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Cosmic microwave background polarization constraints on radiative feedback

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ABSTRACT

We compute the imprints left on the cosmic microwave background (CMB) by two cosmic reionization models consistent with current observations but characterized by alternative radiative feedback prescriptions (*suppression* and *filtering*) resulting in a different suppression of star formation in low-mass haloes. The models imply different ionization and thermal histories and 21-cm background signals. The derived Comptonization, u, and free–free distortion, y_B, parameters are below current observational limits for both models. However, the value of $u \simeq 1.69 \times 10^{-7}$ ($\simeq 9.65 \times 10^{-8}$) for the suppression (filtering) model is in the detectability range of the next generation of CMB spectrum experiments. Through, the dedicated Boltzmann code CMBFAST, modified to include the above ionization histories, we compute the CMB angular power spectrum (APS) of the TT, TE and EE modes. For the EE mode, the differences between these models are significantly larger than the cosmic and sampling variance over the multipole range $\ell \sim 5$–15, leaving a good chance of discriminating between these feedback mechanisms with forthcoming/future CMB polarization experiments. The main limitations come from foreground contamination: it should be subtracted at per cent level in terms of APS, a result potentially achievable by novel component separation techniques and mapping of Galactic foreground.

Key words: galaxies: formation – intergalactic medium – cosmic microwave background.

1 INTRODUCTION

The accurate understanding of the ionization history of the Universe plays a fundamental role in the modern cosmology. The classical theory of hydrogen recombination for pure baryonic cosmological models (Peebles 1968; Zel'dovich, Kurt & Sunyaev 1968) has been subsequently extended to non-baryonic dark matter models (Zabotin & Naselsky 1982; Jones & Wyse 1985; Seager, Sasselov & Scott 2000), and recently accurately updated to include also helium recombination in the current cosmological scenario (see Switzer & Hirata 2007, and references therein). Various models of the subsequent Universe ionization history have been considered to take into account additional sources of photon and energy production, possibly associated to the early stages of structure and star formation, able to significantly increase the free electron fraction, x_e, above the residual fraction ($\sim 10^{-3}$) after the standard recombination epoch at $z_{rec} \simeq 10^3$. These photon and energy production processes associated to this reionization phase may leave imprints in the cosmic microwave background (CMB) providing a crucial 'integrated' information on the so-called *dark* and *dawn ages*, that is, the epochs before or at the beginning the formation of first cosmological structures. For this reason, among the extraordinary results achieved by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) mission, the contribution to the understanding of the cosmological reionization process has received a great attention.

To first approximation, the beginning of the reionization process is identified by the Thomson optical depth, τ. The values of τ compatible with *WMAP* 3-yr data, possibly complemented with external data, are typically in the range $\sim$0.06–0.12 (corresponding to a reionization redshift in the range $\sim$8.5–13.5 for a sudden reionization history), the exact interval depending on the

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considered cosmological model and combination of data sets (Spergel et al. 2007). While this simple 'τ-parametrization' of the reionization process and, in particular, of its imprints on the CMB anisotropy likely represents a sufficiently accurate modelling for the interpretation of current CMB data, a great attention has been recently posed on the accurate computation of the reionization signatures in the CMB for a large variety of astrophysical scenarios and physical processes (see e.g. Peebles, Seager & Hu 2000; Doroshkevich & Naselsky 2002a; Doroshkevich et al. 2002b; Cen 2003; Ciardi, Ferrara & White 2003; Hansen & Haiman 2004; Kasuya, Kawasaki & Sugiyama 2004; Popa, Burigana & Mandolesi 2005; Wyithe & Cen 2007) also in the view of *WMAP* accumulating data and of forthcoming and future experiments beyond *WMAP*. In this context, this work represents a step forward of our previous paper (Schneider et al. 2007) dedicated to the study of the impact of reionization, and the associated radiative feedback, on galaxy formation and of the corresponding detectable signatures. In that work we carried out a detailed comparison of two well-defined alternative prescriptions (*suppression* and *filtering*) for the radiative feedback mechanism suppressing star formation in small mass haloes showing that they are consistent with a wide set of existing observational data but predict different 21-cm background signals accessible to future observations. We focus here specifically on the signatures detectable in the CMB.

We observe that all viable (i.e. data consistent) reionization models require radiative feedback. In fact, in the absence of radiative feedback Population (Pop) III stars would be allowed to form efficiently down to low redshifts, and, in order to match the low-z Gunn–Peterson data, a decreased Pop III star formation efficiency is required, in turn yielding a too low Thomson optical depth.[1] In other words, some feedback mechanism is necessary to have enough photons at high z and to avoid at the same time an excess of photons at late times. Our paper indicates how to discriminate between the two most physical radiative feedback prescriptions with future CMB data.

The paper is organized as follows. In Section 2, we briefly summarize the main theoretical and observational aspects of the considered models focussing on those relevant for the analysis of the features in the CMB. In Section 3, we present the results of our computation for the CMB spectral distortions (Section 3.1) and anisotropies in total intensity and polarization (Section 3.2) and compare them with the foreground and sensitivity limitation of future CMB anisotropy missions (Section 3.3). Finally, Section 4 summarizes our conclusions.

Through this paper we assume a flat Λcold dark mater (ΛCDM) cosmological model consistent with *WMAP* described by matter and cosmological constant (or dark energy) density parameters $\Omega_{\rm m} = 0.24$ and $\Omega_\Lambda = 0.76$, reduced Hubble constant $h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}}) = 0.73$, baryon density $\Omega_{\rm b}h^2 = 0.022$, density contrast $\sigma_8 = 0.74$, and adiabatic scalar perturbations (without running) with spectral index $n_{\rm s} = 0.95$. We assume a CMB background temperature of 2.725 K (Mather et al. 1999).

2 REIONIZATION MODELS

The latest analysis of Lyα absorption in the spectra of the 19 highest redshift Sloan Digital Sky Survey (SDSS) quasars [quasi-stellar objects (QSOs)] shows a strong evolution of the Gunn–Peterson Lyα opacity at $z \sim 6$ (Fan et al. 2006; Gallerani, Choudhury & Ferrara 2006). The downward revision of the electron scattering optical depth to $\tau = 0.09 \pm 0.03$ in the release of the 3-yr *WMAP* data (Page et al. 2007; Spergel et al. 2007), is consistent with 'minimal reionization models' which do not require the presence of very massive ($M > 100\,{\rm M_\odot}$) Pop III stars (Choudhury & Ferrara 2006; Gnedin & Fan 2006). We can then use these models to explore the effects of reionization on galaxy formation, to which we will refer to as 'radiative feedback'.

Recently, Choudhury & Ferrara (2005, 2006) developed a semi-analytic model to jointly study cosmic reionization and the thermal history of the intergalactic medium (IGM). According to Schneider et al. (2007), the semi-analytical model developed by Choudhury & Ferrara (2005) complemented by the additional physics introduced in Choudhury & Ferrara (2006) involves: (i) the treatment of IGM inhomogeneities by adopting the procedure of Miralda-Escudé, Haehnelt & Rees (2000); (ii) the modelling of the IGM treated as a multiphase medium, following the thermal and ionization histories of neutral, H II and He III regions simultaneously in the presence of ionizing photon sources represented by Pop III stars with a standard Salpeter IMF extending in the range 1–100 $\rm M_\odot$ (Schneider et al. 2006), Pop II stars with $Z = 0.2\,{\rm Z_\odot}$ and Salpeter IMF, and QSOs (particularly relevant at $z \lesssim 6$); (iii) the chemical feedback controlling the prolonged transition from Pop III to Pop II stars in the merger-tree model by Schneider et al. (2006); (iv) assumptions on the escape fractions of ionizing photons, considered to be independent of the galaxy mass and redshift, but scaled to the amount of produced ionizing photons. It then accounts for radiative feedback inhibiting star formation in low-mass galaxies. This semi-analytical model is determined by only four free parameters: the star formation efficiencies of Pop II and Pop III stars, a parameter, $\eta_{\rm esc}$, related to the escape fraction of ionizing photons emitted by Pop II and Pop III stars, and the normalization of the photon mean free path, λ_0, set to reproduce low-redshift observations of Lyman-limit systems (Choudhury & Ferrara 2005).

A variety of feedback mechanisms can suppress star formation in mini-haloes, i.e. haloes with virial temperatures $T_{\rm vir} < 10^4$ K, particularly if their clustering is taken into account (Kramer, Haiman & Oh 2006). We therefore assume that stars can form in haloes down to a virial temperature of 10^4 K, consistent with the interpretation of the 3-yr *WMAP* data (Haiman & Bryan 2006; but see also Alvarez et al. 2006). Even galaxies with virial temperature $T_{\rm vir} \gtrsim 10^4$ K can be significantly affected by radiative feedback during the reionization process, as the increase in temperature of the cosmic gas can dramatically suppress their formation. Based on cosmological simulations of reionization, Gnedin (2000) developed an accurate characterization of the radiative feedback on low-mass galaxy. This study shows that the effect of photoionization is controlled by a single mass scale in both the linear and non-linear regimes. The gas fraction within dark matter haloes at any given moment is fully specified by the current filtering mass, which directly corresponds to the length-scale over which baryonic perturbations are smoothed in linear theory. The results of this study provide a quantitative description of radiative feedback, independently of whether this is physically associated to photoevaporative flows or due to accretion suppression.

Following Schneider et al. (2007), we consider here two specific alternative prescriptions for the radiative feedback by these haloes.

(i) *Suppression model* – following Choudhury & Ferrara (2006), we assume that in photoionized regions, haloes can form stars *only*

[1] The filtering model implies a value of τ lower than that obtained in the suppression model (as explained in the next Section); decreasing it further would push the value of τ below the 1σ limit set by *WMAP* 3-yr data.

if their circular velocity exceeds the critical value $v_{\rm crit} = 2k_B T/\mu m_{\rm p}$; here, μ is the mean molecular weight, $m_{\rm p}$ is the proton mass and T is the average temperature of ionized regions, computed self-consistently from the multiphase IGM model;

(ii) *Filtering model* – following Gnedin (2000), we assume that the average baryonic mass $M_{\rm b}$ within haloes in photoionized regions is a fraction of the universal value $f_{\rm b} = \Omega_{\rm b}/\Omega_{\rm m}$, given by the fitting formula $M_{\rm b}/M = f_{\rm b}/[1 + (2^{1/3} - 1)\ M_{\rm C}/M]^3$, where M is the total halo mass and $M_{\rm C}$ is the total mass of haloes that on average retain 50 per cent of their gas mass. A good approximation for the characteristic mass $M_{\rm C}$ is given by the linear theory filtering mass, $M_{\rm F}^{2/3} = (3/a) \int_0^a {\rm d}a' M_J^{2/3}(a')[1 - (a'/a)^{1/2}]$, where a is the cosmic scalefactor, $M_J \equiv (4\pi/3)\bar{\rho}(\pi c_{\rm s}^2/G\bar{\rho})^{3/2}$, is the Jeans mass, $\bar{\rho}$ is the average total mass density of the Universe and $c_{\rm s}$ is the gas sound speed.

The model free parameters are constrained by a wide range of observational data. Schneider et al. (2007) reported the best-fitting choice of the above four parameters for these two models that well accomplish a wide set of astronomical observations, such as the redshift evolution of Lyman-limit absorption systems, the Gunn–Peterson and electron scattering optical depths, the cosmic star formation history and number counts of high-redshift sources in the NICMOS *Hubble Ultra Deep Field*.

The two feedback prescriptions have a notable impact on the overall reionization history and the relative contribution of different ionizing sources. In fact, although the two models predict similar global star formation histories dominated by Pop II stars, the Pop III star formation rates have markedly different redshift evolution. Chemical feedback forces Pop III stars to live preferentially in the smallest, quasi-unpolluted haloes (virial temperature $\gtrsim 10^4$ K, Schneider et al. 2006), which are those most affected by radiative feedback. In the suppression model, where star formation is totally suppressed below $v_{\rm crit}$, Pop III stars disappear at $z \sim 6$; conversely, in the filtering model, where haloes suffer a gradual reduction of the available gas mass, Pop III stars continue to form at $z \lesssim 6$, though with a declining rate. Since the star formation and photoionization rate at these redshifts are observationally well constrained, the star formation efficiency and escape fraction of Pop III stars need to be lower in the filtering model in order to match the data. Therefore, reionization starts at $z \lesssim 15$ in the filtering model and only 16 per cent of the volume is reionized at $z = 10$ (while reionization starts at $z \sim 20$ in the suppression model and it is 85 per cent complete by $z = 10$). For $6 < z < 7$, QSOs, Pop II and Pop III give a comparable contribution to the total photoionization rate in the filtering model, whereas in the suppression model reionization at $z < 7$ is driven primarily by QSOs, with a smaller contribution from Pop II stars only.

The predicted free electron fraction and gas temperature evolution (see Fig. 1) in the redshift range $7 < z < 20$ is very different for the two feedback models. Bottom panel of Fig. 1 compares the evolution of the gas kinetic temperature and CMB temperature for the two models. In particular, in the filtering model the gas kinetic temperature is heated above the CMB value only at $z \lesssim 15$.

The Thomson optical depth, $\tau = \int \chi_{\rm e} n_{\rm e} \sigma_{\rm T} c {\rm d}t$, can be directly computed for the assumed ΛCDM cosmological model parameters given the ionization histories shown in the top panel of Fig. 1. We find $\tau \simeq 0.1017$ and 0.0631 for the suppression and the filtering model, respectively. Note that these values are consistent with the Thomson optical depth range derived from *WMAP* 3-yr data (Spergel et al. 2007) but with $\sim 1\ \sigma$ difference among the two models, leaving a chance of probing them with forthcoming CMB anisotropy experiments.

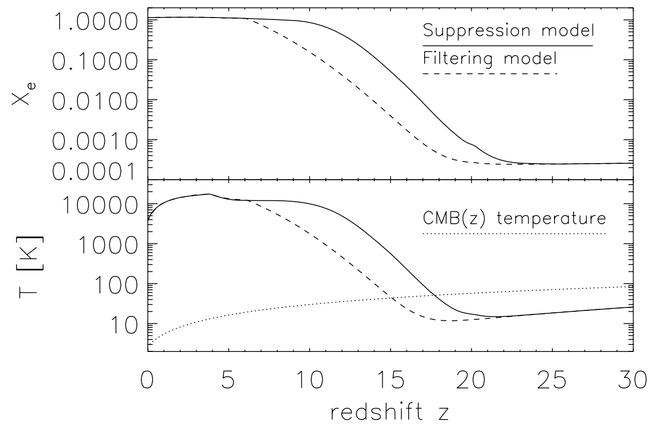

Figure 1. Redshift dependence of the fraction of free electrons (top panel) and of the gas kinetic temperature (bottom panel) for the two considered models. See also the text.

3 SIGNATURES ON THE CMB

The cosmological reionization leaves imprints on the CMB depending on the (coupled) ionization and thermal history. They can be divided into three categories:[2] (i) generation of CMB Comptonization and free–free spectral distortions associated to the IGM electron temperature increases during the reionization epoch, (ii) suppression of CMB temperature anisotropes at large multipoles, ℓ, due to photon diffusion and (iii) increasing of the power of CMB polarization and temperature-polarization cross-correlation anisotropy at various multipole ranges, mainly depending on the reionization epoch, because of the delay of the effective last scattering surface.

The imprints on CMB anisotropies are mainly dependent on the ionization history while CMB spectral distortions strongly depend also on the thermal history.

It is interesting to compare the imprints left in the CMB for the two models considered here to understand if they could be distinguished by forthcoming and future experiments.

3.1 Spectral distortions

The Compton scattering of CMB photons with the electrons heated during the reionization process implies the generation of a global Comptonization distortion (Zel'dovich & Sunyaev 1969; Zel'dovich, Illarionov & Sunyaev 1972) characterized by the Comptonization parameter $u \simeq (1/4)\Delta\epsilon/\epsilon_i$, where $\Delta\epsilon/\epsilon_i$ is the fractional amount of energy exchanged between matter and radiation. In addition, we expect also the generation of a free–free distortion, physically coupled to the Comptonization one, because of the bremsstrahlung photon production process (Karsaz & Latter 1961; Rybicki & Lightman 1979) in the hot gas. Its amplitude is characterized by the so-called free–free distortion parameter, $y_{\rm b}$. For late processes, as in this case, the resulting distorted spectrum can be

[2] Inhomogeneous reionization also produces CMB secondary anisotropies that dominate over the primary CMB component for $l \gtrsim 4000$, and can be detected by upcoming experiments, like the Atacama Cosmology Telescope or Large Millimeter/submillimeter Array (Salvaterra et al. 2005; Iliev et al. 2007).

fully described to a very good precision with the analytical formalism described in Burigana, De Zotti & Danese (1995) based on the computation of the Comptonization and free–free distortion parameters, by simply modifying (Burigana et al. 2004) the cosmic expansion time to take into account the cosmological constant (or dark energy) contribution, dominant at low redshifts. By exploiting the ionization and thermal histories shown in Fig. 1, we find $u \simeq 1.69 \times 10^{-7}$, $y_b \simeq 9.01 \times 10^{-10}$ and $u \simeq 9.65 \times 10^{-8}$, $y_b \simeq 5.24 \times 10^{-10}$, respectively, for the suppression and the filtering model: these values are clearly well below the *COBE*/Far Infrared Absolute Spectrophotometer (FIRAS) limits (Fixsen et al. 1996; Salvaterra & Burigana 2002). The two models show similar ionization and thermal histories at $z \lesssim 6$ while important differences are predicted at $z \gtrsim 6$. These explain the different spectral distortion levels generated in the two cases. In fact, considering only redshifts at $z \gtrsim 6$, we find $u \simeq 7.98 \times 10^{-8}$, $y_b \simeq 4.37 \times 10^{-10}$ and $u \simeq 1.05 \times 10^{-8}$, $y_b \simeq 8.26 \times 10^{-11}$, respectively, for the suppression and the filtering model. We note that while the free–free distortion levels predicted in these models are too small to be detected even by long wavelength (i.e. at $\lambda \gtrsim 1$ cm) spectrum experiments with precision comparable to – or even significantly better than – that of *COBE*/FIRAS (Kogut 1996; Burigana & Salvaterra 2003), such Comptonization distortion prediction levels are comparable to those that could be, in principle, observed by a future generation of CMB spectrum experiments, in particular, at millimetre wavelengths, able to improve by ≈30–100 times the *COBE*/FIRAS results (Fixsen & Mather 2002; Burigana, Salvaterra & Zizzo 2004). In this perspective, future accurate measurements at long wavelengths (Burigana et al. 2007) could significantly improve the reliability of the detection of such Comptonization distortions, removing the approximate degeneracy in the joint determination of early (Bose–Einstein like, Sunyaev & Zel'dovich 1970) and late distortion parameters that remain in the presence of accurate spectrum measures only at millimetre wavelengths.

3.2 Anisotropies

The detailed computation of the reionization imprint in the CMB anisotropy angular power spectrum (APS), C_ℓ, requires the use of dedicated Boltzmann codes, properly implemented to have the possibility of introducing the adopted ionization history. We have modified the public version (4.5.1) of the CMBFAST code[3] (see e.g. Seljak & Zaldarriaga 1996) to properly replace (Popa et al. 2005) the simple step function (or Heaviside function) approximation for the ionization fraction adopted there to model the reionization process with the considered ionization histories shown in Fig. 1. Our results are reported in Fig. 2. Having neglected for simplicity tensor perturbations, we focus here on the TT (total intensity, i.e. temperature), TE (temperature-polarization cross-correlation) and EE polarization modes of the CMB anisotropy APS. In Fig. 2, we also display the APS of the foreground in the *V* band (centred at 61 GHz) of *WMAP* 3-yr data,[4] a frequency channel where the foreground is found to be minimum (or almost minimum) in both temperature and polarization (Bennett et al. 2003; Page et al. 2007) at the angular scales larger than $\sim 1^\circ$ of relevance in this context. It is simply derived with the ANAFAST facility of the HEALPIX[5] package (Górski et al. 2005) analysing the difference between the original map and the CMB map, and adopting the mask used by the *WMAP* team for the

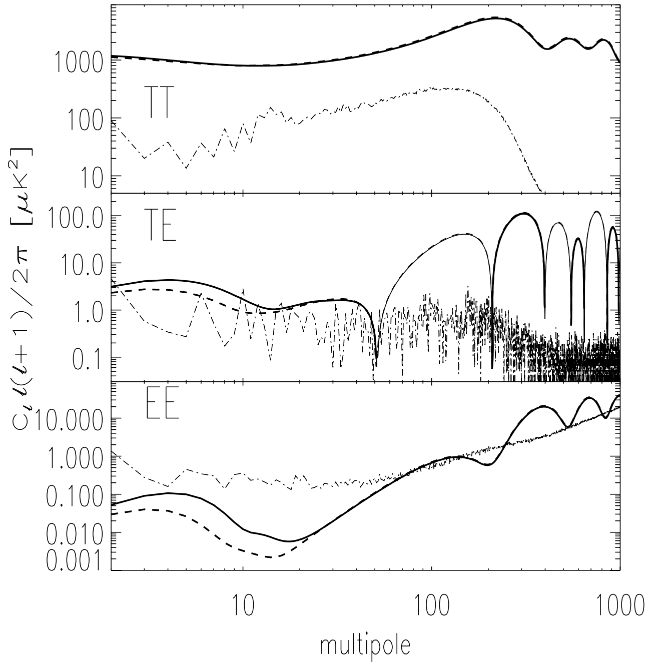

Figure 2. APS of CMB anisotropies for the three considered modes TT, TE, EE, reported in each panel and computed by introducing the ionization and thermal histories shown in Fig. 1 in the CMBFAST code (solid lines: suppression model; dashes: filtering model). Thick lines denote correlation, while thin lines denote anticorrelation (appearing for the TE mode at $\ell \gtrsim 50$). The APS of the foreground, dominated by the Galactic contribution, is reported for comparison (dot–dashes). The *WMAP* 3 yr *V*-band data are considered here. See also the text. [Results expressed in terms of thermodynamic temperature fluctuations.]

polarization analysis (covering ≃ 74 per cent of the sky). For sake of simplicity, no attempt is made in these foreground plots to subtract the noise contribution to the overall APS.[6] We are in fact interested here to low multipoles ($\ell \lesssim$ few tens) where the differences between these two models show up, as expected for relatively late reionization processes, and the signal power dominates over the noise one. Note that the relative difference between the APS computed for the suppression and filtering model as well as the foreground impact compared to the CMB signal increase going from the TT, to the TE and then to the EE mode.

3.3 Foreground and perspectives from *Planck* and future polarization experiments

To understand if these classes of models can be distinguished with forthcoming and future CMB anisotropy experiments, we compare their relative difference with the cosmic and sampling variance limitation, $\Delta C_\ell / C_\ell$, (Knox 1995), that is, neglecting the contribution by the instrumental noise and a potential residual foreground contamination. At the low multipoles ($\ell \lesssim 20$–30) relevant here (see Fig. 2) the *direct* (ideal) instrumental noise limitation is in fact not critical for current and future space missions. On the contrary, the experiment sensitivity and frequency coverage and, in particular, the rejection (by instrument design and/or by subsequent data analysis)

[3] http://www.cmbfast.org/
[4] http://lambda.gsfc.nasa.gov/product/map/current/
[5] http://healpix.jpl.nasa.gov/

[6] The relevance of the noise term – important at high multipoles – obviously increases going from the TT, to the TE and then to the EE mode because of the decrease of the signal-to-noise ratio.

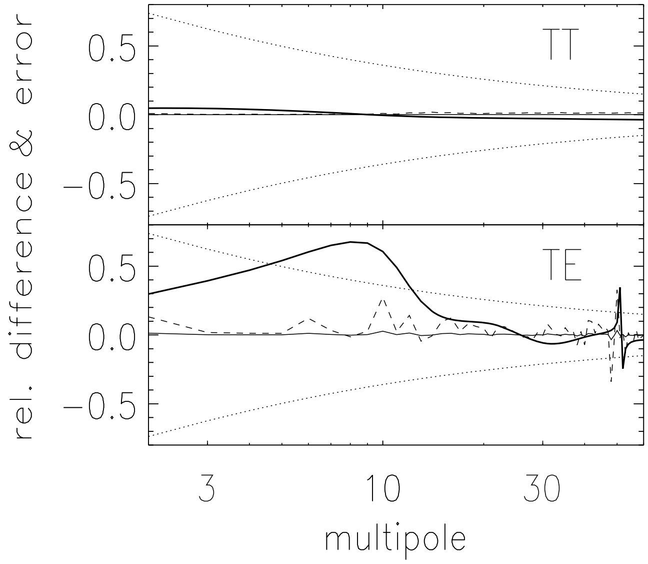

Figure 3. Relative difference, $\delta^{S,F}$, between the (TT and TE mode) APS of CMB anisotropies for the suppression and filtering models reported in Fig. 2 (thick solid lines) compared with the cosmic and sampling variance limitation corresponding to a sky coverage of $\simeq 74$ per cent (region between the dotted lines). We report for comparison the APS from a potential residual foreground (dot–dashes) corresponding to two different values of *f*: 0.1 (dashed line) and 0.01 (three dots–dashed line). See also the text.

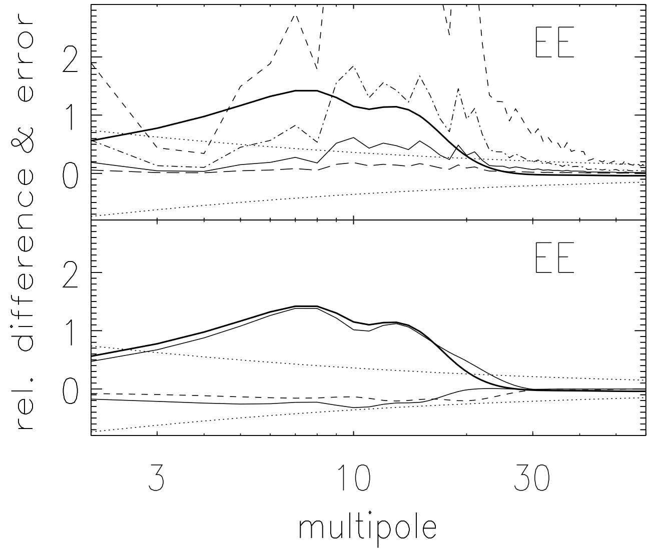

Figure 4. Relative difference, $\delta^{S,F}$, between the (EE mode) APS of CMB anisotropies for the suppression and filtering models reported in Fig. 2 (thick solid lines) compared with the cosmic and sampling variance limitation corresponding to a sky coverage of $\simeq$74 per cent (region between the dotted lines). In the top panel we report also for comparison the APS from a potential residual foreground (dot–dashes) corresponding to different values of *f*: 0.1 (dashed line), 0.03 (dots–dashed line), 0.01 (three dots–dashed line), and 0.003 (long dashes). In the bottom panel we show also $\delta^{SH,FH}$ computed by replacing the two considered models with those obtained assuming the simple step function implemented in the public CMBFAST code for the reionization history (thin solid lines) for the corresponding values of optical depth. The relative difference between the results based on the suppression (respectively filtering) model and its step function approximation with $\tau \simeq 0.1017$ (respectively with $\tau \simeq 0.0631$) is shown by the dashed line (respectively three dots–dashed line). See also the text.

of the various classes of systematic effects are critical to have the possibility to accurately subtract the foreground contribution and to effectively achieve the ultimate cosmic variance limit (see e.g. Mennella et al. 2004; Popa et al. 2007, and references therein, for reviews devoted to these aspects in the context of the *Planck* mission). So, the results reported here apply to the case of the forthcoming *Planck* mission,[7] at least in the best case of an effective excellent rejection of all the potential systematic effects, and to the next generation of CMB polarization anisotropy experiments with a (nearly) all-sky coverage studied in the NASA (Inflation Probe, CMBPol) and the ESA (B-Pol[8]) context.

Following Naselsky & Chiang (2004), we compute the quantity $\delta^{M,N} = (C_\ell^M - C_\ell^N)/[0.5(C_\ell^M + C_\ell^N)]$ where the index *M* or *N* specifies the APS calculated for a given model (for simplicity, we omit here the indices TT, TE or EE; they are reported in each figure panel). A potential foreground residual contamination, resulting from a non-perfect (possibly biased) component separation, is modelled here as $\delta^{\rm Fore} = f C_\ell^{\rm Fore}/[0.5(C_\ell^M + C_\ell^N)]$, where $C_\ell^{\rm Fore}$ is the foreground APS and the *effective* parameter *f* characterizes the accuracy of the component separation method in the considered range of multipoles.

Figs 3 and 4 summarize our results. We display $\delta^{M,N}$ for $M = S$ (suppression model) and $N = F$ (filtering model). In the case of the EE mode, we report also the results obtained exploiting the Heaviside function approximation of the two reionization histories with corresponding optical depths, $M = SH$ and $N = FH$. It is also interesting to consider $\delta^{M,N}$ for $M = S$ and $N = SH$ and for $M = F$ and $N = FH$ in order to quantify the relative error implied by the step function approximation of a more complex time-dependent reionization history.

As evident from Fig. 3 (top panel), the difference between the two models is overwhelmed by the cosmic and sampling variance in the case of temperature anisotropy measures. The difference in the TE mode (see bottom panel of Fig. 3) turns to be well above the foreground limitation even for a removal accuracy of about 10 per cent. Unfortunately, it is above the cosmic and sampling variance limitation by a factor of $\sim$1.5 only and for a small range of multipoles ($\ell \sim 7$–10).[9] On the contrary, for the polarization EE mode APS the difference between the two considered models is significantly larger than the cosmic and sampling variance over a interesting range of multipoles ($\ell \sim 5$–15), as shown by Fig. 4 (top panel). In this case, the main limitation derives from a possible residual foreground contamination: as evident, a foreground removal accuracy at per cent level (or better) in terms of APS is necessary to accurately exploit the information contained in CMB polarization about the cosmological reionization process. Note that, possibly except for some sky areas at very low foreground contamination level (Carretti, Bernardi & Cortiglioni 2006), similar (respectively or better) accuracies are needed for the observation of BB polarization mode of the CMB anisotropy[10] for ratios of tensor to scalar perturbations $\lesssim$ some $\times 10^{-3}$ on typical sky regions at low/moderate

[7] http://www.rssd.esa.int/planck

[8] http://www.th.u-psud.fr/bpol/index.php

[9] The apparently large features at $\ell \sim 50$ result from the very small absolute value of the TE mode close to its change of sign with the consequence of large relative differences between the two models but only on a very small multipole range (see also Fig. 2).

[10] http://www.b-pol.org/pdf/BPOL_Proposal.pdf

foreground contamination level (respectively at low multipoles) (La Porta et al. 2006). This calls for a further progress in component separation techniques in polarization (see e.g. Baccigalupi et al. 2004; Stivoli et al. 2006; Aumont & Macias-Pérez 2007; Page et al. 2007, for promising developments) and for an accurate mapping of the (mainly Galactic) polarized foregrounds in radio and far-infrared bands[11] to complement microwave surveys by improving both the foreground physical modelling and the component separation accuracy.

Finally, we observe that, particularly at $\ell \simeq 10$–20, the step function approximation of the reionization history adopted in the simple τ-parametrization, although adequate to reveal the bulk of the difference between these models, implies an error on the EE mode comparable to the cosmic and sampling variance[12] (see bottom panel of Fig. 4). Therefore, a proper treatment of the cosmological reionization history in the Boltzmann codes is necessary for a fine comparison with the high-accuracy data from forthcoming and future CMB polarization anisotropy experiments.

4 CONCLUSION

We have analysed the implications for the CMB of the self-consistent semi-analytical model developed by Choudhury & Ferrara (2005, 2006) to describe the effect of reionization and its associated radiative feedback on galaxy formation, modelling the suppression of star formation in low-mass galaxies due to the increase in temperature of the cosmic gas in ionized regions according to two different feedback prescriptions, the *suppression* and the *filtering* model. These two models predict different ionization and thermal histories, in particular, at $z \gtrsim 6$, resulting into Thomson optical depths $\tau \simeq 0.1017$ and 0.0631, respectively, consistent with the *WMAP* 3-yr data.

According to the usual semi-analytical approach to model CMB spectral distortions, we computed the Comptonization and free–free distortion parameters, u and $y_{\rm b}$. They are found to be well below the current observational limits. In particular, the values obtained for the Comptonization parameter ($u \simeq 1.69 \times 10^{-7}$ and 9.65×10^{-8} for the suppression and the filtering model, respectively) are in range accessible to a future generation of CMB spectrum experiments, in particular at millimetre wavelengths, able to improve by $\approx$30–100 times the *COBE*/FIRAS results.

We have modified the Boltzmann code CMBFAST to introduce the considered ionization histories and compute the CMB angular power spectrum [namely, the APS of temperature (TT), temperature-polarization correlation (TE) and polarization EE modes] improving the step function approximation adopted in the simple 'τ-parametrization'. The differences between the predictions of the two models are negligible for the TT mode and small for the TE mode when compared to cosmic and sampling variance limitation but are of particular interest for the EE polarization mode. They are significantly larger than the cosmic and sampling variance over the multipole range $\ell \sim 5$–15, leaving a good chance of discriminating between the two feedback mechanisms with forthcoming and future CMB polarization anisotropy experiments and, in particular, in the view of the forthcoming ESA *Planck* satellite that will launched in about one year. The main limitation derives from foreground contamination: it should be subtracted at per cent level in terms of APS, a result achievable with joint efforts in component separation techniques and in the mapping and modelling of the Galactic foreground. Also, a particular care should be taken in the control of potential systematic effects down to negligible levels and in the precise reconstruction of the APS from the data at low multipoles.

Our analysis indicates that forthcoming CMB anisotropy polarization data together with future 21-cm data (Schneider et al. 2007) will play a crucial role in breaking current degeneracies and constraining the cosmological reionization process and the astrophysical properties of the sources responsible for it at high redshifts ($z \gtrsim 6$).

[11] See e.g. the talks by J. P. Leahy and J.-P. Bernard at http://www.th.u-psud.fr/bpol/talks_orsay_meeting/Talks.html.

[12] A similar analysis for the TT (respectively TE) mode shows that this kind of error is overwhelmed by (respectively about one order of magnitude less than) the cosmic and sampling variance.

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[13] http://www.arcetri.astro.it/science/cosmology

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