Cosmological constraints in the presence of ionizing and resonance radiation at recombination

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With the recent measurement of full sky cosmic microwave background polarization from WMAP, key cosmological degeneracies have been broken, allowing tighter constraints to be placed on cosmological parameters inferred assuming a standard recombination scenario. Here we consider the effect on cosmological constraints if additional ionizing and resonance radiation sources are present at recombination. We find that the new CMB data significantly improve the constraints on the additional radiation sources, with \(\log_{10}[\epsilon_1] < -0.5\) and \(\log_{10}[\epsilon_2] < -2.4\) at 95\% c.l. for resonance and ionizing sources respectively. Including the generalized recombination scenario, however, we find that the constraints on the scalar spectral index \(n_s\) are weakened to \(n_s = 0.98 \pm 0.03\), with the \(n_s = 1\) case now well inside the 95\% c.l.. The relaxation of constraints on tensor modes, scale invariance, dark energy and neutrino masses are also discussed.

I. INTRODUCTION

The recent measurements of the Cosmic Microwave Background (CMB) flux provided by the three year Wilkinson Microwave Anisotropy Probe (WMAP) mission (see [1, 2, 3, 4]) have confirmed several of the results already presented in the earlier data release, but also pointed towards new conclusions. The better treatment of systematics in large scale polarization data, in particular, has now provided a lower value for the optical depth parameter \(\tau\). This, together with an improved signal in the temperature data at higher multipoles, has resulted in a lower value of the spectral index parameter \(n_s = 0.959 \pm 0.016\). A determination of this parameter can play a crucial role in the study of inflation. Soon after the WMAP data release, several papers have indeed investigated the possibility of discriminating between single-field inflationary models by making use of this new, high quality, dataset [5, 6, 7, 8, 9, 10, 11, 12, 13]. One of the main conclusions of these papers is that some inflationary models, such as quartic chaotic models of the form \(V(\phi) \sim \lambda \phi^4\), may be considered ruled out by the current data while others, such as chaotic inflation with a quadratic potential \(V(\phi) \sim m^2 \phi^2\) are consistent with all data sets.

While the WMAP result is of great importance for inflationary model building, one should be careful in taking any conclusion as definitive since the constraints on \(n_s\) are obtained in an indirect way and are, therefore, model dependent. Similar considerations apply to other cosmological constraints, such as those on the dark energy equation of state and neutrino masses. Combining CMB anisotropies with galaxy clustering and supernovae type Ia data, the dark energy equation of state parameter (dark energy pressure over density) has been constrained to \(w = -1.08 \pm 0.12\) at 95\% c.l. (see [1]). Using the same dataset, but under the assumption of a cosmological constant, it is possible to constrain the neutrino masses to \(\sum n_i < 0.66\text{eV} \) at 95\% c.l. where \(i = 1, \ldots, 3\) and indicates the neutrino flavor. Again, while those constraints play a very important role in our understanding of the dark energy component and neutrino physics, they are obtained in an indirect way and under several assumptions.

The importance of the model dependency of the cosmological constraints has been recently discussed by several authors. The impact of isocurvature modes on the determination of the neutrino mass [14], dark energy properties [15], scalar spectral index [16] and baryon density [17] is just one example.

Here we investigate possible deviations in the mechanism on which CMB anisotropies are highly dependent: the process of recombination.

In a previous paper [18], we analyzed modified recombination processes in light of the WMAP first year data. Here we assess the improvements given by more recent data, in particular the inclusion of CMB polarization spectra, and also extend the analysis to a larger set of parameters. We will indeed not only provide new and more stringent constraints on modified recombination but we also consider its impact on inflationary, dark energy and neutrino parameters.

The recombination process can be modified in several ways. For example, one could use a model-independent, phenomenological approach such as in [19] where models are specified by the position and width of the recombination surface in redshift space. Here we instead focus on theoretically motivated mechanisms based on extra sources of ionizing and resonance radiation at recombination (see e.g. [20]). While the method we adopt will be general enough to cover most of the models of this kind, as discussed in the next section, we remind the reader that there exist other ways in which to modify recombination, for instance, by having a time-varying fine-structure constant [21].

Following the seminal papers [22, 23] detailing the recombination process, further refinements to the
standard scenario were developed \cite{21}, allowing predictions at the accuracy level found in data from the WMAP satellite and the future Planck satellite \cite{22, 23}. With this level of accuracy, it becomes conceivable that deviations from standard recombination maybe be detectable \cite{24, 25, 26}, although further refinements could be required to get the Thomson visibility function below percent level accuracy \cite{27, 28, 29}.

The paper proceeds as follows: in section II we describe a model which can produce deviations from the standard recombination scenario. In III we describe how these deviations might affect the CMB temperature and polarization power spectra and conduct a likelihood analysis using the recent CMB data from WMAP and other cosmological observables. In particular, we will study the impact that a modified recombination scheme can have on several cosmological and astrophysical parameters. In IV we draw together the implications of the analysis.

II. A MODIFIED IONIZATION HISTORY

The evolution of the ionization fraction, $x_e$, of atoms, number density $n$, can be modeled in a simplified manner for the recombination of hydrogen, \cite{22, 23},

$$\frac{dx_e}{dt} |_{std} = C \left[ a_c n x_e^2 - b_c (1 - x_e) \exp \left( \frac{\Delta B}{k_B T} \right) \right]$$

where $a_c$ and $b_c$ are the effective recombination and photo-ionization rates for principle quantum numbers $\geq 2$, $\Delta B$ is the difference in binding energy between the 1st and 2nd energy levels and

$$C = \frac{1 + K \Lambda_{1s2s} n_{1s}^2}{1 + K (\Lambda_{1s2s} + b_c) n_{1s}}$$

$$K = \frac{\lambda_\alpha^3}{8\pi H(z)}$$

where $\lambda_\alpha$ is the wavelength of the single Ly-$\alpha$ transition from the 2p level, $\Lambda_{1s2s}$ is the decay rate of the metastable 2s level, $n_{1s} = n(1 - x_e)$ is the number of neutral ground state $H$ atoms, and $H(z)$ is the Hubble expansion factor at a redshift $z$.

We include the possibility of extra photons at key wavelengths that would modify this recombination picture, namely, resonance (Ly-$\alpha$) photons with number density, $n_{\alpha}$, which promote electrons to the 2p level, and ionizing photons, $n_i$, \cite{22, 23, 24, 25, 26}

$$\frac{dn_{\alpha}}{dt} = \varepsilon_{\alpha}(z) H(z) n_i$$

$$\frac{dn_i}{dt} = \varepsilon_i(z) H(z) n_i$$

which leads to a modified evolution of the ionization fraction

$$\frac{dx_e}{dt} = - \frac{dx_e}{dt} |_{std} - C \varepsilon_i H - (1 - C) \varepsilon_{\alpha} H.$$  \hfill (4)

Extra photon sources can be generated by a variety of mechanisms. A widely considered process is the decay or annihilation of massive particles \cite{20, 22, 23, 24, 25, 26, 27, 28}. The decay channel depends on the nature of the particles, and could, for example, include charged and neutral leptons, quarks or gauge bosons. These particles may then decay further, leading to a shower /cascade that could, amongst other products, generate a bath of lower energy photons that could interact with the primordial gas and cosmic microwave background. Interestingly these models, as well as injecting energy at recombination, $z \sim 1000$, boost the ionization fraction after recombination and can distort the ionization history of the universe at even later times, during galaxy formation and reionization $z \sim 5 - 10$ \cite{29, 30, 31, 32, 33}. Other mechanisms include evaporation of black holes \cite{27, 34} or inhomogeneities in baryonic matter \cite{25}.

We employ the widely used RECFAST code \cite{24}, in the cosmomc package \cite{45} modifying the code as in \cite{46} to include two extra constant parameters, $\epsilon_{\alpha}$ and $\epsilon_i$. In addition to the ionizing sources, we assume a single, swift reionization epoch at a redshift $z_{re}$. In Figure \hfill (4) we show the effect of additional resonance and ionizing radiation on the CMB TT, TE and EE spectra, in comparison to a fiducial best fit model to the WMAP 3-year data. From identical initial power spectra, the inclusion of additional resonance photons slightly boosts the ionization fraction at and after recombination, suppressing TT power at small scales, while the large scale EE spectra is largely unaffected. Ionizing photons significantly boost the ionization fraction post recombination and therefore as well as significantly suppressing TT power on small scales, they also can generate a boost in the large scale EE signal akin to an early partial reionization.

III. LIKELIHOOD ANALYSIS

The method we adopt is based on the publicly available Markov Chain Monte Carlo package cosmomc \cite{45}. We sample the following dimensional set of cosmological parameters, adopting flat priors on them: the physical baryon and Cold Dark Matter (CDM) densities, $\omega_b = \Omega_b h^2$ and $\omega_c = \Omega_c h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling, $\theta_s$, the scalar spectral index, $n_s$, and the optical depth to reionization, $\tau$. As described in the previous section, we modify recombination by considering variations in the $\epsilon_{\alpha}$ and $\epsilon_i$ parameters. Furthermore, we consider purely adiabatic initial conditions and we impose flatness. We also consider the possibility of having a tensor (gravity waves) component with amplitude $r$ respect to scalar, running of the spectral index $dn_{\alpha}/dk$ at $k = 0.002 h^{-1} Mpc$ and a non-zero, degenerate, neutrino mass of energy density:

$$\Omega_\nu h^2 = \frac{m_\nu}{92.5 eV}$$  \hfill (5)
Finally, we will also investigate the possibility of a dark energy equation of state, $w$, different from $-1$ but constant with redshift. The MCMC convergence diagnostics is done on 7 chains though the Gelman and Rubin “variance of chain mean”/“mean of chain variances” $R$ statistic for each parameter. Our 1D and 2D constraints are obtained after marginalization over the remaining “nuisance” parameters, again using the programs included in the \texttt{cosmomc} package. In addition to the WMAP data, we also consider the constraints on the real-space power spectrum of galaxies from the Sloan Digital Sky Survey (SDSS) \cite{1}. We restrict the analysis to a range of scales over which the fluctuations are assumed to be in the linear regime ($k < 0.2h^{-1}\text{Mpc}$). When combining the matter power spectrum with CMB data, we marginalize over a bias $b$ considered as an additional nuisance parameter. Furthermore, we make use of the Hubble Space Telescope (HST) measurement of the Hubble parameter $H_0 = 100h$ km $s^{-1}$Mpc$^{-1}$ \cite{17} by multiplying the likelihood by a Gaussian likelihood function centered around $h = 0.72$ and with a standard deviation $\sigma = 0.08$. When considering dark energy models, we also include information from luminosity distance measurements of type Ia Supernovae from the recent analysis of \cite{48}. Finally, we include a top-hat prior on the age of the universe: $10 < t_0 < 20$ Gyrs.

IV. RESULTS

Our main results are plotted in Figure 2 where we show the 68% and 95% c.l. on the $n_s - \log_{10}(\epsilon_a)$, $\sigma_8 - \log_{10}(\epsilon_a)$, $n_s - \log_{10}(\epsilon_i)$ and $\sigma_8 - \log_{10}(\epsilon_i)$ plane.

In the top portion of Figure 2 we consider only the WMAP data (plus a prior on the Hubble parameter), while in the lower portion, we add SDSS. Let us first consider the case of WMAP alone. As we see, using this dataset alone, we can put interesting new bounds on the recombination parameters. Marginalizing over the remaining, “nuisance”, parameters we indeed obtain $\log_{10}(\epsilon_a) < -0.81$ and $\log_{10}(\epsilon_i) < -2.31$ at 95% c.l.

As suggested by Figure 1 we find ionizing photons are better constrained with current data since the ionization fraction is significantly boosted at and beyond the onset of recombination. This results in a suppression of TT power and boosting of EE power even on large scales, well constrained by WMAP data. Resonance photons have a more subtle effect only slightly increasing the ionization fraction after the onset of recombination. This leads to a suppression of small scale TT power but little effect on large scale EE. The constraints on both types of radiation should be noticeably improved therefore by future experiments, such as the planned PLANCK satellite, which better characterize small scale TT and EE power \cite{28}.

Moreover, there is a clear degeneracy between $\log_{10}(\epsilon_a)$ and the spectral index $n_s$. Indeed, a modification of the recombination scheme allows us to suppress the amplitude of the peaks in the CMB power spectrum in a way similar to a later recombination but without altering the large-scale polarization signal. This changes in a drastic way the constraints on the scalar spectral index and $\sigma_8$. Marginalizing over the recombination parameters, we get $n_s = 0.978^{+0.032}_{-0.029}$ and $\sigma_8 = 0.80^{+0.08}_{-0.09}$ at 95% c.l.. Those results should be compared with the constraints $n_s = 0.959^{+0.026}_{-0.027}$.

FIG. 1: (From left to right) The comparison of ionization fraction evolution, and TT (left), TE (center) and EE (right) CMB spectra comparing a best fit $\Lambda$CDM fiducial model to models with the same cosmological parameters but with additional resonance (top) and ionizing (bottom) radiation. WMAP binned data are shown as blue shaded regions.
FIG. 2: The 68% and 95% likelihood contours in the $n_s$ and $\sigma_8$ plane (left) and $n_s$ and $\sigma_8$ vs $\epsilon_i$ (right). The analysis considers (top/blue) the 3-years WMAP data and a HST prior on the Hubble parameter, $h$, alone and (bottom/red) also including SDSS galaxy matter power spectrum data.

$\sigma_8 = 0.78^{+0.08}_{-0.07}$, again at 95% c.l., obtained using the same dataset and priors but with standard recombination.

Including SDSS data, as is shown in the lower panel in Figure 2, does not significantly improve our constraints on $\epsilon_\alpha$ and $\epsilon_i$. The SDSS power spectrum indeed prefers a higher value of the $\sigma_8$ parameter than WMAP. While the tension is not strong enough to provide any evidence for modified recombination, the constraints are lowered to $\log_{10}(\epsilon_\alpha) < -0.51$ for $\epsilon_\alpha$ and almost stable to $\log_{10}(\epsilon_i) < -2.24$, for $\epsilon_i$ at 95% c.l.. The constraints on $n_s$ and $\sigma_8$ are also affected. Including SDSS we find $n_s = 0.994^{+0.040}_{-0.035}$ and $\sigma_8 = 0.87^{+0.07}_{-0.06}$ at 95% c.l..

Interestingly, we find that the constraints on other key parameters ($\tau$ or $\Omega_b$) are robust to the modifications in the recombination scenario. It is interesting to extend the analysis to other inflationary parameters such as the amplitude of a tensor component $r$ or a running of the spectra index $dn_s/dlnk$. In Figure 3 (top panel) we plot the 68% and 95% likelihood contours in the $n_s - r$ plane in the standard and in the generalized recombination case. As one can see, relaxing our knowledge about recombination strongly affects the final constraints: the scalar spectral index can be more consistent with $n_s > 1$ and the upper limit on the tensor component can be a factor 2 larger than in the standard case. As one can see from the bottom panel of Figure 3, a degeneracy between $\epsilon_\alpha$ and the running $dn_s/dlnk$ is also present. Standard analyses prefer a negative running of the spectral index with significance slightly above $1\sigma$ (see [1]). This can be compensated for by a non-standard recombination with $\epsilon_\alpha > 0.1$.

In Figure 4, we report on the impact of non-
FIG. 4: The impact of a modified recombination scheme on constraining a constant dark energy equation of state, \( w \). We show the 68% and 95% likelihood contours in the \( w \) vs \( \varepsilon_\alpha \) plane from WMAP+SDSS+HST+SN-Ia (see text). Non-standard recombination relaxes the constraints towards more negative values for \( w \).

五行 5: The effect of a modified recombination scheme on constraining neutrino masses. We show the 68% and 95% likelihood contours in the \( \Sigma m_\nu \) vs \( \varepsilon_\alpha \) plane from WMAP+SDSS+HST (see text). Non-standard recombination relaxes the constraints towards larger masses.

standard recombination on the equation of state parameter, \( w \). We find an important degeneracy only with \( \varepsilon_\alpha \): allowing \( \varepsilon_\alpha \) to vary enlarges the constraints on \( w \) towards more negative values. A future, combined, indication for \( w < -1 \) could, therefore, provide a hint of a non-standard recombination process and one should be careful in interpreting it as evidence for a phantom-like dark energy component. In a more generalized recombination scenario, we find the constraints on \( w \) are relaxed to \( w = -1.2^{+0.28}_{-0.44} \) at 95% c.l..

Finally, in Figure 5, we report the constraints on neutrino masses. As one can see, non-standard recombination also relaxes constraints on this parameter. We find that values as large as \( \Sigma m_\nu \sim 1.2eV \) are consistent with the data, relaxing by \( \sim 50\% \) the standard constraint \( \Sigma m_\nu < 0.72eV \) (see e.g. [1, 49]).

V. CONCLUSIONS

In this paper, we update the upper bounds that can be placed on the contribution of extra Ly-\( \alpha \) and ionizing photon-producing sources in light of the new WMAP data. We find that, adopting a simple parametrization using constant effective values for \( \varepsilon_\alpha \) and \( \varepsilon_i \), the WMAP data constraints \( \log_{10}[\varepsilon_\alpha] < -0.5 \) and \( \log_{10}[\varepsilon_i] < -2.4 \) at the 95% level. Physically motivated models for non-standard recombination which generate ionizing and resonance radiation, like those based on primordial black hole or super-heavy dark matter decay, remain feasible.

We find that a modified recombination scheme may affect the current WMAP constraints on inflationary parameters like the spectral index \( n_s \) and its running. In particular, if recombination is changed, Harrison-Zel’dovich spectra with \( n_s = 1 \), larger tensor modes and positive running are in agreement with observations. Moreover, constraints on particle physics parameters like the neutrino mass are also relaxed when non-standard recombination is considered.

Future observations in both temperature and polarization, such as those expected from the Planck satellite [28], will provide more precise small scale TT and EE measurements needed to more stringently test these models and, crucially, will reduce the dependency of other cosmological parameters on them.

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