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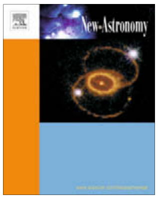

Model independent approaches to reionization in the analysis of upcoming CMB data

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ABSTRACT

On large angular scales, CMB polarization depends mostly on the evolution of the ionization level of the IGM during reionization. In order to avoid biasing parameter estimates, an accurate and model independent approach to reionization is needed when analyzing high precision data, like those expected from the Planck experiment. In this paper, we consider two recently proposed methods of fitting for reionization and we discuss their respective advantages. We test both methods by performing a MonteCarlo Markov Chain analysis of simulated Planck data, assuming different fiducial reionization histories. We take into account both temperature and polarization data up to high multipoles, and we fit for both reionization and non-reionization parameters. We find that while a wrong assumption on reionization may bias τ_e, A_s and r by 1–3 standard deviations, other parameters, in particular n_s, are not significantly biased. The additional reionization parameters introduced by considering the model independent methods do not affect the accuracy of the estimates of the main cosmological parameters, the biggest degradation being of order ~15% for τ_e. Finally, we show that neglecting helium contribution in the analysis increase the bias on τ_e, r and A_s even when a general fitting approach to reionization is assumed.

1. Introduction

The upcoming measurements of cosmic microwave background (CMB) by the Planck mission will allow for an unprecedented accuracy in the determination of the CMB angular power spectra. Due to its full-sky coverage and sensitivity, Planck will provide an accurate characterization of E-mode polarization autocorrelation power spectrum, C_l^{EE}, at large angular scales, and either detect or significantly improve the current limits on the B-mode polarization power spectrum, C_l^{BB}. While other CMB polarization are currently planned (e.g. Taylor et al., 2004; Yoon et al., 2006; MacTavish et al., 2007; Samtleben et al., 2008), none of them is expected to provide a measurement of the lowest C_l^{EE} multipoles with an accuracy better than Planck. To a first approximation, the average power of C_l^{EE} on these scales depends mostly on the optical depth to Thomson scattering due to reionization, τ_e. The value of τ_e also determines the suppression of the intermediate to high multipoles of the temperature power spectrum, C_l^{TT}. Current data by the Wilkinson microwave anisotropy probe (WMAP) imply a value $\tau_e = 0.087 \pm 0.017$, with variations of $\Delta\tau_e \simeq 0.01$ depending on the details of the analysis procedure and data sets considered (Dunkley et al., 2008). These constraints assume that reionization is a sharp transition occurring at a given redshift z_r.

However, theoretical and numerical studies suggest that reionization is a fairly complex process, possibly resulting from the sum of several contributions occurring over different time frames (e.g. Barkana and Loeb, 2001; Venkatesan et al., 2003; Wyithe and Loeb, 2003; Cen, 2003; Haiman and Holder, 2003; Shull et al., submitted for publication). In addition, observations of Lyα emitters in the redshift range $6 < z < 7$, show a rapid evolution of the neutral hydrogen fraction of the intergalactic medium (IGM) (Ota et al., 2007). In the context of a sharp reionization, a reionization redshift $z \simeq 7$ implies $\tau_e \simeq 0.04$, and WMAP 5-year data rule out such scenario at more than 3.5σ significance level. In order to represent our ignorance of the reionization process, it is then necessary to relax the hypothesis on reionization, and consider more complex reionization histories.

In this case, the low C_l^{EE} and C_l^{BB} multipoles depend not just on τ_e but also on the detailed redshift evolution of the (assumed homogeneous) number density of free electrons in the IGM, $x_e(z)$, expressed in units of the hydrogen atoms number density. For fixed values of τ_e and all other relevant cosmological parameters, differences in $x_e(z)$ affect the shape of the polarization power spectra up to multipoles $l \simeq 40 - 50$. An incorrect ansatz on reionization may lead to a strong bias in the determination of τ_e (Kaplinghat et al., 2003; Holder et al., 2003; Colombo et al., 2005). In turn a bias on τ_e may result in errors on related parameter, such as the normalization of the primordial power spectrum of density fluctuations, A_s, and the tensor-to-scalar ratio r. At the sensitivity level of current WMAP data, such bias is a fraction of the

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experimental error, and current constraints on the optical depth can be considered safe. In turn, this implies that constraints on the other main cosmological parameters, in particular on n_s, are not strongly dependent on the value of τ_e (Dunkley et al., 2008). Planck sensitivity, however, will be $\sim$10 times better than WMAP 5-year data[1] making an accurate and model independent approach to reionization a requirement for correct determination of τ_e and the other cosmological parameters.

One such approach is to simply divide the redshift interval relevant for reionization in a number of bins and try to directly constrain the averaged value of $x_e(z)$ in each bin (Lewis et al., 2006). The implementation of the method is straightforward and allows to easily take into account direct constraints on $x_e(z)$ (e.g. from 21 cm measurements (Tashiro et al., submitted for publication)). However, the choice of bins characteristics is not obvious, and allowing for a fine redshift resolution implies the addition of a significant number of strongly correlated parameters.

A principal component (PC) approach (Hu and Holder, 2003; Mortonson and Hu, submitted for publication-a) is a possible alternative. The reionization history is decomposed over a set of eigenmodes, which encode the effects of a change in $x_e(z)$ on C_l^{EE}. The amplitude of each eigenmode is left as a free parameter to be determined from the data. The advantage of the method lies in that a reduced number ($\sim$5) eigenmodes is sufficient to approximate the effects of a generic reionization history on the C_l^{EE}'s. Using a Monte Carlo Markov chains (MCMC) approach (Mortonson and Hu, submitted for publication-a, submitted for publication-b) showed that PC analysis allows to correctly recover the value of τ_e, also avoiding the introduction of spurious effects on r. These results considered only the $l < 100$ polarization multipoles, and assumed that the remaining cosmological parameters were fixed to their correct value. However, actual data analysis needs to include also temperature data and high multipoles, and simultaneously fit for the whole set of cosmological parameters.

CMB data allow to probe a large number of different parameters and Planck is expected to measure the basic cosmological parameters with high accuracy (Planck Blue Book, 2005), providing reference values for other kinds of measurements which probe only a subset of the parameter space (e.g. SNIa data) and/or cover different redshift ranges and scales (e.g. galaxy surveys, Lyα measurements). However, estimates of Planck performances typically take into consideration only the basic sharp reionization model, which can be accurately described by one parameter. Introduction of new (reionization) parameters in the model may give rise to new degeneracies, which in turn may bias the estimates of the other parameters and worsen the accuracy of their determinations. In addition, degeneracies also decrease the efficiency of the parameter estimation procedure. In the light of the upcoming Planck data, it is then relevant to compare how these methods affect the whole parameter estimation process, i.e., considering also TT and TE spectra and high-ℓ's, and including also non-reionization parameters, under the same set of conditions.

Moreover, previous studies did not take into account helium reionization (see, e.g. Shull, 2004; Furlanetto and Peng, submitted for publication and references therein). Helium reionization has been often neglected in CMB studies, as it contributes at most 10% of the total optical depth. However, the Planck satellites is expected to measure τ_e with a precision of a few percent (Planck Blue Book, 2005) and it is interesting to study whether helium contribution must be explicitly accounted for in the modeling of reionization. In addition to the physical aspects of reionization modeling and their impact on parameter estimation, the computational aspects of the problem need to be factored in. The analysis of current and future experiments require significant numerical resources. Choosing an inappropriate parametrization can greatly decrease the efficiency of MCMC methods, even more so when including a large number of parameters poorly constrained by data. In this paper, we perform a comparison of the performances of the two approaches by simulating future Planck data, corresponding to different fiducial reionization histories both with and without helium contribution, and analyze them assuming either sharp reionization or the two methods outlined below. We consider in the analysis polarization and temperature data up to multipoles $l = 2000$, and fit simultaneously for the main cosmological parameters. We discuss the the advantages of each methods, both in terms of the effects on the recovered parameters and in terms of computational cost.

The outline of the paper is as follows: in Section 2, we briefly review the proposed model independent methods. In the following Section 3, we discuss the fiducial reionization histories considered and our simulations of experimental data and MCMC analysis. We present our results in Section 4 and we draw our conclusions in Section 5.

2. Model independent approaches to reionization

2.1. Binning the reionization history

We consider the redshift set $z_0 < z_1 < z_2 < \ldots < z_N$, dividing the interval (z_0, z_N) into N bins, so that

$$x_e(z) = x_{e,i} \quad z_{i-1} < z < z_i, \quad i = 1, \ldots, N. \tag{1}$$

In modeling the reionization history, we neglect helium reionization and assume $x_e(z) = 1$ for $z < z_0$ while for $z > z_N$ we match $x_e(z)$ to the small residual ionization level from incomplete recombination. In particular, according to data on Lyα emitters (Ota et al., 2007) and quasar spectra (Fan et al., 2006), we assume $z_0 = 6$. Fixing $z_N = 30$ allows for the contributions of the first stars and/or early black holes (Ricotti et al., 2005) to τ_e; we ignore here the possible X-ray emission from high-z dark-matter interactions (e.g. Hansen and Haiman, 2004; Mapelli, 2006). The interval (z_0, z_N) is then divided into $N = 6$ equal bins.

To avoid instabilities during numerical integration, we in practice enforce an analytical expression for $x_e(z)$:

$$x_e(z) = \sum_{i=1}^{N} x_{e,i}\chi_i(z), \tag{2}$$

$$\chi_i(z) = \frac{1}{2}\left\{\tan h\left[\alpha\frac{\eta(z) - \eta(z_{i-1})}{\eta(z_{i-1})}\right] - \tan h\left[\alpha\frac{\eta(z) - \eta(z_i)}{\eta(z_i)}\right]\right\}; \tag{3}$$

where $\eta(z)$ is the conformal time at redshift z and α governs the sharpness of the transition. Following CAMB[2] (Lewis et al., 2000), we usually take $\alpha = 150$. We also assume a flat prior on the $x_{e,i}$. As pointed out by Lewis et al. (2006), constraints on the $x_{e,i}$ may depend significantly on the details of the binning kernels and the priors, if the data are poor. In addition, results for adjacent bins will usually be strongly correlated.

2.2. Principal component analysis

Following Mortonson and Hu (submitted for publication-a, submitted for publication-b), we divide the interval (z_0, z_N) in N equal bins of width $\Delta z = 0.25$, and consider a fiducial binned reionization history $\{x_{e,i}\}, i = 1, 2, \ldots, N$. We take $z_0 = 6$ and $z_N = 30$ and define $x_e(z)$ outside this interval as we did in the previous section. An esti-

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[1] Comparing the nominal single channel WMAP sensitivity with the specifications for Planck 143 GHz channel.

[2] <http://www.camb.info/>.