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Maps of the Cosmos: The Cosmic Microwave Background

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Abstract.   Since the IAU XXIV meeting in 2000, the CMB anisotropy has matured from being one of a number of cosmological probes to forming the bedrock foundation for what is now the standard model of cosmology. The large advances over the past three years have come from making better and better maps of the cosmos. We review the state of measurements of the anisotropy and outline some of what we have learned since 2000. The recent advancements may be placed roughly into three categories: 1) What we learn from the CMB with minimal input from other cosmic measurements such as the Hubble constant; 2) What we learn from the CMB in combination with other probes of large scale structure; and 3) What we learn by using the CMB as a back light. Future directions are also discussed. It is clear: we have much more to learn from the CMB anisotropy.

1.   Introduction

It has long been appreciated that the CMB anisotropy could be a powerful probe of cosmology. The foundations of the anisotropy calculations we do today were set out over thirty years ago by Sachs & Wolfe (1967), Rees (1968), Silk (1968), Peebles & Yu (1970), and Sunyaev & Zeldovich (1970). Plots of the acoustic peaks were shown in Doroskevich, Zeldovich, & Sunyaev (1978) and Bond & Efstathiou (1984) gave the results of detailed numerical calculations.

On the measurement side, the tension between expectations and continuously improving upper limits (e.g., Weiss 1980, Wilkinson 1985, Partridge 1995) was finally alleviated by the discovery of the anisotropy by *COBE* (Smoot et al. 1992). At that time, the measured Sachs-Wolfe plateau ($l < 20$) was a factor of two *higher* than expectations based on the standard cold dark matter model in which $\Omega_m \approx 1$.[1] There were many measurements of the anisotropy at the *COBE* scales and finer between 1992 and 2000 (e.g., see Page 1997 for a table) that culminated in observations of the first acoustic peak (Dodelson & Knox 2000, Hu 2000, Pierpaoli, Scott & White 2000, Knox & Page 2000).

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[1] We use the convention that $\Omega_m = \Omega_{cdm} + \Omega_b + \Omega_\nu$ is the cosmic density in all matter components where cdm is cold dark matter, b is for baryons, and ν is for neutrinos; Ω_r is the cosmic radiation density (now minuscule); Ω_Λ is the corresponding density for a cosmological constant; and Ω_k is the corresponding curvature parameter. The Friedmann equation tells us: $1 \equiv \Omega_\Lambda + \Omega_k + \Omega_m = \Omega_{tot} + \Omega_k$. The physical densities are given by, for example, $\omega_b = \Omega_b h^2$.
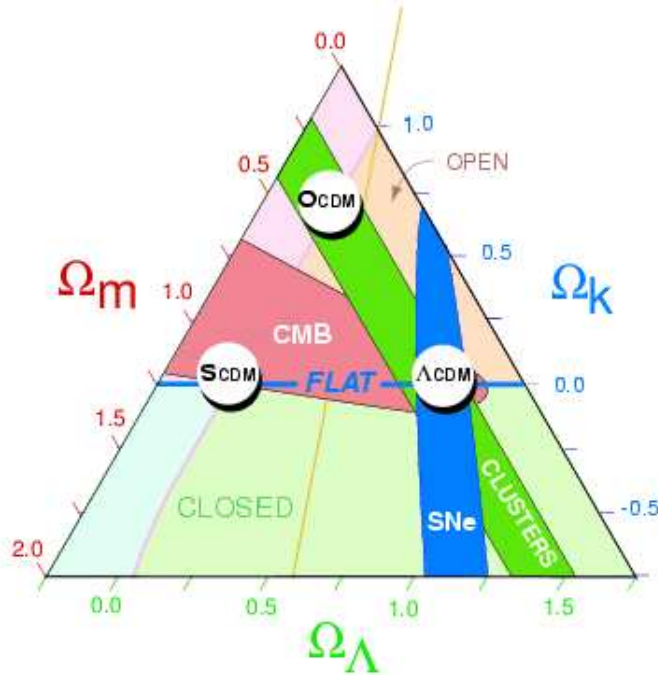
Figure 1.   The Cosmic Triangle from Bahcall et al. (1999). This shows the concordance model for cosmological observations at the end of the last millenium. Three different classes of observations, supernovae, clusters, and CMB anisotropy, are consistent if we live in a spatially flat universe with a cosmological constant.

Amidst theories that did not survive observational tests and false clues, a standard cosmological model emerged. Even over a decade ago, the evidence from a majority of independent tests indicated $\Omega_m \approx 0.3$ (e.g., Ostriker 1993). It was realized by many that a flat model ($\Omega_k = 0$) with a significant cosmic constituent with negative pressure, such as a cosmological constant, was a good fit to the data. Then, in 1998 measurements of type 1a supernovae (Riess et al. 1998, Perlmutter et al. 1999) directly gave strong indications that the universe was accelerating as would be expected from a cosmological constant. The state of the observations in 1999 is summarized in Figure 1. If the Einstein/Friedmann equations describe our universe, the data were telling us that the universe is spatially flat with matter density $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$. Independent analyses came to similar conclusions (e.g., Lineweaver 1998, Tegmark & Zaldarriaga 2000). The story since the last IAU meeting is that the concordance model does in fact describe virtually all cosmological observations astonishing well. There is now a well agreed upon standard cosmological model (Spergel et al. 2003, Freedman & Turner 2003).

In the rest of this article we briefly review the CMB observations in §2 and summarize what we learn from (almost) just the CMB in §3. We then, in §4, outline the things we learn by combining the CMB with other maps of the cosmos, in particular the 2dF Galaxy Redshift Survey (Colles et al. 2001). In

§5 we indicate the sorts of things we hope to learn by using the CMB as a back light for lower redshift phenomena. We conclude in §6.

2. CMB Observations

To be sure there have been advances in all cosmological observations over the past three years, but the most dramatic improvements have come from observations of the CMB anisotropy. First came the BOOMERanG results which gave us high resolution and high signal-to-noise maps of the anisotropy (deBernardis et al. 2000). The data analysis improved considerably over the three years (e.g., Netterfield et al. 2002) culminating in the Ruhl et al. (2003) analysis. Concurrent with BOOMERanG was the MAXIMA experiment (Hanany 2000, Lee 2001). MAXIMA gave similar results though over a smaller fraction of the sky. For many, the greatest advance from these experiments was not so much the new measurement of curvature, but rather the ability to probe ω_b and ω_m with better than 30% precision using the CMB. In more general terms, they gave new and strong evidence that the concordance model in Figure 1 was correct.

In the year before the *WMAP* release (Bennett et al. 2003), the Archeops team published (Benoit 2002) results from a map that covered roughly 30% of the sky. The goal of the experiment, in addition to serving as a test bed for the Planck HFI instrument, was to bridge the angular range from the 7° *COBE* resolution to 1° resolution. The ACBAR experiment (Kuo et al. 2002), done from the South Pole, was aimed at pushing to angular scales beyond what *WMAP* could reach. Its resolution is 0.08° as opposed to *WMAP*'s 0.21°. BOOMERanG, MAXIMA, Archeops, and ACBAR achieved their greatest sensitivity at 150 GHz using radiometers based on the Berkeley/Caltech/JPL spiderweb bolometers (Bock et al. 1996) with passbands defined by filters developed by Peter Ade and colleagues at Cardiff.

Great strides were made in CMB interferometry during the past three years. The three primary instruments were DASI (Halverson et al. 2002), VSA (Grainge 2003), and CBI (Mason 2003, Pearson 2003). All were based on broadband 30 GHz HEMT amplifiers designed by Marian Pospieszalski at the National Radio Astronomy Observatory (Pospieszalski 1992). Results from DASI first complemented and extended the framework that was becoming evident. After adding the polarization capability, DASI discovered the intrinsic polarization in the CMB at the predicted level (Kovac et al. 2002). This was an important piece of evidence that decoupling occurred as predicted. The VSA interferometer gave similar results to DASI though over a wider range in l. The CBI interferometer clearly observed the suppression of the anisotropy at $l > 1000$ due to Silk damping and the finite thickness of the decoupling surface. CBI also showed hints of observing the formation of non-linear structure at $l > 2000$, though more investigation is needed as emphasized by the CBI team.

Though the advances since IAU XXIV by ground and balloon based CMB experiments were tremendous, the results from *WMAP* are in a different category. Not only did *WMAP* have the unprecedented stability achievable only from deep space, but it mapped the entire sky. The systematic error limits achieved on multiple different aspects of the experiment and analysis were roughly an order of magnitude (sometimes two orders) improvement over what had been
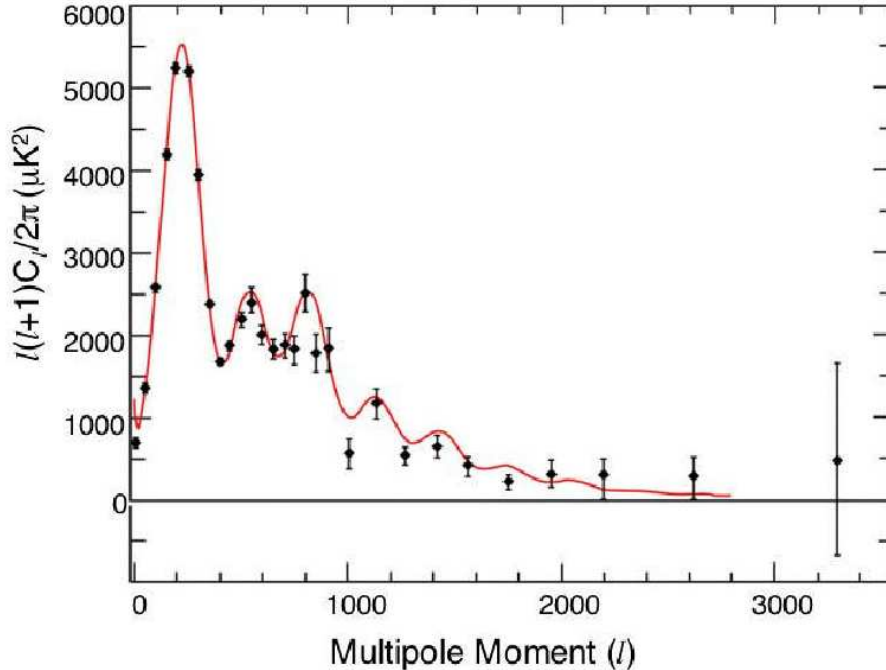
Figure 2.   The Grand Unified Spectrum based on Bond, Contaldi, & Pogosyan (2003). The y axis shows the fluctuation power per logarithmic interval in l. The x-axis may be converted to angular scale by $\theta_{deg} = l/200$. This spectrum is derived from the combination of 28 anisotropy experiments as of July 2003. The first and second peaks from the acoustic oscillations are clearly evident, the third peak is almost resolved, and the damping tail at $l > 1000$ is evident. The line is the best fit model.

achieved previously. The data are so clean that 99% of the time ordered data goes into the final map. There is a low level of filtering and a 1% transmission imbalance is corrected, but other than this no other sytematic error corrections or selection criteria are applied. Finally, all the data from the experiment are publicly available so they may be checked. For a description of the *WMAP* mission see the article by Chuck Bennett in these proceedings.

The new CMB observations have narrowed the CMB swath in Figure 1 by roughly an order of magnitude. More importantly, they have told us that adiabatic scale invariant fluctuations seeded the formation of cosmic structure and that the contents of the universe are baryons, some form(s) of dark matter, and some form(s) of dark energy. A snapshot of all the CMB anisotropy data as of July 2003 has been compiled by Bond, Contaldi, & Pogosyan (2003) and a version is shown as a Grand Unified Spectrum (GUS) in Figure 2.

This IAU is a particularly good time to take stock of where we are. Another chapter in the study of the CMB has been finished with the release of the first

Figure 3.   David Wilkinson (left), Dick Bond (center) and Rashid Sunyaev (right) at the *WMAP* launch, June 2001. They are standing in front of a Saturn V rocket (*WMAP* used a Delta II). Prof. Rashid Sunyaev was the recipient of the 2003 Gruber Prize in Cosmology which was presented at the IAU symposium.

year *WMAP* data. Sadly, Dave Wilkinson, a pioneer of the CMB field for 35 years and a founder of both the *WMAP* and *COBE* satellite missions, died in the end of 2002 after battling cancer for 17 years. Fortunately Dave saw the *WMAP* maps in their full glory. The *MAP* satellite was renamed in his honor. Figure 3 is from the *WMAP* launch and shows three of CMB science's pioneers.

3.   What the CMB data alone tell us.

As a good first approximation, one should think of a map of the CMB anisotropy as a picture of the universe at a redshift of $z_{dec} = 1089$, when the CMB decoupled from the primordial plasma. Thus, the CMB tells us about the universe when it was less than $t_{dec} = 379$ kyrs old and a much simpler place. In this epoch, the early universe acts as though it is spatially flat, independent of the values of the dark energy and dark matter today.

The variation in temperature from spot to spot across the sky arises from the primordial plasma responding to spatial variations in the gravitational potential. In turn, the gravitational landscape is the manifestation of quantum fluctuations in some primordial field. In the inflationary model, one imagines these fluctuations stretched by at least 10^{28} so that they are super-horizon size, and then expanded with the expansion of the universe.

Observing the CMB is like looking at a distant surface[2] at the edge of the observable universe. As the universe expands, the pattern in the anisotropy will shift as new regions of the gravitational landscape are sampled. For example, one may imagine that the quadrupole ($l = 2$) may rotate $90°$ in one Hubble time (30 mas/century), with higher multipoles changing faster. In a similar vein, the light from the clusters of galaxies that formed in the potential wells that gave rise to cold regions on the decoupling surface has not has enough time to reach us.

The processes of the formation of stars, galaxies, and clusters of galaxies takes place between us and the decoupling surface. As a first approximation, photons from the decoupling surface come to us unimpeded. The lower redshift properties do, though, affect the light from the decoupling surface but in characteristic and definable ways as discussed below.

A full analysis of the CMB involves accurately comparing the measured power spectrum, Figure 2, to models. The simplest model that describes the CMB data is flat and lambda-dominated. The results for this parametrization derived from *WMAP* alone (Spergel et al. 2003) and the independent GUS analysis are shown in Table 1.

Table 1.   Cosmic Parameters from CMB measurements

Description	Parameter	*WMAP*	GUS	w/2dF
Baryon density	$\Omega_b h^2$	0.024 ± 0.001	0.023 ± 0.002	0.023 ± 0.001
Matter density	$\Omega_m h^2$	0.14 ± 0.02	0.14 ± 0.01	0.134 ± 0.006
Hubble parameter	h	0.72 ± 0.05	0.71 ± 0.05	0.73 ± 0.03
Amplitude	A	0.9 ± 0.1	0.85 ± 0.06	0.8 ± 0.1
Spectral index	n_s	0.99 ± 0.04	0.967 ± 0.029	0.97 ± 0.03
Optical depth	τ	$0.166^{+0.076}_{-0.071}$	$\cdots$	0.148 ± 0.072

We can get at the essence of what the CMB is telling us from the following. Let us focus on the decoupling surface. There is a natural length scale in the early universe that is smaller than the horizon size. It corresponds to the distance over which a density perturbation (sound wave) in the primordial plasma can propagate in the age of the universe at the time of decoupling ($t_{dec} = 379$ kyr). It is called the acoustic horizon. Once we know the contents of the universe from the overall characteristics of the power spectrum, we can compute the size of the acoustic horizon. It is roughly $r_s \approx c_s t_{dec} z_{dec}$ where c_s is the sound speed in the plasma. In the full expression (Hu & Sugiyama 1995), r_s depends on only the physical densities of matter and radiation and not on the Hubble parameter, h. We may think of r_s as a standard yard stick embedded in the decoupling surface. From a map of the anisotropy, we measure the angular size, θ_A, of the

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[2]This is the "surface" at which the CMB decoupled from the primordial electrons and baryons. It is sometimes called the last scattering surface, but since $\approx$15% of the CMB photons were really last scattered when the universe was reionized near $z = 20$, we prefer decoupling.

feature corresponding to r_s. From *WMAP*, $\theta_A = 0.598° \pm 0.002$. By definition then,

$$\theta_A \equiv \frac{r_s(z_{dec})}{d_A(z_{dec})} \tag{1}$$

where d_A is the angular size distance to the decoupling surface. In d_A we can trade off the geometry, $\Omega_k = 1 - \Omega_r - \Omega_m - \Omega_\Lambda$, with h. Thus to determine the geometry without recourse to appealing to the simplest model, we must make a prior assumption on h. The dependence is not strong. If one assumes $h > 0.5$ then one finds $0.98 < \Omega_{tot} < 1.08$ (95% cl), where again we have used the *WMAP* data for illustration. The progress in our knowledge of Ω_{tot} as determined by all available data roughly between the past two IAU symposia (starting with Figure 1, Bond et al. 2003) is:

Table 2. Total Cosmic Density, Ω_{tot} (1σ errors)

January 2000	$\Omega_{tot} = 1.06^{+0.16}_{-0.10}$
January 2002	$\Omega_{tot} = 1.035^{+0.043}_{-0.046}$
January 2003	$\Omega_{tot} = 1.034^{+0.040}_{-0.042}$
March 2003 (+*WMAP*)	$\Omega_{tot} = 1.015^{+0.063}_{-0.015}$

One way to see what the CMB alone can tell us is to plot the data in the $\Omega_m - \Omega_\Lambda$ plane for a pure cosmological constant, or equation of state $w = -1$. This is shown in Figure 4 for the *WMAP* data. All simple open, flat, and closed cosmological models satisfying the Friedmann equation can be plotted here. One picks a point in the space, a single source of the fluctuations (e.g., adiabatic fluctuations in the metric from an inflationary epoch), $w = -1$, and marginalizes over the other parameters (n_s, ω_b, τ, A) with uniform priors. The possibilities are labeled by the Hubble parameter that goes with them.

There are a number of things the plot pulls together. First, there is a large degeneracy in the CMB data along the line that runs above the line for flat universe. This is called the "geometric degeneracy" and is essentially the observation noted above that one must pick h to determine d_A to complete the equation $\theta_A = r_s/d_A$. The degeneracy line clearly misses a model in which the universe is flat with $\Omega_m = 1$ ($\Omega_\Lambda = 0$), the Einstein-deSitter case. If one stretches the data slightly, it is possible to have a model with $\Omega_m \approx 1.3$ ($\Omega_\Lambda = 0$) but the price one pays is a Hubble parameter near 0.3. This value is in conflict with a host of other non-CMB observations. In addition, when one considers the Integrated Sachs-Wolfe (ISW) induced cross-correlation between cosmic structure, as measured by radio sources, and the CMB anisotropy, this solution is disfavored at the 3σ level (Nolta et al. 2003). Thus, in this minimal picture, there are no models with $\Omega_\Lambda = 0$ that fit the data.

Once one moves off the x axis, the intersection of the flat universe line, $\Omega_\Lambda + \Omega_m = 1$, and the geometric degeneracy is the next least baroque point, at least by today's standards of baroqueness. It is very satisfying that h for the intersection is very close to the value obtained from the Hubble Key Project
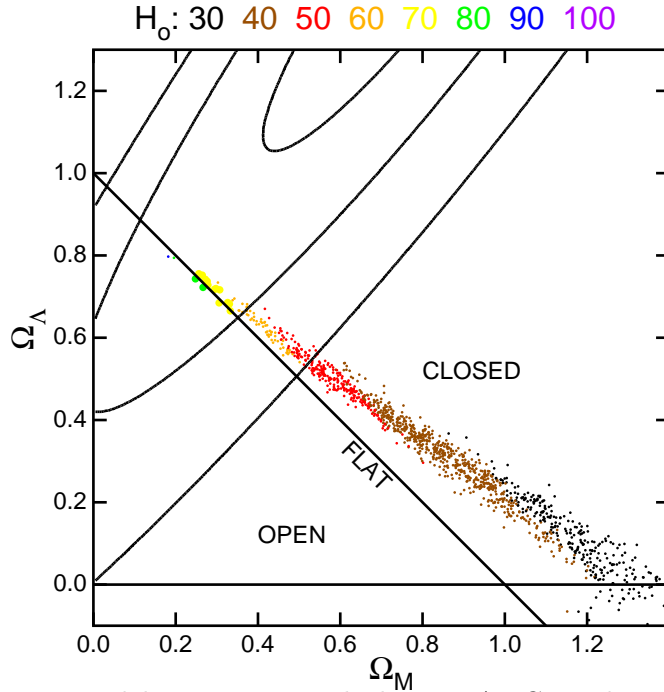
Figure 4.   Models consistent with the *WMAP* CMB data in the $\Omega_\Lambda - \Omega_m$ plane. The flat models correspond to the line with $\Omega_\Lambda + \Omega_m = 1$. This plot assumes that the dark energy has $w = -1$. The code at the top gives the values of the Hubble constant as one moves along the geometric degeneracy. It is striking that the value picked out by the CMB for a flat universe, $h = 0.71$, is in such agreement with the value from the HST key project. The observations behind these two probes are completely different and correspond to times separated by a good fraction the age of the universe. The 1σ, 2σ, and 3σ contours for the supernovae are plotted as well (Tonry et al. 2003). Constraints from large scale structure would correspond to roughly a vertical swath centered on $\Omega_m = 0.3$. This plot is courtesy of Ned Wright.

($h = 0.72 \pm 0.03(stat) \pm 0.07(sys)$, Freedman et al. 2001). Additionally, the values agree with probes of the large scale structure and the supernovae data. From the plot, it is easy to see why such a weak prior on h (or Ω_m) picks out a flat universe. A number have noted that all determinations of Ω_{tot} are greater than unity. The plot shows that with the priors we have chosen, there are more solutions with $\Omega_{tot} > 1$. This may bias the solution somewhat.

4.   The CMB in combination with other cosmic probes

We learn much more about cosmology when we add to the CMB anisotropy lower redshift observations. The primary CMB anisotropy comes from a surface behind the galaxies and clusters of galaxies which are roughly between us and $z \approx 2$ (or between now, $t_U = 13.7$ Gyr, and when the universe was 3.3 Gyr). In regards to cosmic parameters, lower redshift measurements sample the universe

in a much different state of it evolution and therefore with different parameter degeneracies. In regards to understanding structure formation, the CMB gives us the initial conditions whereas the lower redshift measurements of the large scale structure (LSS) give us the current condition.

There are a number of ways in which lower z measurements complement the CMB: (a) through measuring the current expansion rate with the Hubble constant; (b) through measuring the current baryon density with quasar absorption systems; (c) through measuring the current mass density with galaxy velocities or the mass-to-light ratio; (d) through measuring the ages of the oldest objects; and (e) through measuring the matter power spectrum with gravitational lensing (e.g., Contaldi, Hoekstra, & Lewis 2003) or galaxy surveys such as 2dFGRS and SDSS (e.g., Gunn et al. 1998).[3]

The complementarity of the Hubble constant has been discussed above; and the other probes, of course, have a rich history. Since the last IAU, huge strides were made in determining the matter power spectrum as we discuss below. The supernovae results are not included in the list because it still seems best to treat the CMB+LSS as an independent probe of negative pressure.

The power spectrum from galaxies, $P_g(k)$, and the CMB power spectrum are intimately related. However, technical issues arise when comparing the two because one is not certain how fluctuation in the number density of galaxies trace the fluctuations in matter. In other words, the galaxy population might be *biased* with respect to the matter density which the CMB probes. The bias is quantified as $P_g(k) = b^2 P(k)$ where $P(k)$ is the matter power spectrum and b is the bias factor. For example, it is observed that redder (e.g., IRAS) galaxies cluster together less strongly than do optically selected ones and are thus less strongly biased (Fisher et al. 1994). Similarly, luminous galaxies are more biased than less luminous ones (Norberg et al. 2001).

The amplitude of the matter power spectrum is set by σ_8, the rms fluctuations in the matter mass density in a comoving sphere of diameter 8 Mpc. In order to determine σ_8, one needs to know the cosmic matter density, Ω_m, which is only determined to 30% accuracy (as opposed to the physical matter density which is determined to 15% accuracy). In the CMB, σ_8^2 simply scales the overall amplitude of the angular power spectrum, whereas ω_m is sensitive to the shape of the spectrum.

Figure 5 shows a comparison of the CMB power spectrum and $P(k)$. The big leap in galaxy surveys in the past few years is that the 2dFGRS survey was able to measure the matter power precisely and over a large range in k, particularly values of k directly probed by the CMB. The two data sets are combined by comparing their shapes and amplitudes as discussed in Verde et al. (2003).

The primary observables that 2dF adds are the extended baseline over which the fluctuations are measured and an independent measure of the dark matter power spectrum. (A value of the bias of $b = 1.06 \pm 0.11$ (Verde et al. 2002) was used in the *WMAP* analysis.) These break a number of parameter degeneracies inherent in just $l < 1000$ CMB measurements. For example, it is clear that with a longer baseline in k the spectral index, or overall tilt of the spectrum, can be

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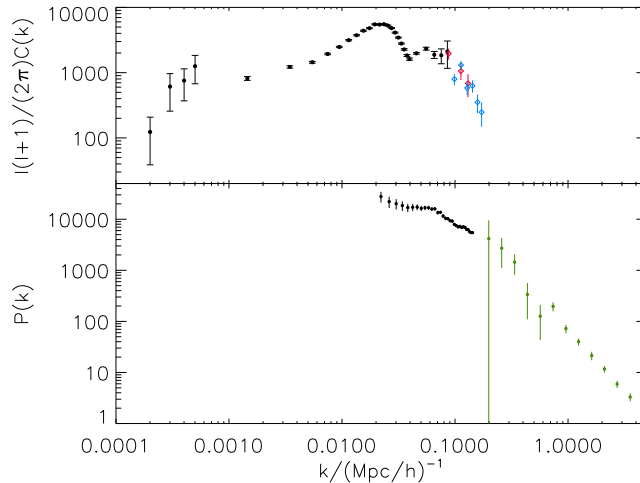[3]The SDSS/*WMAP* analysis came out after the IAU.

Figure 5.   Top: the CMB angular power spectrum as a function of comoving wavenumber k ($k \approx l/14400$). The points to the left are from *WMAP*, the data for $l > 875$ are from CBI and ACBAR. Bottom: the LSS data from 2dFGRS ($0.01 < k < 0.15$) and the Lymanα survey (Croft et al. 2002). The power spectra have been rescaled to $z = 0$. To compare the LSS data to the CMB on must take into account redshift-space distortions, non-linearities, bias, window functions, etc. This figure from Verde et al. (2003)

better determined. It is then easier to determine the optical depth, τ, and the matter density ω_m. In Table 1, one can see the improvement in what one can say when the 2dF data are added to the CMB data (WMAP+ACBAR+CBI, Spergel et al. 2003).

The high-z/low-z combination leads to other science as well. With the emergence of these precise probes, one can now constrain the neutrino mass at the levels being probed by particle physics experiments. The phenomena is as follows. When they are relativistic, neutrinos free-stream out of the potential wells. Because neutrinos are relativistic at early times and cool with the expansion of the universe, clustering by neutrinos is suppressed on small scales with respect to large scales. As one increases the cosmic mass density of neutrinos, Ω_ν, while holding $\Omega_m = \Omega_{cdm} + \Omega_\nu + \Omega_b$ fixed, the net matter fluctuations, $P(k)$, are also suppressed on small scales (high k). At the same time, the length scale of the suppression moves to smaller values (higher k). By comparing the $P(k)$ from 2dF with the *WMAP* CMB fluctuations, one finds $\Omega_\nu h^2 < 0.007$ (95% cl) or $\Sigma m_\nu < 0.7$ eV (95% cl) for three degenerate neutrino species. In a sense, we have started addressing questions of classic particle physics with cosmological probes.

There are also direct correlations expected between the CMB anisotropy and galaxy surveys in addition to the relation between power spectra. Crittenden & Turok (1996) pointed out that in a Ω_Λ dominated universe, there should be measurable correlations between the CMB anisotropy and the matter as traced by x-ray or radio sources at large angular scales. The mechanism is that the gravitational potential wells change, due to the Λ-induced acceleration, while a CMB photon traverses it. This in turn affects the energy of the photons (ISW effect). These same potential wells are traced by galaxy populations around $z \sim 2$. The correlation has been seen albeit at only about the 3σ level (Boughn & Crittenden 2003, Nolta et al. 2003, Fosalba, Gaztananga & Castander 2003, Scranton et al. 2003).

The standard model has many predictions and consistency checks that are currently being tested. For the CMB, a number of the correlations that should exist are given in Peiris & Spergel (2000). Of course, the pay dirt is in the inconsistencies!

5.   The CMB as a back light

The physical processes that gave rise to cosmic structure leave characteristic and identifiable signatures on the CMB that can be seen by using the CMB as a back light. The key aspects of the CMB as an illumination source are that we know the redshift at which the fluctuations were imprinted and we know the frequency spectrum to high accuracy. Probably the best known examples of using the CMB as a back light are the Sunyaev-Zeldovich (SZ) effects (1972). These were discussed in a companion session by John Carlstrom and so I'll not discuss them here. Instead, I'll focus on the formation of the first stars and on gravitational lensing.

The process of formation of the first stars is not well understood and not well observationally constrained. However, it is known that the intergalactic hydrogen in the universe was predominantly neutral after decoupling and is predominantly ionized now. It was the formation of the first stars that reionized the universe. The free electrons from the reionization leave an imprint on the CMB. It can be shown that scattering by an electron in a quadrupolar radiation background polarizes the CMB. Because this happens at low redshifts, $z \approx 20$, the CMB appears polarized at large angular scales. This effect was seen in the first year *WMAP* data through the polarization-temperature correlation (Kogut et al. 2003).

With the large angular scale anisotropy, one measures the amount of polarized emission and directly infers an optical depth to polarization, τ. The most likely value from WMAP is $\tau = 0.17 \pm 0.04$. In other words, roughly 15% of the CMB photons were rescattered by the formation of the first stars (Zaldarriaga 1997). The redshift of $z \approx 20$ is obtained by integrating back over a completely ionized universe until $\tau = 0.17$ is reached. This corresponds to an age of 200 million years after the bang. There is still much more work to be done to understand the ionization history of the universe.

The reionization suppresses the CMB fluctuations at medium scales but gives rise to a new fluctuations at smaller angular scales through the Ostriker-Vishniac effect (OV, Ostriker & Vishniac 1986). The physics is similar to that

of the kinetic SZ effect though is applied to density perturbations instead of clusters per se. In other words, the CMB photons are scattered by ionized gas with some peculiar velocity. The effect has the frequency spectrum of the CMB and must be separated from the primary anisotropy through spatial filtering and higher order statistics. Its measurement is one of the goals of the next generation of experiments. Not only is it of intrinsic interest, but it also will be a new handle on breaking the $n_s - \tau$ cosmic parameter degeneracy.

The CMB is lensed, like distant galaxies, by the intervening mass distribution. A picture of this is shown in Figure 6. The effect of the lensing is large but it will challenging to separate the intrinsic CMB from what we measure (the lensed CMB). The pursuit is worthwhile because from the lensing one can extract $P(k)$ without bias (Seljak & Zaldarriaga 1999, Okamoto & Hu 2003). To a first approximation, lensing redistributes the phase of the anisotropy and so the power spectra of the lensed and unlensed sky are the same. However, there is also a net redistribution of power and so lensing enhances the angular power spectrum at high l.

There are two avenues to detecting lensing. One is through higher order statistics (e.g., the four point function, Bernardeau 1997). Because lensing distorts the intrinsic hot and cold spots, a lensed sky has more complicated statistics than the two-point function that describes the intrinsic anisotropy. One can get a sense for this from Figure 6: the difference map has elongated features. Detection through this method requires a high fidelity map. The other avenue is through the CMB polarization. Lensing distorts the E-mode CMB polarization from the decoupling surface, producing B-modes (Zaldarriaga & Seljak 1998). Indeed, it is the largest B-mode signal at $l > 200$. In a sense, one uses the polarization to filter out the lensing signal from the intrinsic CMB and OV effects.

A goal for cosmologists over the next few years is to use these probes together to study the growth of cosmic structure as a function of redshift. For example, reionization tells us what's happening at $z \approx 20$, the OV effects and diffuse thermal SZ probe the early stages of structure formation, the kinetic and thermal SZ effects in clusters, and the lensing of the CMB probe the later stages of structure formation. By combining these probes, one estimates that the equation of state, w, can be measured to 10% accuracy and the neutrino mass to 0.1 eV. The new thing is that these determinations will be tied to the CMB and will not rely on galaxy surveys. In addition, there is a rich set of correlations and cross checks between various measurements, both within the CMB and between the CMB and optical lensing, that should permit us to build confidence in any conclusions we may draw.

6. Concluding Remarks

Over the past few years, and especially with *WMAP*, the CMB data has become the foundation for the standard cosmological model. Any model that purports to explain the birth and evolution of the universe must be able to predict the results in Figure 2. This is a very stringent requirement. The model elements implicit in the figure—superhorizon fluctuations with cosmic structure seeded by a scale invariant spectrum with Gaussian fluctuations in the metric are at the core of
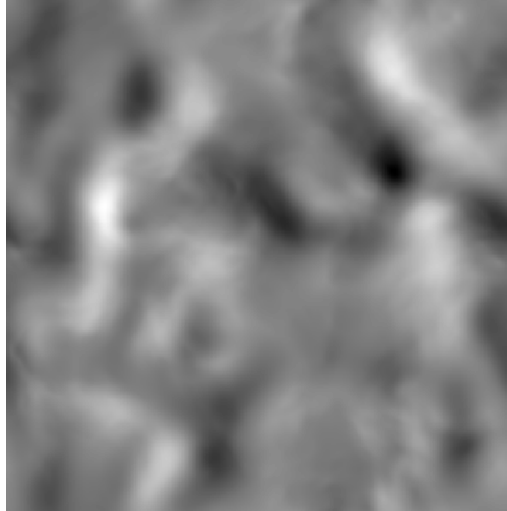
Figure 6.   The difference between a lensed and unlensed CMB field. The image is 1° on a side. The rms amplitude is a few μK with several peaks reaching 20-30 μK. Note the coherence in the lensed features. Figure courtesy of Uros Seljak.

our conception of the universe. They are also at the heart of inflation. Indeed, we have started to directly constrain models of inflation (Peirie et al. 2003). This is not to say that our currently favored model is correct. There are elements of the observations, for example the apparent suppression of fluctuations on the largest angular scales, that may call for something beyond the standard model. However, it is truly astounding that we have a model that naturally explains almost all cosmological observations. The model is eminently testable and precise enough to be experimentally challenged. The model is also young enough to admit new discoveries in such areas as dark energy, dark matter, and the birth and growth of cosmic structure.

We have much more to learn from the CMB. To borrow from Winston Churchill, *WMAP* marks not the end, not even the beginning of the end, but rather the end of the beginning of what we can learn from the CMB. In IAUs ahead we may hope to hear of how observations of the CMB in combination with other cosmic probes determine the mass of the neutrino or the equation of state of the dark energy. Detection of polarization B-modes (See A. Couray, these proceedings) may be be able to tell us the energy scale of inflation. From the ground, new experiments such as ACT, APEX, and SPT are pushing CMB anisotropy measurements to high l and high sensitivity. New experiments such as BICEP, CAPMAP, Polarbear, QUAD, *SPORT*, are applying new techniques to measure the polarization in the CMB. There is already talk of *CMBPOL*, a post-Planck satellite dedicated to polarization measurements. No doubt, precise

measurements of the CMB will continue to shed light on fundamental physics, cosmology, and astrophysics for years to come.

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