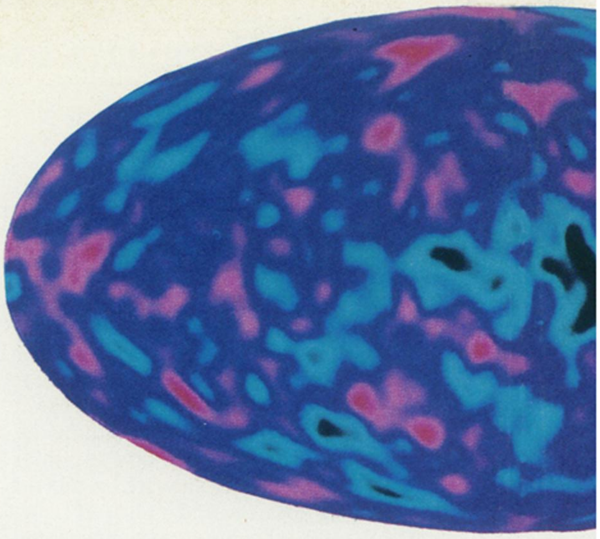
Cosmological Controversy: Inflation, Texture, and Waves

Competing theories about how the universe got its lumps



Second of two articles

By RON COWEN

"The time has come," the Walrus said,
"To talk of many things:
Of shoes – and ships – and sealing-wax –
Of cabbages – and kings –
And why the sea is boiling hot –
And whether pigs have wings."
–Lewis Carroll, *Through the Looking Glass*

Among the many riddles about the nature of the universe, none seems more puzzling than this: If the cosmos began as a hot, uniform soup of radiation and particles, how did it evolve into clumps of stars and clusters of galaxies? For more than a decade, cosmologists have argued over which of a myriad of scenarios best explains how the modern cosmos got its lumps (SN: 3/24/90, p.184).

One year ago, after astronomers announced that a U.S. satellite had discovered evidence for the seeds of lumpiness early in the history of the universe, some researchers expected the arguing to diminish. But if anything, the debate has intensified. While the findings from the satellite, known as the Cosmic Background Explorer (COBE), pose problems for some theories, tinkering with details of the models seems to have kept many of the proposals afloat. "I don't think COBE has ruled out any theory that wasn't ruled out before," says cosmologist P.J.E. Peebles of Princeton University.

But the time has come, says Paul J. Steinhardt of the University of Pennsylvania in Philadelphia, "to pursue each model to its limit, so that we can find the smoking gun that will eliminate some of the theories."

Many scientists hope to do this by piecing together the COBE findings with experiments that look for the seeds of cosmic structure in patches of sky much smaller than the satellite can study. COBE looks for lumpiness on angular scales greater than 7°, while other experiments search for lumpiness on scales of 1° or less. "We're likely to get very important microwave background observations on the degree, arc-minute, and arc-second scales," says David N. Spergel of Princeton University. "I think once we have the full set of observations, we'll be able to know a great deal [more] about the initial conditions for forming galaxies."

Several experiments now monitor the faint microwave background – the relic radiation from the Big Bang – one small patch of sky at a time (SN: 5/8/93, p.296). These surveys have not yet provided results as definitive as COBE's. But like COBE, some of these studies have detected tiny hot spots or cold spots in the cosmos, which may prove to be small temperature fluctuations in the seemingly uniform microwave background. Understanding the nature of these temperature fluctuations may help solve the riddle of cosmic evolution.

Many astronomers believe that the microwave background represents a snapshot of the universe as it appeared a mere 300,000 years after the Big Bang. Before that time, the cosmos consisted of a foggy mixture of radiation, ions, and electrons. Electrons would have scattered the radiation this way and that, obscuring how lumpy the universe was at that early time.

But as the cosmos cooled, much of the celestial fog lifted: Ions and electrons combined into atoms, which absorb and scatter radiation less. During that crucial era, when the cosmos was about one-thousandth its current size, the universe became transparent. Light and matter went their separate ways. As they did, matter left an indelible mark on the radiation, which some 15 billion years later has now reached Earth.

Variations in the temperature of the microwave background radiation mark how smoothly matter was distributed at the time the universe became transparent, Steinhardt notes. That relationship stems from Einstein's general theory of relativity, which holds that mass exerts an influence on particles of light, even though these particles are massless.

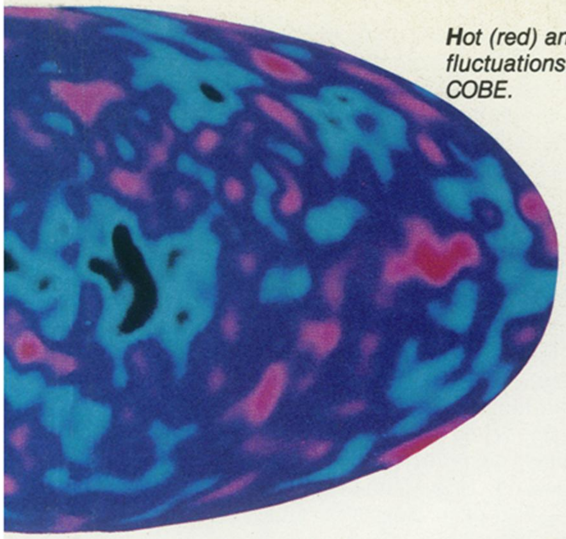
While gravity can't slow the speed of light, it does shift this radiation to lower or higher energies. At the moment the universe became transparent, it was as if the cosmos were a rubber sheet riddled with tiny hills and valleys. Clumps of matter created the valleys; the bigger the clump, the deeper the valley. In effect, light near a mass clump would have had to climb out of a valley – expend energy – in order to reach Earth. When radiation lost energy, it shifted to a longer wavelength and appeared colder. In contrast, light would easily depart a region with a lower-than-average mass density. Unencumbered by the gravitational tug that light elsewhere in the universe must contend with, this radiation effectively got an extra kick, as if it were sliding down a hill. Light emitted from low-density parts of the cosmos thus gained energy and now appears shifted to shorter wavelengths, or hotter temperatures.

In this way, explains Steinhardt, large-scale cold spots in the microwave background reveal regions where matter has clumped together, while hot spots indicate regions with an unusually low density of matter.

The vast hot and cold spots measured by COBE, as well as other experiments that measure temperature fluctuations on an angular scale greater than 2°, may have special significance. They apparently correspond to clumps that came into being a tiny fraction of a second after the birth of the universe.

With its limited resolution, COBE only detects hot and cold patches so large that a flash of light emitted at one end couldn't have reached the other end in the 300,000 years it took the universe to become transparent. Since nothing travels faster than light, that means the two ends were entirely oblivious to each other. Matter at one edge of the patch couldn't influence matter at the other edge.

So if such a patch – indicating a large lump of matter – truly existed, it could not have formed gradually over an extended period. Instead, it would seem to represent a primordial ripple in the fabric of space that must have resided there as far back as a tiny fraction of a second after the birth of the universe. Moreover, these large-scale hot and cold spots in the microwave background would signify structures 10 times larger than any so far observed in the universe.



Hot (red) and cold (blue) spots indicate tiny temperature fluctuations in the cosmic microwave background seen by COBE.

NASA/Goddard Space Flight Center

Smaller hot and cold spots, examined by ground-based and balloon-borne experiments that have a much higher spatial resolution than COBE, also provide a snapshot of the universe's clumpiness when it became transparent. But, because such spots are smaller, light emitted at one end of a patch *can* reach the other side in 300,000 years.

This means that changes in the lumpiness of matter at one end could trigger changes in the lumpiness of matter at the other end. Thus, these smaller hot and cold spots would seem to trace two sources of lumpiness: the primordial, initial lumpiness of the universe as well as further clumping that took place sometime later during those first 300,000 years. Moreover, these finer-scale ripples in the uniform microwave background signify the seeds of smaller structures—those on the scale of clusters or superclusters of galaxies—that astronomers have actually observed.

Because of the different information each experiment provides, combining data about temperature fluctuations in the microwave background on both small and large angular scales provides a more rigorous test of theories of how the universe evolved, notes Neil Turok of Princeton University. "COBE was never intended to settle all our questions about cosmology," he says. "It's an opening of a window."

Most cosmologists don't dispute the primordial nature of the fluctuations seen by COBE and other large-angle experiments. But that's where the agreement ends. In one scenario, large hot and cold spots began as tiny quantum fluctuations during the explosive birth of the universe. In a mere 10^{-34} second, according to this model, these microscopic fluctuations became enormously magnified as the universe underwent a cosmic burp — a period of rapid expansion known as inflation.

Theorists have proposed that the vast majority of matter in the inflation model consists of a hypothetical, invisible material known as cold dark matter. Under the influence of gravity, this weakly interacting, slow-moving material can clump earlier and faster than ordinary matter. As a result, concentrations of cold dark matter might more easily account for the lumpy nature of the modern universe.

Inflation plus cold dark matter creates a "flat" universe — one in which the total mass density is such that the cosmos is poised between collapse and expansion. Cosmologists describe the balance by invoking the parameter omega, defined as the ratio of the actual mass density in the universe to the critical density needed to create a flat universe. Many astronomers favor inflation because in this model omega equals one and remains constant with time. In other models, omega changes with time. For example, consider a universe in which the total density of mass is too small to stop the cosmos from expanding forever. In this "open universe" omega would become smaller and smaller as the universe grew bigger and bigger.

Such a model would indicate that we live at a special time, when the ever-changing density in the universe is just right to sustain structures such as galaxies and galaxy clusters. At an earlier time, the mass density of the universe would have deviated from that required for a flat universe by no more than about one part in a million. And at a later time, the mass density would have been so low that the cosmos could not have made clusters of galaxies.

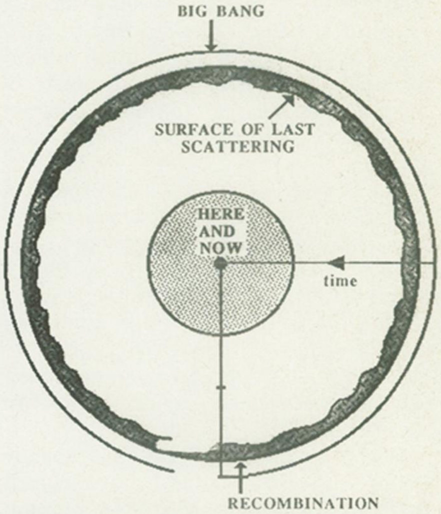
"I find the open universe a fairly unpleasant idea," says Steinhardt. "It requires us to be living in a very peculiar epoch." He notes that inflation explains the near-uniform glow of the microwave background and the formation of large-scale structures without making any assumptions about the current era of the universe.

Spergel, however, says the observed motion and distribution of galaxies "are more consistent with an open universe than with a flat [inflationary] universe."

Inflation plus cold dark matter has several testable features. The model fashions a cosmos in which temperature fluctuations are tiny and evenly distributed: Rather than having a few very hot and very cold spots, the sky should be littered with spots that show just a tiny deviation from the average temperature of the microwave background. Moreover, at angular scales down to about 1°, the temperature variations should be nearly identical on all angular scales. In other words, big patches of sky should show the same variations in temperature as smaller patches. And finally, on any given angular scale, the fluctuations have a high probability of looking the same no matter what region of the sky is studied.

But the temperature variations in the microwave background seen by COBE, only a few ten-millionths of a kelvin, are about twice as large as those predicted by the standard cold dark matter model — if the theory is to account for the observed distribution of galaxies and clusters of galaxies. Conversely, if cosmologists adjust the theory to match the fluctuations seen by COBE, then it predicts too much clumping on the scale of galaxies and galaxy clusters.

In addition, a balloon-borne experiment called MAX has found tentative evidence for dramatically different variations in temperature from two different patches of the sky. Those variations might simply represent spurious microwave emissions from our galaxy or the experiment itself. But if future balloon flights verify the MAX results, the standard cold dark matter scenario cannot survive, Turok says.



Charles Bennett/Goddard Space Flight Center

The microwave background may provide a snapshot of the universe as it appeared about 300,000 years after the Big Bang, when electrons and ions combined to form atoms and radiation was less readily scattered.

Notes Peebles: "You can wiggle a little bit with one angular scale measurement; you can't wiggle nearly as much with two different measurements."

To fit their theory with COBE and other findings, some researchers have proposed an ad-hoc assumption: Dark matter, they say, actually consists of a mixture of cold and hot dark material, the latter composed of low-mass particles moving at the speed of light. Because hot dark matter moves at high speed, only large aggregates of the stuff can easily form lumps; smaller groupings would fly apart. Thus, the additional presence of hot dark matter would limit the amount of clumpiness on smaller angular scales. Peebles calls the modification "bells and whistles" added solely to keep intact a problematic theory.

Researchers also tinker with cold dark matter theory in other ways. Some suggest that the universe has a cosmological constant, which is equivalent to assuming that empty space has a constant energy density associated with it. Albert Einstein first made such an assumption in 1917 in order for his equations of general relativity to yield a static, rather than expanding, universe. He later called the idea the worst mistake of his career. But modern-day cosmologists say that if 80 percent of the energy density of the universe comes from a cosmological constant and just 20 percent comes from cold dark matter, it may explain the COBE findings as well as telescope observations of large-scale clustering of galaxies.

One alternative theory, proposed by Turok, explains the primordial fluctuations seen by COBE by a mechanism far different from inflation. Unlike inflation, this scenario requires the universe to have begun with a perfectly smooth distribution of matter. He suggests that topological defects created tiny fluctuations in the uniform distribution of matter about 10^{-30} second after the birth of the universe. Such fluctuations could act as seeds for the eventual formation of galaxies.

The defects may have arisen as parts of the universe underwent a phase transition from a state of high energy to a state of lower energy, much as the molecules of liquid water lose energy to become ice. Turok proposes that the transition is not perfectly smooth; some high-energy regions become trapped during the transition, akin to cracks in the formation of an ice crystal.

One type of defect, called a cosmic texture, resembles a knot that unwinds at the speed of light. Matter – predominantly cold dark matter in Turok's model – congregates around the texture as it unwinds. Thus, textures could act as seeds for the tiny clumps of matter in the young cosmos. Under the influence of gravity, some clumps could grow to form clusters of galaxies. Although quite different in its assumptions, the texture model yields "patterns very similar to that predicted by inflation on large scales," says George P. Efstathiou of the University of Oxford in England.

Turok notes that a cosmic texture begins as a defect confined to a tiny region in space. Some regions have defects while others do not. In this way, the model explains why different parts of the universe would become slightly clumpier than other parts – a feature consistent with the preliminary MAX results. Textures would also enable clusters of galaxies to form relatively early in the history of the universe. This feature dovetails with observations of some distant quasars and galaxies, which appear fully developed even though astronomers see them as they looked when the cosmos was 10 percent of its current age.

In contrast, cold dark matter plus inflation requires most large-scale structures in the universe to have formed relatively recently.

Alas, Turok and other researchers note, the texture model also has its down side. It predicts temperature fluctuations that are about twice as big as those suggested by the COBE results so far reported, which are based on one year's worth of data from the satellite. Turok hopes that the mismatch will not be as great when the COBE team releases data, possibly this summer, from the second year of the four-year mission.

"There are problems with the theory," admits Turok, "but it's not dead yet."

Recently, several scientists have focused new attention on an older idea. According to some models of inflation, the early universe could have generated ripples in space-time known as gravity waves. Just as a stick striking a drumhead sets off vibrations, upheavals in the rubber-like fabric of space-time could create gravity waves. These waves would scatter radiation in the early universe. As a result, over large patches of sky, primordial gravity waves could mimic the influence of stationary mass clumps, leaving their imprint on the microwave background by shifting the radiation to longer or shorter wavelengths.

Thus, COBE may have viewed hot and cold spots in the microwave background due to *two* sources: clumps of matter, which form the precursors of galaxies; and gravity waves, which disperse and don't give rise to structure. But as long as lumps of matter far outnumbered primordial gravity waves, interpretation of the COBE findings wouldn't change much. However, some researchers, including Steinhardt and COBE team member George F. Smoot of the University of California, Berkeley, now calculate that primordial gravity waves could have created as many as half of the ripples in the microwave background recorded by COBE. That highly speculative notion could send some cosmologists back to the drawing board.

For starters, it would mean the universe began with fewer lumps of mass than the COBE data at first suggested – a result that would alter the fit between the inflation plus cold dark matter theory and the satellite's findings.

No one knows whether primordial gravity waves actually exist. But Smoot says that smaller angular-scale experiments now under way could test for their presence. It turns out, he says, that the greater the proportion of gravity waves to mass clumps in the early universe, the greater the likelihood that there will be smaller temperature fluctuations on smaller angular scales. It's too soon to tell if the ground-based and balloon experiments that search for smaller-scale ripples in the microwave background are seeing such an effect, Steinhardt says. But as more data accumulate, these surveys will become crucial for making or breaking the gravity-wave theory.

While the continuing search for small-angle hot and cold spots will give cosmological theories "a kick in the pants," Peebles notes, the new maps of the clustering of galaxies in the universe are providing additional constraints. A repaired Hubble Space Telescope might finally indicate when galaxies first formed. The new Keck Telescope atop Mauna Kea in Hawaii and the European Southern Observatory's Very Large Telescope in La Serena, Chile, may look back in time far enough to catch clusters of galaxies in the act of forming.

In a separate effort, British astronomers have embarked on a project to measure the distances of nearly a million galaxies. This survey should more accurately determine how galaxies cluster in the sky and over how large a scale. Outfitting the 4-meter Anglo-Australian Telescope in Siding Spring, Australia, with a spectrograph and special optics will allow the astronomers to examine a wide swath of sky at high resolution. The researchers expect to begin their study late next year.

Other researchers, including Edmund Bertschinger of the Massachusetts Institute of Technology in Cambridge, are working to improve maps of the velocities of galaxy clusters. Assuming that galaxy clusters move solely in response to the tug of matter, regardless of its composition, velocity maps have the advantage of indicating the distribution of all mass in the universe – whether it's visible mass or dark matter. Notes Efstathiou: "We can see how the galaxies are distributed, but if 95 percent of the matter in the universe is dark, how can we be sure of how matter is distributed?"

If researchers find that cold dark matter clumps less strongly than the visible mass in galaxies, the theory would better match the COBE results, Efstathiou notes. But Bertschinger says it appears so far that visible mass and dark matter have about the same clumpiness. He adds, however, that these results are sill preliminary. And Efstathiou cautions that the velocities of galaxy clusters, gleaned by a crazy quilt of different observational studies, are notoriously difficult to compute – let alone compile on the same map.

"I hope no one is making up their mind right now about which theory [of the evolution of the universe] is correct," Turok says. "For 10 years cosmologists have tried to explain complex phenomena with simplistic theories. Now it's the experimentalists' turn. Things may change dramatically in the next few years." ☐