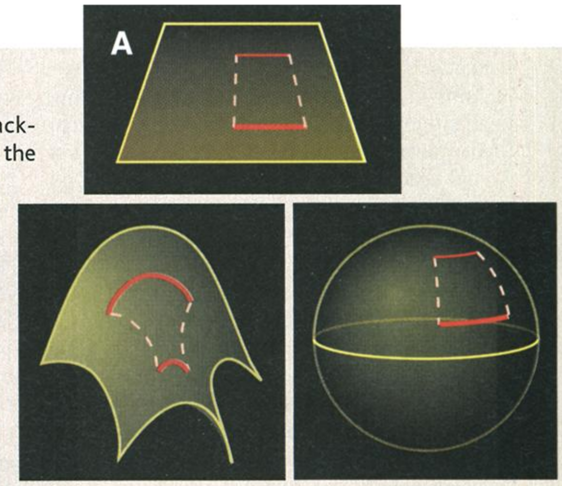
Once physicists knew the CMB existed, they set to work figuring out its attributes. They concluded that the background radiation had to look like a "blackbody" spectrum—the sort of light that an object radiates because of its thermal energy. Furthermore, its spectrum must bear the stamp of the tiny mass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

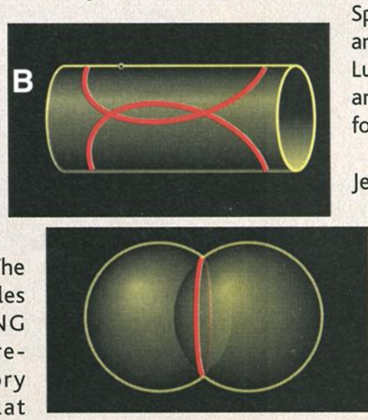
ILLUSTRATIONS: A. STONEBRAKER

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).

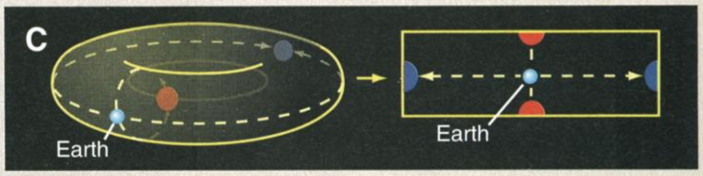


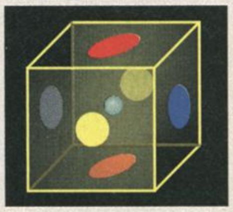
Because curved manifolds distort light differently from flat ones, they should also give rise to different sorts of CMB. The 1-degree-wide ripples that BOOMERANG observed were precisely what theory predicted for a flat universe—a conclusion that most physicists fully expect the Microwave Anisotropy Probe's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