The Seeds of Cosmic Structure

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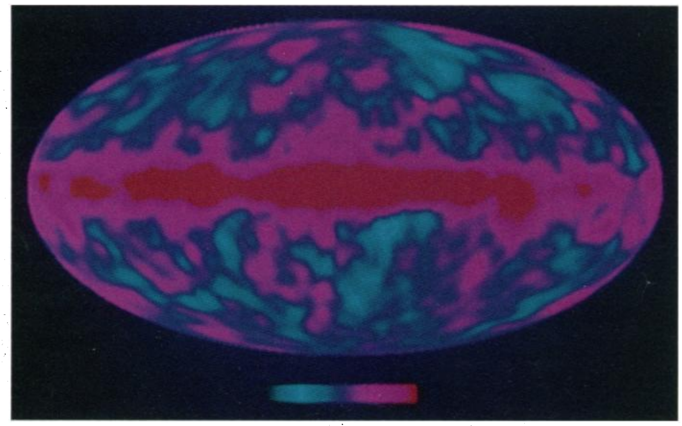
The popular press got the story wrong: the latest results from NASA's Cosmic Background Explorer (COBE) satellite did not "prove" the Big Bang theory of the universe—that was settled nearly three decades ago. Rather, COBE has taken a snapshot of the early universe, a portrait of the distant past in which a sketch of the present architecture of the universe is dimly visible. In an experimental tour de force, COBE has detected the seeds of cosmic structure that grew into the galaxies and clusters of galaxies we see today.

That the Big Bang theory correctly describes the early universe was established 27 years ago by the discovery of heat radiation left over from the early phase of high density and temperature. In the expansion of the universe over the past 15 billion years, that radiation has cooled to 3 K but not vanished and now pervades the universe. This cosmic background was discovered by Arno Penzias and Robert Wilson (*1*) and is now called the cosmic microwave background radiation (CBR). Later observations including some from COBE (*2*) have confirmed that the CBR has a backbody spectrum, as expected if it originated in a hot, dense phase. Thus, most cosmologists were convinced of the Big Bang theory decades before COBE's launch. The recently announced detection of small variations in the temperature of the CBR across the sky has a different story to tell.

Soon after the discovery of the CBR, it was recognized (*3*) that observations of its distribution across the sky could provide important information about the origin of the structure we see in the universe today. The photons making up the CBR travel to us from an early epoch in the history of the universe, 300,000 years after the Big Bang. What we see when we look out beyond the most distant quasar, and therefore far back in time, is the surface where the CBR photons last scattered from matter. A cumulus cloud provides a useful analogy. We see the surface of the cloud, not its interior, because the photons reaching us last scatter at the cloud's surface. In effect, a map of the CBR is a snapshot of a particular moment early in the history of the universe.

If the matter on this surface of last scattering was lumpily distributed, fluctuations in the temperature of the CBR would be induced by a variety of mechanisms, including gravitational redshift. Thus, the CBR maps will not be absolutely uniform, and the measured temperature of the CBR will vary from place to place on the sky.

The exact relationship between the amplitude of the lumps and the amplitude $\Delta T/T$ of the temperature fluctuations in the CBR visible today depends on the physics of the early universe. For instance, the amplitude of $\Delta T/T$ depends in part on the dominant form of matter in the universe. If ordinary, baryonic matter dominates, relatively large values of ΔT are expected. Observations already available have essentially ruled out this possibility. On the other hand, there are good reasons to believe that the gravitational dynamics of the universe may be dominated by nonbaryonic matter of a kind as yet undetected—the so-called dark matter. If so, smaller values of ΔT are expected. The rate of expansion of the early universe also plays an indirect role. If the universe goes through a very early period of rapid exponential expansion (called inflation) as some theorists suggest (*4*), perturbations in both the radiation and the matter of the early universe are naturally produced. In turn, these produce larger values of $\Delta T/T$ than in some other theories. Thus the amplitude of $\Delta T/T$ is linked to the physics of the early universe.



Initial conditions. One of three full-sky COBE maps of the cosmic background radiation (at 5.7 mm wavelength). The horizontal band is foreground radio emission from our galaxy. The lumpy texture maps the distribution of matter only 300,000 years after the Big Bang. [COBE Science Working Group]

In addition to the amplitude of the temperature fluctuations, their spectrum is also of interest. We can ask how the amplitude of $\Delta\rho/\rho$ (where ρ is the mass density) depends on the mass of the lumps. The theories based on inflation do provide one specific answer. That in turn translates into another relationship or "spectrum"—the amplitude of temperature fluctuations as a function of their angular scale on the sky, $\Delta T(\theta)$. On the large angular scales probed by COBE, this primordial spectrum of temperature fluctuations is directly visible, unaffected by subsequent physical processes.

Maps of the CBR thus can provide us with crucial information about the seeds of present-day structure in the universe. Further, the spectrum and amplitude of these fluctuations can in principle provide information about physical processes which operated much earlier in the history of the universe, perhaps even back to the epoch of inflation itself at 10^{-30} second or earlier! For all these reasons, experimental groups have been avidly searching for fluctuations in the CBR ever since 1965. Over the past 27 years, there have been no reliable reports of such fluctuations on any angular scale. Using conventional radio telescopes, specially designed instruments carried aloft by balloons and arrays of radio telescopes, astronomers in this country and many others have driven upper limits on the fractional temperature fluctuation, $\Delta T/T$, down from 10% or so to a few parts per hundred thousand (*5*). The most sensitive of the recent experiments were limited by either instrumental noise (receivers that were too noisy or observing periods that were too short) or patchy emission from the earth's atmosphere.

The first detection of significant CBR fluctuations was announced at an April meeting of the American Physical Society in Washington, D.C., by the COBE Science Working Group. Brief reports on the COBE results are forthcoming, coauthored by George Smoot and his many collaborators from Berkeley, the University of California at Santa Barbara, MIT, Princeton, UCLA, and various NASA branches (*6*).

The COBE satellite, launched 18 November 1989, had as one of its primary goals to map the entire celestial sphere at several microwave frequencies and thus to provide several independent "snapshots" of the CBR. While the instruments employed were if anything less sensitive than those

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used in recent ground-based observations, the satellite was not troubled by atmospheric emission and observed the celestial sphere uninterrupted for many months. Thus, because a huge amount of data has been collected and analyzed, the final results are of unprecedented sensitivity. The angular resolution of the COBE instruments was about 7° (equivalent to the angle subtended by one's fist held at arm's length). Thus the COBE maps do not have high angular resolution, but the pixel-to-pixel noise of the maps is very low, equivalent to 4×10^{-5} to 9×10^{-5} K—an improvement by a factor of 3 to 5 over the best previous ground-based experiments. That improvement was just enough to reveal the existence of the long-sought fluctuations in the CBR.

COBE observed the sky at three microwave wavelengths, 3.3, 5.7, and 9.5 mm; these data were supplemented by balloon-borne observations made by Steve Boughn *et al.* (7) at 1.5 cm. The use of several different wavelengths allowed the experimenters (8) to correct for emission from the plane of the galaxy or other foreground radio sources (all sources are foreground to the CBR). Great care was also taken to analyze and correct for other possible sources of systematic error (such as the effect of the earth's magnetic field on the instruments, radio emission from the earth leaking into the antennas, and many others). The dominant foreground source, however, was the galaxy, as shown in the figure. Once the galactic signal was subtracted, residual fluctuations exceeding instrumental noise were detected, at a level up to 1.1×10^{-5} in $\Delta T/T$. The detection is statistically robust (at least 7σ). Furthermore, even at 7° resolution, there were enough independent pixels to permit the observers to look for temperature fluctuations on different angular scales from 7° to 90°, and thus to obtain a spectrum for the observed fluctuations. It appears to be a power law in good agreement with the predictions of the inflationary model.

Both the amplitude and the spectrum are of great theoretical interest, and cosmologists are now feverishly interpreting these data. Likewise, observational astronomers (among them Phil Lubin at the University of California at Santa Barbara, Anthony Lasenby at Cambridge University, Charles Lawrence at Cal Tech, and a group involving Haverford and the National Radio Astronomy Observatory) are busy trying to confirm the COBE results and to measure ΔT on smaller angular scales. Extending the results to smaller angular scales is particularly important because COBE's angular resolution was poor. Thus it was unable to detect fluctuations on scales corresponding to the structures we see in the universe today, such as clusters of galaxies. These better observed and better understood scales are 10 to 100 times smaller in angular size than COBE's 7° beam.

Let us not underestimate the importance of the results COBE has provided, however. It has given us for the first time direct observations of the distribution of matter very early in the history of the universe. In effect, we now have initial data to compare with our theories for the formation of large-scale structure in the universe, including galaxies, clusters of galaxies, and the filamentary structure, discovered by optical astronomers, in the larger scale distribution of galaxies.

As we have seen, at first blush the COBE measurements appear to be consistent with the inflationary variant of Big Bang cosmology. If so, we are seeing structure imprinted on the universe in the first 10^{-30} second or less of its existence. The amplitude of the temperature fluctuations seen by COBE is also consistent with the notion that galaxies form from the initial density perturbations by the action of gravitational forces alone. On the other hand, the COBE results have also raised some questions. For instance, the COBE results appear to favor the existence of a particular kind of dark, invisible matter which dominates the gravitational dynamics of the universe—so-called "cold dark matter." But the cold dark matter models are difficult to reconcile with other astronomical data, such as measurements of smaller scale clustering of galaxies or smaller scale velocities. The discrepancies are not major ones, but workers in the field are divided on the question of whether any present theory of galaxy formation correctly explains all the data now in hand. Optimists say yes, and place their bets on an inflationary model with cold dark matter dominating. Others demur, and argue for a more radical reappraisal. Some avoid either extreme and suggest some fine-tuning of the cold dark matter scenario. It is too early to tell which theories will gain luster and which theories will be knocked down by the COBE maps (8). It is not too early to tell that they are among the most important cosmological observations of the century, and that the hundreds of person-years spent in searching for CBR fluctuations have been marvelously justified.

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