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Early reionization and its cosmological implications

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Abstract. We discuss how future CMB polarization measurements will provide detailed information about the reionization history and the implications of early reionization for cosmology.

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1. Introduction

Most of the gas in the universe is ionized out to a red-shift of about 6 [1]. Recent observation of the Gunn–Peterson trough in the spectrum of a $z = 6.3$ quasar hints at the possibility that the universe might be reionized by $z = 6.3$ [2,3].

The optical depth to Lyman-α photon absorbtion exceeds unity even if only a small fraction (about 10^{-4}) of the intervening material is neutral. This limits our ability to probe deep into the dark ages using the Gunn–Peterson trough method. If we assume that the $z = 6.3$ quasar line of sight is typical of the universe at that red-shift then the Gunn–Peterson trough tells us that the neutral fraction must have been at least around 1% at red-shift 6.3. This is significant as it marks the appearance of the first H atoms as we look back in time. We label the red-shift of this epoch as z_{H} and assume $z_{\mathrm{H}} = 6.3$ throughout.

Going forward in time, after recombination the universe was neutral to about 1 part in 10^4. This situation did not change until significant number of stars were formed (black holes) which were able to ionize the universe. Let us label the red-shift of this epoch as z_e when free electrons first start to appear (going forward in time).

The cosmic microwave background (CMB) is sensitive to reionization since the presence of free electrons implies new anisotropy. Current CMB experiments are sensitive to the reionization history through the optical depth to Thomson scattering. This is defined to be

$$\tau = \int_{z_{\mathrm{e}}}^{0} \mathrm{d}z |\mathrm{d}t/\mathrm{d}z| n_{\mathrm{e}}(t) \sigma_{\mathrm{T}}, \tag{1}$$

where n_e is the physical number density of free electrons and σ_T is the Thomson scattering cross-section. Wilkinson microwave anisotropy probe (WMAP) has measured the optical depth [4]; at 95% $0.09 < \tau < 0.28$ with a best-fit value of $\tau = 0.17$.

2. Maximum optical depth

In order to reionize the universe, the ionizing source must have (1) produced at least one ionizing photon ($E > 13.6$ eV) per hydrogen atom and (2) the rate of production of ionizing photons must be sufficient to balance recombinations, and keep hydrogen ionized. Assuming a uniform gas distribution at the mean intergalactic (IGM) density, the hydrogen recombination rate divided by the expansion rate is roughly equal to $(11/(1+z))^{3/2}$, which implies that recombinations are inevitably significant at $z > 10$. The second criterion is therefore the important one.

The ionizing photon production rate in the early universe depends on several factors: the rate at which gas is converted into new ionizing sources, the initial mass function (IMF) of the ionizing source population, the photon production rate per source (as a function of mass), and the fraction of ionizing photons escaping into the IGM.

To get a handle on how the universe could be reionized, let us make some conservative assumptions. Assume that the rate of converting gas into new ionizing sources is given by the fraction of mass collapsed into dark matter halos with virial temperatures of $T > 10^4$ K (computed using the formalism of [5]; see discussion and justification in [6]). Further, assume that all the gas in these halos turns into ionizing sources, and produces 10^4 ionizing photons per baryon. This is a conservative number; massive ($\sim 100 M_\odot$) metal-free stars can actually produce 100 times as many ionizing photons but less than 1% of the total baryons are expected to be bound in these massive stars. We make a further simplification by assuming that all the ionizing photons escape into the IGM. This is certainly not true in the local universe [7] although larger escape fractions have been tentatively inferred for a sample of red-shift $z \approx 3$ galaxies [8].

To calculate the recombination rates one must also include the fact that the ionized gas is clumped. A proper accounting of this effect would force one towards numerical simulations. Let us approximate this effect by assuming a mean clumping factor for the ionized gas. Let us take this factor to be 20 consistent but conservative in comparison with numerical simulations.

Given a cosmology, the above assumptions allow us to predict the maximum reionization red-shift, and hence a maximum optical depth τ_max. As an example, our formalism yields $z_\mathrm{max} = 20.6$ and $\tau_\mathrm{max} = 0.18$ for a flat cosmology with $\omega_m = 0.15$, $\omega_b = 0.02$ and $\sigma_8 = 1$. Note that this upper limit is significantly higher than the expected 'ballpark' values in similar cosmologies [9,10], $z \sim 7$–10. We also reiterate that our result for τ_max is relatively insensitive to our input assumptions, because of the steep decline in the collapsed mass fraction towards high red-shifts.

It should be clear from the above discussion that an optical depth close to 0.18 is hard to arrange for. If the WMAP central value is the true optical depth, then reionization of the universe is a puzzle.

3. Signatures of reionization in the CMB

Reionization affects the CMB temperature anisotropy in a simple manner. On large angular scales, reionization has little effect, while on smaller scales it damps the anisotropy by a factor of $\exp(-2\tau)$. The division into large and small scales is dictated by the angle subtended by the horizon at reionization. The multipole moment this angular scale maps onto is given by $l_r = D_A(z(\eta_r))/\eta_r$, where η_r is the visibility function weighted conformal time [11] and $D_A(z)$ is the angular diameter distance to red-shift z. The above assumes that the photons scattering off the reionized electrons do not pick up additional anisotropy. While not strictly correct, this approximation is good for $\tau \lesssim 0.3$.

The effects of reionization on CMB polarization anisotropy are similar to that on the temperature anisotropy. At $l \gg l_r$, the polarization angular power spectra are suppressed by $\exp(-2\tau)$. However, in contrast to the temperature power spectrum, the effect at $l \lesssim l_r$ is quite dramatic. Note that there is no analog of the Sachs–Wolfe (or the integrated Sachs–Wolfe) effect for polarization. All the polarization signal is generated at the last scattering surface at $z \sim 1000$ in the absence of reionization. Thus without reionization, the polarization power at small multipoles is negligible. In the reionized universe, the rescattering of photons in the presence of a large quadrupole temperature anisotropy results in a broad peak in polarization power at low l. For a detailed discussion of this 'reionization bump', see [12].

An important observational question for the future is whether we can distinguish different reionization histories. Below we will argue that this is indeed possible with future CMB experiments. Another promising avenue is observing the 21 cm absorption and emission (frequency and spatial) anisotropy [13] which allows one to learn about the topology of the ionized regions as a function of time and hence about the reionization history.

To gauge the potential of the CMB to map the reionization history we assume a two-step reionization process. We assume that at some $z_{\rm e} > z_{\rm H} = 6.3$, the universe was partially ionized, the ionized fraction being $x_{\rm e} \leq 1.08$. The ionized fraction is defined here as the ratio of the number density of free electrons to that of hydrogen nuclei. (The present ionized fraction is slightly larger than unity because of the contribution from the complete reionization of ${}^4\mathrm{He} \to {}^4\mathrm{He}^+$.) At $z = 6.3$, new sources turned on, leading to almost complete ionization. If reionization happened gradually (and not in our idealized two-step fashion) then $x_{\rm e}$ provides us with an estimate of the average ionized fraction before $z = 6.3$, and $z_{\rm e}$ an estimate of when the first ionizing sources turned on. The large-scale polarization anisotropy is expected to be insensitive to the topology of the partially ionized regions [14].

In figure 1 we show the predictions for the results achievable with three full-sky (satellite) missions: WMAP, Planck and EPIC. EPIC is a proposal to NASA for a full-sky CMB mission after Planck with the main aim of detecting primordial B modes. The bottom line is that WMAP is only sensitive to the optical depth, but Planck and EPIC have the potential to map out the reionization history [14]. One can go beyond the two-step model and verify that this is true [15].

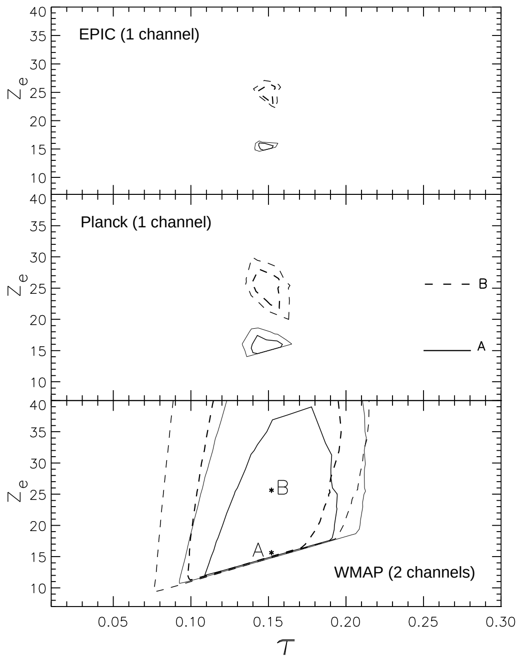

Figure 1. Constant likelihood contours at 10% (thick curves) and 1% (thin curves) of the maximum likelihood – which occurs at the fiducial models labeled by A, B and denoted by asterisks. All the panels have the same fiducial models. The solid curves correspond to model A while the dashed curves to model B. The upper panel is for EPIC (see text), the middle for Planck and the lower panel for WMAP.

4. Cosmological implications

In addition to probing high red-shift structure formation, measuring properties of reionization through the large-angle CMB polarization has important implications for fundamental cosmology. In particular, the presence of free electrons damps the primary anisotropy, and results in a strong degeneracy between the amplitude of primordial fluctuations (A) and the optical depth τ. The quantity A is one of the most important parameters in inflationary cosmology, as it directly probes the inflaton potential. The accuracy to which we know A is determined by the accuracy with which we measure τ. From the above calculations we find (see figure 1) that Planck will measure the optical depth to 0.01 ($1{-}\sigma$) [14,16] which implies a 2% measurement of A. Ultimately an experiment like EPIC can measure A to about 1% [14–16]. Practically such a measurement of the scalar primordial power spectrum is important for low red-shift probes of the matter power spectrum (say through gravitational lensing).

Another important implication of the early reionization concerns the measurement of the primordial tensor power spectrum. Just like the E mode, the B mode polarization anisotropy power spectrum will also show a distinct 'reionization bump'. This could be vital for measuring the primordial B mode power spectrum and hence the primordial gravity wave (or tensor perturbation) power spectrum. The primordial gravity wave contribution is a fundamental quantity of interest since it is proportional to the fourth power of the energy scale of inflation. Including the B mode polarization bump, we can detect gravity waves with EPIC if inflation happened at energy scales down to 1.7×10^{15} GeV [14].

To summarize, CMB is an important tool to study the reionization history. Such a study and the presence of early reionization has important implications for inflation.

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