CONSTRaining Extended Reionization Models Through Arcminute-Scale CMB Measurements

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ABSTRACT

The measurement of the optical depth to free electrons, \( \tau_r \), in the cosmic microwave background (CMB) provides an important constraint on reionization, but is degenerate to more complex reionization models. Small angular-scale CMB measurements of the kinetic Sunyaev-Zeldovich (kSZ) and Ostriker-Vishniac (OV) effects have the potential to break this degeneracy. We calculate the OV signal for various extended reionization histories described by a simple analytic form. These models are parametrized by \( \Delta z \), the duration of the reionization event. For reionization histories with identical values of \( \tau_r \), the OV amplitude at \( l = 3000 (C_{3000}) \) differs by \( \approx 20\% \) between the models with \( \Delta z = 0.1 \) and \( \Delta z = 3.0 \). We demonstrate that the removal of the \( z \lesssim 6 \) component of the OV signal will significantly enhance the ability to differentiate between reionization histories, with \( C_{3000} \) varying by a factor of \( \sim 2 \) between the models with \( \Delta z = 0.1 \) and \( \Delta z = 3.0 \). If the low-redshift OV and related kSZ signal can be adequately subtracted, this would provide an important observational constraint on extended reionization models.

Subject headings: cosmology: theory — cosmology: observations — cosmic microwave background — large-scale structure of universe — radiation mechanisms: non-thermal — scattering

1. INTRODUCTION

The first decade of the 21st century has arguably witnessed the advent of precision cosmology, ushered in by cosmic microwave background (CMB) experiments, such as the Wilkinson Microwave Anisotropy Probe (WMAP, Komatsu et al. (2008)), and large-scale galaxy surveys, such as Sloan Digital Sky Survey (SDSS, Adelman-McCarthy et al. (2006)) and the 2-degree Field Galaxy Redshift Survey (2dFGRS, Colless et al. (2001)). The major cosmological parameters are now known at the percent accuracy level, and \( \Lambda \)CDM has emerged as the cosmology which is most easily reconciled with observations.

The current concordance picture of \( \Lambda \)CDM cosmology holds that after the universe became transparent to the CMB at \( z \sim 1000 \), the baryonic content of the universe was neutral and coupled gravitationally to the dark matter component. Some 100 years after the Big Bang, the collapse of massive halos led to the formation of the first generation of stars and galaxies.

These first-generation stars are believed to be extremely massive (\( M > 100 M_\odot \)) and have extremely hard spectra. The prodigious amounts of \( E \gtrsim 13.6 \) eV photons generated by these stars propagated out of their host protogalaxies into deep space, gradually reionizing the inter-galactic medium (IGM), fully ionizing the universe by \( z \sim 6 \) (see Loeb & Barkana (2001) and Furlanetto & Oh (2008) for reviews on the subject). The reionization process is believed to be highly complex: even though considerable theoretical work (both analytical and simulations) have been carried out to understand this epoch (e.g. Furlanetto et al. (2004); Iliev et al. (2006); Trac & Cen (2007)), the lack of observational evidence has made it difficult to reach consensus on fundamental issues such as the temporal extent of reionization and when it began (e.g. Lidz et al. (2007); Shin et al. (2008)), let alone minuatae such as feedback processes (e.g. Ciardi et al. (2000); Mesinger & Dijkstra (2008)) and the details of ionized bubble percolation (e.g. McQuinn et al. (2007); Lee et al. (2008)) through the universe.

At present, there are two major observational constraints on reionization: (1) The optical depth to free electrons up to the surface of last scattering has been measured through CMB polarization data to be \( \tau_r = 0.084 \pm 0.016 \) (Dunkley et al. 2008), corresponding to a reionization redshift of \( z_r \approx 11 \) assuming unrealistically that reionization occurred instantaneously. (2) The detection of the Gunn-Peterson absorption trough from neutral hydrogen in the Lyman-\( \alpha \) absorption spectra of high-redshift (\( z \sim 6 \)) quasars indicates a rising neutral fraction beginning from this epoch (Fan et al. 2006), hinting at the end of reionization process, although this is by no means certain (Becker et al. 2007; Furlanetto & Mesinger 2008).

Over the next decade and beyond, radio experiments are being designed to probe the 21-cm line of neutral hydrogen, e.g. LOFAR (Zaroubi & Silk 2005), MWA (Morales & Hewitt 2004), and SKA (Terzian & Lazio 2006). These 21-cm tomography experiments promise full 3D imaging of the neutral IGM, allowing reionization to be studied in unprecedented detail. However, these experiments are still in their early stages.

At time of writing, several high angular resolution CMB experiments are ongoing, such as the Atacama Cosmology Telescope (ACT, Kosowsky 2006) and South Pole Telescope (SPT, Ruhl et al. (2004)). These experiments have resolutions approaching 1', with sensitivities of \( \sim nK/\xi \). The temperature-temperature angular power spectra \( C_\ell \) produced by these experiments will,
for the first time, probe small angular scales $l \gtrsim 3000$ at which the primordial CMB power spectrum is no longer the dominant contribution to the anisotropy power. Instead, the secondary anisotropy at these scales will be dominated by foreground astrophysics such as unresolved radio galaxies, far IR/sub-millimetre dusty galaxies and the thermal/kinetic Sunyaev-Zeldovich (tSZ and kSZ, respectively) and Ostriker-Vishniac (OV) effects.

In this paper, we study the sensitivity of the OV effect towards extended reionization models with the same value of $\tau_r$. While the OV and kSZ effects have been extensively studied in the past (Ostriker & Vishniac 1986; Vishniac 1987; Jaffe & Kamionkowski 1998; Hu 2000; Zhang et al. 2004), these studies were made prior to the WMAP 5th Data Release (WMAP5, Dunkley et al. 2008) constraint on $\tau_r$ (and in the earlier papers, before concordance ΛCDM cosmology was widely accepted). McQuinn et al. (2005) made a study on the OV/kSZ signal from different reionization models, but this was based on preliminary WMAP results, and they did not explore the potential of the OV effect to break the degeneracy of $\tau_r$ towards different reionization models.

First, we briefly summarize the derivation of the OV effect before discussing our chosen model for parametrizing reionization histories. We then present our calculations and discuss them in the context of upcoming experiments.

2. THE OSTRIKER-VISHNIAC EFFECT

In this section we summarize the derivation of the CMB anisotropy from the OV effect as elucidated in Vishniac (1987) and Jaffe & Kamionkowski (1998). The fractional temperature change in the direction $\vec{\theta}$ from the scattering of the primordial CMB by bulk motion of free electrons is

$$p(\vec{\theta}) = \frac{\Delta T}{T} = -\int_0^{\eta_0} n_e \sigma_T e^{-\tau} [\vec{v}(w\vec{\theta}, w)] a(w) dw,$$

where $n_e$ is the electron number density along the line of sight, $\vec{v}(w, w)$ is the bulk velocity at comoving distance $w$ in units of the Hubble distance, at conformal time $\eta = \eta_0 - w$ (where conformal time is defined by $d\eta = dt/a$), $\sigma_T$ is the Thomson scattering cross-section, $a(w)$ is the scale factor of the universe at $w$ and we set $c = 1$. $\tau$ is the optical depth to electron scattering to a given epoch, and for a ΛCDM cosmology it can be expressed as a function of redshift thusly:

$$\tau(z) = \frac{\Omega_b \rho_c \sigma_T \eta_0}{m_p} \int_0^z \frac{x_e(z') (1 + z')^2}{\sqrt{\Omega_m (1 + z')^3 + \Omega_A}} dz'$$

$$= 0.046 \frac{h x_e}{\Omega_m} \left[ (\Omega_m (1 + z)^3 + \Omega_A)^{1/2} - 1 \right]$$

where $\Omega_b, \Omega_m$ and $\Omega_A$ are the present-day baryon, matter (dark matter + baryon) and dark energy densities respectively, in units of the critical density $\rho_c$. $x_e$ is the ionization fraction and $m_p$ is the mass of the proton. In the second line, we have assumed that $x_e$ is constant over the period of integration.

The visibility function is defined as

$$g(w) = \bar{n}_e(w) \sigma_T a(w) e^{-\tau} = \frac{d\tau}{dw} e^{-\tau}.$$  \hspace{1cm} (3)

and $\bar{n}_e$ from Eq. 1 has been replaced by the mean electron number density $\bar{n}_e = \Omega_b \rho_c x_e(z)(1 + z)^3/m_p$. $g(w)$ represents the probability distribution of first scattering from reionized scattering (contrast the analogous visibility function in CMB recombination physics, which is the probability distribution of last scattering). The visibility function is normalized such that

$$\int_0^\infty g(w) dw = 1 - e^{-\tau},$$

where $\tau_r$ is the total optical depth to scattering by free electrons up to the surface of last scattering.

The fractional temperature change can then be rewritten as

$$p(\vec{\theta}) = -\int_0^{\infty} g(w) \vec{\theta} \cdot q(w, w)$$

where $q(w, w) = [1 + \delta(w, w)] v(w, w)$ and $\delta(w, w)$ is the fractional density perturbation.

Using the linear theory approximations for $\delta(w, w)$ and $v(w, w)$, and projecting the temperature perturbation onto the sky using the Limber approximation, we get the Ostriker-Vishniac angular power spectrum in terms of multipole moments

$$C_l = \frac{1}{16\pi^2} \int_0^{\infty} \frac{g^2(w)}{w^2} a(w)^2 \left( \frac{\Delta D}{D} \right)^2 S(l/w) dw,$$

where $w = \eta_0 - \eta, D$ is the growth factor (the dotted variable denotes a derivative with respect to time) and the function $S(l/w)$ (sometimes known as the Vishniac power spectrum) is usually written in terms of the comoving wavenumber $k$:

$$S(k) = k \int_0^{\infty} dy \int_1^{\infty} dx P(ky) P(k\sqrt{1 + y^2 - 2xy})$$

$$\times \frac{(1 - x^2)(1 - 2y)^2}{(1 + y^2 - 2xy)^2}$$

where $P(k)$ is the standard linear matter power spectrum using the transfer function from Bardeen et al. 1986, normalized to the latest WMAP5 values.

We now make a brief note on nomenclature regarding the related kSZ and OV effects, which have at times been used interchangeably by authors. The temperature perturbation equation (Eq. 1) was first derived by Zeldovich & Sunyaev (1969), and then studied in the context of the peculiar motion of individual galaxy clusters in Sunyaev & Zeldovich (1980). Ostriker & Vishniac (1986) and Vishniac (1987) were the first to study the effect in the context of large scale structure, specifically with linear perturbation theory. We therefore refer to the OV effect as the temperature anisotropy caused by velocity and density fields in the linear regime, while the kSZ is its non-linear counterpart (which is the effect that accounts for the temperature perturbation from the peculiar motion of galaxy clusters).

3. REIONIZATION HISTORIES

One of the most important outstanding questions on reionization is: when did it happen? The naïve way of answering this is by measuring the total optical depth $\tau_r$ to free electrons from us to the surface of last scattering. One can then invert Eq. 2 to find the epoch of reionization $z_r$. This estimate of
Fig. 1.— Ionization fraction $\bar{x}_e$ (left) and visibility function $g$ (right) as a function of redshift, for 3 reionization histories constrained by $\tau_r = 0.09$. The discontinuity at $6.0 < z < 6.5$ is caused by our linear interpolation scheme which ensures that $x_e(z = 6.0) = 1$ (see discussion in Sec. 3).

Fig. 2.— Reionization histories parametrized by $z_r$ and $\Delta z$ (as described by Eq. 8), solved for $\tau_r = 0.100$ (solid line), $\tau_r = 0.085$ (dotted line) and $\tau_r = 0.070$ (dashed line).

$z_r$ assumes an instantaneous reionization event which is physically unrealistic, while $\tau_r$ by itself is degenerate to more complicated reionization histories.

Until recently, measurements of $\tau_r$ have had considerably worse precision, and authors studying reionization have tended to regard $\tau_r$ as a tunable free parameter in their reionization models. The WMAP5 measurement\(^1\) of $\tau_r = 0.084 \pm 0.016$ (corresponding to an instantaneous reionization redshift $z_r = 10.8 \pm 1.4$) has been precise enough to change this paradigm, and in this paper we regard $\tau_r$ as a fixed value, albeit one that still has non-negligible uncertainties. However, one can expect subsequent WMAP data releases as well as the upcoming Planck space mission (The Planck Collaboration 2003) to further tighten the constraint on $\tau_r$ to $< 10\%$ precision.

Prior analyses of the kSZ or OV effects have tended to assume instantaneous reionization, in which the visibility function $g(z)$ has been calculated assuming that $\bar{x}_e = 1$ at $z \leq z_r$ and $\bar{x}_e = 0$ prior to that.

In order to describe an extended reionization event, we choose a simple parametrization for the mean neutral fraction as a function of redshift, often used to compare results of different reionization models (Zaldarriaga et al. 2004; Alvarez et al. 2006)

$$\bar{x}_{HI}(z) = \frac{1}{1 + \exp[-(z - z_r)/\Delta z]}$$

(8)

where $z_r$ in this case is defined as the redshift at which $\bar{x}_{HI} = 0.5$ and $\Delta z$ parametrizes the duration of the reionization event. The mean ionized fraction is then trivially $\bar{x}_e = 1 - \bar{x}_{HI}$.

Up to this point, we have assumed that the universe is composed solely of hydrogen, and ignored helium reionization. It is often assumed that the He I in the universe becomes singly ionized at roughly the same time as H I as their (first) ionization energies are of the same magnitude (24.6 eV for He I compared with 13.6 eV for H I). To make this assumption, we modify the expression for the number density of electrons used in Eqs. 1–3

$$\bar{n}_e = \left[ 1 - \frac{Y}{m_p} + \frac{Y}{4m_p} \right] \Omega_b \rho_c \bar{x}_e(z)(1 + z)^3$$

(9)

where $Y$ is the helium mass fraction of the universe (in our calculations we use the value $Y = 0.24$). The two terms in the square parentheses correspond to the free electrons contributed by the ionization of hydrogen and the first ionization of helium, respectively.

He II reionization, on the other hand, is a low-redshift ($z \sim 3$) event which is much more amenable to observations (Shull et al. 2004; Furlanetto & Oh 2008) and thus beyond the scope of this paper.

While the functional form of Eq. 8 is believed to describe well the evolution of the neutral fraction during most of the reionization process, it becomes less accurate near the end of reionization as $\bar{x}_{HI} \to 0$. For reionization

\(^1\) http://lambda.gsfc.nasa.gov
histories consistent with $\tau_r \approx 0.09$ and $z_r \approx 10$ the neutral fraction doesn’t drop quickly enough to $\bar{x}_{HI} \sim 10^{-3}$ by $z \lesssim 6.5$, as observed in high-redshift quasar observations. We thus modify our reionization model as follows: the neutral fraction is parametrized by Eq. (8) in the regime $z > 6.5$, and then interpolated linearly to $\bar{x}_{HI} = 0$ at $z = 6.0$. The left-hand plot of Fig. 1 illustrates our chosen form of $\bar{x}_e$.

For a fixed $\tau_r$, this gives a family of reionization models parametrized by $z_r$ or $\Delta z$. In Fig. 2 we compute $\Delta z$ and $z_r$ for reionization histories constrained by 3 different values of $\tau_r$ consistent with WMAP5 (hereafter we use $\Delta z$ to label different reionization histories at fixed $\tau_r$). We see that any given value of $\tau_r$ is degenerate with a wide range of reionization histories ranging from instantaneous ($\Delta z \to 0$) to highly extended ($\Delta z \sim 4-5$). Note that smaller values of $\tau_r$ tend to limit the possible range of $\Delta z$ due to our constraint that reionization completes by $z \sim 6$, as discussed above.

Fig. 1 shows our chosen form of the ionization fraction $\bar{x}_e$ and the corresponding visibility function $g$ as a function of redshift, calculated for several reionization histories which share the same value of $\tau_r$.

4. ANGULAR POWER SPECTRUM CALCULATIONS

Eqs. (6) and (7) are integrated numerically to calculate the OV angular power spectrum. In our calculations we use the WMAP5 recommended values [Dunkley et al. 2008] for the cosmological parameters, $h = 0.71$ (where $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$), $\Omega_m = 0.28$, $\Omega_b h^2 = 0.0227$, $n = 0.96$, $\Delta^2_R(k = 0.002$ Mpc$^{-1}) = 2.41 \times 10^{-9}$.

However, dark energy drops to less than 10% of the total mass-energy of the universe above $z \sim 1.3$, while
the main epoch of interest at which reionization affects the OV signal is \( z > 6 \). We thus make the simplifying assumption of a flat Einstein-de Sitter universe (\( \Omega_m = 0, \Omega_{\Lambda} = 1 \)) for computing the OV angular power spectrum. This allows us to make the substitutions \( a = \eta^2/\eta_0^2 \) and \( D\dot{D}/D_0^2 = 2\eta/\eta_0 \) in Eq. 6. The integrated optical depth \( \tau(z) \), however, is highly sensitive to cosmology and we assume \( \Lambda \)CDM cosmology when calculating this for the visibility function (c.f. Eq. 3).

While comparing the results of our calculations with those in Jaffe & Kamionkowski (1998), we found discrepancies that were eventually traced to an error in their code for calculating \( S(k) \) (c.f. Eq. 7). This error caused an overall underestimate (by \( \sim 10 - 20\% \)) in the OV power of the results presented in their paper. The shape of their \( \mathcal{P}_C \) power spectra should also be slightly more peaked, and the peaks have tended to move to lower \( l \) after the mistake was corrected. Hence, the analytic approximation for \( S(k) \) fitted to their results (Eq. 41 in their paper) is incorrect. Nevertheless, the equations derived in their paper are mostly correct, except for their Eq. 38, which should be identical to the second line of our Eq. 2.

The resultant power spectra for several reionization histories consistent with \( \tau_r = 0.09 \) are shown in Fig. 3. The power spectra peak at \( l \simeq 1000 \) while the variance of the temperature distribution

\[
\langle \frac{(\Delta T)}{T} \rangle^2 = \frac{1}{2\pi} \int l C_l \, dl
\]

(10)
corresponds to a root-mean-squared (r.m.s.) value \( \Delta T \simeq 2.4 - 2.7 \mu \text{K} \). The amplitude of the spectra tends to decline with increasing \( \Delta z \), as this has the effect of spreading \( g(z) \) to higher redshifts (c.f. Fig. 1) while the \( (aD\dot{D}/wD_0)^2 \) parts of the integrand are decreasing functions with redshift. Hence, a more extended reionization event samples the low-redshift part of the integral less than a rapid event, which decreases the power in the signal.

At \( l = 3000 \), where the primary anisotropy drops below the level of the secondary anisotropies, \( C_{3000} \) differs by about 20\% between the cases of near-instantaneous \( (\Delta z = 0.1) \) and highly extended \( (\Delta z = 3.0) \) reionization. However, for the majority of the universe’s lifetime we know the ionization state: \( \bar{x}_e = 1 \) from \( z \lesssim 6 \) onwards irrespective of the reionization model, so if we remove the low-redshift part of the integral we get rid of the part of the signal that is independent of the reionization model.

In Fig. 4 we plot the contribution of different redshifts in the calculation of \( C_{3000} \) (i.e. the integrand of Eq. 6 plotted against redshift for \( l = 3000 \)). We see that a significant portion of the power is contributed from \( z < 6 \). Removing this contribution would increase the contrast between the \( C_l \)'s computed for different reionization histories.

This is duly shown in Fig. 3 where we have removed the \( z < 6 \) portion from the integral in Eq. 6. The remaining power in the anisotropies peak at \( l \simeq 1500 \), but now the r.m.s. temperature perturbation varies from \( \Delta T \sim 1.5 \mu \text{K} \) for \( \Delta z = 0.1 \) to \( \Delta T \sim 1.0 \mu \text{K} \) for \( \Delta z = 3.0 \). \( C_{3000} \) now varies by a factor of \( \sim 2 \) between the near-instantaneous reionization model and the most extended one.

\[\text{Fig. 5.}\] OV anisotropy at \( l = 3000 \), plotted as a function of the contributing redshift for \( \Delta z = 0.1 \) (solid), \( \Delta z = 1.0 \) (dotted) and \( \Delta z = 3.0 \) (dashed).

5. DISCUSSION / CONCLUSION

From our calculations, we have shown that by altering the duration of the reionization event that goes into the visibility function of the Ostriker-Vishniac power spectrum, significant changes are made to the resulting \( C_l \)'s. However, the OV effect is certainly not the only secondary anisotropy to exist at \( l > 10^3 \).

Assuming that instrumental noise issues have been dealt with, the main challenges facing the detection of the kSZ/OV signal at \( l > 2500 \) are the other secondary anisotropies. The galactic foregrounds and far-IR/sub-mm extragalactic sources can be removed by cross-correlating with multi-wavelength data, while the thermal SZ signal can be removed due to its spectral dependency near the CMB peak temperature.

In this paper we have only considered the linear OV effect, and not the full combination of OV (which dominates at high-\( z \)) and non-linear kSZ (which dominates at low-\( z \)). However, the calculation of kSZ is carried out through an integral similar in form to Eq. 6 with the main differences being the calculation of the integral \( S(k) \) (Eq. 7). In practice, these involve using some form of non-linear power spectrum instead of the linear \( P(k) \) we used in Eq. 7 (Hu 2001; Ma & Fry 2002). These calculations are still weighted by the electron visibility function \( g(z) \) in the same manner as the OV, but the fact that the non-linear terms are relatively small compared to the linear terms at \( z > 6 \) mean that the kSZ is less sensitive to the reionization history than the OV; see Hernández-Monteagudo & Hèd (2009) for a recent paper on this. One additional source of OV/kSZ power is from patchy reionization, i.e. the contribution from large ionized H II bubbles which form during reionization (McQuinn et al. 2005). However, this contribution should similarly be weighted by the visibility function and would not qualitatively affect the dependency of the kSZ/OV signal on the reionization history as discussed in this paper.

In the most optimal case, the noise sensitivity of ACT would allow for \( C_l \) measurements at a precision of several percent at \( l \) of several thousand (Kosowsky 2006).
Once the systematic errors from the subtraction of foregrounds, extragalactic point-sources and tSZ are taken into account, it would be challenging to measure the full kSZ/OV signal to sufficient accuracy to distinguish between different reionization histories, for which the values of $C_{3000}$ vary by about 20% between the cases of instantaneous reionization and highly extended ($\Delta z = 3$) reionization.

The key to distinguishing between reionization histories lies in removing the low-redshift ($z < 6$) component from the kSZ/OV signals (specifically the kSZ contribution from non-linear structures, which dominate at low redshift). This would greatly increase the contrast between the different reionization histories, to a factor of $\sim 2$ between the cases of $\Delta z = 0.1$ and $\Delta z = 3.0$ as we have seen above. Ho et al. (2009) have developed a method of measuring the kSZ signal at low redshift. They build a template of the momentum field by reconstructing the momentum field from galaxy redshift surveys, and then cross-correlating this with arcminute-scale CMB data. For a cross-correlation between a 4000 sq. deg. ACT experiment with galaxy survey data from the 3rd phase of the SDSS (SDSS3), Ho et al. (2009) estimate a kSZ detection with a signal-to-noise (S/N) of $\sim 15$. However, this method can only measure the kSZ contribution from relatively low redshifts ($z \lesssim 1$) that can be adequately covered by the galaxy redshift surveys of the foreseeable future.

One possibility would be to construct a kSZ template from the Ly$\alpha$ forest in the spectra of high-redshift quasars, which coincidentally covers the $z \lesssim 6$ redshift region for which we want to subtract the kSZ. This would be complicated by the difficulty of extracting the underlying density field from Ly$\alpha$ data, but even a relatively low S/N estimate of the low-redshift kSZ should allow us to differentiate between instantaneous and highly extended reionization. Considering the current paucity of observational data on reionization, even a rough estimate of $\Delta z$ would provide valuable constraints on reionization.

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