Cosmic Microwave Background Observations in the Post-Planck Era

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ABSTRACT

The Microwave Anisotropy Probe and Planck missions will provide low noise maps of the temperature of the cosmic microwave background (CMB). These maps will allow measurement of the power spectrum of the CMB with measurement noise below cosmic variance for $\ell < 1500$. It is anticipated that no further all sky CMB temperature observations will be needed after Planck. There are, however, other CMB measurements for which Planck will be not the end but the beginning. Following Planck, precise CMB *polarization* observations will offer the potential to study physical processes at energies as high as 10^{19} GeV. In addition, *arcminute scale*, multi-frequency observations will allow study of the early phases of the formation of large-scale structure in the universe.

I.   Scope of Report

The Cosmic Microwave Background Future Missions Working Group (the authors of this report) was created by NASA headquarters to consider new missions to follow a successful Planck mission. The discussion was restricted to missions of cost greater than Explorer Class missions ($200M). This report presents the conclusions of the working group, arrived at after extensive discussions involving the CMB and high energy physics communities. This report is not intended to be a complete review of the literature on CMB science; a few references have been included, however, to serve as starting points for more thorough research.

II.   Introduction

The development of the hot-big-bang model for the early history of the universe is one of the crowning achievements of twentieth century science. It is remarkable that we may now understand what was going on in the universe just one second into the big bang expansion. A cornerstone in our understanding of modern cosmology has been the information gathered from measurements of the Cosmic Microwave Background (CMB) radiation. Just now, at the close of the twentieth century, an important piece of the big-bang puzzle is about to be put into place. Preliminary CMB results announced recently indicate that of the three possible geometries of the universe—open, flat, or closed—ours appears to be flat ($\Omega_{total} = 1$). At the same time, measurements of the flux from distant supernovae indicate that the universal expansion may actually be accelerating, that Einstein's cosmological constant Λ may be significant. These are exciting times: measurements of the cosmological parameters are about to tell us the ultimate fate of the universe; meanwhile observations are confronting us with mysteries such as that of an accelerating universe. Soon, two CMB satellite missions already in the NASA and ESA pipelines (MAP and Planck) are expected to provide precise measurements of Ω and Λ. In addition, these experiments will rigorously test whether the large structures we find in the universe today, such as galaxy clusters and superclusters, grew from a nearly scale-invariant spectrum of tiny primordial density perturbations. They will test the idea that the largest structures in the universe began as minute quantum mechanical fluctuations during an inflationary epoch in the very early Universe. MAP and Planck are extraordinarily capable missions, but are they *ultimate* CMB missions? Are there important issues these two spacecraft do not address? That is the subject of this report. (For more on this issue, see also Halpern and Scott 1999.)

CMB images are maps of ancient temperature structure. A precise measurement of the CMB energy spectrum, carried out using the FIRAS instrument on COBE (Fixsen et al. 1994), showed that the energy spectrum closely follows a Planck curve. Because of this, the CMB is today widely accepted to be the thermal radiation relic of the hot big bang explosion. Under this interpretation we know that most cosmic background photons have traveled freely to us from a last scattering that occurred when the universe first became de-ionized, just 300,000 years after the start of the big bang explosion. The mapping of CMB sky structure therefore amounts to the measurement of

small temperature variations that were present in the universe at that early time.

CMB observations test gravitational collapse models of structure formation. Using DMR on COBE (Smoot et al. 1992; Kogut et al. 1995) the level of CMB sky structure has been measured from 10 to 180 degrees. The sky structure detected falls in line with measurements of large-scale structure in the distribution of galaxies in the universe today. It is therefore generally accepted that at ten degree scales the small temperature differences on the sky measured using CMB telescopes are the result of weak gravitational potential variations (and therefore density variations) in the early universe (Sachs and Wolfe 1967; Bennett et al. 1996; for a review, see White, Scott, and Silk 1994). These weak potential wells acted as seeds for the growth, by gravitational collapse, of the network of galaxy sheets and voids that we find in the universe today. Thus, CMB observations also provide a crucial test of the structure-growth-by-gravitational-collapse paradigm, a key tenet of cosmological theory.

MAP and Planck should tell us the fate of the universe. As seen in Figure 1, at degree angular scales there is now good evidence that CMB sky structure is present at an amplitude about three times as large as that detected with COBE at large angular scales. That amplification is expected; it occurs naturally as a result of acoustic oscillations that took place while the universe was ionized, before age 300,000 years. These oscillations and the sky structure they produce are sensitive to the matter density in the universe today and to the other parameters of the cosmological world model. Measurement of degree angular scale CMB sky structure, at the sensitivity offered using the MAP and Planck spacecraft, is expected to provide, with percent-level precision, a measurement of the density of the universe Ω_{total}, the expansion rate H_o, the cosmological constant Λ, as well as a measurement of the fractions of material present today in the forms of hot and cold dark matter. By accurately determining these cosmological parameters, CMB observations made with MAP and Planck have the potential to tell us the ultimate fate of the universe. Of course, MAP or Planck may find sky structure that is completely different from that expected. If this occurs, we may not be able to extract the cosmological parameters from the CMB data; instead, MAP and Planck will have presented for discussion an exciting new puzzle.

Beyond MAP and Planck

Following Planck there are two interesting new directions for CMB observations. A sensitive CMB polarization experiment can be used to detect the primordial gravitational waves produced during inflation. In addition, fine scale observations can provide images of the largest structures in the universe just as they were beginning to dissipate the heat of their gravitational collapse.

Inhomogeneities in the universe that were present at age 300,000 years were themselves the result of earlier processes. By studying degree angular scale CMB structure we learn about processes, inflation for example, that may have produced gravitational potential perturbations. The careful study of CMB structure, in particular degree angular scale *polarized* sky structure, can be used to detect not just potential perturbations but also gravitational waves (Bond and Efstathiou 1984; Polnarev 1985; Kamionkowski, Kosowsky, and Stebbins 1997; Seljak and Zaldarriaga 1997; Keating et al. 1998) Unlike photons, these gravitational waves travel freely through the ionized early universe, so the study of CMB polarization may allow us to look much further back in time–and at
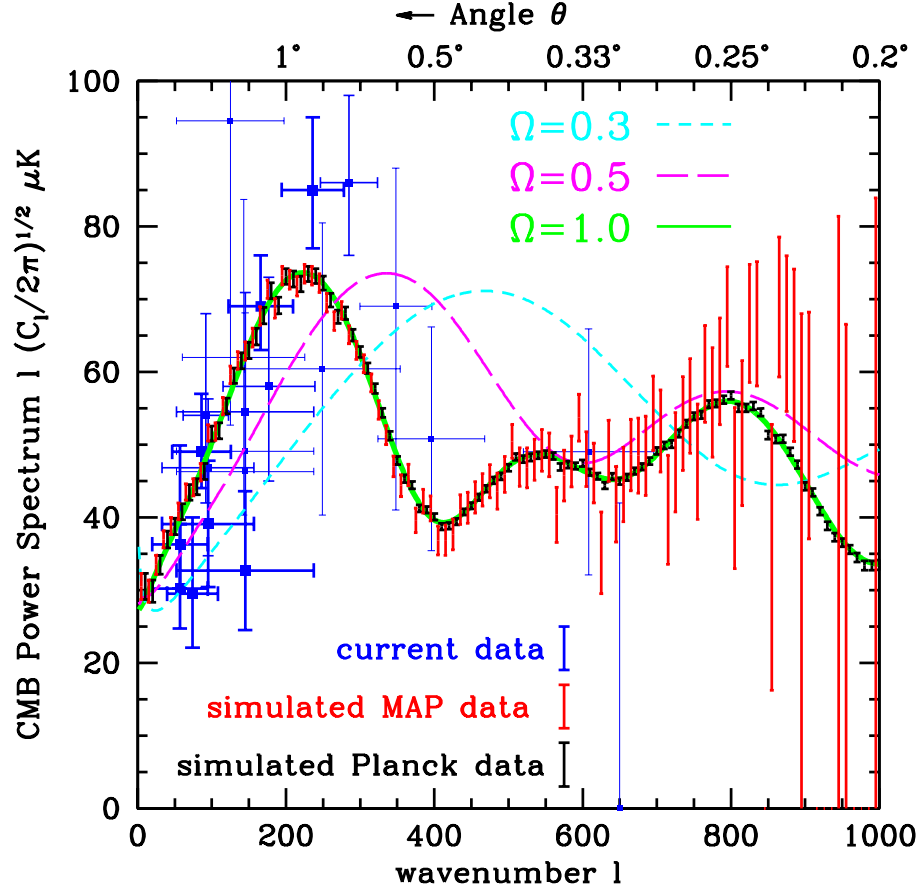
Fig. 1: **Spatial Power Spectrum of CMB Sky Structure.** Shown in this figure (taken from Kamionkowski 1998) are: current CMB power spectrum measurements, plotted as squares with error bars; three theoretical predictions of the power spectrum, plotted as curves; and projected error limits for MAP and Planck, plotted as red and black vertical error bars. The use of a spacecraft will allow measurements of CMB sky structure with precision well beyond that possible from the ground. Because of that precision observations with MAP and Planck are expected to determine the values of the cosmological parameters.

much higher particle energies–than has been possible before. However, the sensitivity needed for these observations exceeds that attainable with the Planck satellite. As described in the Polarization section below, if a new instrument can be built with sufficient sensitivity and with sufficient control of systematic errors, the resulting observations have the potential to allow the study of physics at energy scales as high as 10^{19} GeV, far beyond the reach of the largest feasible particle accelerators (see, e.g., Kamionkowski and Kosowsky 1999 for a recent review).

On angular scales of one arcminute and finer, the CMB picks up an impression from the material it passes through. Since the CMB passed through the dark ages of cosmology, before stars or quasars formed, the study of arcminute scale CMB features is the only technique we know for viewing the very early processes of structure formation. Using the CMB as an intense, very high redshift backlight, we can study the early history of galaxy clusters and we can witness their gradual acceleration as they began to fall into the deepening potential wells around them. We should also be able to view directly, at the time of first formation, the precursors to the 100 Mpc scale sheets (e.g. the "Great Wall") we find in the galaxy distribution today. No other known cosmological observable can provide such direct information on the great structures as they were forming. Because of the high angular resolution required, this work exceeds the capabilities of the MAP and Planck missions. These observations are described in the Fine Scale section below.

III.   Polarization

Polarization of the CMB contains a wealth of information on primordial perturbations that will not be provided by the temperature map. It was recognized early on that CMB sky structure should be polarized (Rees 1968, Kaiser 1983), and theoretical studies of polarization continue. For a tutorial on CMB polarization see Hu and White 1997b. Using temperature information alone it will not be possible to confidently separate the three classes of initial perturbations: density, pressure, and gravitational waves. An example of this degeneracy is shown in Figure 2. Two simulated sky maps of temperature and polarization are shown. In one case the sky structure is due to gravitational waves, in the other case the structure is due to density perturbations. These two temperature maps differ by less than the cosmic variance so no CMB temperature observation can ever distinguish between them. Pressure perturbations can also create temperature structure indistinguishable from the two maps shown in Figure 2. Fortunately, the three sources of primordial perturbations produce distinctly different polarization patterns. Polarization information can break the perturbation-type degeneracy.

Polarization information also allows fine selection among inflation models. Figure 3, from Kinney 1998, shows the selective power of polarization information. Five different inflation models are shown. Without polarization information it is not possible to distinguish the models. However, a polarization experiment with a sensitivity three times better than Planck would allow a strong selection.
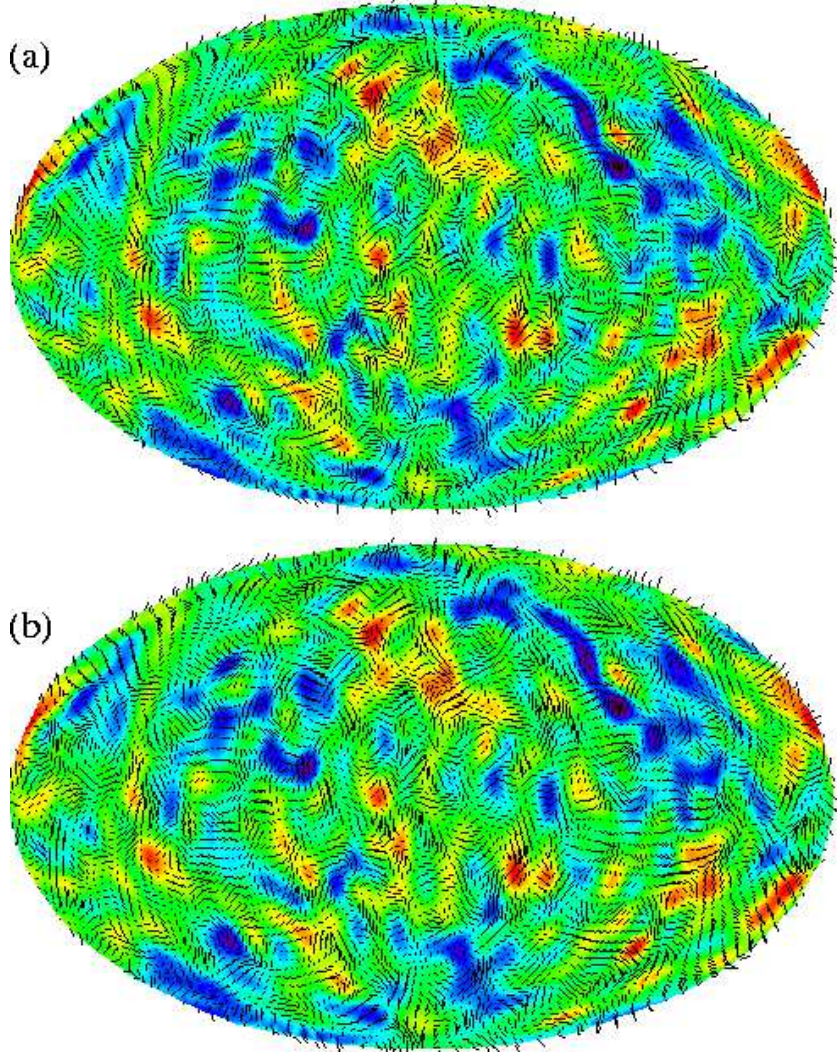
Fig. 2: **CMB Map With Polarization Vectors**   Shown above (from Caldwell, Kamionkowski, and Wadley 1998) are two simulated maps of CMB temperature structure (colors) and polarization fraction (bars). The temperature structure in both maps is the same. The polarization vectors in panel (a) were calculated assuming polarization was produced by gravitational waves during inflation at a high energy. The polarization vectors in panel (b) were calculated assuming polarization was produced by density perturbation due to inflation at a lower energy. The polarization vector field in (a) has curl, but the field in (b) does not. Therefore a precise measurement of the curl of the polarization vector field of the CMB will expose or disprove the existence of gravitational waves, and constrain the energy scale of inflation.
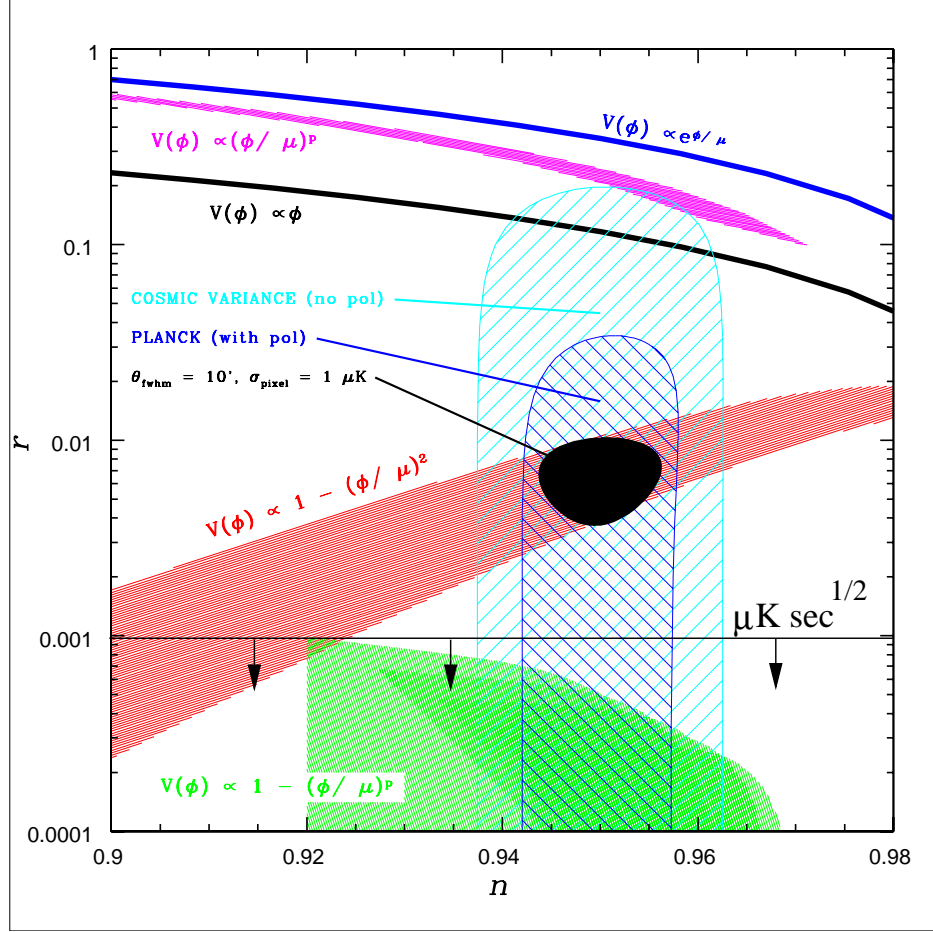
Fig. 3: **Tests of inflation models.** Five types of inflation models are shown in r (tensor/scalar ratio) vs n (spectral tilt index) space. In this simulation it is assumed that the true values of r and n fall in the center of the black region. The outer hatched region shows the constraint in this space possible with noiseless temperature maps, but without polarization information. The inner hatched region is the constraint possible with the currently planned Planck capabilities. The black region shows the constraint possible with a polarization instrument with sensitivity three times better than Planck. (From Kinney 1998.)

Gravitational Waves from Inflation

It is particularly exciting that gravitational waves are potentially detectable through measurement of CMB polarization. The clouds of ionized gas viewed with CMB telescopes were in motion at the time of last scattering. These motions produce patterns in the polarization in the CMB. Fractional polarization of CMB sky structure is expected at the few percent level in all models of the universe. In models with strong gravitational waves, however, swirling motions in the ionized gas produce polarization patterns that differ from gravitational infall patterns due to density perturbations.

A map of polarization vectors on the sky can be decomposed into a curl and a curl-free part. Density perturbations produce scalar perturbations to the spacetime metric. Since density perturbations have no handedness, they cannot produce a curl. On the other hand, gravitational waves are tensor perturbations. They can have a handedness (there are right- and left-handed circularly-polarized gravitational waves), so they do produce a curl. Thus, a curl component in the polarization provides a smoking-gun signature for a gravitational-wave background (Kamionkowski, Kosowsky, and Stebbins 1997; Seljak and Zaldarriaga 1997).

We will only understand the big bang when we also understand high energy physics. The current hot big bang model accounts for the universal expansion, the presence and energy spectrum of the CMB, the light-element abundances, and can certainly accommodate primordial perturbations, but the hot big bang model leaves many questions unanswered. For example, why is the universe flat? Why is it so smooth? Why was there a big bang in the first place? And where did the primordial inhomogeneities mapped with CMB telescopes come from? Just as the light element abundances in today's universe could only be understood through an understanding of the underlying nuclear physics, we now appreciate that the answers to these current questions must be accompanied by development of our understanding of particle theory at very high energy scales. The answers to these questions will probably not be obtained without a concomitant understanding of the unification of the fundamental forces of Nature.

Inflation, a proposed period of accelerated expansion in the early universe driven by the release of vacuum energy, offers answers to all the questions listed above. If MAP and Planck confirm that the universe is flat and if the spatial power spectrum of the CMB agrees with that expected from adiabatic initial perturbations, we may indeed be on the right track with inflation. If so, we must further test the inflationary hypothesis and attempt to determine the physics responsible for inflation.

By precisely mapping CMB polarization we may be able to determine the energy scale of inflation. There is a very broad range of models of inflation that produce a flat universe and a nearly scale-invariant spectrum of primordial density perturbations. A priori, inflation could have occurred when the universe had a temperature anywhere from roughly electroweak scale, 100 GeV/k to the Planck temperature, 10^{19} GeV/k. However, it may be possible to determine the cosmic temperature at the end of the era of inflation because inflation also generically predicts the existence of a stochastic background of long-wavelength gravitational waves (Abbot and Wise

1984). The amplitude of this gravitational-wave background is proportional to the square of the inflationary energy scale. Detection of these gravitational waves would therefore provide a direct measurement of the energy scale of inflation and point to the new physics responsible for inflation. If inflation occurred at very high energies the resultant gravitational waves would have produced large amplitude temperature structure in the CMB. But the COBE sky structure is weak ($\Delta T/T \sim 10^{-5}$), so COBE data can already be used to constrain the energy scale of inflation to be less than $\sim 10^{16}$ GeV. However, since CMB temperature structure from gravitational waves cannot be unambiguously distinguished from that due to density perturbations, we don't know right now which produced the CMB structure that we have detected. Polarization maps will be needed to settle this issue.

If inflation has something to do with GUTs (unified theories of the electroweak and strong interactions), as most theorists surmise, then the inflation era probably occurred at temperature $\sim 10^{16}$ Gev and the gravitational-wave signal is detectable with a next-generation CMB polarization experiment. Detection of such a signal would be truly extraordinary: It would (1) allow us to penetrate the last scattering surface, giving us a glimpse of the universe as it was at a time 10^{-38} seconds after the initial singularity; (2) provide a window to new physics at energy scales more than 12 orders of magnitude beyond those accessible at accelerator laboratories; (3) explain the origin of primordial perturbations. And, since gravitational waves and density perturbations are produced during inflation by an analog of Hawking radiation, detection of a gravitational-wave background would (4) be the first observation of the effects of quantum field theory in curved spacetimes, and thus would provide clues to the nature of quantum gravity.

An observable polarization-curl signal is not guaranteed even if inflation did occur (it may have taken place at a lower energy scale), but the signal should be detectable if inflation took place near the GUT scale. This means that even a null result from a sensitive polarization experiment would be quite interesting. It would indicate that inflation did *not* arise from a GUT phase transition or from quantum gravity effects which also place the inflation epoch at a high temperature.

High-sensitivity polarization maps will be used to study a wide range of interesting cosmological physics in addition to probing gravitational waves. For example, the polarization pattern can be used to isolate the peculiar-velocity contribution to degree-scale temperature anisotropy. This information will be essential to discriminate between various structure-formation models that give rise to the same temperature perturbations. Polarization information can also be used to constrain the ionization history of the universe and thus probe the earliest epochs of formation of gravitationally-collapsed objects in the universe. Polarization can also probe primordial magnetic fields. Perhaps most importantly, polarization data may contain surprises due to unanticipated physical processes.

COBE provided valuable information on the origin of large-scale structure. It confirmed the notion that large-scale structure grew via gravitational infall from primordial density perturbations. Also, the COBE data now provide a normalization for the power spectrum of primordial perturbations in any gravitational growth model. MAP and Planck are designed to accurately measure the CMB temperature structure expected on the sky and thereby provide precise information on the

primordial spectrum of density perturbations. Although both MAP and Planck will provide some polarization information they lack the sensitivity to detect the gravitational wave signal from GUT scale inflation. To complete our study of the primordial fluctuations we must also map the CMB polarization to small angular scales with a sensitivity at the cosmic-variance limit in the same way that Planck will map the temperature structure.

Specifications of a Polarization Experiment

Angular resolution: Although gravitational-wave-produced polarization structure in the CMB occurs over a range of angular scale from 100 to 0.1 degrees, angular resolution finer than one degree is required to see the predicted turnover in the power spectrum (Kamionkowski and Kosowsky 1998). Detecting this turnover will be valuable in discriminating between gravitational waves and an unsubtracted foreground (whose power spectrum would rise at smaller angular scales). A polarization experiment should have an angular resolution of $0.3°$.

Sensitivity: As mentioned above, the amplitude of the gravitational-wave background—and therefore, the amplitude of the gravitational-wave-induced curl component of the polarization— depends on the energy scale of inflation, which is currently unknown. If inflation has something to do with grand unification of fundamental forces, then the polarization signal should be detectable with a next-generation experiment. If inflation had something to do with new physics at much lower energy scales, then the polarization-curl signal could be much too small to ever be detectable.

Figure 3 can be used to make this argument more precise. Shown therein are predictions of the amplitude (r) of the gravitational-wave background (measured via the polarization-curl signal) for five classes of inflationary models. The four classes with the largest r arise in models in which inflation is related to unification of fundamental forces. Generically, models based on grand unification predict r values in this range. The fifth class of models (that with the smallest polarization) usually arises if inflation had something to do with lower-energy physics. To rule out all of the grand unification models shown requires a polarization sensitivity that will allow detection of a gravitational-wave amplitude as small as $r \sim 0.001$. A null result would then indicate that if inflation occurred, it must have arisen from new physics at a lower energy scale.

To measure r with sensitivity 0.001, in the presence of foregrounds, the polarimeter sensitivity required is $\sim 0.1 \ \mu K \sqrt{sec}$, roughly 100 times that of Planck. Such a sensitivity level will be difficult to achieve in the short term. However, an order-of-magnitude improvement over Planck sensitivities should be achievable within the next decade, and this would allow an initial search for a gravitational-wave background and, in turn, a strong selection among inflation models.

Foregrounds: Right now we don't know whether our ability to detect gravitational waves will be limited by detector sensitivity or by foregrounds because the polarization foregrounds are currently very poorly understood. (Tegmark et al. 1999) Even if MAP and upcoming ground- and balloon-based experiments do not have sufficient sensitivity to detect gravitational waves, they will be able to measure the polarization of foreground emission such as the dust grain emission polarization. These measurements will be essential in the design of a future experiment.

Sky Coverage: The current lack of information on polarized foregrounds makes it difficult to

determine the optimum sky coverage for a polarization experiment. If the subtraction of foregrounds is the main difficulty for a sensitive polarization experiment, all sky coverage may be essential. High sensitivity is also needed, however, and better per-pixel sensitivity can be achieved by limiting sky coverage.

Site: A high sensitivity polarization experiment must be done from space for two reasons. First, the sensitivity required for these observations is not likely to be possible from within the atmosphere. Second, uniform coverage over a large region of sky and over a wide range of frequencies will be valuable in separating polarized CMB sky structure from polarized foreground emission. Multi-frequency uniform sky coverage was one of the spacecraft advantages that placed the COBE results head and shoulders above previous results. This advantage will also allow MAP and Planck to succeed where ground and balloon based experiments are struggling. (See Figures 1 and 6.) The same rules will hold for polarization experiments: although good progress will be made from the ground and from balloons, a spacecraft will eventually be needed.

IV.   Fine Scale CMB Sky Structure

As CMB photons travel from the surface of last scattering to the observer, secondary sky structure can arise due to the interaction of the CMB photons with intervening re-ionized matter. This sky structure is called "secondary" in contrast to the primary structure produced at age 300,000 years. One interesting and useful source of secondary structure is the Sunyaev-Zel'dovich effect (Sunyaev and Zel'dovich 1970, Sunyaev and Zel'dovich 1972), a distortion of the CMB energy spectrum that occurs when the CMB photons interact with hot ionized gas. For example, in a rich cluster of galaxies approximately 10% of the total mass is in the form of hot ($\sim 10^8\,$K) plasma. Compton scattering of CMB photons by electrons in this intra-cluster (IC) plasma can present an optical depth of $\sim$0.01, resulting in a distortion of the CMB spectrum at the mK level. See Sunyaev and Zel'dovich 1980; Rephaeli 1995; Birkinshaw 1999 for reviews. Figure 4 shows a simulated fine scale observation. On fine scales it is the thermal S-Z effect that is expected to dominate CMB sky structure.

There are two components of the S-Z effect which result from distinct velocity components of the scattering electrons. The *thermal* component is due to the thermal (random) motions of the scattering electrons. The *kinetic* component is due to the bulk velocity of the IC gas with respect to the rest frame of the CMB. In Figure 5, the spectral distortion produced by each of the two components is shown. As evident from the figure, the two S-Z components have distinct spectra which can be separated by observations at several millimeter wavelengths.

When combined with a measurement of electron temperature, the ratio of the kinetic and thermal component amplitudes provides a direct measurement of the cluster's radial peculiar velocity relative to the rest frame of the CMB. The observed surface brightness difference of both the thermal and kinetic components is independent of the cluster redshift, as long as the cluster is resolved. Clusters are large objects, typically of order 1 Mpc, and subtend an arcminute or more at
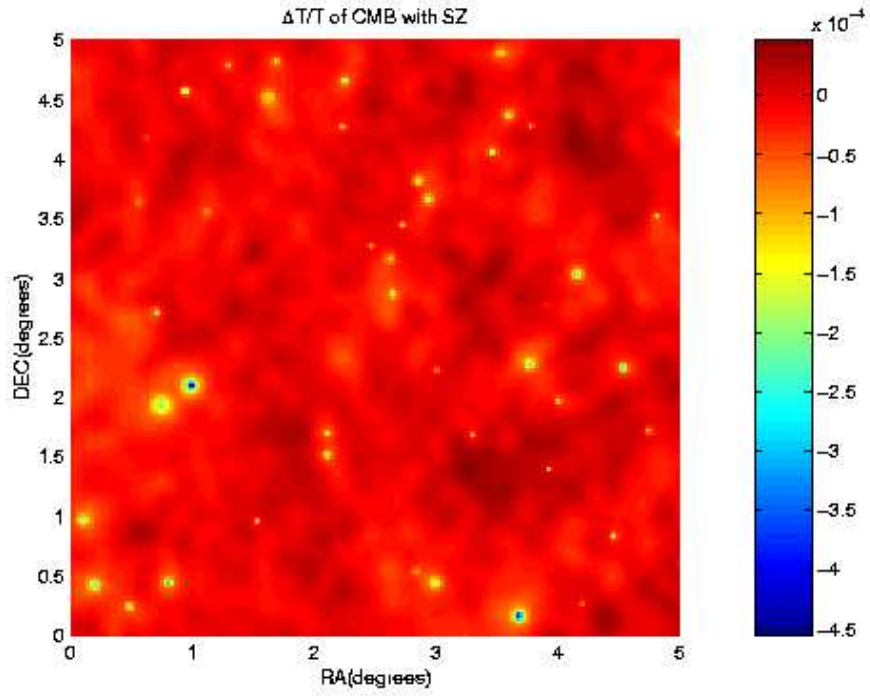
Fig. 4: **Simulated fine angular scale CMB image.** Simulated CMB structure on a five degree square region of sky is shown. The faint extended structure is primary CMB structure, while the strong localized sources are secondary structure due to the Sunyaev-Zel'dovich effect in galaxy clusters. At fine angular scales the S-Z signal dominates. This simulation does not include the S-Z filaments across the sky expected from the collapse of 100Mpc structures.
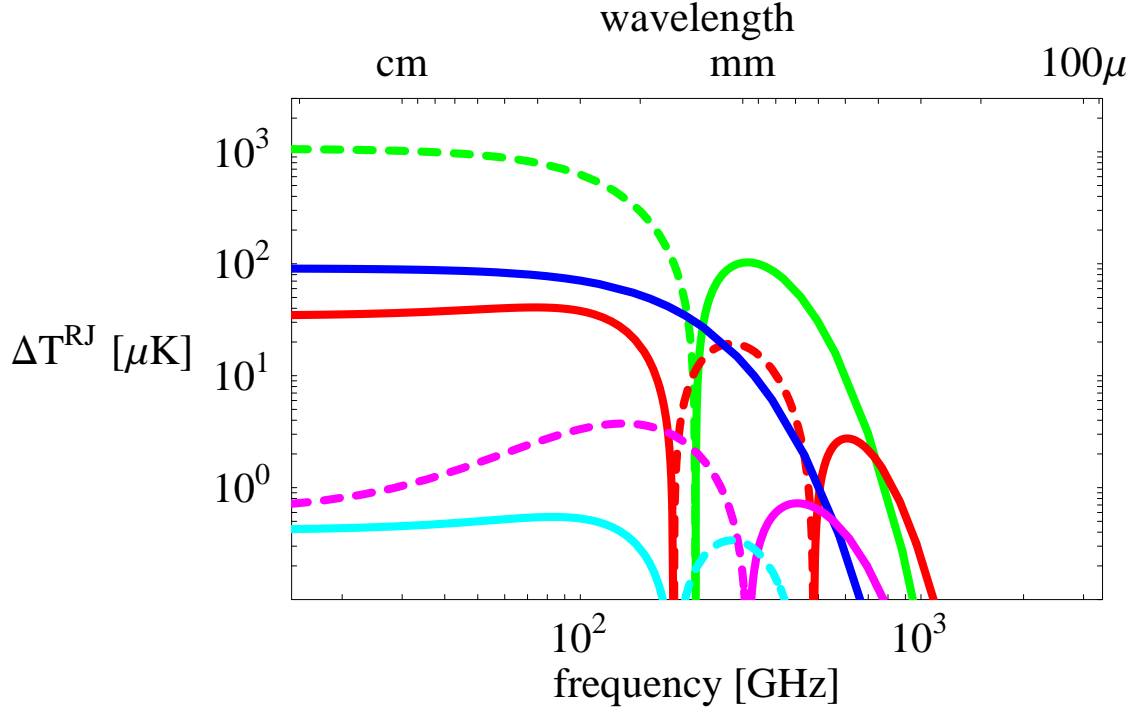
Fig. 5: **The Sunyaev-Zel'dovich Effect**   The Rayleigh-Jeans Temperature (indicating intensity) versus frequency of different components of the Sunyaev-Zel'dovich effect is plotted for gas in a fiducial cluster of galaxies. In this simulation, the gas has temperature, $T = 10\,\mathrm{keV}$; peculiar velocity, $v = 1000 km/sec$ towards us; and a Thompson optical depth of $\tau = 0.01$. Solid curves indicate increments in the CMB temperature, and the dashed curves decrements. These different components can be differentiated by their different spectral shape using sufficiently sensitive detectors with good frequency coverage in the mm and sub-mm bands. From top to bottom the components are 1) the classical thermal S-Z effect ($\propto \tau T$) [green]; 2) the classical kinetic S-Z effect ($\propto v\tau$) [blue]; 3) relativistic corrections to (1) ($\propto \tau T^2$) [red]; 4) thermal corrections to (2) ($\propto v\tau T$) [magenta]; and 5) finite optical depth corrections ($\propto \tau^2 T^2$) [cyan]. By measuring the amplitude of (1) and (3) one may disentangle τ and T; the amplitude of (2) additionally gives v, however, measurements of this amplitude will inevitably be uncertain due to the primary CMB anisotropy behind the cluster which has the same spectral signature. This uncertainty can be removed by measuring the amplitude of (4). A very accurate arcminute angular resolution map of deviations of the CMB spectra from a blackbody spectrum would provide information about the internal density, temperature, and velocity structure of cluster gas at high redshifts.

any redshift. Therefore, accurate S-Z measurements can be made throughout the universe, all the way back to the epoch of formation of the hot IC gas. A sky survey of S-Z determined velocities would provide us a view of the motions of test masses (the clusters) throughout the entire Hubble volume, and show us the evolution of velocity structure over much of the history of the universe. In addition, the evolution of the number density of clusters provides a sensitive test of gravitational collapse models.

Until recently it has been assumed that X-ray measurements would be needed to determine the electron temperature of the IC gas. But the IC electrons are mildly relativistic, and recent calculations of the relativistic S-Z effect indicate that with sufficiently precise CMB measurements it may be possible to determine the electron temperature, and the cluster velocity, without need for X-ray data (Fabbri 1981; Rephaeli 1995; Stebbins 1997; Challinor and Lasenby 1998; Itoh, Kohyama, and Nozawa 1998; Nozawa, Itoh, and Kohyama 1998; see Figure 5). This is particularly important for high redshift clusters since the received X-ray flux falls as $\sim (1+z)^{-4}$ while the S-Z brightness is redshift independent. Of course, for nearby clusters, for which X-ray data is available, both techniques should be used and the results compared.

In the last few years, high signal-to-noise detections and images have been made of the thermal S-Z effect toward several distant clusters ($z > 0.15$). Most of these observations have been made at centimeter wavelengths; observations at $2\,\mathrm{mm}$, however, have also been successful (Birkinshaw 1999). All of these observations have been done using ground based telescopes.

The thermal S-Z distortion is a measure of the thermal history of the universe. There are several potential sources of heating for the intergalactic medium: gravitational collapse, energy input from galaxy superwinds (Pen 1999), and energy input from quasars and AGNs (Natarajan and Sigurdsson 1999). Since the S-Z effect depends upon n_e rather than n_e^2, we can use it to trace the thermal history not only of dense clusters but also of filaments. If the mean electron temperature is 1 keV, then a 1 Mpc wide filament produced by the collapse of a 10 Mpc wave should produce a distortion of 10 μK.

These filaments, one arcminute wide and about a degree long, can be detected by searching for the S-Z thermal effect distortion they produce on the sky. The filaments will be difficult to detect through x-ray emission because the electron density in the filaments is too low; however, the S-Z thermal effect signal they produce should be detectable.

The thermal S-Z effect is expected to be the strongest source of sky structure at arcminute angular scales but other sources of structure can also provide information from the dark ages. Once arcminute resolution multi-frequency CMB maps are available, the regions affected by the thermal S-Z effect can be identified. S-Z free regions can then be studied to detect other sky structure present. The physics responsible for fine scale structure include gravitational lensing, bulk motions of plasma (the Ostriker-Vishniac effect), evolution of the gravitational potentials during the passage of CMB photons (the Integrated Sachs Wolfe effect and the Rees-Sciama effect), and details of the ionization history of the universe. See Hu and White 1997a, Refregier, Spergel, and Herbig 1998, and references therein for details.

Specifications of Fine Scale Observations

Angular resolution: One arcminute resolution will be required. At high redshifts the cores of galaxy clusters subtend about one arcminute. In addition the S-Z filaments produced by gravitational collapse should be about an arcminute across, and as long as a degree. At the millimeter wavelengths needed for CMB observations, arcminute beamwidths translate to a telescope aperture (or longest baseline) of about 10 meters.

Sensitivity: The brightest clusters can produce S-Z amplitudes $\sim$1mK. The kinetic effect is expected to be smaller, $\sim$200 μK. Filaments are expected to produce 10 μK thermal S-Z signals. Currently CMB instruments are measuring the $\sim$100 μK degree scale sky structure with 5 μK precision, so current technology is sufficient for S-Z cluster work. Better sensitivity will be needed to study filaments.

Frequency Range: To separate S-Z thermal, kinetic, and relativistic-electron effects, maps covering the range from 30-400 GHz will be needed. Ideally all these maps should be made using the same instrument. Additional information at lower (5-10 GHz) frequencies and higher (1000-3000 GHz) frequencies will also be needed as an aid in removing emission from unrelated foreground and background sources.

Telescope technology: Both filled aperture and interferometric telescopes can be used for observations at this angular scale and frequency. The advantages of interferometers include: rejection of telescope emission, insensitivity to amplifier gain fluctuations, and fault tolerance. The advantages of filled aperture telescopes include: wide detection bandwidth, wide observing frequency range, lower complexity, and lower cost.

Site: As shown in Figure 6, observations of the thermal S-Z effect in clusters should be attempted from the ground before resorting to spacecraft observations. Currently ground based efforts are making rapid progress on this topic. However, attempts to measure electron temperatures in clusters via the relativistic S-Z effect and attempts to map peculiar velocities over large regions of sky may require spacecraft observations. S-Z filament observations, which require multi-frequency maps covering degrees, along with microkelvin sensitivity, may also benefit from observations done in space.
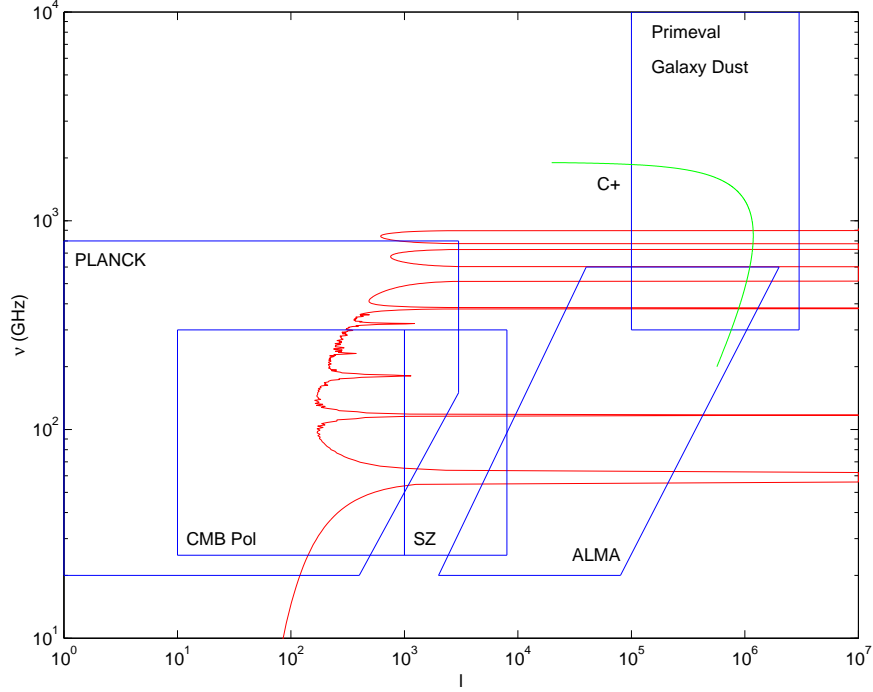
Fig. 6: **Comparison of Experiments**   Shown in angular scale ℓ versus observing frequency ν space are science targets: CMB polarization, Sunyaev-Zel'dovich effect, dust emission by primeval galaxies, and the fine structure line of ionized carbon from a high redshift galaxy. Also shown are the domains of two instruments: the Planck spacecraft and the Atacama Large Millimeter Array (ALMA). (The Millimeter Array Web Site 1999) The red jagged curve is a comparison of atmospheric noise to noise in a spacecraft environment. On this curve the South Pole winter atmospheric emission fluctuations equals the photon fluctuations in a spacecraft environment (assumed due to the brightness of the sky along with photons emitted from a 1% emissivity 70 K surface). Observations above and to the left of this curve derive a noise benefit from being in space. Cluster S-Z observations fall to the right of the noise boundary, and are appropriate for ground based observation, while CMB polarization observations should be done from space.

V. Summary

After the Planck mission, we will need to make precise multi-frequency, all-sky maps of CMB polarization. CMB polarization measurements, because they may allow for the detection of a gravitational wave background, probe much further back in time than any other astronomical observation. In so doing, CMB polarization measurements allow the study of particle physics at energies far higher than are available with any earth-bound accelerator experiment. The processes that may have produced this background of gravitational waves probably involve the unification of the the strong and electroweak forces and may also involve quantum gravity. Because of the ability to constrain physics at enormous energy scales, CMB polarization observations have the potential to revolutionize our understanding of basic physics. Polarization information is also expected to help determine the class of primordial perturbations (density; pressure; gravitational wave), and will allow a strong selection among inflation models.

After Planck it will also be important to make arcminute angular scale observations of the CMB because these observations can probe the dark ages of cosmology. Using fine scale CMB observations we can see the largest structures of the universe, galaxy clusters and galaxy sheets, as they were first forming.

This committee has sought comment from over one hundred cosmologists, as well as from members of the particle physics and general relativity communities. The discussion has been wide-ranging, but the same comment was heard again and again. Because of the potential for discovery of dramatic new physics (gravitational waves from inflation), along with model-testing power, CMB polarization measurements should have the highest priority among CMB observations following Planck.

It would be truly remarkable if, early in the twenty-first century, we could say that we understand what was happening in the universe just 10^{-38} seconds after it began.

VI. Acknowledgements

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