What have we already learned from the CMB?

Charles R. Lawrence[1], Douglas Scott[2] and Martin White[3]

[1]Jet Propulsion Laboratory,
169-506, 4800 Oak Grove Drive,
Pasadena, CA 91109 U.S.A.

[2]Department of Physics & Astronomy,
129-2219 Main Mall, University of British Columbia,
Vancouver, B.C. V6T 1Z4 Canada

[3]Departments of Astronomy & Physics,
University of Illinois at Urbana-Champaign,
103 Astronomy Building, 1002 West Green Street,
Urbana, IL 61801 U.S.A.

ABSTRACT

The COsmic Background Explorer (*COBE*) satellite, and the Differential Microwave Radiometer (DMR) experiment in particular, was extraordinarily successful. However, the DMR results were announced about 7 years ago, during which time a great deal more has been learned about anisotropies in the Cosmic Microwave Background (CMB). We assess the current state of knowledge, and discuss where we might be going. The CMB experiments currently being designed and built, including long-duration balloons, interferometers, and two space missions, promise to address several fundamental cosmological issues. We present our evaluation of what we already know, what we are beginning to learn now, and what the future may bring.

Subject headings: cosmic microwave background – cosmology: observations – cosmology: theory – large-scale structure

All right. But apart from the sanitation, the medicine, education, wine, public order, irrigation, roads, the fresh water system, and public health ... What have the Romans ever done for us?

Reg, spokesman for the People's Front of Judea[1]

1. Introduction

The study of the cosmic microwave background (CMB) radiation has had a long history. Three aspects of the CMB might be considered: its existence, its spectrum, and its anisotropies. By firmly establishing that the Universe expanded from an initially hot, dense state, the *existence* of the CMB underpins our entire cosmological framework. It has been recognized from the beginning as one of the pillars of the hot big bang cosmologies. The spectrum of the CMB is the most precise blackbody spectrum in nature, from which many inferences can be made. Although this discovery is less than a decade old, its impact on models of the early Universe been discussed extensively elsewhere, (e.g. Nordberg & Smoot 1998). In this paper we would like to consider the *anisotropies* in the CMB, the small fluctuations imprinted on the sky by the progenitors of the large-scale structure seen in the distribution of galaxies today.

In the roughly seven years since the *COBE* DMR team announced the first detection of anisotropies in the CMB (Smoot et al. 1992), more than a dozen groups have reported detections, covering the full range of frequencies and a wide range of angular scales (see Smoot & Scott 1998, Bennett, Turner & White 1997). Due in large part to a dramatic increase in detector sensitivity, mapping the CMB anisotropy has become almost routine. Our confidence in the results has grown as multiple observations by the same teams over a period of years, and then later by different experiments at different frequencies and sites, reproduced the same features on the sky and confirmed their black body nature.

Over the same period much progress has been made in data analysis techniques and in the theoretical interpretation of CMB data. Better physical understanding of the anisotropy generation has lead to faster algorithms for its computation (e.g. Seljak & Zaldarriaga 1996, Hu et al. 1998) applicable to an impressively wide range of theories. The high precision calculations and accurate measurements of the anisotropy have spawned numerous ideas in data analysis, with a full likelihood analysis of mega-pixel CMB maps

---

[1]Python, M. 1979

now within reach (Oh, Spergel & Hinshaw 1999).

However, since much of the progress has been incremental, it is not always obvious just how far we have really advanced. It therefore seems appropriate to take stock and ask the question:

What has the CMB ever done for us?

2. The Lists

From a broad perspective, the main impact of CMB anisotropies has been to shrink substantially the range of cosmological models under active discussion. This is not always easy to see, since the *number* of models proposed at any time seems to be determined more by the number of theorists working in the field than by any constraints provided by the data. Moreover, it sometimes seems that no class of model has been ruled out. However, looking back a decade in the literature makes it clear that this is not true.

Even before *COBE*, the high level of isotropy of the CMB was perhaps the best possible evidence that the large-scale properties of the Universe were well described by the Friedman-Robertson-Walker metric. The assumption of homogeneity and isotropy, initially made for purely aesthetic reasons, turned out to be an extremely good approximation to the real Universe. As the limits on anisotropy became stronger and stronger, the number of models based on anything but the FRW metric became fewer and fewer.

Currently popular models assume that the matter in the FRW Universe is composed *mostly* of Cold Dark Matter (CDM), with smaller admixtures of baryons and perhaps massive neutrinos, plus curvature and/or vacuum components. For these CDM-inspired models, the CMB data have been instrumental in narrowing the range of possibilities, and most popular flavours of CDM now give remarkably similar predictions. Models dominated by Hot Dark Matter, already in trouble before *COBE*, are no longer discussed. Two other classes of models, namely defects and isocurvature models, have not been ruled out definitively, but they are now very much on the defensive against the weight of data. Explosion models (Ostriker & Cowie 1981, Ikeuchi 1981, Carr & Ikeuchi 1985, Vishniac, Ostriker & Bertschinger 1985, Wandel 1985, Ostriker & Strassler 1989, Weinberg,

Dekel & Ostriker 1989), super-conducting cosmic string models (Ostriker, Thompson & Witten 1986, Ostriker & Thompson 1987, Borden, Ostriker & Weinberg 1989), and late-time phase transition models (Wasserman 1986, Hill , Schramm & Fry 1989, Press, Ryden & Spergel 1990, Fuller & Schramm 1992, Frieman, Hill & Watkins 1992, Jaffe, Stebbins & Frieman 1994) have essentially vanished.

Figure 1 shows the current state of CMB measurements. Included are all detections we are aware of that have been published or submitted for publication in 1998. The results have been averaged in 12 bins, equally spaced in $\log \ell$ for clarity, and we have omitted the upper limits on smaller angular scales, most of which are off the right of the plot with our chosen ℓ-axis range. This figure is meant to be indicative only. More statistically rigorous approaches exist for combining data sets (e.g. Bond, Jaffe & Knox 1998), and such methods should certainly be used for determining precise constraints on models. However, Fig. 1 gives approximately the correct visual impression for the combined constraining power of today's data.

Below we list two sets of statements that we believe are supported by the data: the first set contains 'fundamental truths' about the Universe; and the second contains statements that will be fundamental truths if confirmed, but that for the present must be regarded more tentatively.

Here is the 'A' list:

A1 Gravitational instability in a dark matter dominated universe grew today's structure

A2 The Universe (re)combined

A3 There is an excess of temperature fluctuations at roughly the predicted angular scale

A4 The polarization of the CMB anisotropy is small

And the 'B' list:

B1 Something like inflation produced adiabatic fluctuations

B2 The large-scale structure of space-time appears to be simple

B3 The gravity wave contribution to the anisotropy is not large

B4 There are constraints on non-standard physics at $z \sim 10^3$

We now discuss these in turn, distinguishing between those demonstrated by *COBE* alone, and those demonstrated by the measurements at smaller angular scales that have been made since *COBE*.

2.A.1 Gravitational instability

Perhaps the most useful result of the *COBE* anisotropy data is the normalization of models of structure formation at large-angles, where the fluctuations in the matter and photons are expected to be in the linear regime. In today's favoured models of structure formation these large-angle anisotropies directly measure the amplitude of the gravitational potential on very large scales, allowing a theoretically clean and precise normalization of the matter power spectrum. This normalization, it turns out (e.g. Bond, Efstathiou & White 1992), is in the right ball-park to explain the amplitude of galaxy clustering (and with a little tuning of this or that parameter it is easy to get complete consistency). This is a vindication of our ideas that galaxies grew gradually under the action of gravitational instability.

Before the *COBE* anisotropy was announced it was often claimed (e.g. Kolb & Turner 1990) that extra physics would be needed if the results turned out to yield yet more upper limits; right up to the DMR announcement it was also commonly perceived that inflationary adiabatic models had difficulty having a high enough amplitude to form structure without violating CMB limits (e.g. Gooding et al. 1993). The fact that the anisotropies were measured at the levels predicted, in models with cold dark matter and adiabatic fluctuations, showed that there is no need to invoke extra magical processes to form structure by the present day. However, since the photons prevent baryonic matter from collapsing before recombination, we infer that the gravitational potentials had to be dominated by matter which was not prevented from collapsing by photon pressure, i.e. matter that was not coupled to photons and was 'dark'. The realization, from studies of

the galaxy distribution in the local Universe, that matter formed 'bottom up' rather than 'top down' constrains the velocity dispersion of the dominant dark matter component to be extremely small – the dark matter must be mostly *cold*.

2.A.2 Recombination

Here we are moving beyond simply an interpretation of the *COBE* data, and looking at the large number of detections of anisotropy at degree and sub-degree scales (see Fig. 1). Early reionization of the Universe gives increased optical depth to Thomson scattering from the present back to the epoch of reionization. The extreme case is a universe which did not (re)combine at all and remained ionized for all time. Multiple scattering erases existing anisotropies on scales smaller the horizon. Thus reionization leads to damping of primordial anisotropies on small scales (Sugiyama, Silk & Vittorio 1993, Hu & White 1997).

The presence of fluctuations at $\ell \gtrsim 100$ is clear evidence that the Universe was not reionized at a very early epoch. We can be confident that the Universe recombined at $z \simeq 10^3$, then remained largely neutral until some redshift $z_{\rm reion}$, after which it was largely ionized (as implied by the absence of Gunn-Peterson absorption in the spectra of high-z quasars). The precise value of $z_{\rm reion}$ derived from fits to the data depends on the cosmological model, but is typically $z_{\rm reion} < 50$ (Scott, Silk & White 1995, Tegmark 1998).

2.A.3 Degree scale power

We believe that Fig. 1 shows a peak in power in the anisotropies at scales around a degree. The *precise* position of this peak, how high it might be, and whether it contains any substructure, are not so clear (see e.g. Scott, Silk & White 1995, Hancock et al. 1997, Lineweaver 1998, Bartlett et al. 1998, Bond, Jaffe & Knox 1998, Tegmark 1998). However, it is striking that this feature is in the general location of the main acoustic peak predicted by currently favoured models, based on the angular size of the horizon at last scattering. It is worth stressing that this prediction was made more than a decade before the experiments were performed (see for example Doroshkevich, Zel'dovich & Sunyaev 1978). We expect the location of the peak to be determined definitively quite soon, by upcoming ground based and balloon experiments, interferometers and *MAP*, leading to very strong observational constraints on the angular diameter distance back to last scattering ($z \sim 10^3$).

2.A.4 Polarization

It is a fundamental prediction of the gravitational instability paradigm that the CMB

anisotropy is linearly polarized. In inflationary CDM-like models the level of polarization is a few percent of the anisotropy, and thus extremely small in absolute terms. There are already many limits on the polarization of CMB anisotropy (see Hu & White 1997 for a list), however they are all nearly an order of magnitude larger than the theoretical predictions. The fact that the CMB is not 'very' polarized tells us important information about the conditions at the last scattering epoch. That the CMB is not very circularly polarized, for example, indicates that there were no large magnetic fields present at last scattering (see also §2.B.4), although we are only aware of very stringent upper limits at the smallest angular scales (Partridge et al. 1997).

2.B.1 Inflation

We put this item at the very top of our 'B'-list since we feel the weight of evidence is becoming very strong for something akin to inflation (for a discussion of whether inflation is really a testable theory, see Barrow & Liddle 1997). To avoid semantic arguments, it is important at the outset to be clear about the meaning of 'inflation'. Here we refer to a period of accelerated expansion in the early Universe. This is the only known mechanism for making an isotropic and homogeneous universe, and at the same time generates apparently acausal adiabatic fluctuations, i.e. fluctuations in spatial curvature on scales larger than the Hubble-length at a particular epoch. We do not intend 'inflation' to carry the additional baggage of an inflaton field with a well-defined potential, connected with particle physics, etc., although ultimately we would all like to see the mechanism of inflation find a realization in a well motivated theory of fundamental physics.

The amplitude and power spectrum of CMB anisotropies from degree-scales up to the largest scales probed by *COBE* seem to indicate that super-horizon size adiabatic fluctuations exist. Our first hint comes from the normalization of the large-scale anisotropies relative to the matter (see e.g. discussion in Scott & White 1996). On dimensional grounds we expect that the amplitude of the temperature fluctuations be $\mathcal{O}(\Phi)$ where Φ is the large-scale gravitational potential. In adiabatic models a cancellation (White & Hu 1997) between intrinsic anisotropies and gravitational redshifts means that the coefficient is reduced to 1/3, i.e. $\Delta T/T = -\Phi/3$ (Sachs & Wolfe 1967). In the simplest isocurvature models the coefficient is 2. Since, as we mentioned before, our currently popular theories 'work', there is little room to absorb a factor of 6 in relative normalization. Of course this alone is not proof of adiabatic fluctuations.

Our next piece of observational evidence is the angular scale of the 'peak' in power. The structure of the peaks (locations, separations, relative heights) is a strong discriminator between adiabatic and isocurvature models (Hu & White 1996). In almost all isocurvature

models the peak is shifted to smaller angular scales. Since we observe excess power at about the right place for adiabatic fluctuations in a flat universe, there is little room for either spatial curvature or isocurvature fluctuations (and the combination is particularly disfavoured!). Since the current evidence for a peak, in contrast to a rise, is modest we have put this in our 'B'-list. The observational situation is likely to change rapidly. In the future we can hope that detection of polarization on degree scales will finally pin down the fluctuation type beyond any argument (Hu, Spergel & White 1997, Hu & White 1997), but this is a difficult measurement due to the low levels of signal.

Thus there is reasonable evidence for adiabatic fluctuations in a spatially flat universe. The latter has long been hailed as a 'prediction' of inflation. The former is also tantamount to a 'proof' of inflation, in the sense that the only *causal* means for generating nearly scale-invariant adiabatic fluctuations is a period when $\ddot{a} > 0$ in the early Universe (see e.g. Hu, Turner & Weinberg 1994, Liddle 1995). Of course this condition is neither entirely necessary nor sufficient. On the sufficiency side, it is no doubt possible to imagine inflationary models which have fluctuations of an entirely different character, but it would seem pathological to deliberately avoid explaining density perturbations. And on the necessary side, one could in principle imagine some early Universe physics which somehow mimics the effects of inflation by producing super-horizon adiabatic modes, and yet is not inflation. We would argue that this is a purely semantic distinction: if it looks like inflation and smells like inflation, then let's call it inflation while leaving open the possibility that current inflationary ideas may one day be shown to be part of some better paradigm. In the same vein it may also be argued that some Planck-era physics somehow generates apparently acausal modes. Again we would say that is either isomorphic with inflation, or simply an attempt to push the question of initial conditions into the realm of metaphysics.

2.B.2 Space-time structure

We have already mentioned that the extreme isotropy of the CMB is a strong indication that the FRW metric is an excellent approximation to the large-scale properties of space-time. Strong quantitative limits on the rotation and shear of space-time for specific Bianchi models have been obtained from the *COBE* data (Bunn, Ferreira & Silk 1996, Kogut, Hinshaw & Banday 1997). And limits on the geometry for general models can be placed at the $\sim 10^{-5}$ level (Smoot 1991).

CMB anisotropies probe the Universe on the largest accessible scales, and so they also constrain things like the large-scale topology. There are quite stringent constraints in the simplest background models (Stevens, Scott & Silk 1993, de Oliveira-Costa, Smoot & Starobinsky 1996). However, in principle there may yet be observational consequences for

compact topologies, in an open universe in particular (Levin et al. 1997, Cornish, Spergel & Starkman 1998, Souradeep, Pogosyan & Bond 1998). Exactly how stringent the current constraints are, for general classes of cosmology on the largest scales, is still a matter of debate. Nevertheless, we probably know at this point that the Universe isn't *very* strange on Gpc scales, quite an advance over our previous ignorance.

2.B.3 Gravity waves

If whatever produces the initial density perturbations doesn't discriminate on the basis of perturbation type we would expect that scalar, vector and tensor fluctuations would be produced at early times in roughly equal amounts. The vector modes, representing fluid vorticity, decay with time and so would not be present after a few expansion times. Thus we would expect today to see only scalar (density) perturbations and tensor (gravity wave) perturbations. Both of these types of perturbation would give rise to large-angle anisotropies, though only the former will seed large-scale structure. Due to the aforementioned close consistency between the amplitude of the clustering on galaxy scales and the anisotropy seen by *COBE* there is a limit to how much the gravity wave signal can contribute to *COBE*. Roughly speaking, the tensor to scalar ratio $T/S < 1$ (see Salopek 1995, Markevich & Starobinsky 1996, Zibin, Scott & White 1999). If the tensor perturbations are not too different from scale-invariant this means that the possibility of seeing primordial gravity waves with detectors such as LIGO or LISA is small (Krauss & White 1992, Turner 1997, Liddle 1994, Caldwell, Kamionkowski & Wadley 1999).

As has been argued by Lyth (Lyth 1997), the low-level of gravity waves is good news for our current ideas about realizing inflation in simple particle physics inspired models. In the most popular models today, the scalar modes are expected to dominate over the tensor modes by many orders of magnitude. The expectation is therefore that the tensor signal may not be measurable with any existing or planned experiments, or conversely that a positive detection of gravity waves would have profound implications for our ideas about inflation. However, for the time being, the constraints on the gravity wave contribution have not reached the level where we learn much about early Universe physics – that will await future experiments.

2.B.4 Physics at $z \sim 10^3$

It is possible to use the fact that the CMB anisotropies are largely as expected to limit the magnitude of any surprises at the last-scattering epoch. The arguments are much akin to those using the observed abundances of the light elements and Big Bang Nucleosynthesis

theory to limit 'exotic' physics at early times. If something 'exotic' would dramatically alter the theoretical predictions, it can be strongly constrained. A great many possible physical effects have been studied, but here we will list only a few things for which it is already possible to place observational bounds. Strong limits exist on domains of anti-matter (Kinney, Kolb & Turner 1997), particle decays near $z \sim 10^3$ (Pierpaoli & Bonometto 1998), primordial voids from an early phase transition (Sakai, Sugiyama & Yokoyama 1997) and primordial magnetic fields (Barrow et al. 1997, Subramanian & Barrow 1998), among other things.

3. The Future

It was stated in the early 1960s, shortly before the discovery of the CMB, that there were only $2\,^1/_2$ facts in cosmology (by Peter Scheuer, see Longair 1993). In a similar spirit, we have argued that there are perhaps 4 facts and 4 half facts currently known from CMB anisotropies.

It has been recognized for some time that these anisotropies may answer some of our most fundamental questions about the Universe. The current CMB data already indicate that gravitational instability, in a mostly cold dark matter dominated universe, amplified initially small adiabatic fluctuations into the large-scale structure that we see today. There is the potential to show what inflationary-like process happened in the early Universe. And ultimately, the precise shape of the angular power spectrum holds the key to determining many of the fundamental cosmological parameters, either directly or in combination with other measurements.

However, while it is interesting to track progress in this field and to speculate on what it all means, it seems clear that theorists have had long enough to manoeuvre that the present data no longer strongly constrain any popular cosmological model. With the coming of long duration balloon flights, the imminent launch of the MAP satellite, and the commissioning of three new CMB interferometers, we expect that to change. The BOOMERANG team has already had a successful long duration balloon flight, and the analysis of that data set is eagerly awaited. Similar flights will undoubtedly follow, along with other large data sets from new ground-based experiments. The race is on, since MAP is scheduled for late 2000. A little later, sometime around 2006, will see the launch of the Planck Surveyor. Planck should supply us with essentially cosmic-variance limited information on all the angular scales relevant to primary anisotropies, over the full range of relevant frequencies. Figure 2 is an estimate of how well the power spectrum might be constrained after MAP and after Planck. With the proliferation of high precision data

future 'A' and 'B' lists will be correspondingly longer and more detailed. Our attempt at prognostication is represented in our list 'C':

C1 Cosmological parameters will be precisely determined

C2 Polarization will be measured over a range of scales

C3 We will learn about early Universe physics

C4 We will learn much about non-linear astrophysics

Item 1 is in fact already happening, as discussed earlier. However, the current set of anisotropy data is not very constraining, since there is enough parameter freedom to fit models with quite different values of any individual parameter (Tegmark 1998). This situation will undoubtedly improve in the future (unless of course *none* of the current models fits the data, which is surely the most exciting prospect of all!). Certainly some degenerate parameter combinations will continue to exist in the model space (particularly in models with the same 'angular diameter distance'), but these degeneracies can be broken through combinations with other astrophysical data sets (White 1998, Eisenstein, Hu & Tegmark 1998). If systematic errors can be kept under control, the combination of Planck and data from redshift surveys will be particularly powerful at determining the cosmology.

Item 2 will be difficult, but we have no doubt that it will happen. *MAP* may yield some information, how much is difficult to estimate without more insight into the foregrounds. Currently planned ground-based experiments may also give detections. And Planck should provide polarization measurements over a reasonable range of scales. However, a full investigation of CMB polarization (and certainly the 'curl' or B-mode component produced by tensors) may have to await an experiment even beyond Planck.

Item 3 potentially involves information from both 1 and 2. Ultimately we will learn something about high energy physics through understanding the way in which fluctuations were laid down in the early Universe, whether this involves discriminating any tensor component, measuring a changing spectral index, non-Gaussian signatures, or something else. Since the relevant energies are so far beyond what is achievable in particle accelerators, it is likely that cosmological phenomena will be the only way of constraining such models

for quite some time. In addition to the 'initial conditions', the evolution of the fluctuations will provide us with information on the properties of the dark matter in the Universe which may tie in directly to particle physics theories at the electroweak scale.

Item 4 includes a whole suite of potentially measurable effects, which can be thought of as processing the primary anisotropies. Examples include gravitational lensing, non-linear potential growth, Sunyaev-Zel'dovich effects, details of the reionization process, and extragalactic sources. There is a grey area between what is considered cosmic signal and what is considered a 'foreground'. But whatever you call it, there is little doubt that data from the Planck mission, for example, are likely to be mined for many years for the additional astrophysical information they contain.

We expect rapid experimental progress in the next few years, and we trust that theoretical effort will be similarly feverish (Bond 1996). As a result, there will no doubt be more physical processes uncovered which affect CMB anisotropies. At present the CDM-dominated inflationary paradigm looks like it's in pretty good shape. Our 'C' list may end up being quite inaccurate, and we can even imagine trouble for some entries in our 'B' list. However, the spectral information from the CMB, together with the 'A' list, provides a very solid foundation for the physics which generates the anisotropies. Therefore we are confident that whatever proves to be the ultimate such list, a thorough investigation of CMB anisotropies will hold the key to learning about the background space-time and formation of large-scale structure in the Universe.

REFERENCES

Barrow, J.D., Ferreira, P.G., & Silk, J, 1997 Phys. Rev. Lett., 78, 3610 [astro-ph/9701063]

Barrow, J.D., & Liddle, A.R., 1997 Gen. Rel. Grav., 29, 1503 [gr-qc/9705048]

Bartlett, J.G., Blanchard, A., Le Dour, M., Douspis, M., & Barbosa, D., 1998 in 'Fundamental Parameters in Cosmology', Moriond proceedings, in press [astro-ph/9804330]

Bennett, C.L., et al., 1996 ApJ, 464, L1, astro-ph/9601067

Bennett, C.L., Turner, M.S., & White, M., 1997 Physics Today 50, 32

Bond, J.R., 1996 in 'Microwave Background Anisotropies', Proc. of XXXI Recontres de Moriond [astro-ph/9610119]

Bond, J.R., Efstathiou, G., & White, S.D.M., 1992 MNRAS, 258, 1P

Bond, J.R., Jaffe, A.H., & Knox, L.E., 1998 submitted to ApJ [astro-ph/9808264]

Borden, D., Ostriker, J.P., & Weinberg, D.H., 1989 ApJ, 345, 607

Bunn, E.F., Ferreira, P., & Silk, J., 1996 Phys. Rev. Lett., 77, 2883 [astro-ph/9605123]

Caldwell, R.R., Kamionkowski, M., & Wadley, L., 1999 Phys. Rev., D59, 027101 [astro-ph/9807319]

Carr, B., & Ikeuchi, S., 1985 MNRAS, 213, 497

Cornish, N.J., Spergel, D.N., & Starkman, G.D., 1998 Phys. Rev., D57, 5982 [astro-ph/9708225]

de Oliveira-Costa, A., Smoot, G., & Starobinsky, A., 1996 ApJ, 468, 457 [astro-ph/9510109]

Doroshkevich, A.G., Zel'dovich, Ya.B., & Sunyaev, R.A., 1978 Sov. Astron., 22, 523

Eisenstein, D.J., Hu, W., & Tegmark, M., 1998 submitted to ApJ [astro-ph/9807130]

Frieman, J., Hill, C.T., & Watkins, R., 1992 Phys. Rev., D46, 1226

Fuller, G., & Schramm, D.N., 1992 Phys. Rev., D45, 2595

Gooding, A.K., Park, C., Spergel, D.N., Turok, N., & Gott, R., 1992 ApJ, 393, 42

Hancock, S., Rocha, G., Lasenby, A.N., & Guttiérrez, C.M., 1998 MNRAS, 294, L1 [astro-ph/9708254]

Hill, C.T., Schramm, D.N., & Fry, J., 1989 Comments. Nucl. Part. Phys., 19, 25

Hu, W. Seljak, U., White, M., & Zaldarriaga, M., 1998 Phys. Rev., D57, 3290 [astro-ph/9709066]

Hu, W. Spergel, D.N., & White, M., 1997 Phys. Rev., D55, 3288 [astro-ph/9605193]

Hu, W., & White, M., 1996 Phys. Rev. Lett., 77, 1687 [astro-ph/9602020]

Hu, W., & White, M., 1997 ApJ, 479, 568 [astro-ph/9609079]

Hu, W., & White, M., 1997 NewA, 2, 323 [astro-ph/9706147]

Hu, Y., Turner, M.S., & Weinberg, E., 1994 Phys. Rev., D49, 3830 [astro-ph/9302002]

Ikeuchi, S., 1981 PASJ, 33, 211

Jaffe, A.H., Stebbins, A., & Frieman, J., 1994 ApJ, 420, 9 [astro-ph/9301011]

Kinney, W.H., Kolb, E.W., & Turner, M.S., 1997 Phys. Rev. Lett., 79, 2620 [astro-ph/9704070]

Kogut, A., Hinshaw, G., & Banday, A.J., 1997 Phys. Rev., D55, 1901 [astro-ph/9701090]

Kolb, E.W., & Turner, M.S., 1990 'The Early Universe', Addison-Wesley, Redwood City, p. 498

Krauss, L.M., & White, M., 1992 Phys. Rev. Lett., 69, 869

Levin, J., Barrow, J.D., Bunn, E.F., & Silk, J., 1997 Phys. Rev. Lett., 79, 974 [astro-ph/9702242]

Liddle, A.R., 1994 Phys. Rev., D49, 3805 [astro-ph/9307036]

Liddle, A.R., 1995 Phys. Rev., D51, 5347 [astro-ph/9410083]

Lineweaver, C.H., 1998 ApJ, 505, L69 [astro-ph/9805326]

Longair, M.S., 1993 QJRAS, 34, 157

Lyth, D.H., 1997 Phys. Rev. Lett., 78, 1861 [hep-ph/9606387]

Markevich, A.V., & Starobinsky, A.A., 1996 Astron. Lett., 22, 431

Nordberg, H.P., & Smoot, G.F., 1998 submitted to ApJ [astro-ph/9805123]

Oh, S.P., Spergel, D.N., & Hinshaw G., 1999 ApJ, in press [astro-ph/9805339]

Ostriker, J.P., & Cowie, L., 1981 ApJ, 243, L127

Ostriker, J.P., & Strassler, M.J., 1989 ApJ, 338, 579

Ostriker, J.P., & Thompson, C., 1987 ApJ, 323, L97

Ostriker, J.P., Thompson, C., & Witten, E., 1986 Phys. Lett., B280, 231

Partridge, R.B., Richards, E.A., Fomalont, E.B., Kellerman, K.I., & Windhorst, R.A., 1997 ApJ, 483, 38

Pierpaoli, E., & Bonometto, S.A., 1998 submitted to MNRAS [astro-ph/9806037]

Press, W.H., Ryden, B., & Spergel, D., 1990 Phys. Rev. Lett., 64, 1084

Python, M., 1979 quoted in 'The Life of Brian', Mandarin Paperbacks, London (1993)

Sachs, R.K., & Wolfe, A.M., 1967 ApJ, 147, 73

Sakai, N., Sugiyama, N., & Yokoyama, J., 1997 preprint [astro-ph/9712153]

Salopek, D.S., 1995 in 'Current Topics in Astrofundamental Physics: The Early Universe', ed. N. Sanchez, A. Zichichi, Kluwer, p. 179 [astro-ph/9412012]

Scott, D., Silk, J., & White, M., 1995 Science, 268, 829

Scott, D., & White, M., 1996 Comments on Astrophysics, 18, 289 [astro-ph/9601170]

Seljak, U., & Zaldarriaga, M., 1996 ApJ, 469, 437 [astro-ph/9603033]

Smoot, G.F., 1991 in 'Observational Tests of Cosmological Inflation', ed. T. Shanks, et al., Kluwer, p. 395

Smoot, G.F., et al., 1992 ApJ, 396, L1

Smoot, G.F., & Scott, D., 1998 in Caso C., et al., Eur. Phys. J., C3, 1, the Review of Particle Physics. p. 127 [astro-ph/9711069]

Souradeep, T., Pogosyan, D., & Bond, J.R., 1998 in 'Fundamental Parameters in Cosmology', Proc. of XXXIII Recontres de Moriond, in press [astro-ph/9804042]

Stevens, D., Scott, D., & Silk, J., 1993 Phys. Rev. Lett., 71, 20

Subramanian, K., & Barrow, J.D., 1998 Phys. Rev. Lett., 81, 3575 [astro-ph/9803261]

Sugiyama, N., Silk, J., & Vittorio, N., 1993 ApJ, 419, L1

Tegmark, M., 1998 submitted to ApJ [astro-ph/9809201]

Turner, M.S., 1997 Phys. Rev., D55, 435

Vishniac, E.T., Ostriker, J.P., & Bertschinger, E., 1985 ApJ, 291, 399

Wandel, A., 1985 ApJ, 294, 385

Wasserman, I., 1986 Phys. Rev. Lett., 57, 2234

Weinberg, D.H., Dekel, A., & Ostriker, J.P., 1989 ApJ, 336, 9

White, M., 1998 ApJ, 506, 495 [astro-ph/9802295]

White, M., & Bunn, E.F., 1995 ApJ, 450, 477 [astro-ph/9503054]

White, M., & Hu, W., 1997 A&A, 321, 8 [astro-ph/9609105]

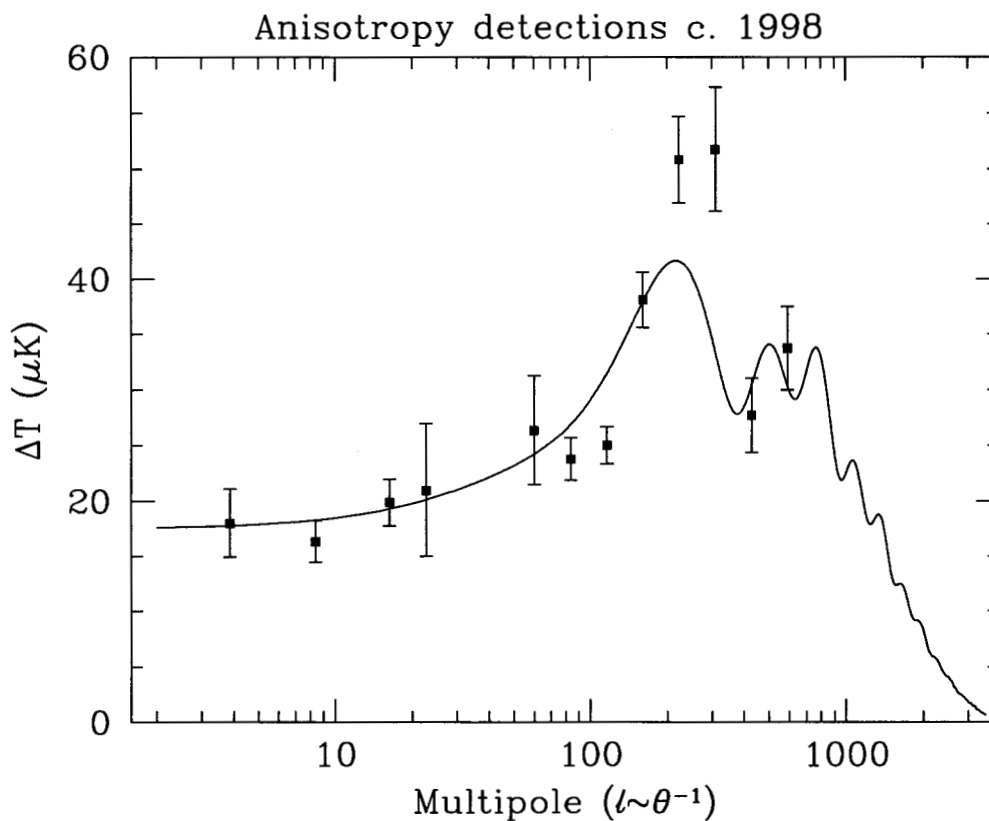Zibin, J., Scott, D., & White, M., 1999 submitted to Phys. Rev. D [astro-ph/9901028]

Fig. 1.— The current CMB anisotropy detections, averaged in 12 bins equally spaced in $\log \ell$ (with some bins missing, where no experimental window functions peak). The y-axis measures the rms fluctuation averaged over the range of angular scales within the bin, the x-axis is the multipole number $\ell \sim \theta^{-1}$, with $1°$ near $\ell \sim 10^2$. The solid line is the prediction of the 'standard' cold dark matter model, and is included only as an example. We note that creating plots like this is cosmetology rather than cosmology; such binned data are qualitatively useful, but should not be used for statistical purposes.
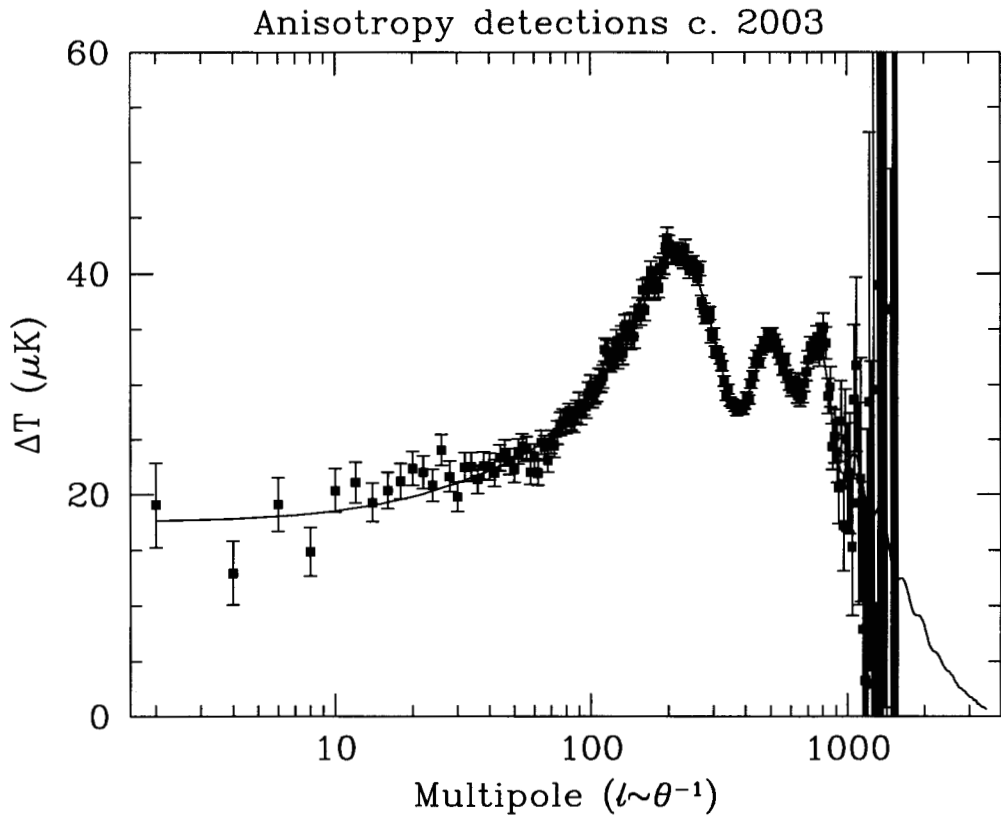
Anisotropy detections c. 2008
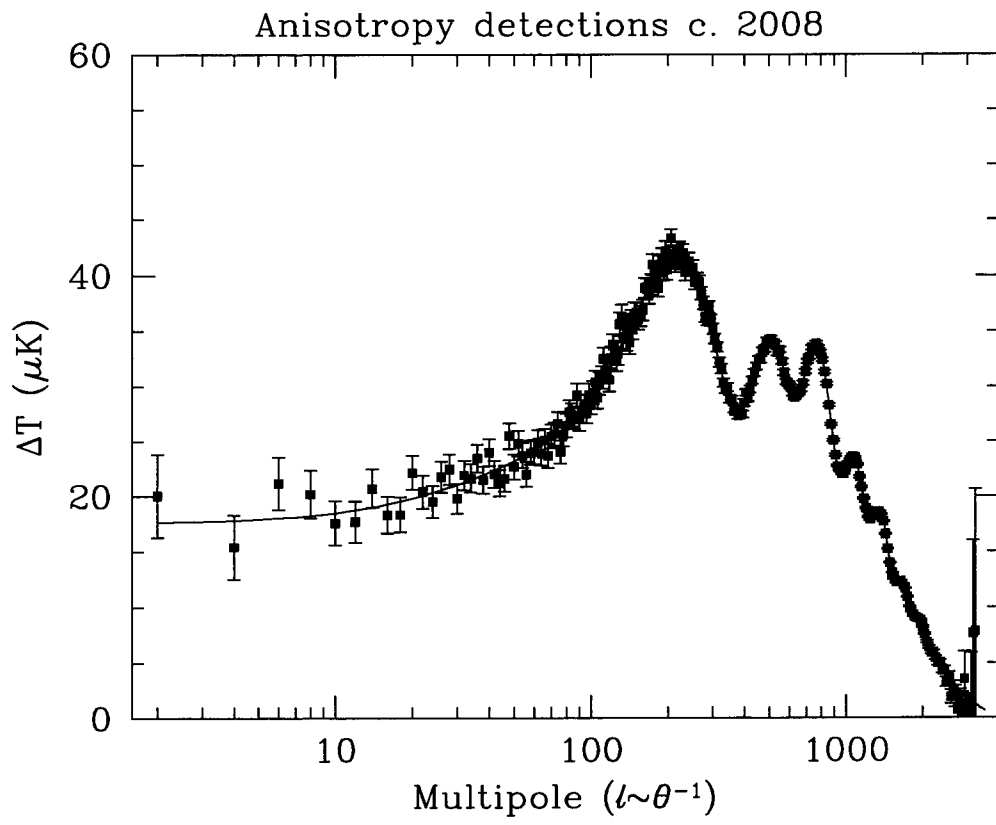
Fig. 2.— The future of CMB anisotropies as possibly detected by *MAP* and by Planck, representing the potential state of knowledge roughly 5 and 10 years after the present.