From Soup to Us

Cosmic ripples test inflation

By RON COWEN

First of a two-part series

In the economic heyday of the 1980s, frenzied traders vied for untold fortunes in the bull market. For cosmologists mining the riches of the early universe, the 1980s were also a time of wild speculation, when anything and everything seemed possible. Flush with success at decoding some of the mysteries of quantum field theory, theorists of all stripes eagerly tackled the cosmos' ultimate riddle.

To wit: If the universe began as a smooth, hot soup of elementary particles, how did it ever become the lumpy collection of individual galaxies, clusters, and superclusters that now stretch across the sky for millions of light-years?

The Microwave Anisotropy Probe, scheduled for launch in 2000.

The standard answer had been that gravity amplified tiny fluctuations in the density of the infant cosmos. Over the past 15 billion years or so, gravity gathered matter around these seeds to form the cosmic structure observed today. That simple model works extremely well, up to a point. It doesn't explain where those initial fluctuations came from, nor does it account for why the universe, on the largest scales, looks the same in every direction (SN: 5/10/97, p. 287).

In 1980, a young physicist named Alan H. Guth, now at the Massachusetts Institute of Technology, found a way around these problems and opened up a new way of thinking about the very earliest moments in the universe. Other researchers had already posited that when the universe was very young and very hot, a special kind of symmetry held sway: The forces of nature were indistinguishable. The tremendous energy available during this early epoch, Guth realized, would endow the infant cosmos with a kind of antigravity. This repulsive force provided a humongous growth spurt (SN: 6/9/90, p. 358), and in much less than a trillionth of a trillionth of a second, the cosmos ballooned from a radius one-millionth the size of a proton to literally cosmic proportions.

The impact of this process—called inflation—on the evolution of the universe was similarly enormous. In one fell swoop, inflation could explain both the uniformity and the lumps in the cosmos.

The difficulty in accounting for these features harks back to Einstein's theory of special relativity, which holds that communication between any two points in the universe cannot travel faster than the speed of light. When the universe was very young, not enough time had elapsed for a light signal to travel more than a short distance from its point of origin. In the lingo of physics, any point beyond that distance lies outside the event horizon. That horizon grows larger as the universe expands.

Since two regions outside each other's event horizon cannot exchange information, there is no a priori reason why they should look anything like each other. In addition, the tiny lumps, or slight overdensities in matter, that would later give rise to galaxies would have been bigger than the event horizon until the cosmos was 1 year old. That would seem to make it impossible for any ordinary physical process to have produced the lumps.

Inflation explains away these two puzzles. The period of rapid, early expansion spreads out tiny regions that had been in close contact during the first fraction of a second of the universe. Suddenly separated by large distances, these regions still had the same physical properties. In this way, inflation allowed cosmic uniformity to be established on a large scale. Indeed, most inflationary models generate a region of uniformity many times bigger than the relatively small neighborhood of the universe we can observe today.

Second, inflation can explain the existence of the initial fluctuations. The rapid expansion takes quantum mechanical variations in energy—random, microscopic ripples in space that ebb and flow like ocean surf—and blows them up to macroscopic proportions. In preserving and enlarging these chance differences, inflation allows them to evolve into slight underdensities or overdensities in mass that gravity could then mold into the present-day universe.

"One of the most striking predictions to come out of [inflation] is that all these structures that we see in the universe today, from stars and galaxies to voids and Great Walls, originated from quantum mechanical fluctuations during the earliest moments of the universe," says cosmologist Michael S. Turner of the University of Chicago and Fermi National Accelerator Laboratory in Batavia, Ill.

The theoretical work of the 1980s proved so intriguing, he adds, that scientists paid it the highest compliment—they devised experiments to try to prove it wrong. Today, several experiments have begun testing inflation, and new instruments, including two orbiting observatories, are expected to come on line over the next 5 to 10 years to examine the hypothesis.

"The go-go junk bond days of cosmology are over," Turner declared last April at a meeting of the American Physical Society in Washington, D.C. "Now we have to face the harsh reality.

"If inflation proves to be correct, then we will have started to extend our understanding of the universe all the way back to 10^{-34} seconds.

"If it's wrong, we may have to go back to the drawing board."

Like other theories that account for structure in the universe by modeling conditions far back in time, inflation makes several predictions about the nature of the universe today. Inflation's period of rapid growth makes the universe flat—meaning that on large scales space should have no discernible curvature. In a flat universe, the density of the cosmos must equal the so-called critical density, the value that leaves the cosmos exactly poised between perpetual expansion, resulting from the Big Bang, and ultimate collapse, in response to the gravity of the matter within it.

That prediction would seem to contradict measurements of the abundance of elements forged in the Big Bang. The measurements reveal that the amount of ordinary matter in the cosmos, such as protons, neutrons, and electrons, adds up to only 5 percent of the critical density. If the simplest model of inflation is correct, then 95 percent of the universe is made up of some other, exotic type of material that doesn't emit light and can't be seen.

That notion may seem bizarre, but for entirely different reasons particle physicists had already envisioned a universe filled with such material. To help unify the forces in nature, physicists had proposed that the cosmos contains some type of invisible matter, dubbed cold dark matter, in the same high abundance required by inflation.

As the dominant mass in the cosmos, cold dark matter would control how galaxies and galaxy clusters form. Exactly how much dark matter exists would also determine the fate of the universe.

Finally, inflation would leave its fingerprints on the cosmic microwave background, the whisper of radiation left over from the birth of the universe. The microwave background represents a snapshot of the cosmos at about 300,000 years after the Big Bang.

Before that time, the universe was a mixture of radiation, electrons, and ions. Like light traveling through a dense fog, the radiation would have been scattered this way and that by the electrons, obscuring how lumpy the universe was at this early time.

Then the universe cooled enough for electrons and ions to combine into atoms, which produce much less scattering of light. The fog lifted, light and matter went their separate ways, and the microwave radiation streamed freely into space. Variations in the temperature of the microwave background observed today reveal the slight lumpiness in the distribution of matter at the moment the radiation was set free. A cold spot signifies a slightly overdense region of space, because photons lose energy in escaping from a concentration of matter. Similarly, a hot spot reveals an underdense region.

Theoretical physicist Stephen W. Hawking of the University of Cambridge in England has hailed the long-awaited discovery of those temperature fluctuations by the Cosmic Background Explorer (COBE) as one of the most important discoveries of the 20th century (SN: 5/2/92, p. 292).

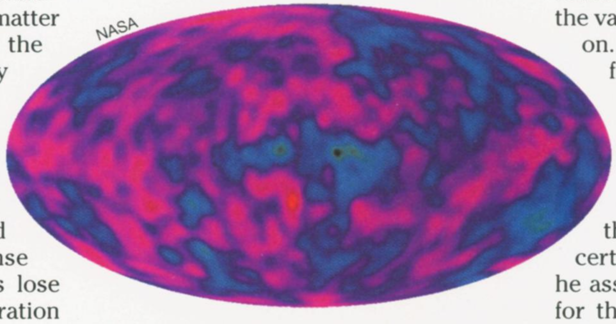
COBE had limited vision, however. It could only detect density fluctuations over patches of sky several times the diameter of the full moon. Such fluctuations occur over areas so broad that they would correspond to structures 10 times larger than any observed in the universe today.

Such large-scale variations represent little more than scaled-up quantum noise, the initial quantum mechanical fluctuations that inflation enlarged. The wavelengths associated with these large-angle variations were longer than the event horizon of the cosmos during this time. The variations therefore have remained essentially frozen, untouched by cosmic events in the 300,000 years between the end of inflation and the time radiation was freed.

To test inflation rigorously, researchers must measure variations over smaller regions of sky, notes Turner. These smaller angular scale fluctuations trace overdense or underdense regions in the early universe that interacted strongly before the electron fog lifted and the microwave background streamed outward. The evolution of such small fluctuations depended on the total matter density of the universe and other characteristics intimately related to inflation theory.

Ground-based and balloon-borne experiments have for several years made such smaller-scale measurements. So far, the fluctuations generally match the predictions of inflation theory, Turner noted at the physics conference. "You can see that we haven't proven inflation yet, but you can see why there's a smile on my face."

Still, notes Neil Turok of Cambridge, these experiments, unlike the Earth-orbiting COBE, can't cover the entire sky and are limited in their ability to subtract sources of noise, such as galactic dust and radio emissions from galaxies, that can mimic cosmic fluctuations.


NASA

Hot (pink) and cold (blue) regions represent tiny fluctuations in the otherwise uniform temperature of the cosmic microwave background, as measured by the Cosmic Background Explorer satellite.

Two satellites now under development may provide a more definitive answer. NASA's Microwave Anisotropy Probe (MAP), scheduled for launch in 2000, is designed to have a resolution 30 times higher than COBE, enabling it to search for variations in the microwave background between patches of sky separated by as little as 0.2°. Five years later, the European Space Agency plans to launch Planck, expected to have even greater accuracy.

"There's a gold mine of information in the data—the value of the total density of the universe, the density [of ordinary matter], the value of the Hubble constant," notes Turner.

In addition to recording fluctuations from the early universe, cosmologists are also seeking a better three-dimensional map of the distribution of galaxies today. The extent to which galaxies cluster on different scales in the sky should reflect the distribution of the earlier variations in density predicted by the inflation model and thus provide another test of the theory. At present, the most complete galaxy survey contains 30,000 galaxies. In contrast, the Sloan Digital Sky Survey, scheduled to begin next year using a telescope at Apache Point in Sunspot, N.M., should obtain the three-dimensional position of a million galaxies.

Scientists have also devised several experiments to search directly for cold dark matter. One study, which hunts for hypothetical particles called axions, relies on the property that these particles transform into microwave photons in the presence of a strong magnetic field. At the Lawrence Livermore (Calif.) National Laboratory, Karl van Bibber of Livermore and Leslie Rosenberg of MIT and their colleagues have built what they hope is an axion trap.

Inflation, notes Turok, is far from a perfect theory. It predicts much more clustering of galaxies than astronomers observe. Moreover, myriad studies suggest that the density of the universe is considerably less than the critical density, the value that inflation pegs its reputation on. If these measurements are confirmed, inflation might only be salvaged by resurrecting the cosmological constant—an antigravity term, usually set to zero—in the equations of general relativity.

Turner argues that at present, the density measurements are uncertain. "This is all about backbone," he asserts, arguing that it's not yet time for theorists to panic and dramatically revise general relativity or the simplest model of inflation.

Turok is a long-time proponent of an alternative model for generating primordial fluctuations. Instead of an initial quantum mechanical fluctuation that gets stretched by inflation, he suggests that some sort of cosmic defect created the density fluctuations. In this scenario, the universe undergoes a transition from a high-energy state to a lower-energy one, similar to the change of phase that occurs when liquid water loses energy to become ice. If the transition isn't perfectly smooth, a defect, like a crack in an ice crystal, may occur.

Recent calculations by Turok and his colleagues show, however, that the topological defect theory may itself be defective. The smaller-scale microwave background experiments show more fluctuations than are permitted by the standard versions of the defect model. Turok says he's not ready to throw in the towel but will abide by whatever verdict future satellite data determine.

One possibility, of course, is that neither theory is correct.

"I know which outcome I prefer," Turner noted recently, "but I cannot be sure which would prove more interesting." ☐

Next: Galaxy formation