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Scaling defect decay and the reionization history of the Universe

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We consider a model for the reionization history of the Universe in which a significant fraction of the observed optical depth is a result of direct reionization by the decay products of a scaling cosmic defect network. We show that such network can make a significant contribution to the reionization history of the Universe even if its energy density is very small (the defect energy density has to be greater than about 10^{-11} of the background density). We compute the Cosmic Microwave Background temperature, polarization and temperature-polarization cross power spectrum and show that a contribution to the observed optical depth due to the decay products of a scaling defect network may help to reconcile a high optical depth with a low redshift of complete reionization suggested by quasar data. However, if the energy density of defects is approximately a constant fraction of the background density then these models do not explain the large scale bump in the temperature-polarization cross power spectrum observed by Wilkinson Microwave Anisotropy Probe.

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I. INTRODUCTION

Two important types of observations have recently begun to probe the reionization history of the Universe. On one hand the spectra of high redshift quasars at $z \sim 6$ revealed the presence of Gunn-Peterson troughs [1] suggesting a very late reionization [2–5], a fact corroborated by the possible detection of first reionization sources around this redshift [6]. On the other hand the measurement by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite [7,8] of a large correlation between the temperature and E-type polarization at large angular scales seems to indicate a high optical depth which was interpreted as evidence for early reionization ($z_{\rm reion} = 11 - 30$). These two apparently contradictory results suggest that the reionization history of the Universe may be more complex that originally thought. In Ref. [5] it was shown that numerical simulations in the context of a "classical model" for cosmological reionization lead to a consistent picture between SLOAN data and WMAP provided there is a slow partial reionization from early epochs reaching total ionization by $z \sim 6$. A number of astrophysical and particle physics models that may help to reconcile CMB and quasar results have recently been suggested. For example, in Ref. [9,10] a double-reionization model in which a first stage of reionization by metal free stars at high redshift is followed by a second one at lower redshifts was studied in detail, while other models with more than one relevant source of reionization have also been investigated [11–13]. An alternative explanation may lie on yet unknown fundamental physics which might be probed by reionization. For example, it was suggested [14,15] that a slower reionization with a high optical depth might be achieved in the context of nongaussian models either in the context of inflation [16] or topological defects [17]. Another possibility that has recently received much attention is the decay of dark matter particles which may release the energy necessary to reionize the intergalactic medium [18–21].

In this article we consider yet another possibility for explaining both WMAP and quasar results in which a significant fraction of the observed optical depth is a result of direct reionization by the decay products of a scaling network of topological defects. We will make our model as general as possible looking at specific signatures of a scaling solution for defect evolution. Scaling is a generic feature of defect models in which the statistical properties of the defect network remain self-similar relative to the Hubble radius. In the most interesting models it implies that the defect energy density is roughly proportional to the background density in the radiation and matter eras. This means that the scaling defect network will loose a roughly constant fraction of its energy each Hubble time. Part of the energy lost by the network may provide a useful contribution to the reionization history of the Universe leaving specific signatures in the CMB, which we investigate in this paper.

The article is organized as follows. In Section II we describe our model and discuss the appropriate modifications to the standard reionization history. In Section III we calculate the evolution of the ionization fraction with redshift, the optical depth, the temperature, E-type polarization and temperature-polarization cross power spectra (TE) for our model comparing with WMAP observations and discussing the results in detail. We summarise our results in Section IV.

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II. THE MODEL

We consider a scaling network [22] for which the energy density, ρ_D, is a constant fraction of the background density, ρ_b. Given that in the matter era $\rho_b \propto t^{-2}$ we have

$$\frac{d\rho_D}{dt} = -2\frac{\rho_D}{t}, \quad (1)$$

where t is the physical time. We shall investigate a nonstandard scenario in which the decay products of a scaling defect network may act as an additional source of ionization. The nature of decay particles produced by a defect network is model dependent and may include a large variety of more or less exotic particles, some of which can in principle make a significant contribution to the reionization history of the Universe. We will assume that a fraction β of the energy lost by the network will affect the reionization history either through direct ionization (a fraction ϵ) or by heating the intergalactic medium (a fraction $1-\epsilon$). The parameter β must be smaller than unity and may be even be much smaller than that depending on the relative importance of the decay mechanisms available to the defect network. For example, if gravitational radiation is the dominant decay channel (as appears to be the case for Abelian Higgs networks [23]—see however Ref. [24]) β will necessarily be small.

In Refs. [20,21] and following the work of Ref. [25] $\epsilon = 1/3$ was taken as a reasonable approximation to the fraction of the energy that goes into ionization for the case where electrons heat the IGM when the gas is mostly neutral. We note that we want our model to remain as general as possible in order to look at specific reionization signatures of a scaling solution for defect evolution. However, our results are weakly dependent on the specific value of ϵ and so we will make the best motivated choice ($\epsilon = 1/3$).

For simplicity, we neglect helium ionization and also assume that the energy going into excitation is negligible. Again this does not greatly affect our results and so we choose to avoid unnecessary complexity.

The defect network will provide an additional ionization source which should be added to the standard ionization equation

$$\frac{dn_e}{dt} = \frac{2\epsilon\beta\rho_D}{I_H t}, \quad (2)$$

where n_e is the number density of free electrons and $I_H = 13.6$ eV. Part of this energy will contribute to heat the intergalactic medium and to this end we added an additional term to the equation which describes the evolution of the gas temperature, T

$$\frac{dT}{dt} = \frac{4\beta\rho_D}{3nk_B t}\left(1 - \epsilon - \epsilon\frac{3k_B T}{2I_H}\right), \quad (3)$$

where n is the particle number density for the gas and k_B is the Boltzmann constant. We modified the RECFAST code [26] by adding the terms in equations (2) and (3) and obtained the temperature, E-type polarization and cross power spectra using CMBFAST [27].

III. RESULTS AND DISCUSSION

We now discuss in more detail how the decay products of a scaling cosmic defect network may affect the reionization history of the Universe. Throughout the paper we shall adopt a cosmological model motivated by the WMAP results (Bennett et al. 2003) with initial gaussian fluctuations and a matter density $\Omega_m^0 = 0.29$, dark energy density $\Omega_\Lambda^0 = 0.71$, baryon density $\Omega_B^0 = 0.047$, Hubble parameter $h = 0.72$, normalization $\sigma_8 = 0.9$, and perturbation spectral index $n_s = 0.99$. Although there may be an important contribution to the reionization history of the Universe coming from nongaussian perturbations [14,15] we shall assume throughout this paper that the energy density of the defect network is very small and, as a consequence, not contributing significantly to structure formation. We calculate the IGM temperature, ionization fraction and optical depth for a number of models con-

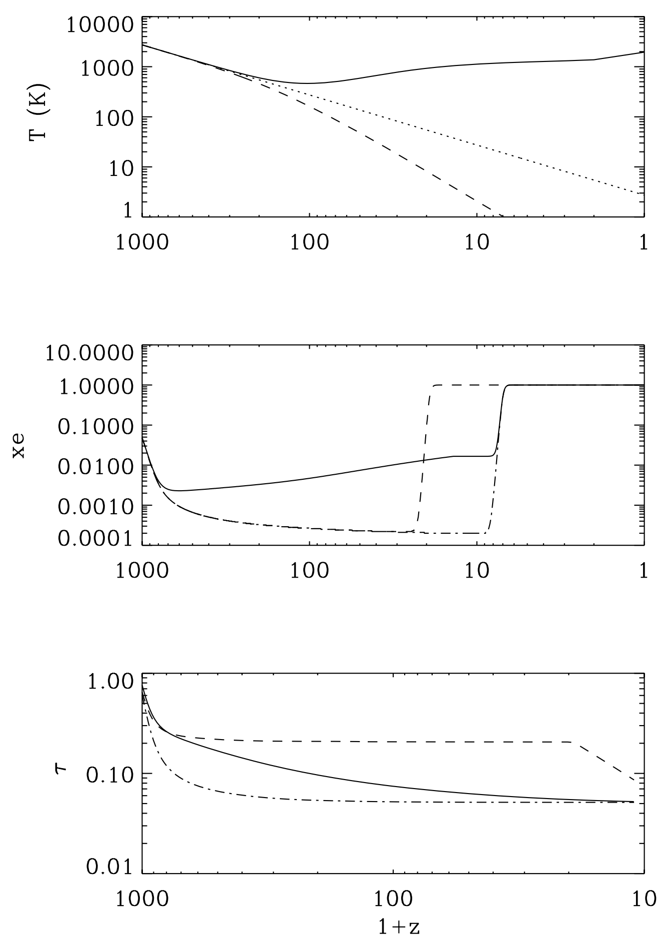

FIG. 1. The IGM temperature, ionization fraction and optical depth for models with fast reionization at $z \sim 17$ (model I - dashed line) and $z \sim 6$ (model II - dot-dashed line) induced by standard sources and the scaling defect model with parameters $\epsilon = 1/3$ and $\Omega_D^0 = 2\beta^{-1} \times 10^{-11}$ with rapid reionization at $z \sim 6$ by standard sources (model III - solid line). In the first plot the dotted line represents the evolution of the CMB temperature.

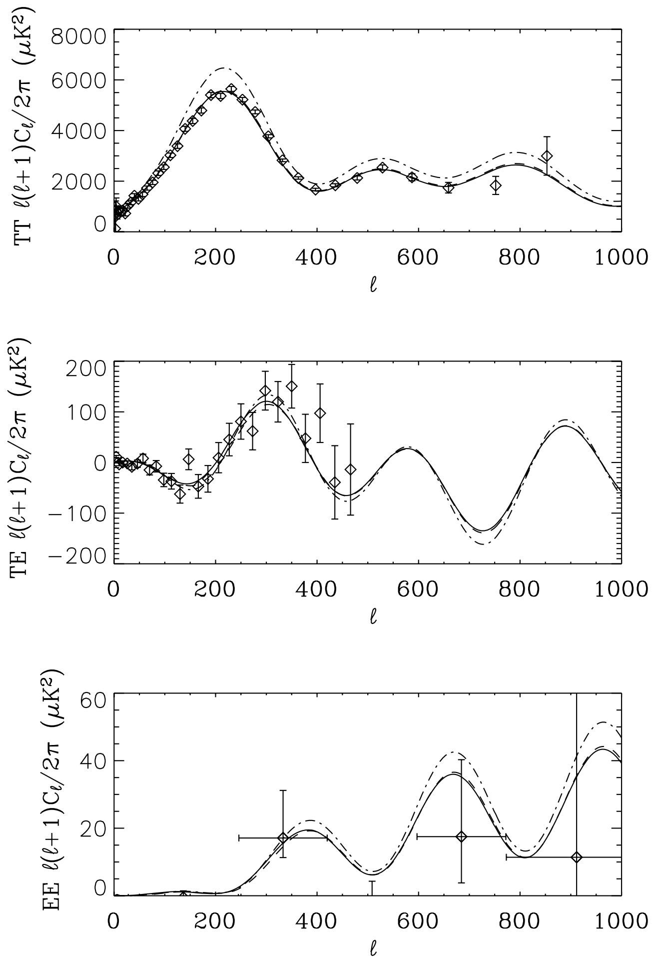

FIG. 2. The CMB temperature (TT), polarization (EE) and cross power spectra (TE) for models I (dashed line), II (dot-dashed line) and III (solid line). The data points with error bars for the TT and TE spectra are the binned data given by the WMAP team while the error bars for the EE power spectrum are the binned data given by the DASI team. We see that the models I and III lead to very similar power spectra.

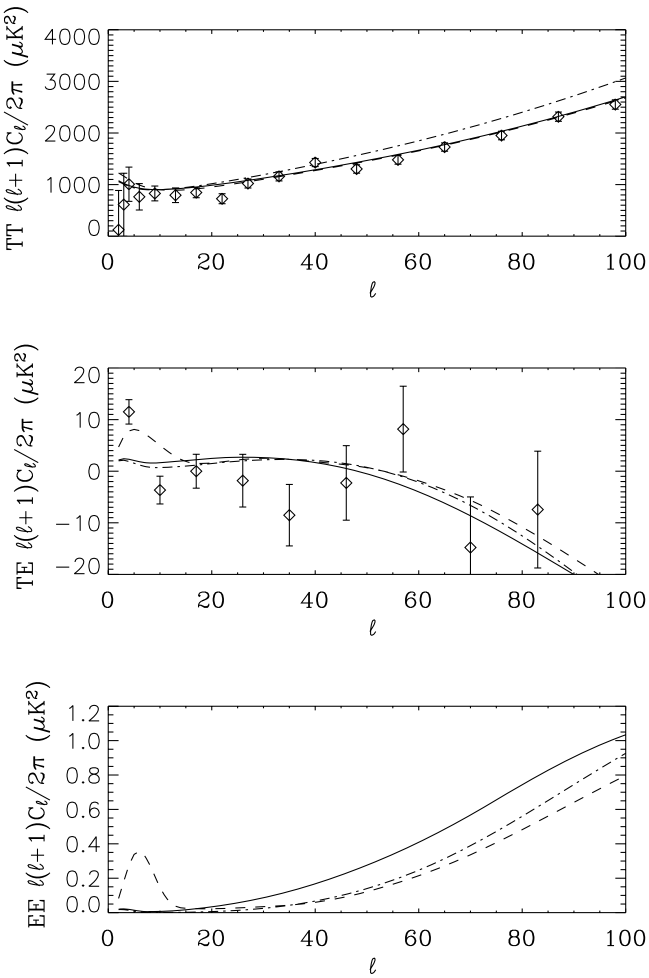

FIG. 3. Same as Fig. 2 but for $\ell \leq 100$. We see that direct reionization due to the decay products of a scaling defect network is not able to explain the low ℓ bump in TE cross power spectrum.

sidering, in particular, fast reionization at $z \sim 17$ (model I - dashed line) and $z \sim 6$ (model II - dot-dashed line) induced by standard sources and a scaling defect model with parameters $\epsilon = 1/3$ and $\Omega_D^0 = 2\beta^{-1} \times 10^{-11}$ with standard reionization induced by standard sources occurring at $z \sim 6$ (model III -solid line). Note that in the particular case of cosmic strings, model III would require a string mass per unit length $G\mu \sim \beta^{-1}10^{-13}$ making it possible (if β is large enough) for cosmic strings to influence the reionization history of the Universe even if they play a negligible role in structure formation.

In Fig. 1 we plot the evolution of the IGM temperature, ionization fraction and optical depth for models I, II and III. The evolution of the IGM temperature is not to be trusted at small z since the evolution of x_e, due to fast reionization by standard sources, was put in by hand and no specific model for the evolution of the gas temperature was specified. We see that although models I and III have roughly the same optical depth up to $z \sim 800$ the reionization history is very different. In particular the residual ionization fraction is much larger in the case of model III and the evolution of the optical depth up to $z = 10$ is much smoother for that model which is related to the specific time dependence of the energy output associated with the scaling solution.

We note that these results are qualitatively in agreement with the results of [18–21] in which an important contribution to the reionization history of the Universe from decaying particles was studied. However, in our case $dn/dt \propto t^{-3}$ (instead of $dn/dt \propto t^{-2}$ caracteristic of decaying particles with a very long lifetime), which results in a slower evolution of T, x_e and τ at low redshifts.

We compute the CMB temperature (TT), polarization (EE) and cross power spectra for models I (dashed line), II (dot-dashed line) and III (solid line). The results are displayed in Figs. 2 (up to $\ell = 100$) and 3 (up to $\ell = 1000$). The data points with error bars for the TT and TE spectra are the binned data given by the WMAP team

[7,8] while the error bars for the EE power spectrum are the binned data given by the DASI team [28]. We see that models I and III lead to power spectra which are very similar showing that the decay products of a scaling defect network may help to reconcile a high optical depth with a low redshift of complete reionization suggested by quasar data. However, we see in Fig. 3 that model III does not explain the low ℓ bump in the TE cross power spectrum. In order to test the models, we attempted a simple likelihood analysis of the three models considered here using the publicly available WMAP 1st year data [7,29] and likelihood code [30]. We note that while our WMAP best fit model gives the lowest χ^2, the defect model is not far away (model I - TT $\chi^2 = 1008$, TE $\chi^2 = 456$; model III - TT $\chi^2 = 1032$, TE $\chi^2 = 460$). Model II is not surprisingly the worst model (with a combined χ^2 equal to 1902).

We have seen that a value of Ω_D^0 as low as 10^{-11} may lead to a significant contribution to the reionization history of the Universe depending on the value of β which parametrizes the fraction of the energy lost by the scaling network which is useful to reionization (we have shown that $\Omega_0^D \beta \lesssim 2 \times 10^{-11}$).

IV. CONCLUSIONS

In this article we studied the contribution to the reionization history of the Universe made by the decay products of a network of scaling cosmic defects with an energy density approximately a constant fraction of the background density. We calculated the TT, TE and EE power spectra showing that this model together with a standard epoch of fast reionization at $z \sim 6$ may explain the observed CMB results with exception of the low ℓ bump in the TE cross power spectrum. In order to leave a significant imprint on the CMB of the defect network energy density has to be at least about 10^{-11} of the background density.

We note that not all scaling defect models have an energy density which scales roughly with the background density. In the particular case of a scaling network of domain walls $\rho_D/\rho_b \propto t$ in the radiation and matter eras. If domain walls are very light they may have a negligible direct impact on the CMB but their decay products could still be able to influence reionization. We verified that the time dependence of the energy input in this model is the same as that of decaying particles with very long lifetime previously studied in Refs. [18–21].

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