

Constraining non standard recombination: A worked example

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We fit the BOOMERANG, MAXIMA and COBE/DMR measurements of the cosmic microwave background anisotropy in spatially flat cosmological models where departures from standard recombination of the primeval plasma are parametrized through a change in the fine structure constant α compared to its present value. In addition to α we vary the baryon and dark matter densities, the spectral index of scalar fluctuations, and the Hubble constant. Within the class of models considered, the lack of a prominent second acoustic peak in the measured spectrum can be accommodated either by a relatively large baryon density, by a tilt towards the red in the spectrum of density fluctuations, or by a delay in the time at which neutral hydrogen formed. The ratio between the second and first peak decreases by around 25% either if the baryon density $\Omega_b h^2$ is increased or the spectral index n decreased by a comparable amount, or if neutral hydrogen formed at a redshift z_* about 15% smaller than its standard value. We find that the present data is best fitted by a delay in recombination, with a lower baryon density than the best fit if recombination is standard. Our best fit model has $z_* = 900$, $\Omega_b h^2 = 0.024$, $\Omega_m h^2 = 0.14$, $H_0 = 49$ and $n = 1.02$. Compatible with present data at 95% confidence level $780 < z_* < 1150$, $0.018 < \Omega_b h^2 < 0.036$, $0.07 < \Omega_m h^2 < 0.3$ and $0.9 < n < 1.2$.

I. INTRODUCTION

Measurements of the Cosmic Microwave Background (CMB) anisotropy provide information about the physical conditions in the universe right before decoupling of matter and radiation, and allow for a precise determination of many cosmological parameters. The recently published results of the BOOMERANG [1] and MAXIMA [2] experiments provide strong confirmation of the presence of the first acoustic peak in the anisotropy angular power spectrum at the degree scale, which suggests that the Universe is very close to spatial flatness. BOOMERANG and MAXIMA also provided high quality data at smaller angular scales, which do not reveal the presence of a prominent second acoustic peak.

The location, height and width of the first peak is in excellent concordance with the simplest spatially flat cosmological models with a nearly scale invariant spectrum of adiabatic density fluctuations (such as those motivated by generic inflationary models) and values of all cosmological parameters in good agreement with independent observations.

The lack of a prominent second acoustic peak requires instead some sort of departure from the simplest models or most likely values of some cosmological parameters. Three possibilities have been highlighted [3–7]: i) the power spectrum of primordial density perturbations is tilted in the direction that suppresses small scale fluctuations; ii) the baryonic matter density is slightly above the upper value expected from big-bang nucleosynthesis; iii) the formation of atomic hydrogen was delayed by some mechanism that perturbed the standard ionization history of the Universe.

The first mechanism reduces the height of the second peak simply because a spectrum tilted towards the red has less power at smaller angular scales. The second and third mechanisms work because the ratio between the heights of the second and first peaks decreases when the ratio $R = \frac{3}{4}\rho_b/\rho_\gamma$ between baryon and radiation energy-densities at decoupling increases [8]. Either if ρ_b is increased or if recombination is shifted to lower redshifts $R(z_*)$ increases and the relative height of the second peak decreases. The shift of z_* to lower redshifts also shifts the location of the peaks in the angular power spectrum towards larger angular scales.

Peebles, Seager and Hu [5] developed a picture where very early sources of Ly α resonance radiation provide a delay in recombination rapid enough to avoid excessive dissipation of the first acoustic peak, and cause a 10% reduction in

the relative height of the second peak along with a 5% shift in the location of the first peak. Their model is essentially parametrized by the rate of excess of radiation by the early sources from that in the primeval plasma.

In this paper we further explore the compatibility of present CMB anisotropy measurements with a non standard recombination history. We parametrize departures from standard recombination through a change in the fine structure constant around decoupling compared to its present value. We then compute constraints in four cosmological parameters plus the fine structure constant from the COBE/DMR, BOOMERANG and MAXIMA data on CMB anisotropy.

In section II we discuss the effects upon the CMB anisotropy spectrum of a variation in the fine structure constant at decoupling compared to its present value, and argue that they mimic the effects of other physical mechanisms that may change the recombination history. In section III we fit the COBE/DMR, BOOMERANG and MAXIMA data within spatially flat cosmological models allowing for variations of the fine structure constant, the baryon and dark matter energy densities, the Hubble constant, and the scalar fluctuations spectral index. We place bounds on the allowed variation of the fine structure constant, which translate into bounds on departures from standard recombination. In section IV we discuss the results.

II. VARIATION OF THE FINE STRUCTURE CONSTANT AS A MODEL OF NON STANDARD RECOMBINATION

Time-dependence in the fine structure constant α modifies the pattern of observed cosmic microwave background fluctuations [9,10]. Qualitatively, the main effect of a variation in α is due to the change in the binding energy of hydrogen. A change in α also changes the Thomson scattering cross section and modifies the recombination rates.

We used the CMBFAST code [11] with appropriate modifications to determine the effects of a change in α , along similar lines and with comparable results as in [9,10].

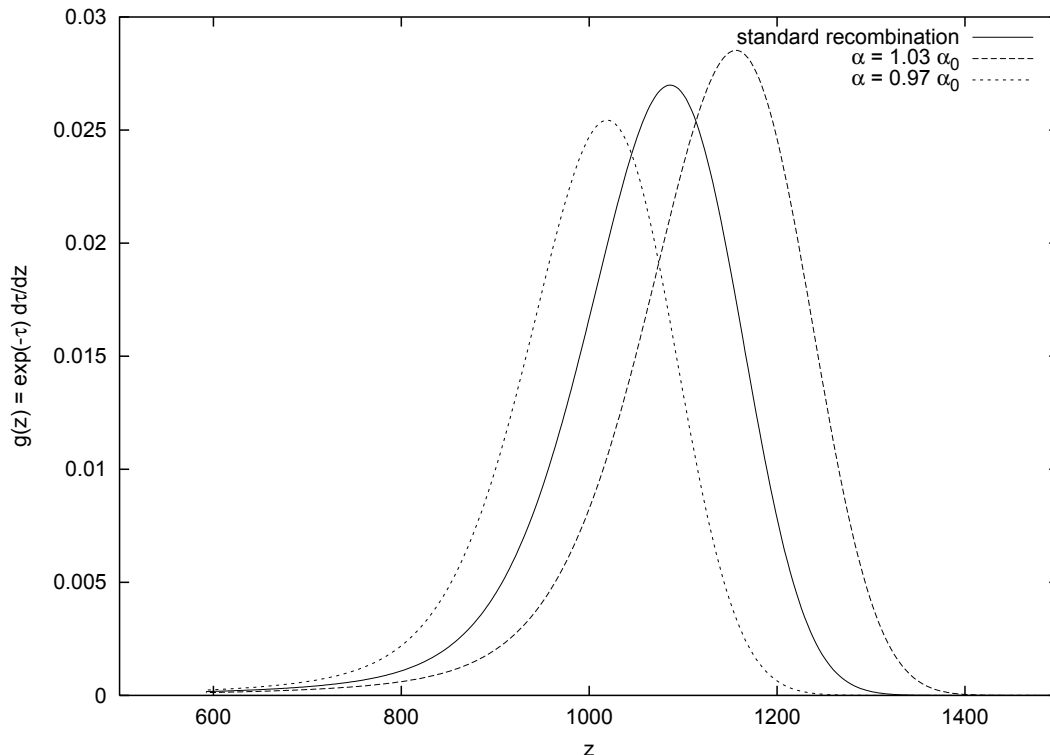


FIG. 1. The visibility function in a model with standard recombination, and with recombination delayed (advanced) through a reduction (increase) of the fine structure constant α around decoupling by 3%

The observed pattern of CMB anisotropies is largely determined by the visibility function, $g(z) = \exp(-\tau(z))d\tau/dz$, which measures the differential probability that a photon last scattered at redshift z . τ is the optical depth due to

Thomson scattering. Of course, $g(z)$ is extremely sensitive to the recombination history, since it largely depends on the time evolution of the fraction of free electrons.

If α was smaller (larger) at recombination than its present value α_0 , the peak in the visibility function shifts towards smaller (larger) redshifts, and its width slightly increases (reduces) [9,10]. These effects can be appreciated in Fig. 1, which displays the results of raising and lowering α by 3% around decoupling compared to its present value.

The hydrogen binding energy scales as $B \propto \alpha^2$. Since the ionization fraction is largely determined by the Boltzmann factor $\exp(-B/T)$, the location of the peak of the visibility function should roughly scale as $\Delta T_*/T_* \propto 2\Delta\alpha/\alpha$ in the limit of small $\Delta\alpha$. Although this scaling is not exact [9], $\Delta z_*/z_* \approx 2\Delta\alpha/\alpha$ provides a reasonably good fit to the shift in the peaks in Fig. 1. The width of the visibility function, δz_* , scales approximately as $\Delta(\delta z_*)/\delta z_* \approx -\Delta\alpha/\alpha$.

Non standard recombination histories should have an effect upon the visibility function similar to that described above, except that the changes in the peak position and width may follow independent rates of change. In this respect, a variation of the fine structure constant alone can not mimic an arbitrary mechanism that may delay or advance recombination. At any rate, a variation of the fine structure constant is a good one-parameter emulator of realistic mechanisms for delayed recombination, since it incorporates the basic feature of shifting the decoupling redshift while maintaining a sufficiently fast recombination rate. Different physical mechanisms may delay recombination increasing the width of the last scattering surface at a different rate, compared to the shift in the peak, than a change in α . The important common feature is that the effect can be differentiated from changes in other cosmological parameters, such as the baryon matter density or the spectral index of density fluctuations.

Indeed, the principal effect of a decrease in the value of the fine structure constant around decoupling is due to the shift of z_* to lower values. The decrease of z_* boosts the location of the acoustic peaks towards larger angular scales. A reduction of z_* also implies an increase in $R(z_*)$, the ratio between baryon and photon energy densities at decoupling, which increases the height difference between even and odd peaks. The height of the first peak is also affected by the change in the contribution of modes that entered the horizon during the radiation dominated period (the ‘‘early integrated Sachs-Wolfe effect’’). Finally, the increase in the width of the visibility function that follows a decrease in the fine structure constant makes diffusion damping more effective, pushing down the damping tail of CMB anisotropies, while slightly increasing the still undetected degree of linear polarization [12]. This extra diffusion damping may help differentiate, when higher angular resolution data becomes available, a decrease of α or a delay in recombination from an increase in the baryon density or a red tilt in the spectral index.

Time dependence of the fine structure constant is actually a theoretical possibility that deserves consideration by its own, not just as a model for delayed recombination. Indeed, unification schemes such as superstrings and Kaluza-Klein theories predict time variation of fundamental constants over cosmological timescales [13–15]. More recently, a number of authors considered cosmological theories where the fine structure constant time dependence is due to the variation of the speed of light [16–18] (constraints on these theories from CMB anisotropy measurements were analysed in [19]). Furthermore, different versions of the above mentioned theories predict different time-dependence of fundamental constants. Thus, experimental bounds on their allowed variation are an important tool to check the validity of these theories.

Constraints on the time variation of the fine structure constant have been placed from geophysical and astronomical methods. The Oklo natural nuclear reactor that operated about 1.8×10^9 yrs ago in Oklo, Gabon [20] yields a constraint of $-0.9 \times 10^{-7} < \Delta\alpha/\alpha < 1.2 \times 10^{-7}$. Laboratory measurements based on comparisons of rates between clocks with different atomic numbers give a limit of $\Delta\alpha/\alpha < 1.4 \times 10^{-14}$ during 140 days [21]. From the analysis of natural long-lived α and β decayers in geological minerals and meteorites Dyson [22] has placed a bound of $\Delta\alpha/\alpha < 2 \times 10^{-5}$. The wealth of local tests, including possible correlated synchronous changes of different physical constants, lead to the estimate $\Delta\alpha/\alpha < 2 \times 10^{-5}$ for variations during the last few billion years [23].

The astronomical methods are based mainly in the analysis of spectra from high-redshift quasar absorption systems [24–27]. Most of the previous mentioned experimental data gave only upper bounds (e.g. the most stringent $\Delta\alpha/\alpha = (-4.6 \pm 5.7) \times 10^{-5}$ for a set of redshifts $z \sim 2 - 4$ [24]). Webb et al. [25], reported a positive measurement of the fine structure constant variation: $\Delta\alpha/\alpha = (-1.09 \pm 0.36) \times 10^{-5}$.

Primordial nucleosynthesis provides a constraint to variations in α at the earliest times, derived from the relative abundance of ${}^4\text{He}$ [28]. However, to compute this constraint a model for the α dependence of the proton to neutron mass ratio must be assumed. L. Bergström *et al.* [29] have arrived at the bound: $\Delta\alpha/\alpha < 2 \times 10^{-2}$ including in their analysis not only the ${}^4\text{He}$ abundances but also the abundances of other lighter elements that are much less model dependent.

III. DATA ANALYSIS

We have performed a maximum likelihood analysis of the COBE/DMR, BOOMERANG and MAXIMA data within spatially-flat cosmological models with adiabatic density fluctuations. We computed the anisotropy correlation multipoles C_l for a grid of models allowing for variations in $\alpha/\alpha_0 = 0.86 - 1.04$, $\Delta\alpha/\alpha_0 = 0.02$; $\omega_b = 0.01 - 0.04$, $\Delta\omega_b = 0.003$; $\omega_m = 0.05 - 0.6$, $\Delta\omega_m = 0.05$; $H_0 = 45 - 95$, $\Delta H_0 = 5$; $n = 0.8 - 1.15$, $\Delta n = 0.05$. Here $\omega_b = \Omega_b h^2$, $\omega_m = \Omega_m h^2$ and α_0 is the present value of the fine structure constant. The cosmological constant was fixed to keep each model spatially flat, so that $\Omega_\Lambda = 1 - (\omega_b + \omega_m)/h^2$. The Hubble constant H_0 is measured in km/s Mpc, and $h = H_0/(100 \text{ km/s Mpc})$. We included calibration errors (20% for BOOMERANG and 8% for MAXIMA) through the covariance matrix of measurement errors as described in [30]. The amplitude A_s of the scalar fluctuation spectrum was fixed minimizing χ^2 for each model.

Our best fit model to the data, with 30 degrees of freedom reduced by 5 parameters, is characterized by:

$$\omega_b = 0.024, \quad \omega_m = 0.14, \quad \frac{\alpha}{\alpha_0} = 0.91, \quad H_0 = 49, \quad n = 1.02, \quad \chi^2 = 30.55 \quad (1)$$

If we fix as a prior that recombination be standard ($\alpha = \alpha_0$) the best fit becomes (with now 30 degrees of freedom reduced by 4 parameters):

$$\omega_b = 0.031, \quad \omega_m = 0.19, \quad H_0 = 81, \quad n = 1.02, \quad \chi^2 = 33.90 \quad (2)$$

If the prior is that the baryonic matter density $\omega_b = 0.019$ (the nucleosynthesis favoured value [31]) the best fit is:

$$\omega_m = 0.1, \quad \frac{\alpha}{\alpha_0} = 0.9, \quad H_0 = 45, \quad n = 0.96, \quad \chi^2 = 34.96 \quad (3)$$

Fig. 2 displays the anisotropy angular power spectrum for the best fit model along with the COBE/DMR, BOOMERANG and MAXIMA data points, as well as the best fit model in the case of a standard recombination history.

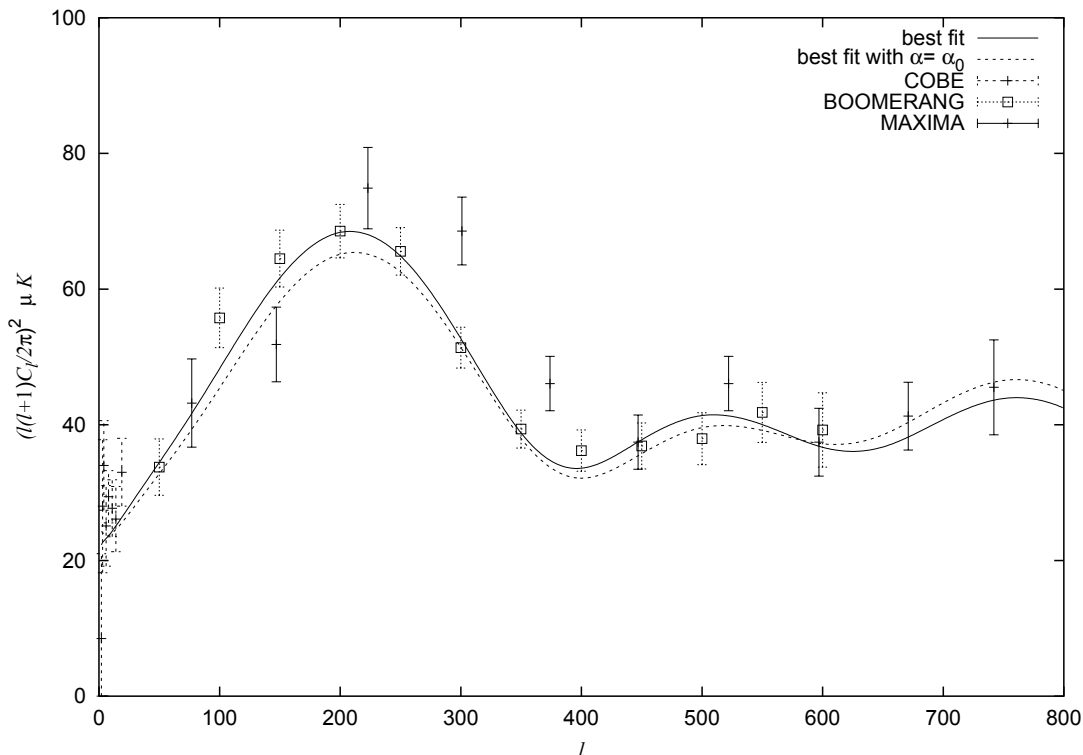


FIG. 2. Best fit model allowing a variation of the fine structure constant (solid line) and best fit model with standard recombination (dashed line).

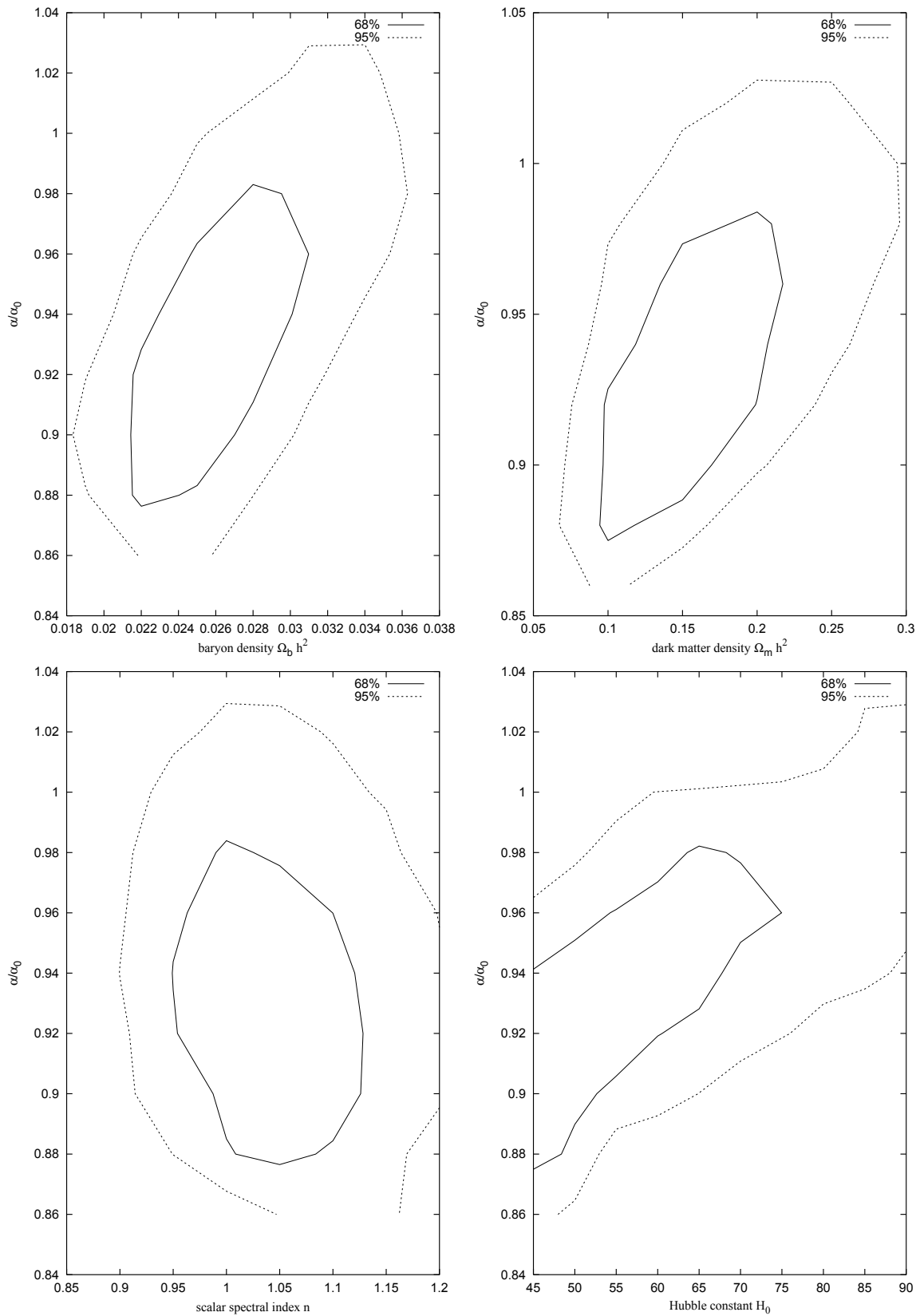


FIG. 3. $1\text{-}\sigma$ and $2\text{-}\sigma$ likelihood contours for $\Omega_b h^2$, $\Omega_m h^2$, H_0 and n vs. the relative change in the fine structure constant in spatially flat cosmological models. The delay in recombination is $\Delta z_*/z_* \approx 2(\alpha/\alpha_0 - 1)$.

Two dimensional marginalized likelihood confidence contours of the four different cosmological parameters considered as a function of the variation of the fine structure constant are shown in figure 3. As we discussed in section I, the lack of a prominent second acoustic peak in the BOOMERANG and MAXIMA data can be accommodated within simple spatially flat cosmological models either with a relatively large baryon density, a tilt towards the red in the power spectrum, or a delay in recombination. Our contours show that current data favour delayed recombination over the other options, which at any rate are all consistent at the 95% confidence level.

The likelihood contour in the plane (ω_b, α) reveals a degeneracy between reducing the baryonic matter density and delaying recombination. The best fit model, in which α is smaller by more than 8% than its present value, and thus recombination is delayed by around 16% in redshift, has indeed a baryon density more than 25% smaller than the best fit model with standard recombination. Still, the best fit model has a baryon density slightly above the nucleosynthesis upper bound.

The best fit when the baryon density is fixed to the nucleosynthesis preferred value ($\omega_b = 0.019$) requires a large (20%) delay in the recombination redshift, in addition to a small (about 4%) tilt of the spectral index towards the red.

The two-dimensional contours also reveal that fit of the data in delayed recombination scenarios is best with relatively small values of the Hubble constant. The degeneracy with the value of the spectral index is instead rather small. All the range allowed for departures from standard recombination at 95% confidence level is compatible with a scale invariant ($n = 1$) spectrum.

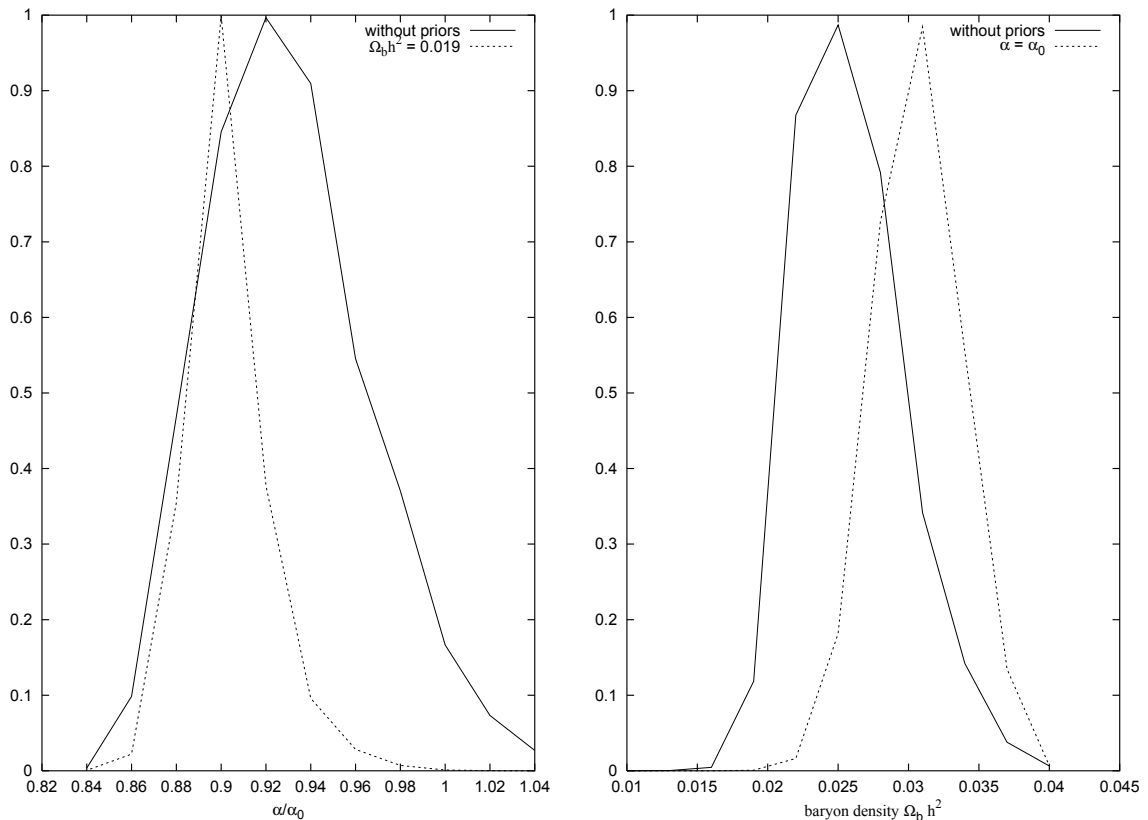


FIG. 4. One dimensional marginalized likelihoods. Left panel: marginalized over ω_b, ω_m, H_0 and n , as a function of α/α_0 (without priors) and with ω_b fixed to its nucleosynthesis prediction; right panel: marginalized over ω_m, H_0, n and α as a function of ω_b (without priors) and with α fixed to its present value α_0 (standard recombination).

One dimensional marginalized likelihoods are shown in figure 4. These make clearer that, within the family of cosmological model considered, the present data are best fit in a delayed recombination scenario. If the baryon density is within the nucleosynthesis bound then delayed recombination is imperative (a tilt in the spectral index alone is not enough).

At 95 % confidence level, the bounds on the constrained parameters are

$$0.018 < \Omega_b h^2 < 0.036, \quad 0.07 < \Omega_m h^2 < 0.3, \quad 0.86 < \alpha/\alpha_0 < 1.03, \quad H_0 < 95, \quad 0.9 < n < 1.2 \quad (4)$$

We can use the CMB anisotropy data to place a bound, within the family of cosmological models considered, upon departures from standard recombination. We computed z_* (determined as the location of the peak in the visibility function) for each model in the grid. Then we found the model with minimum χ^2 for z_* in given fixed intervals. From this result we built a one-dimensional likelihood for z_* , shown in figure 5.

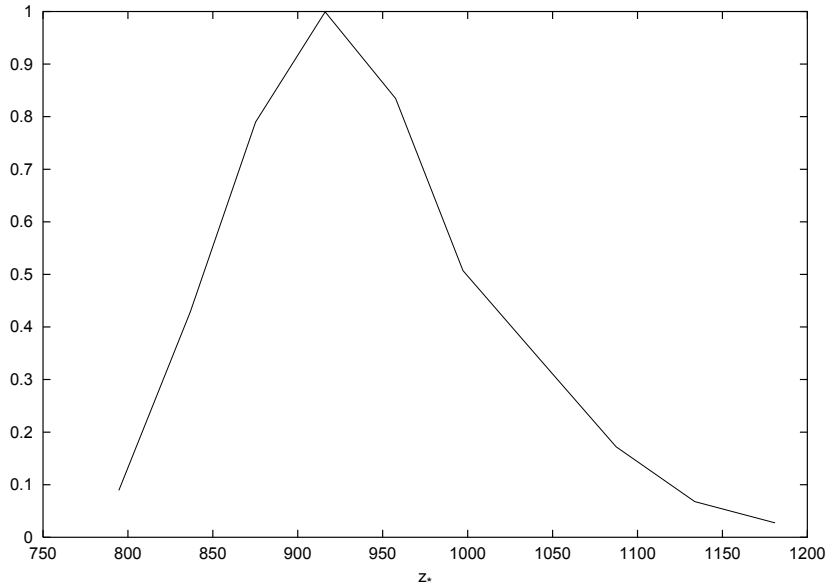


FIG. 5. One dimensional marginalized likelihood for z_*

From figure 5 we estimate the allowed range for z_* to be, at the 95% confidence level,

$$780 < z_* < 1150 \quad (5)$$

with a best fit value around $z_* = 900$.

Notice that the result in eq. 5 is in very good agreement with the range in z_* one would expect from the range $0.86 < \alpha/\alpha_0 < 1.03$ and the approximate scaling $z_* = 1080[1 + 2(\alpha - \alpha_0)/\alpha_0]$.

IV. CONCLUSIONS

We have modeled non standard recombination through a variation of the fine structure constant α around decoupling compared to its present value α_0 . We performed a maximum likelihood analysis of the BOOMERANG, MAXIMA and COBE/DMR measurements of the cosmic microwave background anisotropy in a grid of spatially flat cosmological models with five parameters varied independently: α , $\Omega_b h^2$, $\Omega_m h^2$, h and n . The recombination redshift scales approximately as $z_* = 1080[1 + 2(\alpha - \alpha_0)/\alpha_0]$.

The lack of a prominent second acoustic peak in the data suggests that the best fit should have, within the family of models considered, either a relatively large baryon density compared to the nucleosynthesis value $\omega_b = 0.019$, a tilt away from scale invariance towards the red in the spectrum of density fluctuations, or a delay in the time at which the CMB decoupled from matter. The best fit is that recombination was largely delayed to a redshift around $z_* = 900$, with a nearly scale invariant spectrum of fluctuations, a low value of the Hubble constant, $H_0 = 49$, and a baryon density $\Omega_b h^2 = 0.024$. A delay in recombination allows a good fit to the data with a lower baryon density as compared to a standard ionization history. Acceptable fits with a baryon density as low as $\Omega_b h^2 = 0.018$ can be achieved with longer recombination delays. Good fits with such low baryon densities can not be achieved with just a tilt in the spectral index and a standard recombination history. Recombination can not be delayed beyond $z_* \approx 780$ at 95% confidence level and within the cosmological models considered. Notice that in our grid of models $H_0 > 45$. Recombination may eventually be delayed to lower values of z_* at the same confidence level if this (realistic) prior assumption upon H_0 were lifted.

It is instructive to discuss these results from a semianalytic approach. It has been shown [32] that the power spectrum of CMB anisotropies up to the third acoustic peak can be conveniently characterized by four observables,

namely: the position of the first acoustic peak l_1 , the height of the first peak relative to COBE normalization H_1 , the height of the second peak relative to the first H_2 and the height of the third peak relative to the first H_3 . We have performed a semianalytic fit around our best fit model of eq. (1) assuming a linear dependence on the parameters, with the approximate result:

$$\frac{\Delta l_1}{l_1} = 1.4 \frac{\Delta \alpha}{\alpha} + 0.05 \frac{\Delta \omega_b}{\omega_b} - 0.14 \frac{\Delta \omega_m}{\omega_m} - 0.17 \frac{\Delta H_0}{H_0} + 0.19 \Delta n \quad (6)$$

$$\frac{\Delta H_1}{H_1} = 0.9 \frac{\Delta \alpha}{\alpha} + 0.44 \frac{\Delta \omega_b}{\omega_b} - 0.47 \frac{\Delta \omega_m}{\omega_m} - 0.13 \frac{\Delta H_0}{H_0} + 2.6 \Delta n \quad (7)$$

$$\frac{\Delta H_2}{H_2} = 3.2 \frac{\Delta \alpha}{\alpha} - 0.85 \frac{\Delta \omega_b}{\omega_b} - 0.04 \frac{\Delta \omega_m}{\omega_m} + 0.96 \Delta n \quad (8)$$

$$\frac{\Delta H_3}{H_3} = 2.3 \frac{\Delta \alpha}{\alpha} - 0.35 \frac{\Delta \omega_b}{\omega_b} + 0.38 \frac{\Delta \omega_m}{\omega_m} + 1.2 \Delta n \quad (9)$$

The peaks location and heights of the best fit model are given by $l_1 = 206.5$, $H_1 = 7.8$, $H_2 = 0.37$, $H_3 = 0.43$.

Equation (8) condenses most of the discussion we already made in sections I and II about the effects that can accommodate the absence of a prominent second peak in the present CMB anisotropy data. Indeed, the relative height of the second acoustic peak compared to the first decreases by about 10% if α decreases around 3%. Alternatively, the same reduction in H_2 can be obtained by an increase of around 10% in the baryon density, or a 10% tilt towards the red in the spectral index of density fluctuations. H_2 is instead quite insensitive to ω_m and H_0 .

Notice from eq. (6) that a decrease in α by 3% not only reduces H_2 by around 10% but also shifts the location of the first acoustic peak by almost 5% towards larger angular scales. This coincides with the results of Ref. [5], for a specific model of delayed recombination based in early Ly α sources of ionizing radiation.

The data from BOOMERANG and MAXIMA does not have the accuracy and angular resolution to test for the presence of a third acoustic peak. Consequently, we should not use H_3 as a relevant parameter. Eqs. (6-8) alone are insufficient to analyse degeneracies as a function of just one parameter. It is however quite apparent from the two-dimensional contours of the previous section that the weakest degeneracy is that on the spectral index n , which is quite close to scale invariance. If we assume $\Delta n = 0$ we derive, imposing $\Delta l_1 = \Delta H_1 = \Delta H_2 = 0$,

$$\frac{\Delta \omega_b}{\omega_b} = 3.6 \frac{\Delta \alpha}{\alpha}, \quad \frac{\Delta \omega_m}{\omega_m} = 3.5 \frac{\Delta \alpha}{\alpha}, \quad \frac{\Delta H_0}{H_0} = 6.4 \frac{\Delta \alpha}{\alpha} \quad (10)$$

which is in very good agreement with the shape of the two-dimensional likelihood contours of the previous section.

Variations in ω_b , α and n modify H_2 . Neither the variation of ω_b nor of n have a strong impact upon the location of the first acoustic peak. Variation of α does, as we already discussed. Compensation of the peak shift as α decreases requires a large decrease either of H_0 or of ω_m . Something similar happens with H_1 , which is also very sensitive to changes in the spectral index n . Our results reveal a strong degeneracy in the plane (α, H_0) , which appears to be quite robust, in the sense that it persists with similar strength even under variations of n . The degeneracy in the plane (α, ω_m) is instead quite sensitive to the precise degeneracy in the (α, n) plane. Information on the structure of the angular power spectrum of CMB anisotropies around the location of the third acoustic peak is necessary to more accurately pinpoint this issue and eventually break some of the present degeneracies.

A decrease in α , as well as any delayed recombination mechanism in which there is an increase in the width of the visibility function, makes diffusion damping more effective, which increasingly reduces the heights of the peaks at smaller angular scales. This is already noticeable around the third acoustic peak. A decrease in α that reduces H_2 as efficiently as an increase in ω_b has a stronger effect in reducing H_3 , as can be seen from eqs. (8,9). Notice, for instance, that the best fit model with delayed recombination of Fig. 2 has a third acoustic peak suppressed compared to the best fit with standard recombination, which has a larger baryon density. Measurements of the spectrum around and beyond the third acoustic peak can potentially break the degeneracy between the effects of an increase in ω_b and delayed recombination.

Our results can also be seen as a bound on departures from standard recombination, which can happen at redshifts as low as $z_* = 780$ at 95% confidence level, or as a bound on the time variation of the fine structure constant between decoupling and the present time. The bound we obtain, $0.02 > \Delta \alpha / \alpha > -0.14$, is an order of magnitude weaker than expected in [9] from future satellite measurements. The weakness of this bound is a consequence of the large present degeneracies. More accurate measurements and higher angular resolutions will certainly improve this bound. Whether a full order of magnitude improvement is or is not achieved will depend on how much this degeneracy is actually broken.

Our result that there is a preference for a smaller value of α at decoupling compared to its present value is in agreement with similar conclusions of recent work [33,34] that also analysed BOOMERANG and MAXIMA data

allowing for a variation in the fine structure constant. In the present work we used the time variation of the fine structure constant as an example of how to model non-standard recombination histories. A preprint that develops a two-parameter model for non-standard recombination histories [35] appeared after submission of our paper, with compatible results.

V. ACKNOWLEDGEMENTS

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