CM B polarization constraints on radiative feedback

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ABSTRACT
We compute the imprints left on the CM B by two cosmic reionization models consistent with current observations but characterized by alternative radiative feedback prescriptions (suppression and merging) resulting in a different suppression of star formation in low-mass halos. The models employ different reionization and thermal histories and 21 cm background signals. The derived Comptonization, u, and free-free distortion, yB, parameters are below current observational limits for both models. However, the value of u' ~ (9.55 ± 10)7 for the suppression (merging) model is in the detectability range of the next generation of CM B spectrum experiments. Through the dedicated Boltzmann code CMBFAST, modified to include the above ionization histories, we compute the CM B angular power spectrum (APS) of the TT, TE, and EE modes. For the EE mode the differences between these modes are significant larger than the cosmic and sampling variance over the multipole range' ~ 5 - 15, leaving a good chance of discriminating between these feedback mechanisms with forthcoming future CM B 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: Cosmology: cosm ic microwave background - galaxies: formation - intergalactic medium.

1 INTRODUCTION
The accurate understanding of the ionization history of the universe plays a fundamental role in the mod-
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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 \(10^{-4}\) after the standard recombination epoch at \(z_{\text{rec}}\). These photon and energy production processes associated to this reionization phase may leave imprints in the cosmic microwave background (CMB) providing a crucial integral information on the so-called dark and dawn ages, i.e., the epochs before or at the beginning of the formation of first cosmological structures. For this reason, am ong the extraordinary results achieved by the Wilkinson Microwave Anisotropy Probe (WMAP) mission, the contribution to the understanding of the cosmic reionization process has received a great attention.

To first approximation, the beginning of the reionization process is identified by the Thomson optical depth, \(\tau\). The values of \(\tau\) compatible with WMAP 3 yr data, possibly complemented with external data, are typically in the range \(0.06-0.12\) (corresponding to a reionization redshift in the range \(85-135\) for a sudden reionization history), the exact interval depending on the considered cosmological model and combination of data sets [Spergel et al. 2007]. While this simple \(\tau\)-parametrization of the reionization process and, in particular, of its imprints on the CMB anisotropy likely represents a sufficiently accurate model 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., Pospelov, Seager & Hill 2003; Doroshkevich & Nekrassov 2003; Cen, Ferrara & White 2003; Doroshkevich et al. 2003; Kasuya, Kawasaki & Sugiyama 2003; Hansen & Haiman 2004; Popa, Burigana & Mandelkeri (2005); Wither & Cen 2005) 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. 2003] 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 biasing) for the radiative feedback mechanism suppressing star formation in small mass halos 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 specially 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 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. 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 low redshift. 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 summarises our conclusions.

Through this paper we assume a CDM cosmological model consistent with the WMAP described by the cosmological constant (or dark energy) density parameters \(\Omega_m = 0.24\) and \(\Omega_{\Lambda} = 0.76\), reduced Hubble constant \(H_0 = 73\) km s\(^{-1}\) Mpc\(^{-1}\), baryon density \(\Omega_b = 0.022\), adiabatic scalar perturbations (without running) with spectral index \(n_s = 0.95\), and \(\Omega_{\Lambda} = 0.74\), adiabatic scalar perturbations (without running) with spectral index \(n_s = 0.95\), and a 0.1\% perturba-
Choudhury & Ferrara (2004) concluded that the additional physics introduced in Choudhury & Ferrara (2004) involves: i) the treatment of ISM inhomogeneities by adopting the procedure of dark-Erruclade, H ashmi et al. & Rees (2000); ii) the modding of the ISM treated as a multifluid medium, following the thermal and ionization histories of neutral, HII, and HeII regions simultaneously in the presence of ionizing photon sources represented by Pop III stars with a standard Salpeter IMF extending in the range $1 \text{ } 100 \text{ } M_{\odot}$ (Schneider et al. 2004), Pop II stars with $Z = 0.22$ and Salpeter IMF, and QSO’s (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. (2004); 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 semianalytical model is determined by only four free parameters: the star formation efficiency of Pop II and Pop III stars, a parameter, $\omega$, 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, $\omega$, set to reproduce low-redshift observations of Lyman-$\alpha$ systems (Choudhury & Ferrara 2004).

A variety of feedback mechanisms can suppress star formation in low-mass halos, i.e., halos with virial temperature, $T_{\text{vir}} < 10^4 \text{ } K$, particularly if their clustering is taken into account (Kneer, Haan & Ott 2004). We therefore assume that stars can form in halos down to a virial temperature of $10^4 \text{ } K$, 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, $T_{\text{vir}} > 10^4 \text{ } K$ 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 (2003) 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 regime. The gas fraction within dark matter halos at any given mass moment is fully specifiable by the current Lyman-$\alpha$ 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 with photoevaporative or accretion suppression.

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

i) suppression model (following Choudhury & Ferrara 2004), we assume that in photoionized regions halos can form stars only if their circular velocity exceeds the critical value $v_{\text{crit}} = 2\sqrt{G M_{\odot}/a}$, where $a$ is the mean m.c. radius, $M_{\odot}$ is the halo mass, and $a$ is the average temperature of ionized regions, computed self-consistently from the multifluid ISM model.

ii) merging model (following Gnedin 2003), we assume that the average baryonic mass $M_b$ within halos in photoionized regions is a fraction of the universal value $M_b = \frac{a_n}{a_{\odot}}$, given by the fitting formula $M_b = M_{\odot} (1 + (2+3) \left[ 1 - \frac{a_b}{a_M} \right] )$, where $M_{\odot}$ is the total halo mass and $M_c$ is the total mass of halos that on average retain 50% of their gas mass.

A good approximation for the characteristic mass $M_c$ is given by the linear theory merging mass, $M_c = (3\cdot a)_{\odot} a_M^{2.2}(a_{\odot})^{-2.2}$, where $a$ is the cosmic scale factor, $M > (4 -3) \cdot a_{\odot}^{-c} \cdot 3^{3/2}$ is the Jeans mass, $a_{\odot}$ is the average total mass density of the Universe, and $c$ 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 choice of the above four paramaters for these two models that well account for a wide set of astronomical observations, such as the redshift evolution of Lyman-$\alpha$ absorption systems, the quasar data, and electron scattering optical depths, the cosmic star formation history, and number counts of high redshift sources in the NEMOS Hubble Ultra Deep Field.

The two feedback prescriptions have a noticeable impact on the overall reionization history and the relative contribution of different ionizing sources. In fact, the two models predict similar global star formation histories dominated by Pop II stars, the Pop III star formation mass fraction have markedly different redshift evolution. Chemical feedback forces Pop III stars to live preferentially in the smallest, quasi-unpolluted halos (virial temperature $< 10^4 \text{ } K$, Schneider et al. 2004), which are those most affected by radiative feedback. In the suppression model, where star formation is totally suppressed below $v_{\text{crit}}$, Pop III stars disappear at $z \approx 6$; conversely, in the merging model, where halos suffer a gradual reduction of the available gas, Pop III stars continue to form at $z < 6$, 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 merging model in order to match the data. Therefore reionization starts at $z < 15$ in the merging model and only 16% of the volume is reionized at $z = 10$ (while reionization starts at $z = 20$ in the suppression model and it is 85% complete by $z = 10$). For $5 < z < 7$, QSO’s, Pop II and Pop III give a comparable contribution to the total photo-ionization rate in the merging model, whereas in the suppression
m odel 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. [4] compares the evolution of the gas kinetic temperature and CMB temperature for the two models. In particular, in the "burning" model the gas kinetic temperature is heated above the CMB value only at z < 15.

The Thomson optical depth, \( \tau = \int n_e c dt \), can be directly computed for the assumed CDM cosmological model parameters given the ionization histories shown in the top panel of Fig. [1]. We end the model at z = 0.0631 for the suppression and the "burning" model, respectively. Note that these values are consistent with the Thomson optical depth derived from WMAP 3yr data [Spergel et al. 2007] but with a difference of 1 in the two models, leaving a chance of probing them with forthcoming CMB anisotropy experiments.

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 in three categories: i) generation of CMB Comptonization and free-free spectral distortions associated to the EUV electron temperature increase during the reionization epoch, ii) suppression of CMB temperature anisotropies at large multipoles, \( \ell \), 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 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 Compton distortion [Zel'dovich & Sunyaev 1969; Zel'dovich, Illarionov & Sunyaev 1972], characterized by the Comptonization parameter \( u' = (1 + 4) - 1 \), where \( -1 \) 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 [Karev & Latter 1969; Rubnik & Lichtman 1973], in the hot gas. Its amplitude is characterized by the so-called free-free distortion parameter, \( y_s \). For late processes, as in this case, the resulting distorted spectrum can be fully described to a very good precision with the analytical form allan described in [Burigana, De Zotti & Daddi 2013] 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. [4] we end \( u' \approx 9 \times 10^{-7}, y_s \approx 9 \times 10^{-10} \) and \( u' \approx 9 \times 10^{-7}, y_s \approx 5 \times 10^{-10} \) respectively for the suppression and the "burning" model; these values are clearly well below the COBE/FIRAS limits [Fixsen et al. 1996; Salvaterra & Burigana 2002]. The two models show similar ionization and thermal histories at z < 6 while in the redshift range \( z > 6 \) they are significantly different. In the case of the suppression model, the free-free distortion is not present, while in the "burning" model the suppression is present only at redshifts \( z > 6 \), with \( u' \approx 9 \times 10^{-7}, y_s \approx 4 \times 10^{-10} \) and \( u' \approx 9 \times 10^{-7}, y_s \approx 8 \times 10^{-10} \) respectively for the suppression and the "burning" 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 $\ell \sim 1000$) spectrum experiments with precision comparable to the COBE/FRAS results (Kogut 1996; Bunnana & 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 mm and sub-mm wavelengths, able to improve by a factor of 30, 100 times the COBE/FRAS results (Kogut 1996; Bunnana, Salvaterra & Zizza 2004). In this perspective, future accurate measurements at long wavelengths (Bunnana et al. 2003) 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 & Zeldovich 1976) and late distortion parameters that remain in the presence of accurate spectrum measurements only at mm and sub-mm wavelengths.

3.2 Anisotropies

The detailed computation of the reionization imprint in the CMB anisotropy angular power spectrum (APS), $C_\ell$, 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 (see e.g. Seljak & Zaldarriaga 1996) to properly replace 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 display also the APS of the foreground in the V band (centred at 61 GHz) of WMAP 3yr data\(^3\), 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 1 degree relevant in this context. It is simply derived with the anafast facility of the HEALPix\(^4\) package (Cornsilk et al. 2009) analysing the difference between the original map and the CMB map and adopting the mask used by the WMAP team for the polarization analysis (covering $74\%$ of the sky). For sake of simplicity, no attempt is made in these foreground plots to subtract the noise contribution to the overall APS. We are in fact interested here to low multipoles ($\ell < 50$) 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 reionization model as well as the foreground impact is compared to the CMB signal increase going from the TT, to the TE, and then to the EE mode.

\(^{6}\) The relevance of the noise term is in particular at high multipoles where obviously increases going from the TT, to the TE, and then to the EE mode because of the decreasing of the signal-to-noise ratio.

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\(^3\) http://www.cmbfast.org/
\(^4\) http://lamda.gsfc.nasa.gov/product/map/current/
\(^5\) http://healpix.gsfc.nasa.gov/

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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, C. C. Knox (1995), i.e. neglecting the contribution by the instrumental noise, and a potential residual foreground contamination. At the low multipoles (**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 instrumental sensitivity and frequency coverage and, in particular, the rejection (by instrument design and/or by subsequent data analysis) 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) and 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, 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) context.

Following Nascisky & Chiang (2004), we compute the quantity $\Delta S = (C^M - C^N) - D (C^M + C^N)$ where the indices $M$ 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 graph panel). A potential foreground residual contamination, resulting from a non-perfect (possibly biased) component separation, is modeled here as $C^\text{fore} = f (C^M + C^N)$, where $C^\text{fore}$ 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 $\Delta S$ for $M = S$ (suppression model) and $N = F$ (lighting 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 $\Delta S$ for $M = S$ and $N = SH$ and for $M = F$ and $N = FH$ in order to quantify the relative error incurred by the step function approximation of a more complex 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 measurements. The difference in the $EE$ mode (see bottom panel of Fig. 3) turns to be well above the foreground limitation even for a less than accuracy of 10 per cent. Unfortunately, it is above the cosmic and sampling variance limitation by a factor of 15 only and for a small range of multipoles (**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 effect over the accuracy at the level of 1 per cent (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.

![Figure 3. Relative difference, $\Delta S$, between the $TT$ and $EE$ mode APS of CMB anisotropies for the suppression and lighting models reported in Fig. 2 (thick solid lines) compared with the cosmic and sampling variance limitation corresponding to a sky coverage of 74 per cent (region between the dotted lines). We report for comparison the APS from a potential residual foreground (dot-dashed) corresponding to two different values of $f$: 0.1 (dashed line) and 0.01 (three dots-dashed line). See also the text.](http://www.real.esa.int/planck)

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7 http://www.real.esa.int/planck
8 http://www.jhu.edu/tpol/index.php

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9 The apparently large features at **50** result from the very small absolute value of the $EE$ 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. 4).
Figure 4. Relative difference, $\delta$, between the (EE mode) APS of CMB anisotropies for the suppression and liming models reported in Fig. 3 (thick solid lines) compared with the cosmic and sampling variance limitation corresponding to a sky coverage of $'74$ 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 difference values of $0.01$ (dashed line), $0.03$ (dashed-dotted line), $0.01$ (three dots-dashed line), and $0.003$ (long dashes). In the bottom panel we show also $\delta$ for models that replace the two considered models with those obtained assuming the simple step function in p.m. entered in the public CMBFAST code for the reionization history (thick solid lines) for the corresponding values of optical depth. The relative difference difference between the results based on the suppression (resp. liming) models and its step function approximation is $0.0017$ (resp. $0.0631$) shown by the dashed line (resp. three dots-dashed line). See also the text.

10 http://www.b-pol.org/pdf/BPOL_Proposal.pdf
11 See e.g. the talks by J.P. Leahy and J.P. Bernard at http://www.zm十万fr/bpol/talks/oray/m eeting/Talks.htm

by improving both the foreground physical modelling and the component separation accuracy.

Finally, we observe that, in particular at $'10$ 20, the step function approximation of the reionization history adopted in the simple $-$parametrization, although adequate to reveal the bulk of the difference between these models, in places an error on the EE mode comparable to the cosmic and sampling variance limitation (see bottom panel of Fig. 3). Therefore, a proper treatment of the cosmological reionization history in the Bolzmann code is necessary for a one component model with the high accuracy data from forthcoming and future CMB polarization anisotropy experiments.

4 CONCLUSION

We have analyzed the implications for the CMB of the self-consistent semianalytical model developed by Choudhury & Ferrara (2005, 2006) to describe the effect of reionization and its associated radiative feedback on galaxy formation, modeling 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 liming model. These two models predict different ionization and thermal histories, in particular at $z > 6$, resulting in Thomson optical depths $'6017$ and $'0631$, respectively, consistent with the WMAP 3yr data.

According to the usual semianalytical approach to model CMB spectral distortions, we computed the Comptonization and free-free distortion parameters, $u$ and $v_T$. Their values are found to be well below the current observational limits. In particular, the values obtained for the Comptonization parameter $u$ ($'169$ 10$^7$ and $'9510^8$ for the suppression and the liming model, respectively) are in range accessible to a future generation of CMB spectrum experiments, in particular at mm/3mil extensive wavelengths, able to in probe by 30 100 km 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) by using the step function approximation adopted in the simple $-$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

12 A similar analysis for the TT (resp. TE) mode shows that this kind of error is overestimated by (resp. about one order of magnitude less than) the cosmic and sampling variance.
significantly larger than the cosmic and sampling variance over the multipole range \(6^\circ<\theta<15^\circ\), 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 e-ports 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 systematics 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 \cite{Schneideretal07} 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 \(z>6\).

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