Radiative effects by high-z UV radiation background: Implications for the future CMB polarization measurements

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The radiative effects by high-redshift ultraviolet radiation background (UVB) heats the gas in the IGM and eliminate the neutral hydrogen and helium that dominate the cooling of the primordial gas. We investigate the role of the radiative effects for the temporal evolution of the reionization fraction by using cosmological Smooth Particle Hydrodynamics (SPH) simulations.

We find that the increase of photo-ionization and photo-heating rates due to optical depth effects results in a significantly contribute to the heating of the IGM before and during the reionization. The main effect of the UV radiation spectrum on the temporal evolution of the ionization fraction is given by the value of the reionization redshift, $z_{re}$, and the redshift interval, $\Delta z$, in which the reionization is completed.

We evaluate the effects of the UV radiation background on the CMB angular power spectrum taking into account different temporal evolutions of the ionization fraction. We find that for reionization models with degenerated CMB temperature anisotropy power spectra, the radiative mechanisms leave distinct signatures on the E-mode polarization power spectrum, at large scales ($l < 50$). We show that through E-mode CMB polarization power spectrum measurements, the PLANCK experiment will have the sensitivity to distinguish between different reionization histories even when they imply the same optical depth to electron scattering and degenerated $C_T$ power spectra.

This work has been done in the framework of the PLANCK LFI activities.
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1 Introduction

The detailed study of the intergalactic medium (IGM) is fundamentally important for understanding the large-scale structure properties and the galaxy formation process.

At the epoch of reionization the collapsed objects began to influence the diffuse gas in the IGM and rendered it transparent to the ultraviolet photons. In the hierarchical models of structure formation, an early UV radiation background (UVB) is produced by the first collapsed halos with masses near the cosmological Jeans mass. In order to virialize in the potential wells of the dark matter halos, the gas in the IGM must have a mass, $M_b$, greater than the Jeans mass, $M_J$, which is $\sim 10^5 M_\odot$ at a redshift $z \sim 30$, corresponding to a virial temperature $T_{\text{vir}} \sim 10^4 \text{K}$. Photoionization by the high-redshift UVB heats the low density gas in the IGM before it falls into the dark matter wells, strongly reducing the fraction of neutral hydrogen and helium that dominate the cooling of the primordial gas at temperatures of $T_{\text{vir}}$.

The primordial gas dynamics in the photoionized IGM gives important insight into the epoch of the reionization and the end of the "dark ages" of the universe, believed to have been caused by the light from the first generation of massive stars (see, e.g., the review by Barkana and Loeb (2001) and the references therein).

From the observational point of view, the study of the reionization process itself as well as the properties of the sources driving it is challenged by a variety
of observational probes. A powerful observational probe comes from the Lyα absorption spectra of the high redshift quasars (Becker et al., 2001; Fan et al., 2002; White et al., 2003; Fan et al., 2004) showing that all known quasars with $z > 6$ have a complete Gunn-Peterson (GP) trough and a rapid evolving hydrogen neutral fraction compatible with the final stage of reionization. This conclusion is strengthen by the study of the proximity effects around high redshift quasars (Wyithe and Loeb, 2004; Mesinger and Haiman, 2004). Also, the high value of the IGM temperature inferred from the study of Lyα forest at $z \sim 4$ indicates that the hydrogen neutral fraction changed substantially at $z \leq 9$ (Theuns et al., 2002; Hui and Haiman, 2003).

An other powerful observational probe is represented by the high value of the electron scattering optical depth, $\tau_{es}$, inferred from the Cosmic Microwave Background (CMB) anisotropy measured by the WMAP experiment (Kogut et al., 2003; Spergel et al., 2003; Verde et al., 2003) which requires reionization to begin at $z > 14$.

In order to reconcile these observations a number of semi-analytical models have been developed, the most intriguing possibility being the so called "double reionization" for which the globally-average ionization fraction decreases with cosmic time over a limited period. The resulting reionization histories display a wide range of features extended over a long redshift interval. Some of these works (Cen, 2002; Wyithe and Loeb, 2004) agree on the necessity of a first generation of metal-free stars (Population III) with heavy mass function to produce the large observed value of $\tau_{es}$. Other studies (Ciardi, Ferrara
and White, 2003; Somerville and Livio, 2000) found that the metal enriched stars (Population II) are able to reionize the universe enough early to produce such high values of $\tau_{es}$. These works assume that the total volume fraction of the ionized regions were driven by the ionizing sources located in the dark matter halos. Typically, these scenarios require a number of assumptions on the dynamics of the stellar evolution. Recent works (Scannapieco et al., 2003; Furlanetto and Loeb, 2004) show that the transition redshift at which the star formation switches between the two modes must occur over a large redshift interval and only after the reionization is complete. In this scenarios, the observables characterizing the global reionization history of the universe can be reconstructed with a large range of input parameters.

Other physical mechanisms that can explain the extension of reionization over a long redshift interval are radiative, the most important being the photo-ionization heating. A recent work (Furlanetto and Loeb, 2004) critically examined the plausibility of different mechanisms, showing that double reionization requires a rapid drop in ionizing emissivity over a single recombination time that can be obtained with unusual choices of the physical parameters.

Cosmological N-body simulations provide a completely different approach to model the reionization process (Ostriker and Gnedin, 1996; Gnedin and Ostriker, 1997; Gnedin, 2000; Ciardi, Stoehr and White, 2003), offering the advantage over the semi-analytical models to be able to fully account for the dynamical evolution of the matter contents in the universe. The main limitation of N-body simulations is related to their resolution that turns to be
critical for the reionization studies. At redshifts $z \geq 3$ the quasar population declines (Madau, Meiksin and Rees, 1999) and it could not be able to reionize the gas in the IGM. The bulk of the ionizing photons at high redshifts should be then produced by an early population of stars (see, e.g., Haiman, Abel and Rees, 2000, Barkana and Loeb, 2000, Cen, 2002).

In the hierarchical theories of structure formation the low mass objects collapse first merging then into progressively larger systems. In this scenario, small mass objects ($M \sim 10^5 - 10^7 M_\odot$) are the main contributors at high redshifts while their role becomes much less important at low redshifts in comparison with that coming from objects with higher masses ($M > 10^9 M_\odot$). Thus, numerical simulations are subjected to the difficulty to be able to resolve objects in a large dynamic range with enough resolution.

A number of works have also considered the implications of different reionization mechanisms for the CMB angular power spectra (see e.g., Bruscoli, Ferrara and Scannapieco 2002; Holder et al., 2003; Haiman and Holder, 2003; Naselsky and Chiang, 2004).

Although the electron optical depth to the Thompson scattering of the CMB photons, is an important cosmological parameter (see, e.g., Kaplinghat et al., 2003; Hu and Holder, 2003), the CMB angular power spectrum contains more information about the reionization process than the optical depth integrated over the whole ionization history.

In this paper we study the role of the radiative effects for the time evolution
of the global ionization fraction at sub-galactic scales \((M \sim 5 \times 10^8 M_\odot)\) by using N-body cosmological hydrodynamical simulations.

We evaluate the effects of the UV radiation background amplitude and shape (in both frequency and redshift) on the features of the CMB anisotropy and polarization angular power spectra and address their detectability by ongoing and future CMB anisotropy experiments.

The paper is organized as follows: in §2, we compute the UV radiation background flux as solution to the cosmological radiative transfer equation and discuss the radiative mechanisms that can cause the global ionization fraction to evolve non-monotonically with the cosmic time. We present the various reionization histories obtained for the considered UVB flux models in §3.

In §4 we compute the CMB angular power spectra, in both temperature and polarization, for the various reionization histories by taking into account the radiative mechanisms. The possibility to distinguish among different reionization scenarios with the forthcoming Planck experiment is also discussed in this section. We draw our main conclusions in §4.

Throughout we assume a background cosmology consistent with the most recent cosmological measurements (Spergel et al., 2003) with energy density of \(\Omega_m = 0.27\) in matter, \(\Omega_b = 0.044\) in baryons, \(\Omega_A = 0.73\) in cosmological constant, a Hubble constant of \(H_0 = 72\) km s\(^{-1}\)Mpc\(^{-1}\), an \(rms\) amplitude of \(\sigma_8 = 0.84\) for mass density fluctuations in a sphere of radius \(8h^{-1}\)Mpc, adiabatic initial conditions and a primordial power spectrum with a power-law scalar
spectral index \( n_s = 1 \).

2 Building up the UV radiation background

Reionization is an inhomogeneous process that proceeds in a patchy way. The radiation output associated with the collapsed halos gradually builds up a cosmic UVB.

At early times, most of the gas in the IGM is still neutral and the cosmological \( \text{H}_\text{II} \) regions around the individual sources do not overlap. At this early stage the gas in the IGM is opaque to the ionization photons, causing fluctuations of both ionization fraction and UVB intensity from region to region. At the reionization redshift, \( z_{\text{re}} \), the \( \text{H}_\text{II} \) regions surrounding the individual sources in the IGM overlap. As shown by numerical simulations (see, e.g., Gnedin, 2000, Barkana and Loeb, 2000), at \( z_{\text{re}} \) the UVB intensity increases sharply and the baryonic gas is heated to a temperature \( T_{\text{IGM}} \approx 10^4 \text{K} \). At smaller redshifts, the quasars contribution to the UVB leads to \( T_{\text{IGM}} \approx 4 \times 10^4 \text{K} \) (Theuns et al., 2002).

The cumulative UV background flux, \( J(\nu_o, z_o) \), observed at the frequency \( \nu_o \) and redshift \( z_o \), (in units of \( 10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \)) due to photons emitted from redshifts between \( z_o \) and an effective emission screen located at \( z_{sc} \geq z_o \), is the solution of the cosmological radiative transfer equation (Peebles, 1993;
Haiman, Rees & Loeb, 1997):

\[
J(\nu, z) = \frac{c}{4\pi} \int_{z_0}^{z_\text{sc}} e^{-\tau_{\text{eff}}(\nu, z)} \frac{dt}{dz} \left(\frac{1 + z_0}{1 + z}\right)^3 j(\nu, z) dz,
\]

(1)

where: \( j(\nu, z) \) is the comoving emission coefficient (in units of \(10^{-21} \text{ erg cm}^{-3} \text{ s}^{-1} \text{ sr}^{-1} \)) computed at emission redshift \( z \) and photon frequency \( \nu = \nu_0(1 + z)/(1 + z_0) \), \( \tau_{\text{eff}}(\nu_0, z_0, z) \) is the effective optical depth at the frequency \( \nu_0 \) due to the absorption of the residual gas in the IGM between \( z_0 \) and \( z \) and \( (dt/dz)^{-1} = -H_0(1 + z)\sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda} \) is the line element in our \( \Lambda \text{CDM} \) cosmological model.

Above the hydrogen ionization threshold (\( \nu_\text{th}^{\text{HI}} = 13.6 \text{ eV} \)) the UV radiation background is processed due to the absorption of residual gas in the IGM dominated by neutral hydrogen and helium. At these frequencies the effective optical depth is given by (see e.g. Haiman, Rees & Loeb, 1997):

\[
\tau_{\text{eff}}(\nu_0, z_0, z) = c \int_{z_0}^{z} \frac{dt}{dz} \kappa(\nu, z) dz, \quad \kappa(\nu, z) = \sum_i \sigma_i(\nu)n_i(z),
\]

(2)

where: \( i = (\text{HI}, \text{HeI}) \) and \( \sigma_i \) and \( n_i \) are the cross section and the number density respectively, corresponding to species \( i \).

Below hydrogen ionization threshold, in the frequency range 11.18-13.6 eV (enclosing Lyman and Werner bands of \( \text{H}_2 \)), the UV background spectrum is processed due to the absorption into \( \text{H}_2 \) lines (Ciardi, Ferrara & Abel, 2000; Haiman, Abel & Rees, 2000). The dissociation of \( \text{H}_2 \) molecules removes photons from the UVB and decreases the rate of dissociation process inside the collapsed halos. The magnitude of this process depends on the \( \text{H}_2 \) fraction and
the redshift distribution of the sources. Haiman, Abel & Rees (2000) found that the intergalactic H$_2$ has a negligible effect on the UVB spectrum, both because its effective optical depth is small ($\lesssim 0.1$) and because it is photodissociated at early stages.

To compute the spectrum of the UV radiation background taking into account the radiative transfer effects as given by eq. (1), we assume that the comoving emission coefficient $j(\nu, z)$ has a power-law spectrum with redshift dependent normalization, $j_{21}(z)$, and a free spectral index, $\alpha$, of the form:

$$j(\nu, z) = j_{21}(z) \left( \frac{\nu}{\nu_{HI}} \right)^{-\alpha} \text{ for } 11.18 \text{ eV} < h\nu < 455.6 \text{ eV}. \quad (3)$$

The frequency range corresponds to photons collected at observed frequencies in 11.18 - 13.6 eV bands (LW), observed redshifts in the interval 5 - 50, arriving from emission screens uniformly distributed in space, located between $z_o$ and a maximum redshift $z_{sc}^{max} = 200$.

Similar to the model in Gnedin and Hui (1998), $j_{21}(z)$ was parameterized as a function of the reionization redshift, $z_{re}$, and two free parameters, $A$ and $B$, in the form:

$$j_{21}(z) = A \left[ 1 + \tanh \left( B \frac{z_{re} - z}{1 + z} \right) \right]. \quad (4)$$

For $z \sim z_{re}$, the redshift dependent normalization, $j_{21}(z)$, has a value proportional to $A$ and gradually drops for $z > z_{re}$ in a redshift interval $\Delta z \sim B^{-1}$. This transition period is motivated by numerical simulations (Gnedin and
Fig. 1. Panel a): Redshift evolution of the averaged UVB flux (units of $10^{-21}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$) in LW bands. Panel b): Redshift evolution of the averaged effective optical depth in LW bands assuming a constant H$_2$ fraction of $2 \times 10^{-6}$. The model parameters are indicated in the Table.

Ostriker, 1997) showing that the hydrogen neutral fraction drops steadily as the formation rate of collapsed regions of high density increases in time. The ionizing intensity climbs gradually until the gas becomes highly ionized ($H_I \lesssim 10^{-4}$), thus completing the reionization process.

Each choice of the parameter vector $\mathbf{p} = (A, B, z_{re}, \alpha)$ in eq. (4) defines an UV background flux model.

Panel a) from Fig. 1 presents the evolution with redshift of the UV back-
ground flux averaged in LW bands obtained for different parameterizations of the comoving emission coefficient as indicated in the Table. Panel b) of the same figure presents the evolution with redshift of the effective optical depth averaged in LW bands computed by using the same procedure as Haiman, Abel & Rees (2000), for a constant H$_2$ fraction of $2 \times 10^{-6}$ ($\approx$ the H$_2$ fraction at recombination). As at smaller redshifts the H$_2$ fraction is substantially reduced, the effective optical depth of the IGM due to absorption into H$_2$ lines is even smaller. We found that by neglecting the absorption into H$_2$ lines the UVB flux is affected by maximum 10% for redshifts higher than 30.

Panel a) from Fig. 2 presents the evolution with redshift of the UVB flux at $\nu_{th}^{H_I} = 13.6$ eV ($\approx$1 Ryd). We also indicate (thick dotted line) the critical UVB flux below which ($T_{vir} \leq 10^{2.4}$K) the star formation is prevented (Haiman, Abel & Rees, 2000).

The photo-ionization rates, $\Gamma_{\gamma_i}$, and the photo-heating rates, $\epsilon_{\gamma_i}$, of any species $i$ are related to the UVB flux, $J(\nu, z)$, through:

$$\Gamma_{\gamma_i} = \int_{\nu_{th_i}}^{\infty} \frac{J(\nu, z)\sigma_i(\nu)}{h\nu} d\nu \quad \epsilon_{\gamma_i} = \int_{\nu_{th_i}}^{\infty} \frac{J(\nu, z)\sigma_i(\nu)(h\nu - \nu_{th_i})}{h\nu} d\nu,$$

where $\sigma_i(\nu)$ are the photo-ionization (dissociation) cross-sections (Abel et al. 1997) and $\nu_{th}^{i}$ are the ionizing threshold frequencies of species $i$ ($\nu_{th}^{H_I} = 13.6$eV, $\nu_{th}^{He_{I}} = 24.6$eV, $\nu_{th}^{He_{II}} = 54.4$eV).

We compute $\Gamma_{\gamma_i}$ and $\epsilon_{\gamma_i}$ for those choices of parameters $p = (A, B, z_{re}, \alpha)$ in eq. (4) that constraint the hydrogen photo-ionization rate at $z \approx 6$ to
Fig. 2. Left panel: Evolution with redshift of the UVB flux at $\nu^h_{HI} = 13.6$ eV ($\approx 1$ Ryd). The critical UVB flux below which ($T_{vir} \leq 10^{2.4}$K) the star formation is prevented (thick dotted line) is from Haiman, Abel & Rees (2000). Right panel: Redshift evolution of the hydrogen photo-ionization rate for the UVB models presented in the right panel. The observational upper limits based on Ly$\alpha$, Ly$\beta$ and Ly$\gamma$ Gunn-Peterson troughs at $z = 6.05$ are from Fan et al. (2002). We indicate by $M_5^{thin}$ the hydrogen photo-ionization rate obtained by neglecting the optical depth effects for model $M_5$. The model parameters are indicated in the Table.

$\Gamma_{\gamma HI} \approx 8 \times 10^{-14}$ s$^{-1}$, as indicated by the observational upper limits based on Ly$\alpha$, Ly$\beta$ and Ly$\gamma$ Gunn-Peterson troughs (Fan et al. 2002).

Panel b) from Fig. 2 shows the evolution with redshift of hydrogen photo-ionization rates corresponding to the UVB models presented in panel a). We
Fig. 3. Redshift evolution of the mean excess energy of H, HeI and HeII ionizing photons for simulation $M_1$ (solid line) and $M_2$ (dashed line).

also indicate by $M_5^{thin}$ redshift evolution of the hydrogen photo-ionization rate obtained by neglecting the optical depth effects for simulation $M_5$. The comparison between two cases shows that the optical depth effects results in a gradually increase of photo-ionization rate over a larger redshift interval.

The differences between various UVB models can be understood in terms of energy input of the ionizing photons before and during the reionization. In Fig. 3 we show the redshift evolution of the mean excess energy of ionizing photons, $E_{\text{ph}}^i = \epsilon_{\gamma_i}/\Gamma_{\gamma_i}$, for models $M_1$ and $M_4$. Before and during reionization the mean excess energy is higher for model $M_4$. For this case the redshift interval, $\Delta z \sim B^{-1}$, in which the reionization is completed is larger (see also Fig. 2). For both models the mean excess energy is dominated by the input energy from HeII ionizing photons.

We find that, at $z \approx 6$ the mean excess energy from HeII ionizing photons is $\sim 0.42\nu_{\text{HeII}}^{th}$ for model $M_1$ and $\sim 0.5\nu_{\text{HeII}}^{th}$ for model $M_4$. This corresponds to
a He\textsubscript{II} photo-heating rate about 1.2 times larger for model $M_4$ at $z \approx 6$. The increased He\textsubscript{II} photo-heating rate results in an increase of the IGM temperature before and during the reionization, as it has been demonstrated by Abel and Haehnelt (2000).

### 3 The ionization fraction in the presence of UVB flux

We modify the Smooth Particle Hydrodynamics (SPH) code HYDRA(v4.2)\textsuperscript{2} (Couchman, Thomas and Pearce, 1995; Theuns et. al., 1998) to study the redshift evolution of the ionization fraction in the presence of UV radiation background taking into account the radiative transfer effects, as given by eq. (1).

Cosmological hydrodynamic simulations have proven successful in studying the IGM reionization at sub-galactic scales (see e.g. Hernquist et al. 1996; Miralda-Escudé et al. 1996; Ciardi et al. 2000; Ciardi, Stoehr & White, 2002). It is useful to note the importance of the resolution and the volume of simulations aimed the study of reionization process. The resolution must be high enough to follow the formation and evolution of the objects responsible for producing the bulk of the ionization radiation. At the same time, a large simulation volume is required in order to have a region with representative properties and to avoid the bias due to the variance on small scales.

\footnote{http://hydra.mcmaster.ca/hydra}
Fig. 4. The mutual dependence on the simulation box length of the mass per gas particle, $M_b$, (solid line) and of the *rms* linear overdensity of a sphere with the mass equal to that of the simulation box at present time, $\sigma_0$, (dashed line).

Ciardi et al. (2000) derived the minimum mass of the objects that contribute substantially to the reionization process. They show that at $z > 15$ the main contribution to $\text{H}_\text{II}$ filling factor comes from small mass objects, $M \sim 10^7 M_\odot$, while at lower redshifts, when the formation of such objects is suppressed by the feedback mechanisms, the main contribution comes from objects with masses $M > 10^9 M_\odot$.

In Fig. 4 we show the mutual dependence on the simulation box length of the mass per gas particle, $M_b$, and of the *rms* linear overdensity of a sphere with the mass equal to that of the simulation box at present time, $\sigma_0$. One should note that once the value of $\sigma_0$ for a given run is selected, the redshift values of simulation output with $\sigma$ lower than $\sigma_0$ are uniquely specified [$\sigma \sim \sigma_0/(1+z)$].
In this paper we present cosmological hydrodynamical simulations obtained for 128$^3$ dark matter particles and the same number of gas particles in boxes with comoving lengths of 16$h^{-1}$ Mpc and a total mass per cell of $M = 6.1 \times 10^8 h^{-1} M_{\odot}$ ($M_b = 1.02 \times 10^8 h^{-1} M_{\odot}$ for gas particle and $M_{cdm} = 5.1 \times 10^8 h^{-1} M_{\odot}$ for cold dark matter particles).

This choice allows us to study large enough simulated regions and to resolve objects with masses $M \sim 5 \times 10^8 M_{\odot}$, responsible for photon production at reionization redshifts $\sim 15$, studied in this paper. At the same time, this choice ensures that at the end of the simulation the volume is large enough to provide a proper average (e.g. $\sigma \approx 0.07$ at $z = 6$).

The initial particle positions and velocities were set up at $z_i = 50$ by using the transfer functions calculated with CMBFAST code (Seljak & Zaldarriaga, 1996) for our $\Lambda$CDM cosmological model.

As at early times the Compton cooling is very efficient due to the coupling of the free electrons (left from recombination) to the CMB photons, we assume an initial IGM temperature $T \simeq T_{CMB} = 2.726 \times (1 + z) \simeq 139 K$ (Theuns et al. 1998).

Our cosmological simulations include the physical processes relevant for the primordial gas dynamics in the photo-ionized IGM (Anninos et al. 1997; Abel et al. 1997; Theuns et al. 1988 and references therein). The baryonic gas is composed by neutral ($H_I$, $He_I$) and ionic ($H_{II}$, $He_{II}$, $He_{III}$) species, with a primordial composition of 76% hydrogen and 24% helium by mass. The fractional densities of the various gas species are denoted with the standard nomenclature
by normalizing their comoving number densities to the present hydrogen number density $n_0^H$, \[ n_0^H = n_{H_1}/n_0^H, \] where $n_0^H = 1.88 \times 10^{-7} (\Omega_b h^2/0.022) \text{ cm}^{-3}$. The cooling model includes collisional ionization, recombination, collisional excitation, bremsstrahlung, inverse Compton cooling on the CMB, and cosmological expansion cooling. Also, the relevant heating mechanisms, photoionization (dissociation) and photo-heating of hydrogen and helium are included.

HYDRA(v4.2) uses functional forms of cooling and recombination rates based on the atomic physics coefficients collected by Cen (1992) for use in cosmological hydrodynamic simulations (see Appendix B from Theuns et al. 1988). We check out them satisfactorily against those quoted using updated atomic data by Abel et al. (1997).

The simulations are integrated in time up to a final epoch, $z_f$, where the baryonic gas reach its thermal equilibrium determined by the balance between the heating, $H_{ph}$, and cooling, $C$, rates defined as:

\[
H_{ph} = (H_{I} \epsilon_{\gamma H_I} + H_{e I} \epsilon_{\gamma e I} + H_{e II} \epsilon_{\gamma e II})/n_0^H, \quad C = \sum_{i=1}^{11} c_i(T) + C_{ad}(T),
\]

where: $\epsilon_{\gamma H_I}$, $\epsilon_{\gamma e I}$ and $\epsilon_{\gamma e II}$ are the photo-heating rates of $H_I$, $e_I$ and $e_{II}$ respectively and $c_i$ are the cooling rates whose functional dependence on temperature are given in Appendix B1 from Theuns et al. (1998).

In the above equation $C_{ad} = 3k_B TH(z) \rho/\mu m_p$ is the adiabatic cooling rate due to the cosmological expansion, $H(z)$ is the Hubble expansion rate, $k_B$ is the Boltzmann constant, $\mu$ is the mean molecular weight and $m_p$ is the proton
mass.

The code chooses the output time steps determined by the maximum instantaneous values of particle velocities and accelerations. An optimal low-order integration scheme is used for advancing particle positions and velocities (Couchman, Thomas, & Pearce, 1995).

At each simulation output time step, for each gas particle $i$, we read out the
density, $\Delta_i = \rho_i / \bar{\rho}_b$ (in units of the mean baryon density, $\bar{\rho}_b$) and temperature, $T_i$, (converted from the internal energy). Then, we compute the abundances of all neutral and ionic species and the ionization fraction defined as:

$$x_e(z) = \frac{e(z)}{e(z) + H_1(z) + He_1(z)},$$

where $e=H_{II} + He_{II} + He_{III}$ is the total free electron fraction ($e=n_e/n_{H}^0$). With this definition $x_e \to 1$ for a fully ionized gas and $\chi \to 0$ for a fully neutral gas.

Fig. 5 presents the redshift evolution of the heating and cooling rates (bottom panel) and the coupled evolution of the IGM temperature and ionization fraction (top panel) for simulation $M_5$. In order to stress the importance of the radiative transfer effects, we present these dependences obtained by neglecting the optical depth effects (thin case) and by considering the optical depth effects (thick case). The increase of photo-ionization and photo-heating rates due to the optical depth effects results in an increase of the IGM temperature, leaving distinct features on the temporal evolution of the ionization fraction.

In Fig. 6 we present a projection of the ionization fraction in $\log \Delta_i - T_i$ plane at $z = 6$ for simulation $M_5$.

The ionization histories obtained for the UV radiation background models discussed before are presented in Fig. 7. The model parameters are chosen to investigate the effects of Thomson optical depth in the range $\tau_{es}=0.05 - 0.1$ and to study the possibility to distinguish between models with the same values of $\tau_{es}$. Models $M_4$ and $M_5$ are chosen to have the same $\tau_{es}$ and the same
Fig. 6. A projection of the ionization fraction in $\log \Delta_i - T_i$ plane at $z = 6$ from simulation $M_5$.

value of the reionization redshift (see also the Table). We note that while different ionization histories can be distinguished by the corresponding value of $\tau_{es}$, the same value of $\tau_{es}$ can be produced by different parameterizations of UVB flux.

4 CMB angular power spectra in presence of the UV background

To evaluate the effects of the radiative feedback on the CMB angular power spectra we modified the CMBFAST code to include the redshift evolution of various ionization histories presented in Fig 6. The corresponding CMB anisotropy temperature, $C_T(l)$, and E-mode polarization, $C_E(l)$, power spec-
Fig. 7. The evolution with redshift of the ionization fraction obtained for the UVB models presented in Fig. 2. The model parameters and the corresponding electron optical depth to the Thompson scattering, $\tau_{es}$, are indicated in the Table.

Fig. 8. Power spectra are presented in Fig. 8.

One should note in Fig. 8 that while $C_T(l)$ power spectra are almost degenerated, the differences in different reionization histories produce undegenerated signatures on $C_E(l)$ power spectra at low multipoles ($l \leq 50$). This can be explained by the fact that while polarization is projecting from the epoch of reionization at angular frequencies $l = k(\eta_0 - \eta_{ri})$ (here $k$ is the wave number, $\eta_0$ and $\eta_{ri}$ are the conformal times today and at the epoch of reionization) the temperature is projecting from the (further) last scattering surface (Zaldarriaga, 1997).

The differences between the reionization models in comparison with the expected sensitivity of the future PLANCK mission can be expressed in terms
Fig. 8. The CMB angular power spectra, $C_T(l)$ and $C_E(l)$ for the reionization histories presented in Fig. 7. The model parameters and the corresponding electron optical depth to the Thompson scattering, $\tau_{es}$, are indicated in the Table.

The relative difference between the power spectra $C_E(l)$ of the E polarization component as (Naselsky and Chiang, 2004):

$$D_{i,j}(l) = \frac{2[C_{E,i}(l) - C_{E,j}(l)]}{C_{E,i}(l) + C_{E,j}(l)},$$

where the indices $i$ and $j$ denote different reionization models. We compare the amplitude of the function $D_{i,j}(l)$ with the expected relative error of the $C_E(l)$ anisotropy power spectrum for the PLANCK experiment. If systematic and foreground effects are successfully removed, the corresponding error bar
is given by:

\[
\frac{\Delta C_E(l)}{C_E(l)} = \frac{1}{\sqrt{f_{\text{sky}}(l + \frac{1}{2})}} [1 + w^{-1} C_E^{-1}(l) W_l^{-2}]
\]

(8)

where \(f_{\text{sky}} \approx 0.65\) is the sky coverage, \(w = (\sigma_p \theta_{\text{FWHM}})^{-2}\), \(\sigma_p\) is the sensitivity per resolution element \(\theta_{\text{FWHM}} \times \theta_{\text{FWHM}}\), \(W_l = \exp[-l(l+1)/2l_s^2]\) is the beam window function and \(l_s = \sqrt{2\ln2\theta_{\text{FWHM}}^{-1}}\). For all the frequency channels of the PLANCK experiment \(\theta_{\text{FWHM}}\) is less then \(\sim 30\) arcminutes and at low multipoles \((l \lesssim 50)\) the dominant term in eq. (8) is the first term, due to the combined cosmic and sampling variance.

In Fig. 9 we plot the function \(D_{i,j}(l)\) obtained for the models with the same value for \(\tau_{es}\) compared with the PLANCK sensitivity at the corresponding multipoles. One can see that in all cases the deviation function \(D_{i,j}(l)\) lies above the cosmic variance region, indicating that the upcoming PLANCK satellite will allow to distinguish among E-polarization power spectra with the same electron optical depth \(\tau_{es}\) and also the same reionization redshift \(z_{re}\), provided that they have been generated by sufficiently different reionization histories.

We observe that, in practice, the possibility to determine the CMB angular power spectra at \(l \lesssim 50\) with a sensitivity limited essentially only by cosmic and sampling variance relies on the accuracy of the removal of systematic effects (see, e.g., the review by Mennella et al., 2004 and reference therein) and foreground contamination. In particular, even for an ideal experiment (i.e. without systematic effects) Galactic foregrounds represent the main limita-
Fig. 9. Relative differences between couples of E-mode polarization angular power spectra corresponding to models having the same value of $\tau_{es}$: $D_{12}$ for models $M_1$ and $M_2$ (solid line), $D_{34}$ for models $M_3$ and $M_4$ (dashed line) and $D_{56}$ for models $M_5$ and $M_6$ (dash-dotted line). The model parameters and the corresponding electron optical depth to the Thompson scattering, $\tau_{es}$, are indicated in the Table.

![Graph](image_url)

Formation in the recovery of the CMB angular power spectra. The accuracy of their modeling and subtraction from microwave maps depends on the experiment sensitivity and resolution. This aspect is particularly crucial for CMB polarization anisotropy analyses, because of the low polarization degree of the CMB anisotropy. Baccigalupi et al. (2004) show that at the PLANCK sensitivity level a blind (i.e. not critically dependent on the assumptions on the properties of the maps to be recovered) and accurate (i.e., in this context, precise enough to avoid significant errors in the recovery of the angular power spectrum of the CMB component) separation between the Galactic and CMB polarized
signals from multifrequency maps is possible at multipoles $l \lesssim 100$ while a worse sensitivity has a critical impact on the accuracy of this separation. For this reason a high sensitivity experiment, like PLANCK, is crucial to remove all systematic effects and separate the CMB from the foregrounds with an accuracy good enough to measure the CMB E-mode signal at the limit of the cosmic variance.

5 Conclusions

In this paper we study the role of radiative effects for the reionization history of the universe and address the detectability of their features by the future CMB polarization measurements.

We present cosmological hydrodynamical simulations at sub-galactic scales that allow to resolve objects with masses of $M \sim 5 \times 10^8 M_\odot$, responsible for the photon production at reionization redshifts $z_{re} \sim 15$, ensuring in the same time a proper average of the simulation the volume at smaller redshifts.

Our cosmological simulations include the radiative mechanisms relevant for the primordial gas dynamics: photo-ionization, photo-heating and cooling of the hydrogen and helium in the expanding universe.

We compute the mean specific UVB flux as solution to the radiative transfer equation for those parameterizations of the comoving emission coefficient that constaine the hydrogen photo-ionization rate value to the upper limit indicated by the experimental measurements.
We find that the increase of photo-ionization and photo-heating rate due to optical depth effects results in a significantly contribute to the heating of the IGM before and during the reionization.

We show that the main effect of the UV radiation spectrum on the temporal evolution of the ionization fraction is given by the value of the reionization redshift, $z_{re}$, and the redshift interval, $\Delta z$, in which the reionization is completed. As reionization proceeds, the excess energy of ionizing photons builds up a sufficient UV radiation background that rises the IGM temperature. The net effect is a decrease of the global ionization fraction with cosmic time over a limited period.

We evaluate the effects of the UV radiation background on the CMB angular power spectrum taking into account different temporal evolutions of the ionization fraction.

We find that for reionization models with degenerated CMB temperature anisotropy power spectra, $C_T$, the radiative feedback mechanisms leave distinct signatures on the E-mode polarization power spectrum, $C_E$, at large scales ($l < 50$). We show that through E-mode CMB polarization power spectrum measurements, the PLANCK experiment will have the sensitivity to distinguish between different reionization histories even when they imply the same optical depth to electron scattering and degenerated $C_T$ power spectra.
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Table 1

Parametrization of the comoving emission coefficient for the UVB flux models studied in this papers. We also indicate the corresponding electron optical depths to the Thomson scattering, $\tau_{es}$.

| Model | $\mathbf{p} = (A, B, z_{re}, \alpha)$ | $\tau_{es}$ |
|-------|---------------------------------|-------------|
| $M_1$ | (0.065, 11.25, 12, 1.8)          | 0.05        |
| $M_2$ | (0.068, 12.50, 17, 2)            | 0.05        |
| $M_3$ | (0.075, 13.75, 15, 2)            | 0.08        |
| $M_4$ | (0.039, 10.00, 15, 1)            | 0.08        |
| $M_5$ | (0.057, 7.70, 18, 1.8)           | 0.1         |
| $M_5^{thin}$ | (0.012, 7.70, 18, 1.8) | 0.04 |
| $M_6$ | (0.050, 6.90, 17, 1.8)           | 0.1         |