

WMAP Constraints on varying α and the Promise of Reionization

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Abstract

We present up-to-date constraints on the value of the fine-structure constant at the epoch of decoupling from the recent observations made by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite. In the framework of models we considered, a positive (negative) variation of the value of α at decoupling with respect to the present-day value is now bounded to be smaller than 2% (6%) at 95% confidence level. We point out that the existence of an early reionization epoch as suggested by the above measurements will, when more accurate cosmic microwave background polarization data is available, lead to considerably tighter constraints. The so-called ‘reionization bump’, in particular, will be extremely useful for this purpose. We find that the tightest possible constraint on α is about 0.1% using CMB data alone—tighter constraints will require further (non-CMB) priors.

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I. INTRODUCTION

Now that WMAP has validated beyond reasonable doubt the so-called concordance (or is it conspiracy?) model of cosmology [1, 2, 3, 4], it is time to proceed to the next level of questioning and start asking what are the ‘dark components’ that make up about 96% of the energy budget of the universe. Most of this is in some non-baryonic form, for which there is at present no direct evidence or solid theoretical explanation. Understanding its nature will clearly require further progress in fundamental physics.

Cosmology and astrophysics provide a laboratory with extreme conditions in which to test fundamental physics and search for new paradigms. Currently preferred unification theories [5, 6] predict the existence of additional space-time dimensions, which have a number of possibly observable consequences, including modifications in the gravitational laws on very large (or very small) scales [7] and space-time variations of the fundamental constants of nature [8, 9]. Recent evidence of a time variation of fundamental constants [10, 11, 12] offers an important opportunity to test such fundamental physics models. It should be noted that the issue is not *if* such theories predict such variations, but *at what level* they do so, and hence if there is any hope of detecting them in the near future.

The most promising case is that of the fine-structure constant α , for which some evidence of time variation at redshifts $z \sim 2 - 3$ already exists [10, 11]. Since one expects α to be a non-decreasing function of time [13, 14, 15], it is particularly important to try to constrain it at earlier epochs, where any variations relative to the present-day value should be larger. (On the other hand, local laboratory tests can also provide useful constraints [16].) The cosmic microwave background (CMB) anisotropies provide such a probe, being mostly sensitive to the epoch of decoupling, $z \sim 1100$. Here we extend our previous work in this area [17, 18, 19] by analyzing the recently released WMAP first-year data and providing updated constraints on the value of α at decoupling. We emphasize that in previous work, constraints on α were obtained with the help of additional cosmological datasets. Here, by contrast, we will analyse the WMAP dataset alone. We also discuss how these constraints can be improved in the future, when more precise CMB polarization data will be available. In particular, we show that the existence of an early reionization epoch is of significant help in further constraining α . A more detailed analysis of this issue can be found in a companion paper [20].

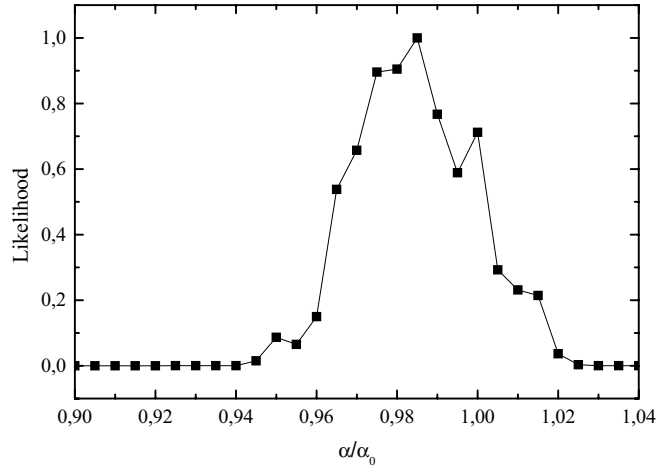


FIG. 1: Likelihood distribution function for variations in the fine structure constant obtained by an analysis of the WMAP data.

II. WMAP CONSTRAINTS ON α

We compare the recent WMAP temperature and cross-polarization data with a set of flat cosmological models adopting the likelihood estimator method described in [4]. The models are computed through a modified version of the CMBFAST code with parameters sampled as follows: physical density in cold dark matter $0.05 < \Omega_c h^2 < 0.20$ (step 0.01), physical density in baryons $0.010 < \Omega_b h^2 < 0.028$ (step 0.001), cosmological constant $0.0 < \Omega_\Lambda < 0.95$ step 0.05, $0.80 < \alpha_{\text{dec}}/\alpha_0 < 1.18$ (step 0.02). Here h is the Hubble parameter today, $H_0 \equiv 100h$ km s⁻¹ Mpc⁻¹ which is related to the above quantities by the flatness condition, while α_{dec} (α_0) is the value of the fine structure constant at decoupling (today). We verified that the marginalized likelihood distribution from WMAP for each of the above parameters has negligible values when computed at the extrema of the range allowed in the database. We also vary the optical depth τ in the range $0 - 0.30$ (step 0.04) and the scalar spectral index of primordial fluctuations $0.88 < n_s < 1.08$ (step 0.005). The upper limit for the optical depth is well motivated by numerical simulations (see e.g. [21]).

We don't consider gravity waves, running of the spectral index or iso-curvature modes since these further modifications are not required by the WMAP data.

The likelihood distribution function for $\alpha_{\text{dec}}/\alpha_0$, obtained after marginalization over the remaining parameters, is plotted in Figure 1. We found, at 95% C.L. that $0.94 < \alpha_{\text{dec}}/\alpha_0 <$

TABLE I: Experimental parameters for Planck (nominal mission). After removal of the foregrounds, f_{sky} is the effective fraction of the sky covered, while ℓ_{max} is the largest multipole attained.

	Planck HFI		
ν (GHz)	100	143	217
θ_c (arcmin)	10.7	8.0	5.5
σ_{cT} (μK)	5.4	6.0	13.1
σ_{cE} (μK)	n/a	11.4	26.7
$w_c^{-1} \cdot 10^{15}$ ($\text{K}^2 \text{ ster}$)	0.215	0.158	0.350
ℓ_c	757	1012	1472
ℓ_{max}	2000		
f_{sky}	0.80		

1.01, improving previous bounds (see [19] for the previous tighter bound, and [17, 18, 22] for earlier work) based on CMB and complementary datasets. Thus when it comes to constraining α in the primordial universe, the WMAP dataset alone is at least as good as everything else before it put together.

III. THE FUTURE: POLARIZATION AND REIONIZATION

In our previous work [19], only the CMB temperature was taken into account. The precision with which cosmological parameters can be reconstructed using both CMB temperature and E-polarization measurements is now re-examined by means of the Fisher Matrix Analysis (FMA) technique. This technique was first applied in this context by [23] (see also [24]). We consider the planned Planck satellite and an ideal experiment which would measure both temperature and polarization to the cosmic variance limit (in the following, ‘CVL experiment’).

Cosmological models are characterized by the 8 dimensional parameter set

$$\Theta = (\Omega_b h^2, \Omega_m h^2, \Omega_\Lambda h^2, \mathcal{R}, n_s, Q, \tau, \alpha), \quad (1)$$

where $\Omega_m = \Omega_c + \Omega_b$ is the energy density in matter and Ω_Λ the energy density due to a cosmological constant, and the Hubble parameter h is a dependent variable. The quantity

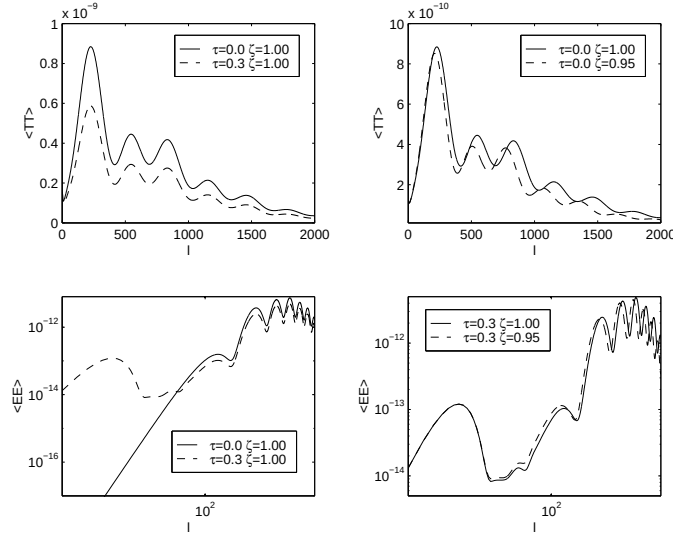


FIG. 2: Contrasting the effects of varying α and reionization on the CMB temperature and polarization. Here $\zeta = \alpha_{dec}/\alpha_0$.

$\mathcal{R} \equiv \ell_{\text{ref}}/\ell$ is the ‘shift’ parameter and $Q = \langle \ell(\ell+1)C_\ell \rangle^{1/2}$ denotes the overall normalization, where the mean is taken over the multipole range $2 \leq \ell \leq 2000$. We assume purely adiabatic initial conditions and we do not allow for a tensor contribution. The Fisher matrix expansion is done around a fiducial model with parameters $\omega_b = 0.0200$, $\omega_m = 0.1310$, $\omega_\Lambda = 0.2957$ (and $h = 0.65$), $\mathcal{R} = 0.9815$, $n_s = 1.00$, $Q = 1.00$, $\tau = 0.20$ and $\alpha/\alpha_0 = 1.00$. In our previous work [19] the numerical accuracy of the FMA was limited by the fact that differentiating around a flat model requires computing open and closed models, which are calculated using different numerical techniques. Here we instead differentiate around a slightly closed model (as preferred by WMAP) with $\Omega_{\text{tot}} = 1.01$ to avoid extra sources of numerical inaccuracies. We refer to [19, 20] for a detailed description of the numerical technique used. The experimental parameters used for the Planck analysis are in Table I, and we use the first 3 channels of the Planck High Frequency Instrument (HFI) only. Note that we account for possible issues arising from point sources, foreground removal and galactic plane contamination by assuming that once these have been taken into account we are left with a ‘clean’ fraction of the sky given by f_{sky} . For the cosmic variance limited (CVL) experiment, we set the experimental noise to zero, and we use a total sky coverage $f_{\text{sky}} = 1.00$. Although this is never to be achieved in practice, the CVL experiment illustrates the precision which can be obtained *in principle* from CMB temperature and E-polarization measurements.

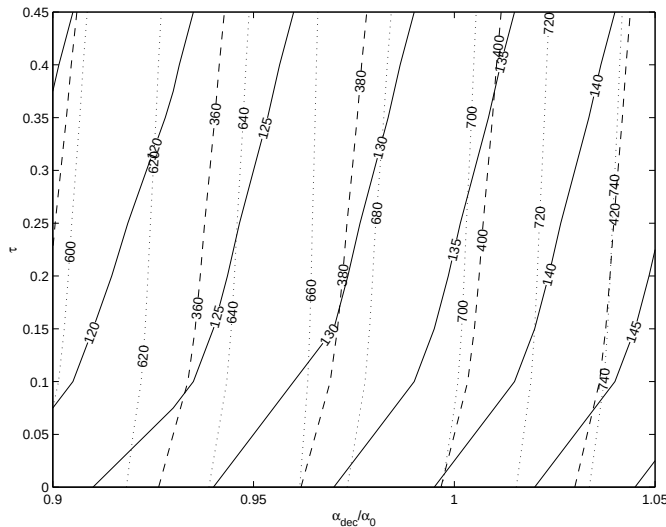


FIG. 3: The separation in ℓ between the reionization bump and the first (solid lines), second (dashed) and third (dotted) peaks in the polarization spectrum, as a function of α at decoupling and τ . An instantaneous reionization model is assumed.

Fig. 2 illustrates the effect of α and τ on the CMB temperature and polarization power spectra—see [20] for a more detailed discussion. The CMB power spectrum is, to a good approximation, insensitive to *how* α varies from last scattering to today. Given the existing observational constraints, one can therefore calculate the effect of a varying α in both the temperature and polarization power spectra by simply assuming two values for α , one at low redshift (effectively today’s value, since any variation of the magnitude of [10] would have no noticeable effect) and one around the epoch of decoupling, which may be different from today’s value. For the CMB temperature, reionization simply changes the amplitude of the acoustic peaks, without affecting their position and spacing (top left panel); a different value of α at the last scattering, on the other hand, changes both the amplitude and the position of the peaks (top right panel). The outstanding effect of reionization is to introduce a bump in the polarization spectrum at large angular scales (lower left panel). This bump is produced well after decoupling at much lower redshifts, when α , if varying, is much closer to the present day’s value. We emphasize that, for the reason pointed out above, *we do not need specify a redshift dependence for the variation*, although we could if we so choose. If the value of α at low redshift is different from that at decoupling, the peaks in the polarization power spectrum at small angular scales will be shifted sideways, while the reionization bump

TABLE II: Fisher matrix analysis results for a model with varying α and reionization: expected 1σ errors for the Planck satellite and for the CVL experiment (see the text for details). The column *marg.* gives the error with all other parameters being marginalized over; in the column *fixed* the other parameters are held fixed at their fiducial value; in the column *joint* all parameters are being estimated jointly.

	1σ errors (%)					
	Planck HFI			CVL		
	marg.	fixed	joint	marg.	fixed	joint
	E-Polarization Only (EE)					
α	2.66	0.06	7.62	0.40	< 0.01	1.14
τ	8.81	2.78	25.19	2.26	1.52	6.45
	Temperature Only (TT)					
α	0.66	0.02	1.88	0.41	0.01	1.18
τ	26.93	8.28	77.02	20.32	5.89	58.11
	Temperature + Polarization (TT+EE)					
α	0.34	0.02	0.97	0.11	< 0.01	0.32
τ	4.48	2.65	12.80	1.80	1.48	5.15

on large angular scales won't (lower right panel). It follows that by measuring the separation between the normal peaks and the bump, one can measure both α and τ , as illustrated in Fig. 3. Thus we expect that the existence of an early reionization epoch will, when more accurate cosmic microwave background polarization data is available, lead to considerably tighter constraints on α .

Table II and Fig. 4 summarize the forecasts for the precision in determining τ and α (relative to the present day value) with Planck and the CVL experiment. We consider the use of temperature information alone (TT), E-polarization alone (EE) and both channels (EE+TT) jointly. Note that one could use the temperature-polarization cross correlation (ET) instead of the E-polarization, with the same results. As it is apparent from Fig. 4, TT and EE suffer from degeneracies in different directions, because of the reasons explained above. Thus combination of high-precision temperature and polarization measurements can constrain in the most effective ways both variations of α and τ . Planck will be essentially

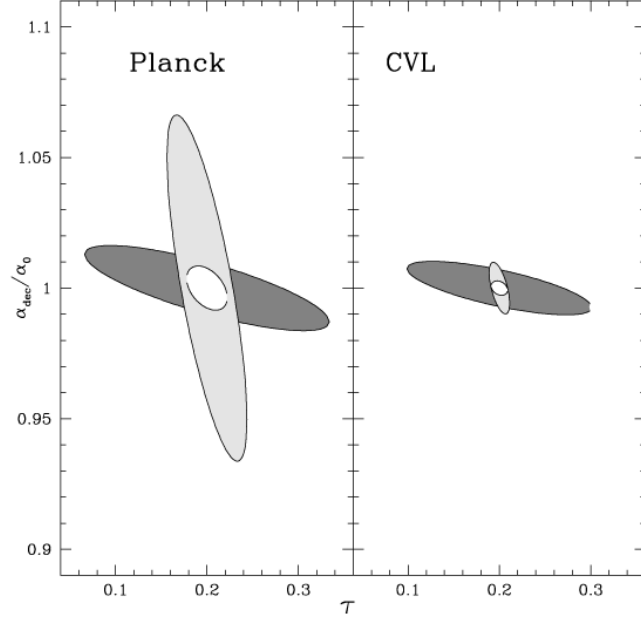


FIG. 4: Ellipses containing 95.4% (2σ) of joint confidence in the α vs. τ plane (all other parameters marginalized), for the Planck and cosmic variance limited (CVL) experiments, using temperature alone (dark grey), E-polarization alone (light grey), and both jointly (white).

cosmic variance limited for temperature but there will still be considerable room for improvement in polarization (Table II). This therefore argues for a post-Planck polarization experiment, not least because polarization is, in itself, better at determining cosmological parameters than temperature. We conclude that Planck alone will be able to constrain variations of α at the epoch of decoupling within 0.34% (1σ , all other parameters marginalized), which corresponds to approximately a factor 5 improvement on the current upper bound. On the other hand, the CMB *alone* can only constrain variations of α up to $\mathcal{O}(10^{-3})$ at $z \sim 1100$. Going beyond this limit will require additional (non-CMB) priors on some of the other cosmological parameters. This result is to be contrasted with the variation measured in quasar absorption systems by Ref.[10], $\delta\alpha/\alpha_0 = \mathcal{O}(10^{-5})$ at $z \sim 2$. Nevertheless, there are models where deviations from the present value could be detected using the CMB.

IV. CONCLUSIONS

We have tightened the CMB constraints on the value of the fine-structure constant at the epoch of decoupling, using the WMAP satellite data. We emphasize that this is the first constraint coming from the analysis of a single CMB measurement. Previous constraints on α used a combination of various CMB and other cosmological observables, such as supernovae, nucleosynthesis or the Hubble constant, in order to impose stronger priors on other key cosmological parameters. In this sense, the current WMAP data alone is at least as good as everything else before it put together. As in previous work [17, 18, 19], the current data is consistent with no variation, though the likelihood is skewed towards smaller values at the epoch of decoupling.

We have shown that CMB data alone will be able to constrain α up to the 0.1% level. Tighter constraints than this will require invoking further (non-CMB) priors. Nevertheless, the existence of an early reionization epoch as suggested by WMAP turns out to be a blessing for these measurements, once more accurate cosmic microwave background polarization data is available, and in particular we have proposed a novel way of exploiting it. These points are discussed in more detail in [20].

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