CURRENT STATUS OF THE COSMIC MICROWAVE BACKGROUND RADIATION

R. B. PARTRIDGE

Haverford College
Haverford, PA 19041 USA
bpartrid@haverford.edu

Abstract.

My goal is to summarize our understanding of the cosmic microwave background radiation (CMBR) at this interesting moment after the detection of fluctuations in the background and before the next generation of satellite experiments. I begin by listing recent reviews and papers on the spectrum of the CMBR. I then sketch the current theoretical description of the power spectrum of fluctuations in the CMBR. Astronomical foregrounds and the nature of secondary fluctuations are treated next. Then I turn to observations, with special emphasis on the final results of the COBE–DMR experiment, on the growing evidence for $\Delta T/T = 2 - 3 \times 10^{-5}$ fluctuations at degree scales, and on what they tell us about cosmological parameters.

1. Introductory Remark

I should begin by explaining that I am preparing this review because a colleague had to withdraw at the last minute. I regret she could not come to Kyoto; I'll do my best to fill in for her. While I may not be the most appropriate reviewer, this *is* an appropriate time to assess the cosmic microwave background radiation (CMBR). On the observational side, there has been rapid progress. Equally, though, there is a momentary lull as we await two satellite experiments specifically designed to extract cosmological information from detailed mapping of angular variations in the background.

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2. Reviews

CMBR studies are now mature enough that both reviews and pedagogical articles are beginning to appear, eg. in IAU Symposium 168 (Kafatos and Kondo, 1996). At about the same time, a monograph appeared (Partridge, 1995). In the past few years, several conferences or workshops have been devoted to the CMBR: see Lineweaver *et al.* (1997) and electronic proceedings on **http://www.mrao.cam.ac.uk/ppeuc/proceedings.** Readhead and Lawrence (1992) summarized searches for anisotropies in the CMBR just before the recent explosion of observational activity. Other reviews of some observations are given by Scott and Smoot (1997) and Netterfield *et al.*(1997).

Theoretical predictions of the scale and amplitude of anisotropies in the CMBR are now both sophisticated and widely agreed on. White, Scott and Silk (1994) provide a very useful summary and review. Other useful summaries have been prepared by theorists working with teams planning satellite missions: see, for instance, Bond, Efstathiou and Tegmark (1997) and Zaldarriaga, Spergel and Seljak (1997). Let me also mention two useful "pedagogical" articles which in many ways parallel the much briefer treatment in Section 3 below: Hu *et al.* (1997) and Hu and White (1997b), see also Sugiyama's article here.

Finally, since I will have nothing further to say about spectral measurements of the CMBR, let me present a brief annotated list of useful references; see also my 1995 book. At all wavelengths $\leq 1cm$, the best spectral measurements are those of the FIRAS instrument on COBE (see Mather *et al.*, 1994) and the rocket experiment conducted by Gush and his colleagues (1990). The essentially final analysis of the COBE–FIRAS data gives $T_0 = 2.728 \pm 0.004K$ (Fixsen *et al.*, 1996); the constraints set by these observations are discussed by Wright *et al.* (1994), by Burigana *et al.* (1991) and Fixsen *et al.* (1996). At longer wavelengths, observations are less precise. In particular, work at $\lambda \gtrsim 15cm$ is plagued by Galactic foreground emission. Nevertheless, work is continuing—see Staggs *et al.* (1996a), for instance, who report $T_0 = 2.65^{+0.33}_{-0.30}K$ at $\lambda = 21cm$, and more recently $2.730 \pm 0.014K$ at $3cm$ (1996b). A paper deserving more notice is one by Ajello *et al.* (1995) on atmospheric emission at cm wavelengths.

3. Theory of CMBR Fluctuations and the Cosmological Parameters They Reveal

It has been recognized for three decades (Sachs and Wolfe, 1967; Silk, 1968) that cosmic density inhomogeneities will produce fluctuations in the CMBR. What has emerged in the past few years is widespread agreement on the angular scale and amplitude of such fluctuations, on the best way

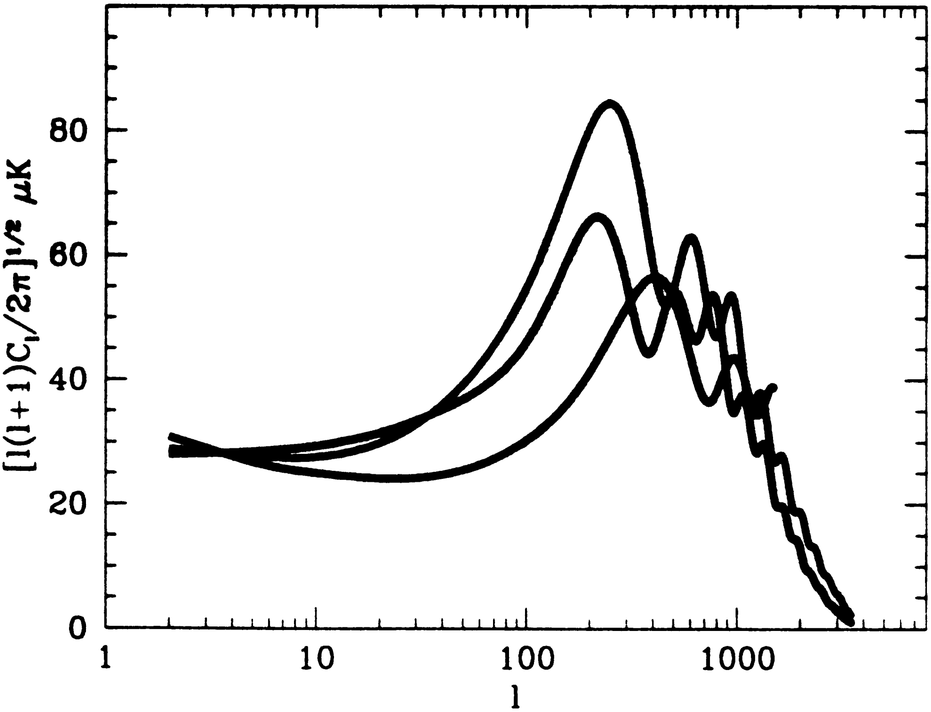

Figure 1. Predictions by M. Tegmark of CMBR anisotropy for several cosmological models (see Tegmark, 1996). The solid line shows C_ℓ for a standard cold dark matter model with $\Omega = 1$ (and $\Omega_b = 0.05$); note the prominent acoustic peaks. The dashed line is a similiar model for $\Omega = 0.3$; note the shift of the first acoustic peak to larger values of ℓ. Finally, the dotted curve is for a model with non-zero cosmological constant, as an example of how other cosmological parameters can affect the amplitude and placement of the acoustic peaks.

to characterize them for comparison with observational results, and on the physical processes which "translate" density inhomogeneities into temperature fluctuations at various scales. Theoretical predictions are now conventionally presented as power spectra C_ℓ of fluctuations in the CMBR, where ℓ is the multipole moment. One set of calculations is shown as figure 1.

3.1. BASIC FEATURES OF POWER SPECTRA OF THE CMBR

There are three general characteristics of these curves: a "plateau" at small ℓ (large angular scales); an oscillating region at $100 \lesssim \ell \lesssim 1000$; and a cutoff at $\ell \gtrsim 2000$. Each has an interesting cosmological explanation.

The plateau at $\ell \lesssim 100$, or angular scales greater than the horizon scale

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$\theta_H \sim 2°$, corresponds to a physical scale $\sim ct$, with t the epoch of last scattering ($\sim 300,000 yr$). Physical processes cannot have operated over scales exceeding the horizon scale. Thus the density perturbations and the resulting temperature fluctuations we see on this and larger scales are unaffected by any physical process, so we observe directly the primordial spectrum. At low ℓ, Sachs–Wolfe (1967) fluctuations dominate. These are independent of θ or ℓ (hence the flat plateau), provided the index of the power–law spectrum of density fluctuations is n=1, as expected in inflationary models.

At angular scales $< \theta_H$, physical processes could and did operate at and before the epoch of last scattering at $z = 1000$. Thus smaller scale fluctuations are model dependent, and it is observations on angles $\leq 2°$ that will allow us to discriminate between various models for the formation of large–scale structure and to determine some cosmological parameters (see Sugiyama here for further details).

Finally, on scales $\theta < \theta_d = 7'\Omega,^{1/2}$ CMBR fluctuations are damped out (for details, see Hu and White, 1997a). The characteristic scale θ_d represents the finite thickness of the last scattering surface. Observations on angular scales $< \theta_d$ average over both positive and negative density fluctuations within the finite thickness of the surface of last scattering. Thus at smaller values of θ, or ℓ of > 2000, the amplitude of temperature fluctuations drops off rapidly. A consequence is that any CMBR fluctuations observed on scales $\lesssim 7'$ cannot result from density perturbations on the surface of last scattering at z = 1000. Thus they cannot be *primary*. Some mechanisms for the production of small scale *secondary* fluctuations, introduced at lower redshifts, are discussed in §3.4.

To complete our cartoon of theorists' models for C_ℓ as a function of ℓ or angular scale, we consider *cosmic variance*. Theoretical models of temperature fluctuations fix their overall amplitude. Different realizations of the same theoretical model, however, can produce different values for the coefficients $C_{\ell,m}$. Thus there is some intrinsic uncertainty, called cosmic variance, in a particular realization of the model. The cosmic variance is

$$\sigma_\ell / C_\ell = \sqrt{2/(2\ell + 1)},$$

provided measurements extend across the whole sky. Clearly, cosmic variance is small for large ℓ, where many samples of C_ℓ are available.

3.2. EXTRACTION OF COSMOLOGICALLY SIGNIFICANT SIGNALS IN THE PRESENCE OF FOREGROUNDS AND INSTRUMENTAL SYSTEMATICS

The presence of astrophysical foregrounds and of statistical and systematic errors in observations obviously limits our ability to match observations of

C_ℓ to theoretical predictions such as those presented above.

For simple one–dimensional scans of sky (see §4.2 below) relatively simple corrections for foreground emission can be applied. These corrections generally involve point–by–point scaling of observations or maps made at other frequencies to the frequency of observation. The COBE–DMR maps, on the other hand, spanned the entire sky, with nonuniform coverage. In addition, the DMR instruments recorded only temperature *differences* between two points in the sky. Hence the corrections for foregrounds and instrumental effects are more complex. Among the recent papers treating foregrounds in the COBE data are a series of *Ap. J. Letters*, vol. **464**.

The problem of foregrounds continues to be of interest as we plan higher sensitivity satellite observations. Brandt *et al.* (1994) examine the foreground question using Monte Carlo simulations of the CMBR and foregrounds. More recently, several analytical approaches have been introduced (e.g., Tegmark and Efstathiou, 1996). Building on earlier results developed by Cheng *et al.* (1994) for the analysis of COBE–DMR data, Dodelson (1997) has extensively investigated degradation of cosmic signals caused by foregrounds. He shows that the degradation can be measured by a simple scalar, and that for the kind of frequencies being discussed for satellite experiments, the degradation factor ranges between ~ 1 and ~ 4. He also provides a brief but useful comparison to earlier work referred to above.

All of these authors consider primarily Galactic foregrounds (which certainly dominated the COBE error budget). The higher sensitivity and resolution of planned satellite observations (especially the Planck–Surveyor) make them more susceptible to foreground noise from discrete extragalactic sources, including both radio sources and S–Z fluctuations imprinted on CMBR (see Fomalont's paper here). Foreground fluctuations from radio sources are treated in detail by Toffolatti *et al.* (1997). The error radio sources introduce drops rapidly as frequency increases, since most extragalactic radio sources have spectra with a $\alpha \lesssim -2$ (see Condon *et al.*, 1995 for an encouraging limit on sources with a spectral peak in the GHz range). It is worth remarking that two new wide–area surveys, FIRST (Becker *et al.*, 1995) and NVSS (Condon *et al.*, 1996), will prove useful in locating extragalactic radio sources bright enough to affect CMBR maps. What is missing is information about the *spectrum* of these sources, especially at frequencies $> 10\ GHz$ where CMBR measurements are made.

3.3. POLARIZATION

A variety of mechanisms will introduce linear polarization into the microwave background on a range of angular scales. Except in special cases, the amplitude of the polarized signal is $\lesssim$10% of the amplitude of total

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power fluctuations, or very roughly $\Delta T_p/T \lesssim 10^{-6}$. However, contamination from foregrounds may be sharply reduced (few astrophysical sources are strongly polarized), and measurements of polarization are free of some systematics which affect total power measurements. Nevertheless, we currently have only upper limits on linear polarization of the CMBR (see Table 1).

TABLE 1.

Reference	Approx. Scale, ℓ	Upper Limit on $\Delta T_p/T$
Lubin, Melese, Smoot (1983)	$\ell = 2$	$\lesssim 7 \times 10^{-5}$
Netterfield *et al.*(1995)	$50 \lesssim \ell \lesssim 100$	$\lesssim 0.6 \times 10^{-5}$
Partridge *et al.*(1997)	$\ell \sim 4000$	$\leq 1.0 \times 10^{-5}$
Partridge *et al.*(1997)	$\ell \sim 50,000$	$\leq 7.4 \times 10^{-5}$

Despite our failure to detect CMBR polarization, it is a topic of considerable interest now. One reason is that planned satellite missions may well have the sensitivity to map polarization on scales $0.1° - 100°$. Another is that detection and characterization of polarized CMBR fluctuations will allow us to determine some cosmological parameters with either greater precision or greater confidence than the measurement of C_ℓ in total power alone (see Hu and White, 1997b for an excellent review). Two physical principles are involved. First, polarized fluctuations are induced *only* on the surface of last scattering, unlike total power fluctuations which continue to evolve as the CMBR photons move through non–uniform gravitational potentials (Sachs and Wolfe, 1967). Polarized fluctuations thus provide the clearest "snapshot" of the surface of last scattering. Second, the angular dependence of the polarization pattern has distinct and different characteristics for each of the three modes of density perturbation: scalar, vector and tensor (Hu and White, 1997b). All–sky maps of linear polarization and of the signal produced by correlating polarization with total power fluctuations may allow us to assess the relative contributions of these three modes. It has also been recognized for some time (e.g., Bond and Efstathiou, 1987) that the angular scale of polarized fluctuations depends on the epoch of last scattering (from the first principle above). Polarization measurements thus provide a useful means of searching for full or partial reionization, which would shift the epoch of last scattering to $z = 10 - 100$, say.

3.4. REIONIZATION AND SECONDARY FLUCTUATIONS

Let us look more generally at the issue of reionization and its effect on models for C_ℓ. Reionization, by whatever means (QSO formation? the first generation of stars?), if it occurs at a large enough redshift, reintroduces

Thomson scattering. Photon directions are scrambled and primary CMBR fluctuations washed out (see Partridge, 1995 for a heuristic discussion).

However, if the reionized material is non–uniform, as it is expected to be, new anisotropies can be imprinted on the CMBR, referred to as *secondary* fluctuations. Because there is no agreement on what causes reionization, or at what epoch it occurs, models for secondary fluctuations are less well developed than those for primary fluctuations. Work on secondary fluctuations is being driven both by the promise of future satellite measurements and by ground–based observations on scales $< 7'$, where primary fluctuations are absent, so any observed fluctuations *must* be secondary.

I list below some of the mechanisms suggested for the production of CMBR fluctuations on arcminute scales and below, i.e., at $\ell \gtrsim 5000$.

1. Non–linear effects are produced by density perturbations on the new surface of last scattering produced by reionization (Vishniac, 1987).

2. Cosmic strings (e.g., Moessner *et al.*, 1994) introduce step–like discontinuities into the temperature distribution of the CMBR. A network of strings produces CMBR fluctuations with non–Gaussian statistics. High resolution observations (Partridge *et al.*, 1997) place limits on the mass per unit length of cosmic strings in such models.

3. Lyman$-\alpha$ clouds produce bremsstrahlung radiation, which in turn may be detected as fluctuations in the CMBR (Loeb, 1996).

4. Redshifted, far infrared emission from early star–forming galaxies produces fluctuations in the microwave sky, particularly at short wavelengths (Bond *et al.*, 1991).

5. The Sunyaev–Zel'dovich effect (1980 and references therein), caused by the scattering of CMBR photons by electrons in hot plasma, adds both noise and signal. Several sites for such hot plasma have been suggested: Zel'dovich "pancakes," precursors of superclusters, (Subba–Rao *et al.*, 1994) and clusters of galaxies (see Rephaeli, 1995 for a review, Fomalont here and Richards *et al.*1997 for recent observations).

4. Progress on the Observational Side

To what extent are the predictions outlined above supported by observations? As we will see, many are, but the observations are not yet detailed enough to provide competititve values for most cosmological parameters.

4.1. ANALYSES OF 4 YEARS OF COBE–DMR DATA

The major breakthrough on the observational side was the announcement in 1992 (Smoot *et al.*) of the detection of anisotropies in the CMBR by the Differential Microwave Radiometer (DMR) experiment flown on COBE.

The rms amplitude of CMBR fluctuations initially reported was $\Delta T/T \sim 1.1 \times 10^{-5}$. The COBE team has now completed the analysis of a full four years of DMR observations (e.g., Bennett *et al.*, 1996) in a series of papers in vol. **464** of *Ap.J. (Letters)* and in four subsequent papers: Banday *et al.*(1996), Lineweaver *et al.*(1996), Kogut *et al.*(1996a) and Banday *et al.*(1997).

Here, I summarize the basic results. First, COBE-DMR has made an exquisitely accurate measurement of the dipole moment of the CMBR, induced by our peculiar velocity. It is $T_1 = 3.358 \pm 0.023\, mK$ in the direction $\ell = 264°.31 \pm 0°.16, b = +48°.05 \pm 0°.09$ (Lineweaver *et al.*, 1996). Here I quote systematic errors; the statistical uncertainties are much lower. DMR also established that the quadrupole moment is far smaller, an important result that can be used to rule out many classes of anisotropic cosmologies (see Partridge, 1995, for discussion). The measured value is $T_2 = (10.7 \pm 3.6 \pm 7.1)\mu K$ or $\sim 1/300\ T_1$. Here, the statistical uncertainty is given first; it is smaller than the systematic error term of $\pm 7.1 \mu K$, which is largely due to uncertainty in the correction for Galactic microwave emission. Note that T_2 is somewhat lower than the amplitude determined for multipole moments $\ell = 3 - 40$.

In addition, COBE-DMR is ideally suited to determining the amplitude of C_ℓ in the low-ℓ, plateau region. That normalization is conventionally given as the projected amplitude of the quadrupole moment ($\ell = 2$) determined by measurements over a range of ℓ from 2 to ~ 40. (Because of cosmic variance, the $\ell = 2$ moment itself cannot be determined precisely.) This normalization of C_ℓ, $(Q_{rms})_{PS}$, is given as $15.3^{+3.8}_{-2.8} \mu K$ by Bennett *et al.*(1996). The measurements also allow a determination of the index n of the power law spectrum of initial density perturbations, $n = 1.2 \pm 0.3$, consistent with a value of n=1 predicted by most inflationary models. As noted, the value found for the quadrupole moment itself was rather low; a low value at $\ell = 2$ "tilts" the spectrum towards $n > 1.0$ and lowers $(Q_{rms})_{-PS}$. CMBR anisotropies can also be characterized more roughly by the rms fluctuation level averaged across the sky. That parameter (Banday *et al.*, 1997) is $29 \pm 1\ \mu K$, rms or $\Delta T/T = (1.06 \pm 0.04) \times 10^{-5}$.

Kogut *et al.*(1996a) present a detailed error analysis of the 4-year DMR data, and other papers examine the effect of foreground contamination of the CMBR signal. Banday *et al.*(1996) show that extragalactic foregrounds affect the DMR results negligibly and Kogut *et al.*(1996b) examine the effect of Galactic foregrounds, which do contaminate the CMBR signal, especially on the quadrupole scale.

4.2. OBSERVATIONS ON DEGREE SCALES

Encouraged by both the COBE-DMR results and the increasing precision of theoretical predictions, many groups have been carrying out measurements on smaller angular scales, roughly $\ell = 50 - 500$. Both ground-based and balloon-borne experiments have been mounted, and both HEMT and bolometer receivers used. Interestingly, neither technique (and neither detector) has yet emerged as a strong favorite. In Table 2, I have summarized results of recent work on these scales (and a few earlier results on smaller scales). New results appear frequently; observations on degree scale form the most active area of experimental CMBR studies. Here, I will emphasize several new developments, present a summary figure, and try to draw some conclusions on the basis of the results available as of July 1997.

TABLE 2. Some Recent Measurements

Experiment	Freq.(GHz)	Scale (ℓ)	Recent Ref. (all *Ap.J.*)	Approx. $\Delta T/T \times 10^{-5}$
ACME/HACME	26-45	32-109	Gunderson *et al.*1995	$1.8^{+1.6}_{-0.5}$
Saskatoon	26-46	52-401	Netterfield *et al.*1997	See figure 3.
Python	30-90	55-240	Platt *et al.*1997	2.2-2.4
MAX	90-420	78-263	Lim *et al.*1996 Tanaka *et al.*1996	< 1.3 $1.2^{+0.4}_{-0.3}$
BAM	110-250	30-100	Tucker *et al.*1997	$3.1^{+3.3}_{-1.1}$
ARGO	150-600	53-180	Masi *et al.*1996	~ 0.7
MSAM	150-650	69-362	Inman *et al.*1997 Cheng *et al.*1996	$1.9^{+1.3}_{-0.7}$
CAT	13-17	339-722	Scott *et al.*1996	2.0 ± 0.4

4.2.1. *Recent Developments*

First, thanks to improvements in receiver sensitivity, many of these experiments are producing statistically robust detections of CMBR observations in a single flight or campaign. Increased sensitivity has also allowed some

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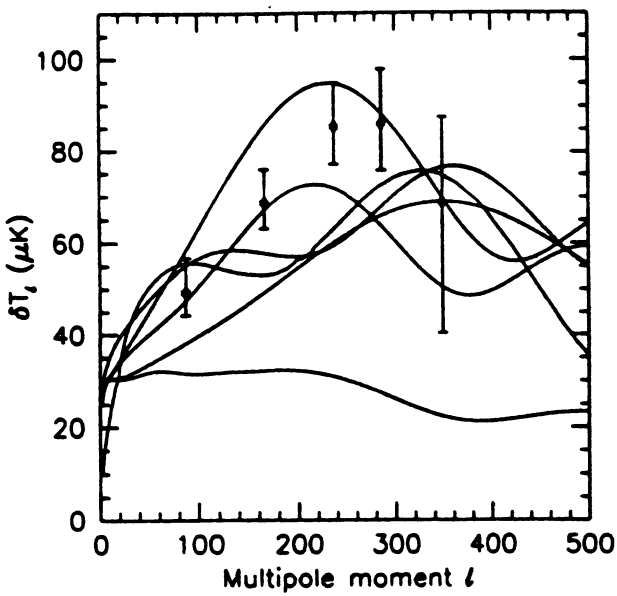


Figure 2. The measurements of Netterfield *et al.*(1997); see reference for description of theoretical curves.

groups to isolate specific features in the CMBR (see Hancock *et al.*, 1995, or Inman *et al.*, 1997). Also, high sensitivity allows such experiments to detect the dipole moment of the CMBR and use it as an internal calibration.

The confrontation of theory with CMBR observations has long been plagued by the problem that different groups look at different regions of the sky, making intercomparison of results difficult. It was a real step forward when Ganga *et al.*(1993) were able to correlate anisotropies observed at 170 GHz with the early COBE maps. Subsequently, both the Tenerife group (Hancock *et al.*, 1995) and the MSAM collaboration (Inman *et al.*, 1997) repeated observations of patches of the sky observed earlier, to confirm reported detections of fluctuations in the CMBR. Another step forward was the Saskatoon experiment (Netterfield *et al.*, 1997) which obtained results over a wide range of ℓ, spanning the first acoustic peak (fig. 2). Thus a single experiment revealed both the rise and the fall in C_ℓ, without the need for intercomparison of measurements from different groups.

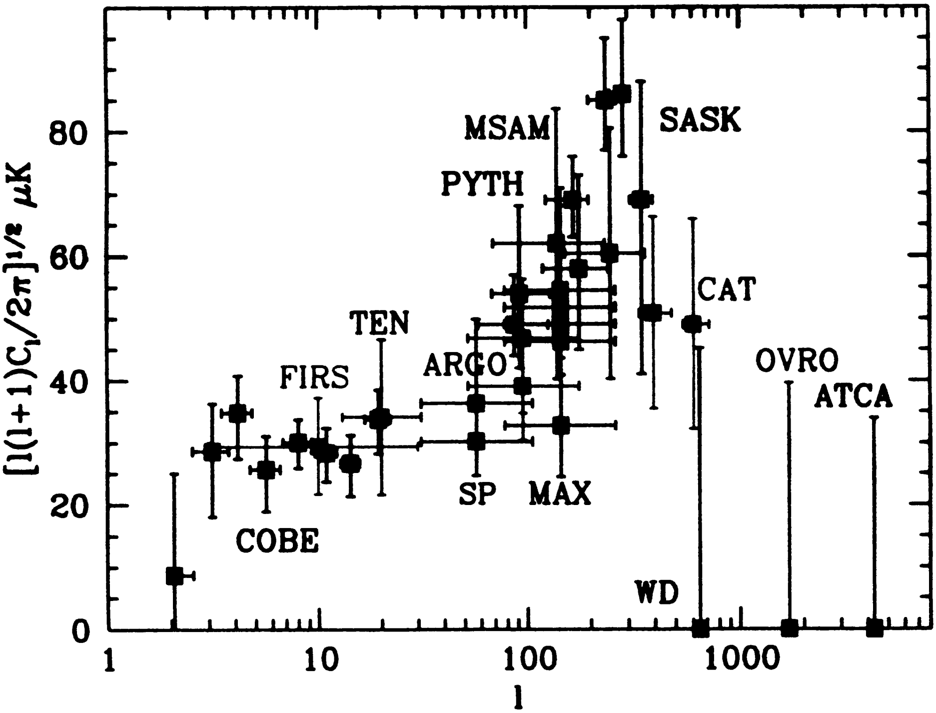
New techniques have been explored. For instance BAM (Tucker *et al.*, 1997) uses a Fourier transform spectroscope to measure ΔT over a large wavelength range (1.1-3.2 mm). Such an instrument, of course, cannot be operated from the ground; it was one of several balloon experiments listed in Table 2. Another new technique (one I believe holds much promise) is the adoption of interferometry to much larger angular scales than usual in microwave aperture synthesis. This requires (and permits) the design of specialized interferometers, like CAT (Scott *et al.*, 1996) which produced a first interferometric map on $\sim 1/4^\circ - 1/2^\circ$ scales last year. The sensitivity obtained in each pixel was roughly comparable to the sensitivity obtained in beam switched experiments. Interferometers like CAT also naturally produce 2-dimensional sky images; groups using beam switched equipment are now interleaving their measurements to produce comparable 2-d coverage (e.g., Platt et al., 1997). Thus, over restricted patches of the sky, we are beginning to build up maps of the microwave sky with angular resolution 10 or more times finer than COBE's.

4.2.2. *What the Observations Show*

What conclusions may we draw from the results assembled in Fig. 3? Clearly, the sensitivity of even the best experiments to date is limited; most exclude $\Delta T = 0$ at only 3σ or so. There are also discrepant results at essentially the same value (or range) of ℓ. Some of the scatter among points in fig. 3 may be due to different techniques used by different groups (including techniques for correcting for foregrounds). Some scatter is surely also due to cosmic variance (recall each experiment samples only a few pixels). Given the size of the error bars, I don't find the discrepancies troubling.

As figure 3 (courtesy M. Tegmark) shows, the plateau region is well characterized. The amplitude determined by COBE is small enough to require some form of dark matter; pure baryon models would produce larger ΔT. The absence of discernible slope in the low-ℓ region suggests the index of density fluctuations is close to the value expected in straightforward inflationary models, $n = 1$; indeed COBE shows $n = 1.2 \pm 0.3$.

Now let us look at what the apparent detection of the acoustic peaks at larger ℓ can tell us (even given the scatter of the data). I would argue that a peak has been detected: ΔTat $\ell \sim 200$ is well above $(Q_{rms})_{PS}$. That alone is enough to cast some doubt on models in which cosmic defects, rather than gravity, drive galaxy formation, since these do not produce acoustic oscillations (see Turok,1997 and Sugiyama here). The lower line in fig. 3 is such a model. The *position* of the acoustic peak, as revealed for instance by the measurements of Netterfield *et al.*(1997), provides constraints on the density parameter, Ω. The argument is a simple one: the relationship between observed angular diameter and linear scale depends on curvature. In a flat model ($\Omega = 1$ if $\Lambda = 0$), we expect the first acoustic peak at $\ell \sim 200$ (close to 1°); if $\Omega = 0.3$, say, the first peak will appear at smaller θ or $\ell \sim 500$. Even the crude measurements now available (fig. 2) favor a



value of $\Omega \sim 1$ from this geometrical argument.

As Sugiyama shows here, the relative amplitudes of the first and subsequent acoustic peaks is determined in part by other cosmological parameters such as Ω_b, Λ and H_o. In my view, the data are not yet clear enough to allow us to say much about any parameter but Ω (but see Lineweaver here). It is the aim of the two planned satellite experiments, MAP and Planck-Surveyor, to measure the acoustic peaks with sufficient precision to determine parameters like H_o, Ω_b, and the ratio of tensor to scalar perturbations, to unprecedented accuracy (e.g., Zaldarriaga *et al.*, 1997).

Finally, observations at arcminute scales and below show that the amplitude of CMBR fluctuations drops below $(Q_{rms})_{PS}$ at $\ell \gtrsim 1000$, consistent with the argument in §3.1 about the thickness of the last scattering surface. The angular scale of the cutoff implies that the epoch of last scattering was indeed at $z \sim 1000$, and that later re–ionization occurred so recently that it did not produce a large optical depth in scattering. When we map the CMBR, we are indeed studying a surface at $z \sim 1000$.

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