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RESEARCH NEWS

Recent COBE results and their cosmological implications

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The theoretical models for galaxy formation predict that the microwave background radiation should exhibit small anisotropies in the temperature distribution. Recent analysis of data from the satellite COBE (Cosmic Background Explorer) has indeed detected anisotropy of $(\Delta T/T) = (1.1 \pm 0.2) \times 10^{-5}$. The result shows that the conventional gravitational instability framework for structure formation in the universe is basically sound. However, it poses interesting problems for detected models.

Models for structure formation and MBR

Our universe today exhibits an interesting pattern: At very large scales ($R \gtrsim 200$ Mpc (650 million light years) or so) the matter distribution appears to be quite homogeneous and expanding in accordance with the Hubble law. At smaller scales, there exist large inhomogeneities in the form of galaxies, clusters and superclusters. The most natural explanation for such a universe is based on the following idea (see, e.g. ref. 1): We assume that in the past the universe was described by a smooth, expanding, Friedmann model which also contained very small inhomogeneities (say, one part in 10^5 when the universe was thousand times smaller). These inhomogeneities have grown through gravitational instability to form structures like the galaxies we see today.

How do we test such a theory? The *smooth* Friedmann model for the past universe is consistent with all known cosmological observations. It receives particularly strong support from the strictly thermal and nearly isotropic nature of the microwave background radiation. In fact, we do not have today any rival theory which is equally successful.

To verify the model fully, we also need to test the hypothesis that there existed small fluctuations in the past. This can be done as follows: When the universe was more than 10^3 times smaller, its temperature would have been high enough to keep the matter fully ionized. During this stage, any small inhomogeneity in the matter distribution would have left its imprint on the radiation. As the universe expands and cools, the plasma recombines to form neutral atoms and the radiation decouples from matter. The relic radiation from this epoch, usually called the 'last scattering surface' (LSS), is what we see as the microwave background. If the theoretical ideas are correct, then this radiation should exhibit small temperature inhomogeneities, which should be detectable. Most viable models predict a temperature fluctuation of the order $(\Delta T/T) \approx (0.1\text{–}2) \times 10^{-5}$.

Such fluctuations have now been detected in the data acquired by the NASA satellite COBE, specially flown for this purpose[2]. The observed value is $(\Delta T/T) = (1.1 \pm 0.2) \times 10^{-5}$, in good agreement with theoretical expectations. The result shows that the basic model for the universe outlined above is sound.

To understand the deeper implications of this result, one needs to describe the sources of MBR anisotropy and models for structure formation in greater detail. I shall now turn to this task.

Sources of anisotropy in MBR

The largest anisotropy expected, and seen, in MBR is purely kinematic. It arises due to the fact that the Sun is not at rest in the cosmic frame but moves in a particular way. This motion causes a Doppler shift in the photons with a characteristic angular dependence. This anisotropy, called 'dipole anisotropy', has been detected long back and COBE has sharpened this observation. The dipole anisotropy measured by COBE is $(\Delta T/T)_D \simeq 1.23 \times 10^{-3}$. The direction of motion of Sun in galactic coordinates is $l = 264.7 \pm 0.8$, $b = 48.2 \pm 0.5$; these numbers are consistent with the previously known results but the error bars have now improved.

The imprints of galaxy formation are contained in quadrapole and higher multipoles. There are basically three different sources for this anisotropy. The first one is the direct coupling which existed between the radiation and matter in the LSS—this is the spatial hypersurface in the past from which we receive the MBR photons today. This anisotropy is maximum ($\sim 10^{-6}$–10^{-5}) at few arc minute scales in the sky and falls as θ^{-2} in most models [here θ stands for the typical angular scale in the sky over which one is measuring the temperature anisotropy]. The second source of anisotropy is the random velocities which would have existed in the plasma in the LSS. These velocities will lead to Doppler shifts in the scattered photons, giving rise to temperature fluctuations. This effect is also maximum ($\sim 10^{-6}$–10^{-5}) at arc minute scales and falls as θ^{-1} at larger scales. The third and the most important contribution, as far as COBE is concerned, is due to the gravitational redshift of photons. The inhomogeneities in the matter distribution will lead to variation in the depth of the gravitational potential in the LSS. Photons climbing out of the hills and valleys of this potential will suffer different amounts of gravitational redshift, which will also show up as temperature anisotropy. This effect, unlike the previous two, is independent of θ for θ larger than a few degrees and has a magnitude of about 10^{-6} to 10^{-5}. The magnitude of this effect is easy to understand. The gravitational potential fluctuations $\delta\phi$ do not change from the epoch of decoupling till today. Hence $\delta\phi$ at LSS can be estimated from the gravitational potential energy of the largest bound structures seen today. For clusters of galaxies exhibiting random velocities of about 10^3 kms^{-1}, $(\delta\phi/c^2) \simeq (10^3/3\times10^5)^2 \simeq 10^{-5}$. This is the expected value of $(\Delta T/T)$ at angular scales larger than about a degree.

The COBE is designed to look for such large-angle anisotropies; in fact, COBE is insensitive to fluctuations at angular scales below about 7°. There is a sound reason behind this design. The temperature fluctuation at angular scales below 1° or so is highly model-dependent. In particular, if any astrophysical process reionizes the matter in the universe after the 'original' decoupling described above, then it is possible for temperature fluctuations at small angular scales to be wiped out completely. Such processes, however, are not effective at scales bigger than a few degrees. In other words, if the current thinking about galaxy formation is correct, then there *must* exist temperature fluctuations at angular scales larger than, say, 10° or so. Since this is a firm prediction, COBE was designed to look at such large angular scales.

Implications of the COBE results

The analysis of the COBE data gives two very useful numbers. The rms fluctuations in temperature averaged over most part of the sky is $(\Delta T/T)_{\rm rms} = (1.1\pm0.2)\times10^{-5}$. The quadrapole contribution to this anisotropy is $(\Delta T/T)_{\rm Q} = (0.48\pm0.15)\times10^{-5}$. These observed numbers can be compared with theoretical models if one knows the power spectrum of density fluctuations, $P(k)$, in the universe. The detailed form of $P(k)$ for large k varies from model to model; but almost all popular models predict that $P(k) \cong Ak$ for small k (that is, at large $R = k^{-1}$). If this is the case, then one finds that (see, refs. 3, 4 for details) $(\Delta T/T)_{\rm Q} = 0.215\,\Phi$ and $(\Delta T/T)_{\rm rms} = 0.5\,\Phi$, where $\Phi^2 = (9/8\pi^2)(A/R_{\rm H}^4)$ is a measure of fluctuations in the gravitational potential and $R_{\rm H} = 3000$ h^{-1} Mpc. The observed range for the ratio $[(\Delta T)_{\rm rms}/(\Delta T)_{\rm Q}] = (1.43-3.94)$ is consistent with the theoretical expectation of 2.38, lending support to the small-k behaviour $P(k) \simeq Ak$. [The errors are consistent with the form $P(k) \propto k^n$ with $n = 1.1\pm0.6$]. The observations also allow us to determine Φ (and hence A); we find from $(\Delta T/T)_{\rm rms}$ that $\Phi = (2.14\pm0.36)\times10^{-5}$.

The shape of the power spectrum,

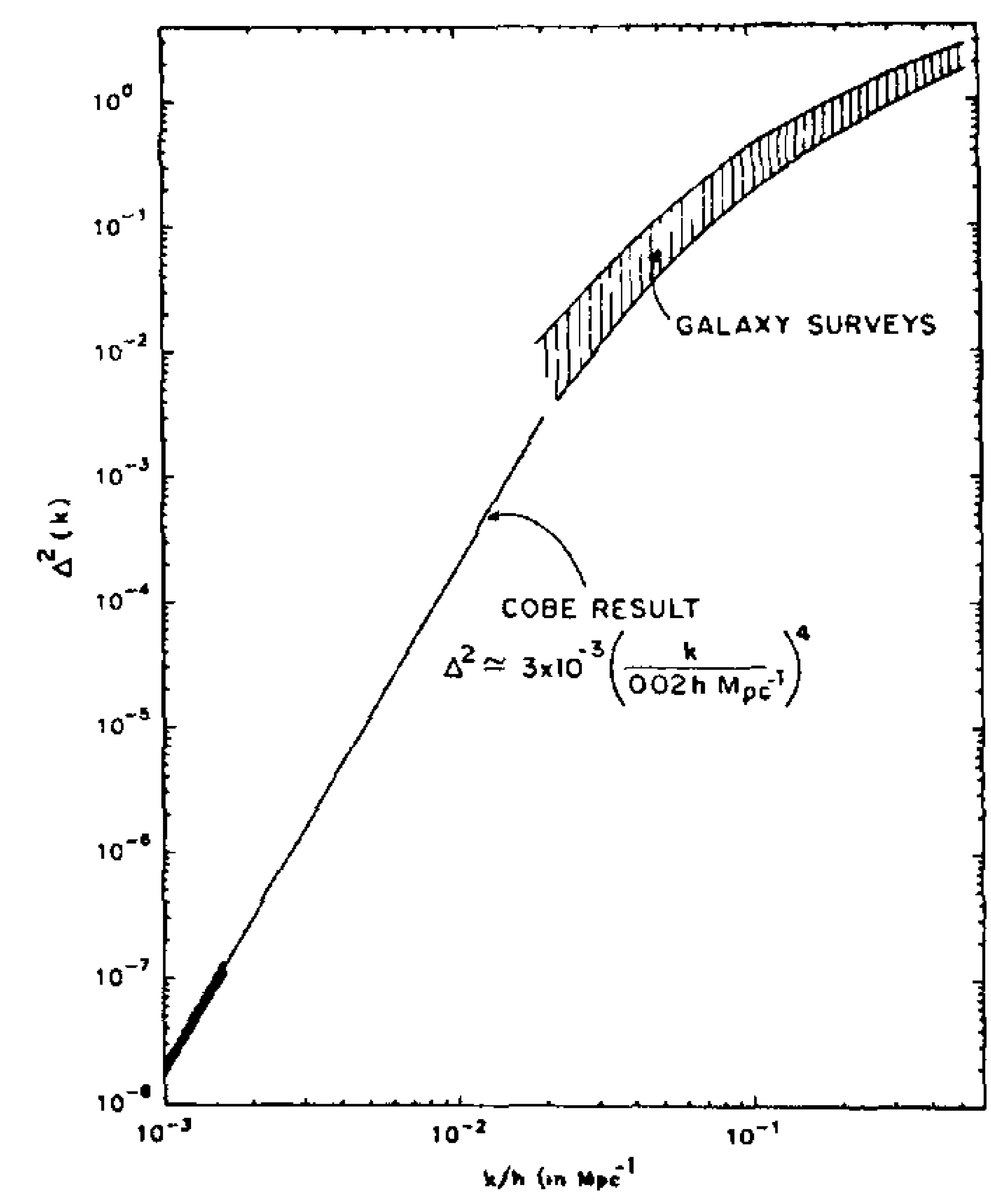

Figure 1. The power in the density fluctuations per octave, $\Delta^2(k) = [k^3 P(k)/2\pi^2]$, is plotted against the wave number k. The line at bottom-left represents the result from COBE extrapolated linearly (thinner part of the curve). The shaded area at right-top represents the power spectrum calculated from several galaxy surveys (see refs. 4 and 6 for details). Two features are clear from this diagram (i) The COBE spectrum $\Delta^2 \propto k^4$ should continue up to $k_c \simeq (0.03$–$0.04)$ h Mpc^{-1} if galaxy survey results are to be reproduced (ii) The spectrum has to bend rather sharply around this value to account for the survey results