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REIONIZATION CONSTRAINTS FROM FIVE-YEAR WMAP DATA

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ABSTRACT

We study the constraints on reionization from five years of *WMAP* data, parametrizing the evolution of the average fraction of ionized hydrogen with principal components that provide a complete basis for describing the effects of reionization on large-scale E-mode polarization. Using Markov Chain Monte Carlo methods, we find that the resulting model-independent estimate of the total optical depth is nearly twice as well determined as the estimate from 3-year *WMAP* data, in agreement with simpler analyses that assume instantaneous reionization. The mean value of the optical depth from principal components is slightly larger than the instantaneous value; we find $\tau = 0.097 \pm 0.017$ using only large-scale polarization, and $\tau = 0.101 \pm 0.019$ when temperature data is included. Likewise, scale invariant $n_s = 1$ spectra are no longer strongly disfavored by WMAP alone. Higher moments of the ionization history show less improvement in the 5-year data than the optical depth. By plotting the distribution of polarization power for models from the MCMC analysis, we show that extracting most of the remaining information about the shape of the reionization history from the CMB requires better measurements of E-mode polarization on scales of $\ell \sim 10-20$. Conversely, the quadrupole and octopole polarization power is already predicted to better than cosmic variance given *any* allowed ionization history at $z < 30$ so that more precise measurements will test the ΛCDM paradigm.

Subject headings: cosmic microwave background — cosmology: theory — large-scale structure of universe

1. INTRODUCTION

The amplitude of fluctuations in the E-mode component of cosmic microwave background (CMB) polarization on large scales provides the current best constraint on the Thomson scattering optical depth to reionization, τ. Assuming that the universe was reionized instantaneously, Dunkley et al. (2008) estimate the total optical depth to be $\tau = 0.087 \pm 0.017$ using five years of *WMAP* data. Theoretical studies suggest that the process of reionization was too complex to be well described as a sudden transition (e.g., Barkana & Loeb 2001). Previous studies have examined how the constraint on τ depends on the evolution of the globally-averaged ionized fraction during reionization, $x_e(z)$, for a variety of specific theoretical scenarios. If the assumed form of $x_e(z)$ is incorrect, the estimated value of τ can be biased; this bias can be lessened by considering a wider variety of reionization histories at the expense of increasing the uncertainty in τ (Kaplinghat et al. 2003; Holder et al. 2003; Colombo et al. 2005).

For the previous release of three years of *WMAP* data, using a more model-independent analysis of reionization based on principal components does not change the basic conclusions of studies that assume instantaneous reionization or other simple models; however, as the polarization power spectrum becomes better determined, it is increasingly important to adopt an approach with sufficient freedom to approximate a variety of possible reionization scenarios in order to minimize parameter biases (Mortonson & Hu 2008a,b). In this letter, we study how model-independent constraints on reionization have changed with the addition of two more years of data from *WMAP* and on what scales further measurements would have the largest impact on ionization constraints. We review the principal component parametrization of the ionization history in § 2. We then present the current constraints on the principal component amplitudes and the optical depth to reionization (§ 3) and the range of polarization power spectra for general models that are currently allowed by the data (§ 4). We discuss these results in § 5.

2. IONIZATION PRINCIPAL COMPONENTS

We parametrize the reionization history as a free function of redshift by decomposing $x_e(z)$ into its principal components (PCs) with respect to the E-mode polarization of the CMB (Hu & Holder 2003; Mortonson & Hu 2008a):

$$x_e(z) = x_e^{\rm fid}(z) + \sum_\mu m_\mu S_\mu(z), \quad (1)$$

where the principal components, $S_\mu(z)$, are the eigenfunctions of the Fisher matrix that describes the dependence of C_ℓ^{EE} on $x_e(z)$, m_μ are the amplitudes of the principal components for a particular reionization history, and $x_e^{\rm fid}(z)$ is the fiducial model at which the Fisher matrix is computed. The components are rank ordered by their Fisher-estimated variances. The lowest-variance eigenmode ($\mu = 1$) is an average of the ionized fraction over the entire redshift range, weighted toward high z. The $\mu = 2$ mode measures the difference between the amount of ionization at high z and at low z, and higher modes follow this pattern with weighted averages of $x_e(z)$ that oscillate with higher and higher frequency in redshift. The main advantage of using principal components as a basis for $x_e(z)$ is that only a small number of the components are required to completely describe the

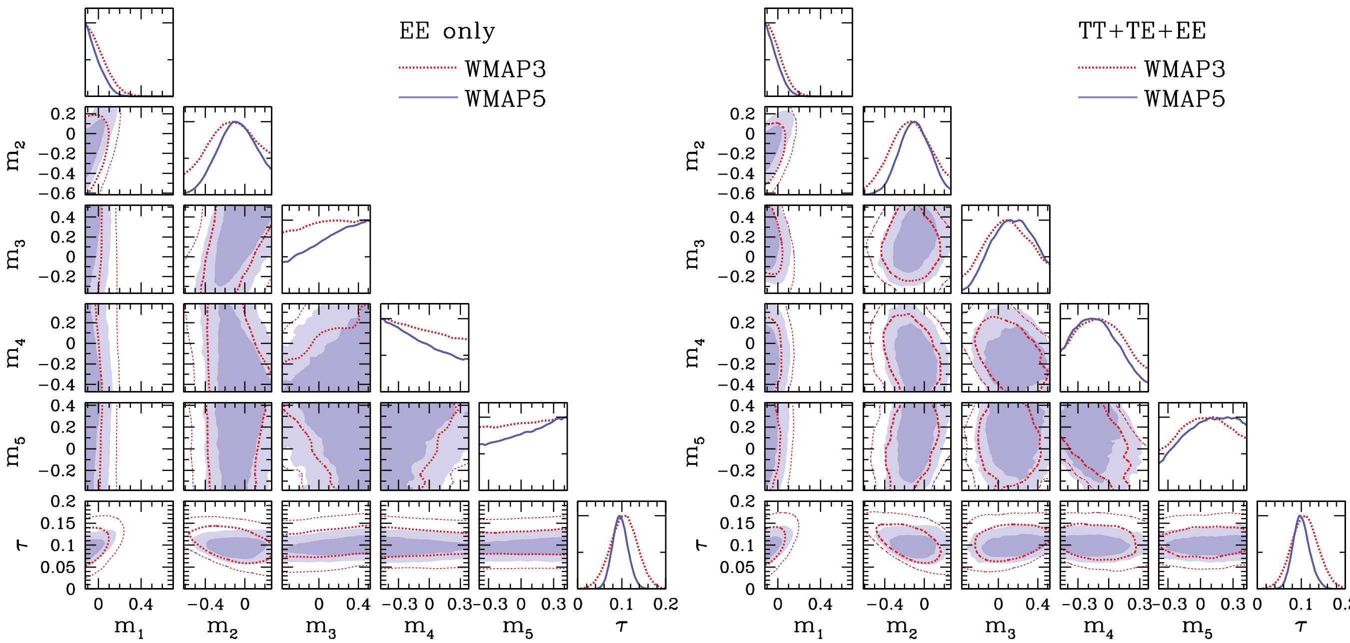

FIG. 1.— Marginalized 2D 68% and 95% CL contours for the optical depth to reionization (τ) and the amplitudes of the 5 lowest-variance principal components of $x_e(z)$ (m_μ, $\mu = 1-5$). Panels along the diagonals show the 1D posterior probability distributions. Constraints are plotted for both 3-year (*red dotted lines*) and 5-year (*blue shading, solid lines*) *WMAP* data. In the left plot, only the low-ℓ reionization peak in the E-mode polarization power spectrum is used for parameter constraints, and all parameters besides the 5 PC amplitudes and τ are held fixed. For the constraints in the right plot, we use both temperature and polarization data and allow five additional parameters to vary: $\Omega_b h^2$, $\Omega_c h^2$, θ_A, A_s, and n_s. The plot boundaries for the PC amplitudes correspond to physicality priors that exclude models that are unable to satisfy $0 \le x_e \le 1$ for any combination of the higher-variance ($\mu \ge 6$) PCs.

effects of reionization on large-scale CMB polarization, so we obtain a very general parametrization of the reionization history at the expense of only a few additional parameters.

The principal components are defined over a limited range in redshift, $z_{\rm min} < z < z_{\rm max}$, with $x_e = 0$ at $z > z_{\rm max}$ and $x_e = 1$ at $z < z_{\rm min}$. We take $z_{\rm min} = 6$, since the absence of Gunn-Peterson absorption in the spectra of quasars at $z \lesssim 6$ indicates that the universe is nearly fully ionized at lower redshifts (Fan et al. 2006). In the MCMC analysis presented here, we always use the five lowest-variance principal components of $x_e(z)$ with $z_{\rm max} = 30$, constructed around a constant fiducial model of $x_e^{\rm fid}(z) = 0.15$. The amplitudes of these components then serve to parametrize general reionization histories in the analysis of CMB polarization data. We refer the reader to Mortonson & Hu (2008a) for further discussion of these choices and the demonstration that five components suffice to describe the E-mode spectrum to better than cosmic variance precision.

We impose priors on the principal component amplitudes corresponding to physical values of the ionized fraction, $0 \le x_e \le 1$, according to the conservative approach of Mortonson & Hu (2008a). All excluded models are unphysical, but the models we retain are not necessarily strictly physical. Finally, we neglect helium reionization, which is a small correction at the current level of precision but will be more important for future analyses (e.g., Colombo & Pierpaoli 2008).

3. OPTICAL DEPTH CONSTRAINTS

We examine the implications of the *WMAP* 5-year data for general models of reionization parametrized by principal components using a Markov Chain Monte Carlo analysis that mirrors our previous study of the 3-year data in Mortonson & Hu (2008a). We consider constraints from either large-scale polarization alone, with parameters that do not directly affect reionization fixed to values that fit the temperature data ("EE"), or from the full set of temperature and polarization data, varying the parameters of the "vanilla" ΛCDM model (baryon density $\Omega_b h^2$, cold dark matter density $\Omega_c h^2$, acoustic scale θ_A, scalar amplitude A_s, and scalar spectral tilt n_s) in addition to the reionization PC amplitudes ("TT+TE+EE"). In both cases, the total optical depth to reionization, τ, is a derived parameter.

The MCMC constraints on principal component amplitudes and the derived optical depth for both of these cases are plotted in Fig. 1, along with the previous constraints from 3-year *WMAP* data (Mortonson & Hu 2008a). While there are some improvements in all 5 of the individual components when considering EE alone, these changes are not as large as the improvement in the optical depth constraint when all of the data are considered. Adding both temperature data and extra parameters in going from EE only to TT+TE+EE has the net effect of slightly strengthening constraints on the higher ranked PC amplitudes, although there is very little effect on τ. The additional constraining power for both 3-year and 5-year data comes mainly from the measured temperature power spectrum at $\ell \sim 10-100$, which excludes models with additional Doppler effect contributions due to narrow features in the ionization history (Mortonson & Hu 2008a).

Modeling reionization as an instantaneous transition at some redshift $z_{\rm reion}$, Dunkley et al. (2008) estimate the optical depth from the 5-year *WMAP* data to be $\tau = 0.087 \pm 0.017$, almost a factor of two more precise than the estimate from three years of data (Spergel et al. 2007).

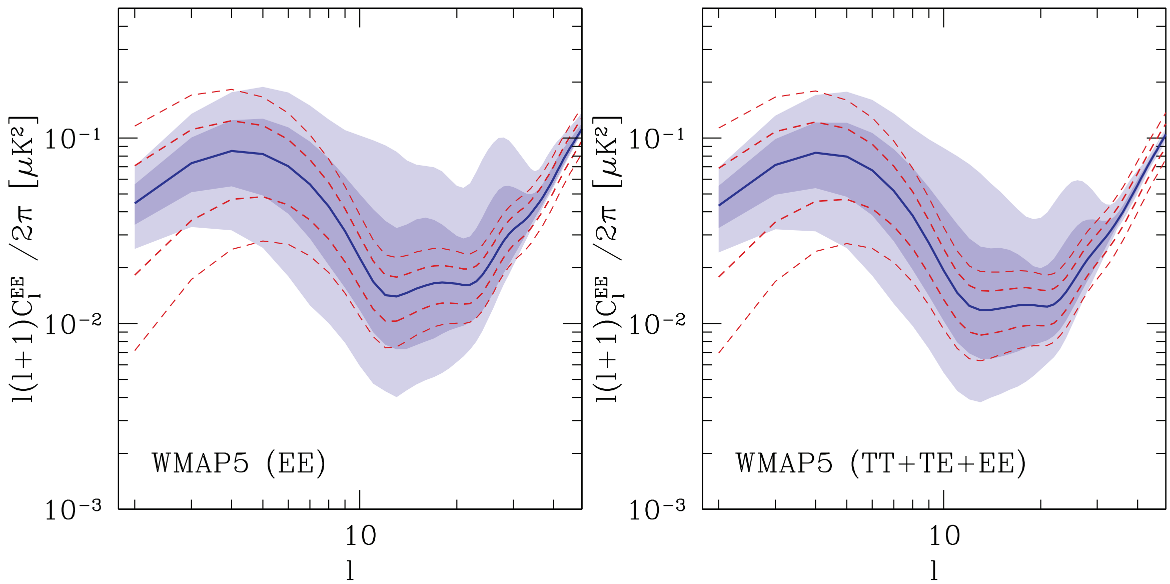

FIG. 2.— Median (*blue solid curve*) and 68% and 95% CL regions (*blue shaded regions*) of polarization power spectra for any ionization history at $z < 30$ allowed by the 5-year *WMAP* data, assuming the standard ΛCDM paradigm. As in Fig. 1, only polarization data are used in the left panel and both temperature and polarization data are included in the right panel. *Red dashed curves*: cosmic variance (68% and 95% CL) around the median model.

For ionization histories parametrized by PCs, we find that the constraint on optical depth is $\tau = 0.097 \pm 0.017$ for the EE case and $\tau = 0.101 \pm 0.019$ for TT+TE+EE. As with the 3-year data, the error on τ is roughly 10% larger with the inclusion of temperature data and a larger set of parameters, and the error in both cases is the same or only slightly larger than for the instantaneous reionization analysis.

The central value of τ for more general ionization histories is higher than the instantaneous reionization value by $\sim 0.5 - 1\ \sigma$; a similar shift toward larger optical depths was seen in PC analysis of the 3-year data (Mortonson & Hu 2008a). The maximum likelihood model, however, has $\tau = 0.088$ for EE data and $\tau = 0.090$ for TT+TE+EE, much closer to the instantaneous reionization maximum likelihood optical depth of $\tau = 0.089$ (Dunkley et al. 2008). The larger mean optical depth is at least partly due to having a large parameter volume of models with finite ionization fraction at high redshift that are still allowed by the data. With flat priors on the principal components, this volume effect can boost the mean optical depth of models even though the mean likelihood of low optical depth models remains the same. Our assumption of full ionization at redshifts below $z_{\rm min} = 6$ for all models also limits how small the optical depth can be. Relative to the best-fit instantaneous model with $z_{\rm reion} = 11.0 \pm 1.4$ (Dunkley et al. 2008), there are simply more ways to increase τ than there are to decrease τ by changing the ionization history, given these priors and the current data.

For the TT+TE+EE analysis, the larger mean optical depth is accompanied by shifts in correlated parameters, particularly the spectral tilt: $n_s = 0.990 \pm 0.024$ with $x_e(z)$ parametrized by PCs, and $n_s = 0.960 \pm 0.015$ for instantaneous reionization (Komatsu et al. 2008). As with the optical depth, however, some of this shift is a parameter volume effect. The maximum likelihood model for the principal component analysis has $n_s = 0.976$. The best fit scale invariant model (fixing $n_s = 1$) is a poorer fit to the data by $\Delta\chi^2_{\rm eff} \equiv -2\ln(\mathcal{L}/\mathcal{L}_{\rm max}) \sim 1$, where $\mathcal{L}_{\rm max}$ is the maximum likelihood. (The instantaneous reionization maximum likelihood model is also at $\Delta\chi^2_{\rm eff} \approx 1$ relative to the best fit with principal components.) As measurements of CMB polarization improve with future data, particularly with detections in the $10 < \ell < 20$ range (see §4), the constraints on parameters such as optical depth and tilt should become less sensitive to our assumptions about the priors.

Unlike the total optical depth, constraints on the optical depth over more limited redshift ranges have only improved slightly. With three years of *WMAP* data, the 95% upper limit on the optical depth from $z > 20$ (allowing for a significant ionized fraction up to $z \sim 40$) was $\tau(z > 20) < 0.08$ (Mortonson & Hu 2008a). The limit from 5-year data is $\tau(z > 20) < 0.07$. If we instead choose the dividing redshift to be the best-fit value of the redshift of instantaneous reionization, $z_{\rm reion} = 11$, we find a similar constraint for the contribution to the optical depth from high redshift: $\tau(z > 11) < 0.07$. Compared to the 3-year data, there is also a more significant (but still weak) preference for nonzero optical depth from $6 < z < 11$.

4. POWER SPECTRA OF ALLOWED MODELS

To better understand at which scales the reionization peak of E-mode polarization is best constrained by the current data, we plot the 68% and 95% CL limits on C_ℓ^{EE} from the Monte Carlo chains in Fig. 2. These limits reflect the range of ensemble-averaged power allowed by the 5-year data and the PC-parametrized reionization histories. Since this parametrization is complete in the power spectrum, the range in Fig. 2 reflects the allowed model power spectra for *any* ionization history at $z < z_{\rm max} = 30$.

At $\ell \lesssim 5$, the variation in allowed models is smaller than the uncertainty due to cosmic variance. In other words, the data at $\ell \sim 5$ in combination with any ionization history and the power law initial power spectrum make a prediction for the ensemble-averaged power at lower ℓ that is sharper than can be measured. Conversely, measurements that violate this prediction at a statistically significant level require modifications to the ΛCDM paradigm itself, much like low measurements of the temperature quadrupole. It is interesting that the maximum likelihood E-mode polarization quadrupole reported by Nolta et al. (2008), $6C_2^{EE}/2\pi \approx 0.15\ \mu\mathrm{K}^2$, is in excess of the 95% cosmic variance region shown in Fig. 2.

The uncertainty in the model space is largest at intermediate scales of $\ell \sim 10-20$, where the large-scale polarization power is expected to be smallest. There is substantial room for improved measurements of the spectrum on these scales before reaching the cosmic variance limit. Tighter constraints on the E-mode power at $10 < \ell < 20$ would better determine the amplitude of principal components beyond the first; such measurements are necessary to be able to discriminate among different reionization histories with the same total optical depth. Physically, these measurements would better constrain the ionization history at high redshifts ($z \gtrsim 15$).

On small scales ($\ell > 30-40$) the limits on power spectra of reionization models from the chains again become tighter than cosmic variance since the theoretical amplitude of the recombination peak is well determined due to constraints on parameters from the temperature data.

Comparison of the two panels in Fig. 2 shows that the main effect of including temperature data in constraints on principal components is to eliminate models with large power at $10 < \ell < 30$. As mentioned in the previous section, these models are excluded by the data due to their increased temperature fluctuations at $\ell \sim 10-100$. Even with TT+TE+EE data, the range of power in models allowed by current data is a few times larger than cosmic variance.

5. DISCUSSION

The 5-year *WMAP* polarization data significantly improve the estimate of the total optical depth, reducing the error from $\sigma_\tau \approx 0.03$ to $\sigma_\tau \approx 0.017$. This improvement is seen in both a model-independent analysis using principal components of the ionization history and in an analysis that assumes instantaneous reionization, although there is a small shift in the central value with the model-independent method preferring a slightly higher mean around $\tau = 0.1$.

As with the 3-year data, the E-mode reionization peak is currently best measured on the largest scales, $\ell \sim 5$. Determining details of the ionization history beyond the optical depth requires information about the full shape of the reionization peak, which can be obtained by supplementing the current observations with better measurements of the E-mode power on scales of $5 < \ell < 30$. In particular, improved knowledge of the power on scales between the main reionization peak and the recombination peak at $\ell \sim 10-20$ would be the most useful for distinguishing models of reionization with different ionization histories but the same optical depth.

Conversely, the data along with *any* allowed ionization history at $z < 30$ in the standard ΛCDM context already predict the ensemble-averaged polarization quadrupole and octopole powers to better than cosmic variance. More precise measurements in this regime can test the standard model itself.

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REFERENCES

Barkana, R. & Loeb, A. 2001, Phys. Rep., 349, 125
Colombo, L. P. L., Bernardi, G., Casarini, L., Mainini, R., Bonometto, S. A., Carretti, E., & Fabbri, R. 2005, A&A, 435, 413
Colombo, L. P. L. & Pierpaoli, E. 2008, arXiv:0804.0278
Dunkley, J. et al. 2008, arXiv:0803.0586
Fan, X.-H., Carilli, C. L., & Keating, B. 2006, Ann. Rev. Astron. Astrophys., 44, 415
Holder, G. P., Haiman, Z., Kaplinghat, M., & Knox, L. 2003, ApJ, 595, 13
Hu, W. & Holder, G. P. 2003, Phys. Rev. D, 68, 023001
Kaplinghat, M., Chu, M., Haiman, Z., Holder, G. P., Knox, L., & Skordis, C. 2003, ApJ, 583, 24
Komatsu, E. et al. 2008, arXiv:0803.0547
Mortonson, M. J. & Hu, W. 2008a, ApJ, 672, 737
—. 2008b, Phys. Rev. D, 77, 043506
Nolta, M. R. et al. 2008, arXiv:0803.0593
Spergel, D. N. et al. 2007, ApJS, 170, 377