CMB Optical Depth Measurements: Past, Present, Future

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Abstract

The polarization of the cosmic microwave background (CMB) is encoded with exactly the same cosmic information as the CMB’s temperature anisotropy. However, polarization has the additional promise of accurately probing the reionization history of the universe and potentially constraining, or detecting, the primordial background of gravitational waves produced by inflation. We demonstrate that these two CMB polarization goals are mutually compatible. A polarimeter optimized to detect the inflationary gravitational wave background signature in the polarization of the CMB is well situated to detect the signatures of realistic first-light scenarios. We also discuss current results and prospects for future CMB polarization experiments.

Key words: cosmology, observation, cosmic microwave background, polarization

1 Introduction

The CMB possesses a wealth of cosmological information owing to its origin 400,000 years after the Big Bang – an epoch when linear cosmological perturbation theory holds. However, the CMB also is imprinted by “first-light” sources at later times that reveal the dynamics of reionization. Even detecting the transition from partial to full-reionization in (physically more plausible) non-instantaneous reionization scenarios is conceivable. The first-year WMAP results demonstrate a nearly 5$\sigma$ detection of a reionization feature in the temperature-polarization cross-correlation power spectrum. This detection, along with WMAP’s detection of the Thomson optical depth, was the first demonstration of CMB polarization’s ability to go “beyond parameter estimation” – making precision measurements of a cosmological epoch which was previously shrouded in mystery. WMAP’s detection was also a tantalizing hint at CMB polarization’s promise to probe vitally important cosmological
parameters that are essentially unobservable using temperature anisotropy alone.

However, as with many groundbreaking experiments, WMAP’s results have generated even more intriguing questions. In particular, why is the Thomson optical depth so much higher for the CMB than that implied by the QSO Gunn-Peterson measurements, e.g. [1,2,3]? Ultimately, the optical depth due to first light sources measured by CMB polarimeters must be reconciled with the Gunn-Peterson absorption feature measurements in the spectra of distant quasars. Several attempts at this reconciliation have been proposed, some of which feature multiple reionizations [4], or a period of partial ionization [5]. Interestingly, it appears that these reionization scenarios, which translate to structure formation scenarios, can indeed be constrained observationally by CMB polarization.

In this paper we discuss the prospects of upcoming ground, balloon, and space CMB polarimeters to measure both the Thomson optical depth and constrain new features in the polarization power spectra characteristic of realistic reionization scenarios. The implications of intrinsic systematic effects such as foregrounds and cosmic variance are also discussed.

2 CMB Polarization

Much of the wealth of cosmological information encoded in CMB polarization is only observable at medium to large angular scales (> 0.5°). Essentially all information on the classical cosmological parameters of the ΛCDM model, e.g., the baryon density, Ω_b, the Hubble parameter, h, the scalar power spectrum’s power law index, n_s, the amplitude of the primordial power spectrum, A_s, the tensor-to-scalar ratio, r, etc, can be obtained from CMB polarization at angular scales > 0.5°. Because the temperature anisotropy is much larger than the polarization signal it can produce higher confidence measurements of the classical cosmological parameters than polarization. However, there are several parameters which only polarization can reveal. In particular, only CMB polarization can probe the imprint of the inflationary gravitational wave background (GWB) on the CMB. This polarization signature occurs at angular scales of ∼ 2°. Reionization primarily affects CMB polarization on angular scales > 4°. We note that the grad-mode polarization, C^{E}_\ell, peaks at \ell \simeq 1000 corresponding to \simeq 10' scales, and that gravitational lensing of the CMB grad-mode polarization by large scale structure produces non-negligible curl-mode polarization C^{B}_\ell at the same \simeq 10' scales [6].
3 Current Results

Fig. 1. Measurements of the large-angular scale gradient-mode polarization power spectrum $C^{E}_\ell$ for $0.5^\circ \leq \ell < 400$. The solid line is the polarization power spectrum for the WMAP best fit cosmological model, with $\tau = 0.17$ [7].

Figures 1 and 2 show the current detections of the grad-mode polarization and the polarization-temperature cross correlation. Currently, only DASI[8] and BOOMERANG[9] have detected grad-mode polarization at angular scales $< 0.5^\circ \leq \ell < 400$, and no experiments have detected the grad-mode polarization for $\ell < 100$. The only other experiments that have detected the grad-mode polarization are CBI[10] and CAPMAP[11], though at smaller angular scales (higher $\ell$) than are considered in this paper.

The primary effects of reionization are encoded in the grad-mode and temperature polarization cross-correlation at $\ell \lesssim 50$. In the absence of detections, the most stringent constraint in this range of multipoles is currently $C^{E}_\ell < 8 \mu K$ at 95% confidence reported by POLAR[12] for $2 < \ell < 20$ (assuming no B-modes). There are many more detections of the temperature-polarization cross correlation than of the grad-mode polarization as figure 2 demonstrates. WMAP[13] reports a large number of highly significant detections, especially at low-$\ell$ due to WMAP’s ability to map most of the sky. CBI, DASI, and BOOMERANG[14] have also detected the cross-correlation spectrum, mainly
Fig. 2. Measurements of the temperature-polarization cross-correlation power spectrum $C^{TE}_\ell$. The solid line is the power spectrum for the WMAP best fit cosmological model, with $\tau = 0.17$ [7].

at much smaller angular scales than WMAP. A complete description of reionization will require significant detections of CMB E-mode polarization for $\ell < 50$. An ancillary benefit of reionization is that it boosts the primary curl-mode power spectrum significantly near $\ell = 10$. Due to reionization, a more stringent limit on the tensor-to-scalar ratio, $r$, in the presence of lensing can be obtained than that calculated in [15,16].

4 The effect of reionization

Reionization produces free-electrons which Thomson-scatter CMB photons and produce CMB polarization. The scattering damps the CMB temperature in direction $\hat{n}$ as $T'(\hat{n}) = e^{-\tau}T(\hat{n})$, where $\tau$ is the Thomson optical depth. Reionization, therefore, damps the anisotropy power spectrum as $C^{T'E}_\ell = e^{-2\tau}C^{TE}_\ell$. The effect of $\tau$ on the temperature anisotropy power spectrum is completely degenerate with the primordial power spectrum’s amplitude, $A$. Fortunately, a new feature, e.g. [17,18], in the polarization power spectra occurs at large angular scales which breaks the degeneracy between normaliza-
Fig. 3. Temperature (color scale) and polarization (lines) realizations in real-space smoothed with a 4° beam. The left panel shows a simulation with no reionization and the right panel shows the effects of instantaneous reionization with $\tau = 0.17$. Reionization does not noticeably affect the large scale temperature pattern but it produces roughly ten-times larger polarization at large scales. These figures have no curl-mode power. The maximum gradient-mode polarization in the right panel is $\approx 800$ nK. Figures courtesy of Eric Hivon.

5 A More Realistic Cosmic Variance Limit.

An all-sky experiment must confront galactic contamination, which can only be subtracted to finite precision. For example, the WMAP team used multiple frequency channels in combination with a sky-cut that left 85% of the sky remaining [13]. This cut also introduced correlations between multipoles at the few percent-level, and a total anti-correlation of 12.4%. Even with sophisticated foreground modelling and multiple frequency coverage the challenges of achieving polarization fidelity at the 100 nK level over $>10^6$ angular scales – required, for example, to detect the signatures of non-instantaneous reionization scenarios (e.g, [5,19]) – are significant.

As a simple, but admittedly conservative, foreground mitigation technique we consider a full-sky map and and omit galactic latitudes within $|b| < b_{cut}$ of the galactic plane. This leaves two circular “cap” regions remaining. This strategy affects the recovery of reionization information in two ways. First it reduces
the resolution in $\ell$-space compared to a true full-sky experiment, leaving a residual correlation between multipoles. Secondly, it increases cosmic variance on the measurement of $C_{\ell}^E$, since the amount of observed sky, $f_{\text{sky}}$ decreases: 

$$\delta C_{\ell} \propto \frac{1}{\sqrt{f_{\text{sky}}}}.$$ 

The effect of this simple foreground mitigation strategy is apparent in parameter estimation. If one (conservatively) insists on using uncorrelated multipoles to estimate parameters, the integrated signal-to-noise ratio \[ \sum_{\ell=2,4,6...} \frac{C_{\ell}^E}{\delta C_{\ell}^E} \]

is reduced significantly. Here $\delta C_{\ell}^E$ is the cosmic variance limited uncertainty on $C_{\ell}^E$, including the inflation of the cosmic variance due to the cut itself, and \( \ell_{\text{cutoff}} \) is the highest multipole afforded by the angular resolution of the telescope or other filtering.

As a numerical example, we consider a galaxy-cut which excludes data with $b_{\text{cut}} = 20^\circ$, corresponding to $f_{\text{sky}} = 75\%$ – not far off from WMAP’s $f_{\text{sky}}$. However, since we insist that the total anti-correlation between multipoles is $\ll 1\%$, the $\ell$-space resolution degrades from $\delta \ell = 1$ to $\delta \ell = 2$. The quadrupole, and all even multipoles are completely uncorrelated.

We find that the signal-to-noise is more than halved relative to a true all-sky experiment \[ \sum_{\ell=2,3,4...} \frac{C_{\ell}^E}{\delta C_{\ell}^E}. \] The halved signal-to-noise ratio of the power spectra does not necessarily translate into a doubling of parameter errors, however. A Fisher matrix analysis, e.g. [20], must be performed to assess the degradation of parameter sensitivity.

A parameter estimation indicates that the new cosmic variance limit on $\tau$ from the $b_{\text{cut}} = 20^\circ$ cut-sky data is $\sigma_\tau = 0.0048$. This is compared to our Fisher matrix results for the ideal full-sky cosmic variance limit: $\sigma_\tau = 0.0029$ – an increase of 65%. This latter limit agrees nearly exactly with the results of Holder et al. (2003)[19]. Due to the nearly degenerate correlation between $\tau$ and the amplitude of the primordial power spectrum, the increase in $\sigma_\tau$ increases the uncertainty on $A$ as well. Figure 4 shows the individual and joint likelihoods for $\tau$ and $A$ for the full-sky and $b_{\text{cut}} = 20^\circ$ simulations.

Additionally, more realistic cut-sky observing strategies have lower $\ell$-space resolution than all-sky surveys which may preclude the detection of features in the polarization power spectra that characterize the dynamics of reionization [5,19]. This may ultimately limit the precision with which the dynamics of non-instantaneous reionization can be reconstructed. Furthermore Kaplinghat et al.[5] estimate that the sensitivity of a CMB polarimeter to the redshift of the onset of reionization is $\sigma_{z_{\text{ri}}} = 333 \sigma_\tau / \sqrt{z_{\text{ri}}}$. This implies that $\sigma_{z_{\text{ri}}}$ for a more realistic observation strategy (i.e., cut-sky) will be determined 65% less
Fig. 4. Individual and joint likelihood functions for the cut-sky and full-sky observations discussed in the text. The errors on $\tau$ and $A$ from the 1D likelihoods for the $b_{\text{cut}} = 20^\circ$ simulation (solid) are inflated by $\sim 65\%$ over the true full-sky experiment (dashed) due to increased cosmic variance and decreased multipole space resolution. The 2D joint likelihood contours show the full-sky survey’s error volume (white) inside the the cut-sky data’s region (black). The contours indicate where the likelihood falls to $1/\sqrt{e}$ of the maximum likelihood for each experiment.

These effects will thus be more pronounced as the sensitivity of CMB polarimeters increase.

This more realistic cosmic variance limit may also strengthen the motivation for ground-based CMB polarization probes of reionization which, due to their significantly reduced sky coverage relative to a satellite or balloon, have received comparatively little attention.

6 A Ground Based Reionization Probe

In this section we explore how well a ground based polarimeter can probe reionization. We seek to quantify the observational requirements to detect $\tau$, as well as to constrain realistic reionization models consistent with both WMAP and quasar absorption measurements. In particular we assess the requirements
to detect a two-step reionization model suggested by [5].

Generally speaking, an instrument optimized to detect gravitational waves will significantly constrain the detailed reionization history, whereas the converse is not necessarily true. For fixed system sensitivity this has implications for both the optical design and observation strategy of the experiment.

Here we will consider a medium angular-scale, ground-based polarimeter’s ability to detect $\tau$ and constrain non-instantaneous reionization scenarios. As a toy experiment, we consider a polarimeter with $1^\circ$ resolution and system sensitivity ($NET_{\text{syst}} = NET_{\text{pixel}}/\sqrt{N_{\text{pixel}}} = 70\mu K s^{1/2}$, observing for one year. The system sensitivity for polarization is $\sqrt{2}$ times higher $NEQ = \sqrt{2}NET$. These detector requirements are well within reach of the current generation of CMB polarimeters.

The problem of optimizing of CMB polarimeters for detection of the inflationary GWB was first studied by [21], and polarimeter optimization in the presence of the gravitational lensing foreground has been studied by Lewis, Challinor, and Turok [22]. Lewis et al. find there is a broad maximum sensitivity achieved by mapping a circular cap of radius $\Theta = 20^\circ$, which corresponds to an $\ell$-space resolution of $\delta\ell \simeq 5$. In the absence of galactic foregrounds, our toy experiment is capable of detecting the curl mode signal imprinted by primordial gravitational waves with a tensor-to-scalar ratio $r = 0.12$ at 95% confidence, with no priors. This is roughly ten-times lower than the limit on $r$ from WMAP, also with no priors [7]. This detection (or limit) would permit discrimination between a broad class of inflationary models [23,24,25]. An exciting ancillary benefit of this experiment is that it is also sensitive to reionization.

To assess the power of the toy experiment to constrain the Thomson optical depth we consider the susceptibility of the E-mode power spectrum to changes in $\tau$: $\partial C_E^{\ell \ell} / \partial \tau$. From the grad-mode (Fig. 5) and curl-mode derivatives (Fig. 6) we see that essentially all the information on $\tau$ comes from $\ell < 50$. If we note that the peak in the curl-mode power spectrum occurs at $\ell \simeq 90$, we see that the scale for completely resolving the effects of $\tau$ is only two-times larger than that required to resolve the curl-mode structure. While most of the $\tau$-constraint comes from $\ell < 10$, a non-negligible amount comes from $10 < \ell < 40$. There is significant power beyond the peak of the low-$\ell$ bump. A Fisher matrix analysis for the toy model indicates its sensitivity to $\tau$ is $\sigma_\tau = 0.08$, competitive with the one-year WMAP results [7] with no priors.

It is instructive to explore how the sensitivity to $\tau$ changes as a function of sky coverage. In table 1 and figure 7 we demonstrate how $\tau-$sensitivity, $\sigma_\tau$, depends on $\ell$-space resolution. The $\ell$-space resolution scales as $\delta\ell \simeq 180^\circ / 2\Theta$. With one exception, for all of the observation strategies we consider we ex-
Fig. 5. The susceptibility of the E-mode power spectrum to changes in $\tau$. The derivatives were computed using a second-order finite difference with steps in $\tau$ of $\delta \tau = 0.001$, around a fiducial value of $\tau = 0.17$, consistent with WMAP. The dominant effect of $\tau$ is at $\ell < 10$, but a non-trivial amount remains for $10 < \ell < 40$ where cosmic variance effects can be dramatically reduced, even for a ground based experiment.

Fig. 6. Same as Fig. 5, but for curl-mode polarization.

include the first $\ell$-bin which is, in principle, observable. This results in $1^{st} \ell$-bin $= 2\delta \ell$. This conservatism is frequently justified since the first $\ell$-bin often is contaminated by an imperfect foreground template and/or by subtraction of the DC-level of the map. WMAP’s purportedly “anomalously-low” first $\ell$-bin, $\ell = 2$ has received much attention, perhaps prematurely. However, some have speculated on the potential for foreground contamination [26] of, or even intriguing new physics[27] in, the quadrupole’s low value.
Table 1

| $\Theta$ | 1st $\ell$-bin | $\delta \ell$ | $f_{sky}$ | $\sigma_{\tau}$ |
|----------|-----------------|--------------|----------|-----------------|
| 18$^\circ$ | 10 | 5 | 2.4% | 0.03 |
| 15$^\circ$ | 12 | 6 | 2.1% | 0.04 |
| 12.9$^\circ$ | 14 | 7 | 1.6% | 0.06 |
| 11.3$^\circ$ | 16 | 8 | 1.3% | 0.08 |
| 9$^\circ$ | 10 | 10 | 0.8% | 0.09 |

Sensitivity to optical depth, $\tau$, versus observation strategy, parameterized by radius of circular cap, $\Theta$, observed by the toy experiment described with system $\text{NET}_{\text{syst}} = 70 \mu\text{Ksl}^{1/2}$. For all of the observation strategies, except $\Theta = 9^\circ$, the first $\ell$-bin is $2\delta \ell$.

Fig. 7. Signal-to-noise ratio for a ground based polarimeter to detect reionization, assuming $\tau = 0.17$. The plot shows the effect of increasing the angular radius of the circular survey, $\Theta$, with constant system sensitivity $\text{NET}_{\text{syst}} = 70 \mu\text{Ks}^{1/2}$. All strategies except $\Theta = 9^\circ$ exclude the first multipole bin from the parameter estimation. Lewis, Challinor, and Turok[22] show that $\Theta = 18^\circ$ is close to optimal sky coverage to detect the inflationary GWB using CMB curl-mode polarization.

COSMOMC is a Monte Carlo approach [28] useful for evaluating sensitivity to cosmological parameters. Figure 9 shows the parameter estimation results of COSMOMC for the toy experiment. Due to the cut-sky and the intrinsically low signal-to-noise ratio of realistic reionization probes, such as WMAP, it is unlikely that the marginalized likelihood functions for $\tau$ will be convincingly gaussian in nature. Indeed, Spergel et al. explicitly points out [7] that $\tau$ is the only parameter with a highly non-gaussian form. COSMOMC facilitates the exploration of the details of the likelihood curves and the effects of adding priors on the Thomson optical depth.
Fig. 8. The effects of including prior information on $\tau$ on the likelihood functions for the toy experiment described in the text. The likelihoods were computed with simulated data for the toy experiment, using priors ranging from $\tau > 0.02$ to $\tau > 0.07$. The likelihood curve for WMAP with no priors is shown for comparison as the dashed curve. The upper 1σ range of the likelihood curve is robust to changing the prior, whereas the lower range is more sensitive.

Figure 8 shows the likelihood functions for $\tau$ for the toy experiment with $\Theta = 18^\circ$ as a function of $\tau$-priors ranging from $0 < \tau < 1$ to $0.07 < \tau < 1$ (weaker constraint than the SDSS Gunn-Peterson observations provide). The toy-experiment is also compared to the WMAP-only likelihood result in the same figure.

As discussed above, Kaplinghat et al. demonstrate that the ability of a CMB polarimeter to constrain the redshift of reionization is $\sigma_{z_{ri}} = 333\sigma_{\tau}/\sqrt{z_{ri}}$. Thus, conservatively, if reionization is consistent with the WMAP 1σ lower limit ($z_{ri} \approx 13$), the toy experiment with ($\Theta = 18^\circ$) could establish (with > 95% confidence) that reionization was earlier than $z = 6.28$. This is the redshift of the SDSS quasar neutral hydrogen fraction determination from Gunn-Peterson QSO absorption features. We note that these results are for analysis of the grad-mode data only. The toy experiment can either use its own data to measure the CMB temperature anisotropy or WMAP’s. Including the temperature-polarization cross-correlation data the precision on $\tau$ improves by $\approx 20\%$. Finally, since $\tau$ and the primordial power spectrum amplitude $A$
Fig. 9. Individual and joint likelihood functions for the toy experiment discussed in the text, with $f_{sky} = 2.4\%$. The uncertainties from the marginalized likelihoods are $\tau = 0.12 \pm 0.038$ and $A = 0.81 \pm 0.15$, given a prior that $\tau > 0.04$. The joint confidence intervals correspond to $1/\sqrt{\tau}$ (inner) and $1/e$ (outer) of the maximum likelihood. This experiment can determine the redshift of the onset of reionization with a precision of $\delta z \leq 3$ if reionization occurred at $z > 10$.

are exactly degenerate, $\sigma_A = 2\sigma_\tau$, and the toy experiment can achieve 6% fractional uncertainty on $A$.

7 Prospects for the future

WMAP’s on-going measurements of CMB polarization are expected to continue until at least 2006. In 2007 Planck will be launched and will start making full-sky observations of the polarization of the CMB. Planck is expected to achieve near-cosmic variance limit on $\tau$. NASA’s Beyond Einstein initiative features a CMB polarimeter called the Inflation Probe[29]. This instrument is designed to detect the signature of inflationary gravitational waves over a wide range of inflationary energy scales. This experiment will achieve cosmic variance limited precision on $\tau$, which is essentially the same as Planck’s sensitivity [30]. The European Space Agency plans a large angular scale polarimeter deployed on the International Space Station called SPORT, which
would also be sensitive to reionization[31].

8 Discussion

This paper has emphasized that there is more to CMB polarization than simply the lifting of cosmic degeneracies. Upcoming experiments will be able to probe the details of reionization and the signature of the gravitational wave background simultaneously. We have emphasized that there is far more information in CMB polarization data than whether or not two power spectra can be distinguished from one another. However, conservative foreground mitigation techniques appear to degrade the precision with which the epoch of reionization, and even the Thomson optical depth itself, can be obtained by a cosmic variance limited experiment. Whether such conservatism is warranted is debateable. But when probing signals below 100$n$K level it is clear that foreground mitigation is vital. More sophisticated techniques may restore limits closer to the full-sky cosmic variance limit. Detailed simulations are warranted. A current generation ground based polarimeter is capable of probing the details of the reionization epoch as well as the signature of inflationary gravitational waves. Clearly, high-fidelity CMB polarization observations are poised to enhance and extend our knowledge of the cosmic Dark Ages.

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References

[1] R. H. Becker, X. Fan, R. L. White, M. A. Strauss, V. K. Narayanan, R. H. Lupton, J. E. Gunn, J. Annis, N. A. Bahcall, J. Brinkmann, A. J. Connolly, I. Csabai, P. C. Czarapata, M. Doi, T. M. Heckman, G. S. Hennessy, Ž. Ivezić, G. R. Knapp, D. Q. Lamb, T. A. McKay, J. A. Munn, T. Nash, R. Nichol, J. R. Pier, G. T. Richards, D. P. Schneider, C. Stoughton, A. S. Szalay, A. R. Thakar, and D. G. York. Evidence for reionization at z6: Detection of a gunn-peterson trough in a z=6.28 quasar. *Astronomical Journal*, 122:2850–2857, December 2001.

[2] S. G. Djorgovski, S. Castro, D. Stern, and A. A. Mahabal. On the threshold of the reionization epoch. *Astrophysical Journal*, 560:L5–L8, October 2001.
[3] X. Fan, V. K. Narayanan, M. A. Strauss, R. L. White, R. H. Becker, L. Pentericci, and H.-W. Rix. Evolution of the ionizing background and the epoch of reionization from the spectra of z~6 quasars. *Astronomical Journal*, 123:1247–1257, March 2002.

[4] R. Cen. The universe was reionized twice. *Astrophysical Journal*, 591:12–37, July 2003.

[5] M. Kaplinghat, M. Chu, Z. Haiman, G. P. Holder, L. Knox, and C. Skordis. Probing the reionization history of the universe using the cosmic microwave background polarization. Ap. J., 583:24–32, January 2003.

[6] W. Hu and T. Okamoto. Mass reconstruction with cosmic microwave background polarization. Ap. J., 574:566–574, August 2002.

[7] D. N. Spergel, L. Verde, H. V. Peiris, E. Komatsu, M. R. Nolta, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters. *Astrophysical Journal Supplement Series*, 148:175–194, September 2003.

[8] E. M. Leitch, J. M. Kovac, N. W. Halverson, J. E. Carlstrom, C. Pryke, and M. W. E. Smith. Degree Angular Scale Interferometer 3 Year Cosmic Microwave Background Polarization Results. Ap. J., 624:10–20, May 2005.

[9] T. E. Montroy, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, P. Cabella, C. R. Contaldi, B. P. Crill, P. de Bernardis, G. De Gasperis, A. de Oliveira-Costa, G. De Troia, G. di Stefano, E. Hivon, A. H. Jaffe, T. S. Kisner, W. C. Jones, A. E. Lange, S. Masi, P. D. Mauskopf, C. J. MacTavish, A. Melchiorri, P. Natoli, C. B. Netterfield, E. Pascale, F. Piacentini, D. Pogosyan, G. Polenta, S. Prunet, S. Ricciardi, G. Romeo, J. E. Ruhl, P. Santini, M. Tegmark, M. Veneziani, and N Vittorio. A measurement of the cme spectrum from the 2003 flight of boomerang. submitted to ApJ, 2005.

[10] A. C. S. Readhead, S. T. Myers, T. J. Pearson, J. L. Sievers, B. S. Mason, C. R. Contaldi, J. R. Bond, R. Bustos, P. Altamirano, C. Achermann, L. Bronfman, J. E. Carlstrom, J. K. Cartwright, S. Casassus, C. Dickinson, W. L. Holzapfel, J. M. Kovac, E. M. Leitch, J. May, S. Padin, D. Pogosyan, M. Pospieszalski, C. Pryke, R. Reeves, M. C. Shepherd, and S. Torres. Polarization Observations with the Cosmic Background Imager. *Science*, 306:836–844, October 2004.

[11] D. Barkats, C. Bischoff, P. Farese, L. Fitzpatrick, T. Gaier, J. O. Gundersen, M. M. Hedman, L. Hyatt, J. J. McMahon, D. Samtleben, S. T. Staggs, K. Vanderlinde, and B. Winston. First measurements of the polarization of the cosmic microwave background radiation at small angular scales from capmap. *Astrophys. J. Letters*, 619:L127–L130, February 2005.

[12] B. G. Keating, C. W. O’Dell, A. de Oliveira-Costa, S. Klawikowski, N. Stebor, L. Piccirillo, M. Tegmark, and P. T. Timbie. A Limit on the Large Angular
Scale Polarization of the Cosmic Microwave Background. *Astrophys. J. Letters*, 560:L1–L4, October 2001.

[13] A. Kogut, D. N. Spergel, C. Barnes, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, E. Wollack, and E. L. Wright. First-year wilkinson microwave anisotropy probe (wmap) observations: Temperature-polarization correlation. *Astrophysical Journal Supplement Series*, 148:161–173, September 2003.

[14] F. Piacentini, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, P. Cabella, C. R. Contaldi, B. P. Crill, P. de Bernardis, G. De Gasperis, A. de Oliveira-Costa, G. De Troia, G. di Stefano, E. Hivon, A. H. Jaffe, T. S. Kisner, W. C. Jones, A. E. Lange, S. Masi, P. D. Mauskopf, C. J. MacTavish, A. Melchiorri, T. E. Montroy, P. Natoli, C. B. Netterfield, E. Pascale, D. Pogosyan, G. Polenta, S. Prunet, S. Ricciardi, G. Romeo, J. E. Ruhl, P. Santini, M. Tegmark, M. Veneziani, and N Vittorio. A measurement of the polarization-temperature angular cross power spectrum of the cosmic microwave background from the 2003 flight of boomerang. *submitted to ApJ*, 2005.

[15] L. Knox and Y.-S. Song. Limit on the detectability of the energy scale of inflation. *Physical Review Letters*, 89(1):011303–+, July 2002.

[16] M. Kesden, A. Cooray, and M. Kamionkowski. Separation of Gravitational-Wave and Cosmic-Shear Contributions to Cosmic Microwave Background Polarization. *Physical Review Letters*, 89(1):011304–+, July 2002.

[17] M. Zaldarriaga. Polarization of the microwave background in reionized models. *Physical Review D.*, 55:1822–1829, February 1997.

[18] B. Keating, P. Timbie, A. Polnarev, and J. Steinberger. Large angular scale polarization of the cosmic microwave background radiation and the feasibility of its detection. *Astrophysical Journal*, 495:580–+, March 1998.

[19] G. P. Holder, Z. Haiman, M. Kaplinghat, and L. Knox. The reionization history at high redshifts. ii. estimating the optical depth to thomson scattering from cosmic microwave background polarization. Ap. J., 595:13–18, September 2003.

[20] S. Dodelson. *Modern cosmology*. Modern cosmology / Scott Dodelson. Amsterdam (Netherlands): Academic Press. ISBN 0-12-219141-2, 2003, XIII + 440 p., 2003.

[21] A. H. Jaffe, M. Kamionkowski, and L. Wang. Polarization pursuers’ guide. Phys. Rev. D., 61(8):083501–+, April 2000.

[22] A. Lewis, A. Challinor, and N. Turok. Analysis of CMB polarization on an incomplete sky. Phys. Rev. D., 65(2):023505–+, January 2002.

[23] W. H. Kinney. Constraining inflation with cosmic microwave background polarization. Phys. Rev. D., 58(12):123506–+, December 1998.

[24] A. R. Liddle and D. H. Lyth. *Cosmological inflation and large-scale structure*. 2000.
[25] W. H. Kinney. The energy scale of inflation: is the hunt for the primordial B-mode a waste of time? New Astronomy Review, 47:967–975, December 2003.

[26] D. J. Schwarz, G. D. Starkman, D. Huterer, and C. J. Copi. Is the Low-L Microwave Background Cosmic? Physical Review Letters, 93(22):221301–+, November 2004.

[27] O. Doré, G. P. Holder, and A. Loeb. The Cosmic Microwave Background Quadrupole in a Polarized Light. Ap. J., 612:81–85, September 2004.

[28] Antony Lewis and Sarah Bridle. Cosmological parameters from CMB and other data: a Monte-Carlo approach. Phys. Rev., D66:103511, 2002.

[29] http://universe.nasa.gov/program/probes.html.

[30] M. Kaplinghat. Applications of high resolution high sensitivity observations of the cmb. New Astronomy Review, 47:893–900, December 2003.

[31] L. P. L. Colombo. Constraining the reionization history with large angle cosmic microwave background polarization. Journal of Cosmology and Astro-Particle Physics, 3:3–+, March 2004.