Recombining WMAP: constraints on ionizing and resonance radiation at recombination

Rachel Bean, Alessandro Melchiorri, and Joe Silk

1 Dept. of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA.
2 Astrophysics, Denys Wilkinson Building, University of Oxford, Keble road, OX1 3RH, Oxford, UK
3 Università di Roma “La Sapienza, Ple Aldo Moro 2, 00185, Rome, Italy

We place new constraints on sources of ionizing and resonance radiation at the epoch of the recombination process using the recent CMB temperature and polarization spectra coming from WMAP. We find that non-standard recombination scenarios are still consistent with the current data. In light of this we study the impact that such models can have on the determination of several cosmological parameters. In particular, the constraints on curvature and baryon density appear to be weakly affected by a modified recombination scheme. However, it may affect the current WMAP constraints on inflationary parameters like the spectral index, $n_s$, and its running. Physically motivated models, like those based on primordial black hole or super heavy dark matter decay, are able to provide a good fit to the current data. Future observations in both temperature and polarization will be needed to more stringently test these models.

I. INTRODUCTION

The recent measurements of the Cosmic Microwave Background (CMB) flux provided by the Wilkinson Microwave Anisotropy Probe (WMAP) mission have truly marked the beginning of the era of precision cosmology. In particular, the position and amplitude of the detected oscillations in the angular power spectrum of the CMB are in spectacular agreement with the expectations of the standard model of structure formation, based on primordial adiabatic and nearly scale invariant perturbations. Assuming this model of structure formation, an indirect but accurate measurement of several cosmological parameters has been reported in agreement with those previously indicated.

However, beside a full confirmation of the previous scenario (with a sensible reduction of the error bars!) the WMAP data set is also hinting towards a modification of the standard picture in several aspects. In particular, the low CMB quadrupole possible scale dependence of the spectral index high optical depth (see e.g. and ) possible deviations from flatness and dark energy have already produced a wide interest. Further, the relatively high $\chi^2$ per degree of freedom of the fiducial model suggests systematics and/or new physics could be considered.

It is therefore timely, with the increased precision of the CMB dataset to further test the standard scenario and to investigate possible deviations.

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

The recombination process can be modified in several ways. For example, one could use a model independent, phenomenological approach such as in where models are specified by the position and width of the recombination surface in redshift space. Here we will instead focus on theoretically motivate mechanisms based on extra sources of ionizing and resonance radiation at recombination (see e.g. ).

II. BEYOND STANDARD RECOMBINATION

In the standard recombination model the net recombination rate is given by

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

where $x_e$ is the ionization fraction, $a_e$ and $b_e$ are the effective recombination and photo-ionization rates for
principle quantum numbers \( \geq 2 \), and \( \Delta B \) is the difference in binding energy between the 1st and 2nd energy levels. In addition to the single Ly-\( \alpha \) transition with wavelength \( \lambda_\alpha \), there is also 2 photon decay from the meta-stable 2s level, with decay rate \( \Lambda_{2s} \). The contribution of this process is reflected in the parameter \( C \),

\[
C = \frac{1 + K \Lambda_{1s2s} n_{1s}}{1 + K (\Lambda_{1s2s} + b_c) n_{1s}}, \quad K = \frac{\lambda_\alpha^3}{8\pi H(z)}
\]

(2)

The standard hydrogen recombination scenario can be simply extended in two ways with the addition of Ly-\( \alpha \) and ionizing photons \( \setminus \).

The extra contributions can be related to the baryon number density through the efficiency functions \( \varepsilon_\alpha \) and \( \varepsilon_i \), respectively,

\[
\frac{dn_\alpha}{dt} = \varepsilon_\alpha(z) H(z) n, \quad \frac{dn_i}{dt} = \varepsilon_i(z) H(z) n
\]

(3)

where \( H(z) \) and \( n \) are the Hubble expansion parameter and mean baryon density (neutral H and protons) respectively. We leave photons produced by two body interactions, for example of annihilation of WIMPs, with \( \frac{dn_i}{dt} = \sigma_{WIMP} n_{WIMP}^2 \) for future investigation.

The addition of extra Ly-\( \alpha \) and ionization photons in equation \( \setminus \) adjusts the recombination rate from the standard model in equation \( \setminus \)

\[
- \frac{dx_e}{dt} = - \frac{dx_e}{dt} \big|_{\text{std}} - C\varepsilon_i H - (1 - C)\varepsilon_\alpha H.
\]

(4)

There are a range of physical mechanisms which could generate additional photons, we review them briefly here, see \( \setminus \) and references therein for a fuller discussion and derivations.

In general \( \varepsilon_\alpha \) and \( \varepsilon_i \) are functions of redshift, dependent upon the particle decay model that is being employed, and the size of the decay lifetime, \( t_x \) in comparison to the lifetime of the universe \( t_0 \).

Primordial black hole (PBH) decay \( \setminus \) at the moment of recombination can be described by a model of the form

\[
\varepsilon_j = c_j \zeta^{-2} \exp(-\zeta^{-2}), \quad \zeta = \frac{1 + z}{1 + z_{\text{dec}}}
\]

(5)

where \( j \) can be \( \alpha \) or \( i \) and \( z_{\text{dec}} \) is the redshift of photon decoupling. The authors of \( \setminus \) use \( c_\alpha \approx 0.3 \) and \( c_i \approx 0.13 \) however these values are dependent on assumptions about the PBH mass and number density distributions, which in turn rely on the nature of the inflationary spectrum \( \setminus \) and the possibility of accretion \( \setminus \).

Electromagnetic cascades from general particle decay can be described by the parameterization \( \setminus \)

\[
\varepsilon_{\alpha,i} \sim 10^{-8} \frac{\Omega_B h^2}{\Omega_B h^2} \Theta[z(t_x)](1 + z)^r
\]

(6)

with \( r = 1/2 \) for particle release from topological defects, \( r = -1 \) for decay of super heavy dark matter (SHDM), and where the normalization is the EGRET energy density \( \setminus \), although one could imagine using a code such as DARKSUSY \( \setminus \) to get a more precise normalization value. The proportionality constant \( \Theta[z(t_x)] \) reflects an alteration required for decay time dependence in the normalization of SHDM scenarios. For short lived SHDM with \( t_x < t_0 \), \( \Theta[z(t_x)] \sim \exp \left( (1 + z[t_x])^{3/2} \right) \) and equals 1 for all other cases. Short lived SHDM can therefore have substantially higher values for \( \varepsilon_{i,\alpha} \).

Note that in both particle and BH decay the models predict \( \varepsilon_i \sim \varepsilon_\alpha \). We demonstrate the size and evolution of \( \varepsilon_i \) for scenarios described above in Fig. \( \setminus \).

The combined effect on reionization from mechanisms such as those described above would obviously require a sum over contributions from all sources. Our aim is to find an upper limit on the overall contribution, independent of source, and as such we adopt a simple parameterization using constant, effective values for \( \varepsilon_i \) and \( \varepsilon_\alpha \). In Figs. \( \setminus \) and \( \setminus \) we plot the temperature (TT) and temperature-polarization cross correlation (TE)
FIG. 2: CMB TT spectra for various values of $\varepsilon_\alpha$ (top) and $\varepsilon_i$ (bottom) showing the increasing suppression and shift of the peaks as one increases the number of extra resonance and ionizing photons, respectively, in comparison to the WMAP best fit fiducial model with $\varepsilon_i = \varepsilon_\alpha = 0$ (full line). Spectra are normalized to $C_{87}$.

FIG. 3: CMB TE spectra for various values of $\varepsilon_\alpha$ (top) and $\varepsilon_i$ (bottom) against a fiducial case with $\varepsilon_\alpha = \varepsilon_i = 0$ (full line). In each case a reionization redshift of $z_{ri} = 7$ is used for comparison.

power spectra for several values of $\varepsilon_\alpha$ and $\varepsilon_i$. Qualitatively, increasing $\varepsilon_\alpha$ broadens the epoch of recombination and lowers the redshift when the optical depth drops through unity. Delaying recombination increases the angular diameter distance at last scattering and therefore shifts the first peak to lower $l$. The delay also increases the optical depth, suppressing the height of the peaks in comparison to the low $l$ plateau and decreasing the ratio of the second to first peaks.

Increasing $\varepsilon_i$ introduces a plateau in ionization fraction, preventing a trend towards full recombination. Boosting the number density of ionizing photons, increases the optical depth significantly more than a similar increase in Ly-\(\alpha\) photons, resulting in a pronounced suppression on the first peak height. Subsequently we would expect much tighter constraints on $\varepsilon_i$ from the TT and TE spectra.

It is interesting to note that introducing a large extra ionizing component can give a large cross-correlation on large scales, similar to that generated by early reionization. However it is unable to account for both the TT and TE observations simultaneously because of the peak suppression in the TT spectrum.

III. LIKELIHOOD ANALYSIS

Our analysis method is based on the computation of a likelihood distribution over a grid of precomputed theoretical models. We restrict our analysis to a flat, adiabatic, $\Lambda$-CDM model template computed with a modified version of CMBFAST, sampling the parameters as follows: $\Omega_{cdm} h^2 \equiv \omega_{cdm} = 0.05, ... , 0.25$, in steps of 0.01; $\Omega_b h^2 \equiv \omega_b = 0.009, ... , 0.030$, in steps of 0.001 and $h = 0.55, ... , 0.85$, in steps of 0.05. The value of the cosmological constant $\Lambda$ is determined by the flatness condition. Our choice of the above parameters is motivated by Big Bang Nucleosynthesis bounds on $\omega_b$ (both from D [32] and $^4$He + $^7$ Li [33]), from supernovae [34] and galaxy clustering observations (see e.g. [35, 36]). From the grid above we only consider models with age of the universe $t_0 > 11$ Gyrs. We vary the spectral index of the primordial density perturbations within the range $n_s = 0.8, ... , 1.2$, we allow for a possible (instantaneous) reionization of the intergalactic medium by varying the reionization redshift $5 < z_{ri} < 25$ and we allow a free re-scaling of the fluctuation amplitude by a pre-factor of the order of $C_{87}$, in units of $C_{87}^{\text{NORM}} = 1.9 \mu K^2$. Finally, we let $\varepsilon_\alpha$ and $\varepsilon_i$ vary as follows: $10^{-4} < \varepsilon_\alpha < 10^2$, and $< 10^{-4} < \varepsilon_i < 10^2$ in logarithmic steps.

The theoretical models are compared with the recent temperature and temperature-polarization WMAP data using the publicly available likelihood code [10, 37].

In Fig. 4 we plot the likelihood contours in the $\varepsilon_\alpha - \varepsilon_i$ plane showing the $2\sigma$ and $3\sigma$ contours. As we can see there is no strong correlation between the two parameters.

Marginalizing over all the remaining nuisance parameters we obtain the following constraints: $\varepsilon_\alpha < 10^{0.5}$ and $\varepsilon_i < 10^{-1.2}$ at 95% c.l.
As we can see, despite the high precision of the WMAP data, substantial modifications to the recombination process might be present. In Table I we demonstrate this for models discussed in section [11]. Ionizing photons from PBH decay are still in good agreement with the data, to within 1σ. Similarly, assuming the normalization prescription given in [25], long lived SHDM particles are not constrained well by the data, however there is a sharp cut off in the likelihood for particles that would decay on timescales shorter than $t(z) = 6$.

Since a modified recombination scheme can still be in agreement with the data, it is interesting to study the impact these modifications might have on the constraints of several parameters determined in the standard analysis. In Fig. [6] we demonstrate the benefits of having both the TT and TE spectra available in breaking potential degeneracies with spatial curvature. With pre-WMAP uncertainties in the TT spectrum peak heights relative to the plateau, a ‘degeneracy’ between curvature and $\varepsilon_\alpha$ existed [10]. A non-zero value of $\varepsilon_\alpha$ can shift the TT spectrum peak positions in an open model so that they have a similar a fiducial Λ CDM case. However the accuracy of WMAP data over the first and second peaks, now allows such an open model to be distinguished by the peak suppression produced by increasing $\varepsilon$. Moreover, the reionization peak is strongly suppressed in the open scenario so the two scenarios are further differentiated by the inclusion of TE data.

In Fig. [6] we probe degeneracies that are less easily distinguished; projecting the constraints on $\varepsilon_\alpha$ and $\varepsilon_i$ in function of the baryon density, the spectral index and its running $dn_s/d\ln k$ at $k_0 = 0.05hMpc^{-1}$. As we can see, the constraints on $\omega_b$ are weakly affected by our simple modifications to the recombination process. The value of $\omega_b = 0.023 \pm 0.001$ is unaffected by the inclusion of $\varepsilon_\alpha$ or $\varepsilon_i$. This can be explained by the high precision measurements of Sachs-Wolfe plateau and the first 2 acoustic peaks made by the WMAP satellite, which breaks the degeneracy between $\omega_b$ and $\varepsilon_i$ found in Seager et al. Increasing $\varepsilon_\alpha$ or $\varepsilon_i$, however, can have an important impact on the determination of $n_s$. Namely, a modified recombination will have effects similar to those of an early reionization process, lowering the small scale anisotropies and allowing greater values of $n_s$ to be in agreement with the data.

**TABLE I:** Difference in $\chi^2$ from the best fit standard recombination model for a range of non-standard recombination scenarios discussed in section II, using WMAP TT and TE data. For the SHDM models we consider a range of decay lifetimes, $t_z$, measured in terms of the lifetime of the universe at a redshift, $t(z)$.

| Scenario | $\Delta \chi^2$ |
|----------|-----------------|
| PBH $c_\alpha = 0.3$, $c_i = 0.13$ | 1.9 |
| SHDM $\Theta \leq 10^7$, $z < 5.3$ | $\leq 0.3$ |
| $\Theta = 10^8$, $z = 6.0$ | 8.7 |
| $\Theta = 10^9$, $z = 6.5$ | 3757 |

**FIG. 4:** Likelihood contour plot in the $\varepsilon_\alpha$-$\varepsilon_i$ plane showing the $2\sigma$ and $3\sigma$ contours.

**FIG. 5:** Figures demonstrating how a potential degeneracy between flat and spatially curved scenarios with non-zero $\varepsilon_\alpha$ is broken with WMAP TT and TE spectra. A WMAP best fit fiducial model with $z_i = 17$ and $\Omega_K = 0$ (full line) is shown against a model with $\Omega_K = 0.6$ and $\varepsilon_\alpha = 10^3$ and $z_i = 17$ (dashed line) that prior to the WMAP data release had some degeneracy with the standard scenario. In particular note how the addition of the TE spectrum strongly breaks the degeneracy, since the open model has a strongly suppressed reionization peak.
FIG. 6: Correlations between $\varepsilon_\alpha$ and $\varepsilon_i$ with several cosmological parameters. The redshift of reionization is fixed at $z_{ri} = 12$ and the Hubble parameter is $h = 0.68$. One can see that while the baryon density is robust to alterations in $\varepsilon_\alpha$ and $\varepsilon_i$, both the scalar spectral index and its running are sensitive.

Finally, it is interesting to study the correlation with a possible running of the spectral index. In Peiris et al. (8), a $\sim 2\sigma$ evidence for a negative running of the spectral index has been found. This is not expected in most common inflationary scenarios and several mechanisms have been proposed to explain the effect (see e.g. 9). However, as we can see from the plots at the bottom of Fig 6 a delayed recombination will in general not solve this problem, but it will enhance it towards a more negative running (in the plots we assume $n_s = 0.93$). A possible solution might come from a speeding up of recombination rather than delay, through having concentrations of baryons in high density, low mass clouds, for example 24. The accelerated recombination, because of the resultant premature reduction in the ionization fraction, can be parameterized by an effective $\varepsilon_\alpha < 0$ with $\varepsilon_i \geq 0$ still. As we see in Fig. 7 negative values of $\varepsilon_\alpha$ are more consistent with a zero running, although are likely not sufficient to fully explain the observed phenomenon.

FIG. 7: Correlation between a negative $\varepsilon_\alpha$ and a running of the spectral index $dn/d\ln k$ at $k = 0.05 h \text{Mpc}^{-1}$. The redshift of reionization is fixed at $z_{ri} = 12$, the Hubble parameter is $h = 0.68$, $n_s = 0.93$ and $\varepsilon_i = 0$.

IV. CONCLUSIONS

We have probed the upper bounds that can be placed on the contribution of extra Ly-\(\alpha\) and ionizing photon-producing sources through their effect on recombination and subsequently on the CMB TT and TE spectra. We have found that, adopting a simple parametrization using constant, effective values for $\varepsilon_\alpha$ and $\varepsilon_i$, the WMAP data constrains $\varepsilon_\alpha < 10^{0.5}$ and $\varepsilon_i < 10^{-1.2}$ at the 95% level.

We have found that the WMAP data is able to break many of the worrying degeneracies between $\varepsilon_\alpha$, $\varepsilon_i$ and the more standard cosmological parameters. In particular, the constraints on curvature and baryon density appear to be weakly affected by a modified recombination scheme. However, it may affect the current WMAP constraints on inflationary parameters like the spectral index $n_s$ and its running.

Physically motivated models, like those based on primordial black hole or super heavy dark matter decay, are able to provide a good fit to the current data. Future observations in both temperature and polarization, from the next WMAP release and the Planck satellite 25, will be needed if we are to more stringently test these models.

Acknowledgements It is a pleasure to thank David Spergel for helpful comments and suggestions. RB is supported by WMAP. We acknowledge the use of CMBFAST 31. We thank the organizers of the CMBNET workshop in Oxford, February 2003, and the Oxford-Princeton Workshop on Cosmology, in Princeton, March 2003, where portions of this work
were completed.