Ringing in the new cosmology

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Balloon experiments over Antarctica have produced a long-awaited temperature map of the microwave sky. The map reveals sound waves that can be used to probe the early Universe.

According to the theory of the Big Bang, the Universe started hot and dense and then expanded and cooled. In the hot, dense conditions of the early Universe, photons were tightly glued to matter. When the Universe was about 300,000 years old the temperature dropped below 3,000 K, allowing atomic hydrogen to form and releasing the photons. These photons, which travelled freely through the Universe as it expanded and cooled, make up the cosmic microwave background (CMB) we see today. Ten to twenty billion years after the Big Bang, the CMB is a cold sea of photons with an average temperature of 2.7 K (−270 °C). These photons are all around us, causing about 1% of the noise on our television sets.

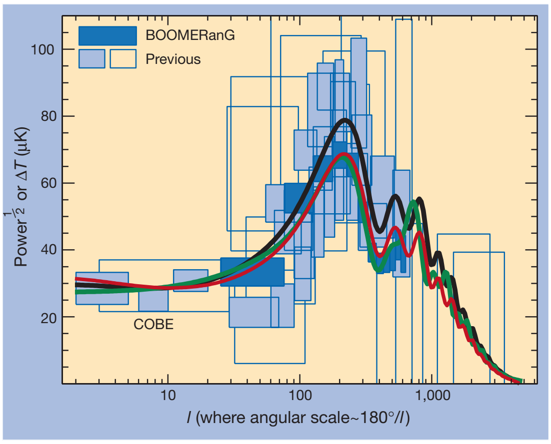
When it was discovered in the 1960s, the CMB was found to be remarkably uniform across the sky. It was not until 1992 that the Cosmic Background Explorer (COBE) satellite[1] discovered temperature variations (or ripples) at the level of 1 part in 100,000. Temperature maps of the CMB form a snapshot image of the Universe when it was extremely young. So these ripples reflect tiny density fluctuations in the primordial soup of particles. These same density fluctuations are thought to grow by gravitational attraction into the familiar structures we see today (stars, galaxies and clusters of galaxies). This is the gravitational instability model of structure formation.

COBE told us what the large-scale fluctuations in the background look like, but cosmologists today are more interested in the small-scale fluctuations. Astronomers divide up the sky into angular degrees, so that 90° is the distance from the horizon to a point directly overhead. COBE measured temperature ripples from the 10° to 90° scale. This scale is so large that there has not been enough time for structures to evolve. At the degree scale, on the other hand, the process of structure formation imprints information in the ripples about conditions in the early Universe.

Since the COBE discovery, many ground and balloon-based experiments have shown that the ripples peak at the degree scale[2,3]. On page 955 of this issue, de Bernadis *et al.*[4] report the first high-resolution maps of the CMB over a significant part of the sky. The results are part of the BOOMERanG experiment, in which a microwave telescope was carried at high altitudes during a long balloon flight over Antarctica. The authors take a power spectrum from their detailed maps of the CMB, much as you would if you wanted to analyse background noise. They find that the peak in the power spectrum of the CMB has exactly the right form to be the ringing or acoustic phenomena long awaited by cosmologists (Box 1). Such acoustic phenomena probe the conditions of the early Universe as a kind of cosmic ultrasound (Fig. 1, overleaf).

The properties of the observed peak have important implications for cosmology[5]. They depend mainly on the spectrum of initial fluctuations and fundamental cosmological parameters. The location and width of the peak strongly imply that the initial fluctuations that created the sound waves were in place on the largest scales at the earliest times. The only known mechanism for setting these perturbations in place is a

Box 1 The second peak in the spectrum



Before the BOOMERanG data[4] discussed here, all the evidence pointed towards a model of the Universe that is flat and lightweight (low dark-matter density), with an initial spectrum of density fluctuations whose power is constant across all length scales[6]. This standard model (black curve) is strongly inconsistent with the observed lack of a prominent second peak in the power spectrum of the cosmic microwave background.

There are at least three possible explanations for the 'missing' peak. First, the initial density fluctuations could actually increase with length scale, thereby suppressing small-scale fluctuations. This is known as a 'tilted' model (red curve, 10% tilt). This solution would have important implications for the particle physics of inflation and observations of gravitational waves.

The second possibility is that the density of baryons (ordinary matter) is as much as 50% higher than the value implied by the abundance of light elements in the Universe and the theory of their synthesis in the first few minutes after the Big Bang (nucleosynthesis)[6]. Any extra baryons cannot be in the stars we see today. If this were the solution, the question of where most of the baryons are today becomes even more puzzling[7]. At the very least, the BOOMERanG data place a lower limit on the baryon density that is comparable to the nucleosynthesis estimate.

A value for the dark-matter density higher than the standard one-third of the critical density also helps fits the power spectrum better (green curve; three times as much dark matter and 50% more baryons), at the expense of agreement with other cosmological data[6]. The standard value can also be made to work by lowering the predicted height of the peaks relative to the COBE measurements at the 10° scale by any one of several effects.

A testable consequence of either high-baryon-density solution is that the third peak should be higher in amplitude than the second.

The final and perhaps most speculative solution is if the formation of atomic hydrogen were to be delayed until the Universe was nearly 30% older, either through an unknown source of energy or through a change in our understanding of atomic physics at early times. This would increase the time available for the acoustic oscillations to dissipate and hence suppress the smaller peaks. A combination of some or all of these solutions may also provide the answer and perhaps avoid any extreme departures from the standard model. **W.H.**

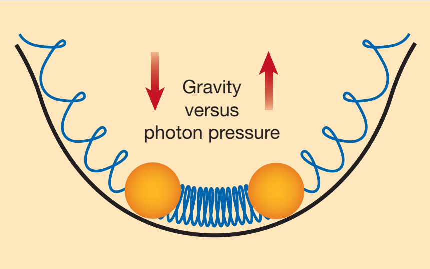


Figure 1 **What astronomers see in the fine structure of the cosmic microwave background is actually sound waves. Acoustic phenomena have long been a general prediction of gravitational instability models of structure formation[8]. Gravitational force compresses the primordial plasma until resistance from photon pressure reverses the motion, leading to acoustic oscillations. Because compression raises the temperature, this results in hot and cold spots that are visible in the microwave sky today.**

period of rapid (faster than light) expansion in the early Universe called inflation. In inflationary models, quantum fluctuations are carried from the microscopic to cosmic scale by the rapid expansion. If this interpretation is correct, then there should be a second peak that is smaller than the first, and a third peak that is comparable to or larger than the second.

In the inflationary context, the structure of the peaks is governed mainly by three fundamental parameters. These are the curvature of the Universe, the density of ordinary matter (or baryons), and the density of dark matter. The location of the first peak in the power spectrum provides the best measure of the curvature of the Universe, and hence the total amount of matter in the Universe. Einstein told us that matter curves space: the familiar force of gravity is no more than the curvature of space–time. To see this fact, consider the surface of the Earth. Two people travelling due north from the Equator on different lines of longitude will nonetheless meet at the North Pole. Ignorant of the curvature of the earth, they might attribute this fact to a strange attractive force.

The same thing happens to CMB photons on their way to the observer if the Universe is spatially curved. The intervening matter and energy acts as a giant (de)magnifying glass that bends the photon trajectories. The BOOMERanG result supports a flat Universe, which means that the total mass and energy density of the Universe is equal to the so-called critical density. A perfectly flat Universe will remain at the critical density and keep on expanding forever, because there is not enough matter to make it recollapse in a 'big crunch'.

Perhaps the most intriguing aspect of the BOOMERanG results is the lack of a prominent second peak at half the angular scale of the first. If the second peak predicted by inflation exists, it is of much smaller amplitude than the first. Indeed it must be significantly smaller than expected from the simplest models (Box 1). The key to resolving the mystery of the second peak will be measurements of higher precision and resolution, perhaps from the forthcoming full analysis of the BOOMERanG data — but, if not, certainly from the MAP satellite to be launched in November. Regardless of the outcome, these data show that we have clearly entered a new era of precision cosmology, in which we can begin to talk with certainty about the origin of structure and the content of matter in the Universe. ■

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