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WMAP 5-year constraints on time variation of α and m_e

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Abstract. We studied the role of fundamental constants in an updated recombination scenario, focusing on the time variation of the fine structure constant α and the electron mass m_e in the early Universe. Using CMB data including WMAP 5-yr release, and the 2dFGRS power spectrum, we put bounds on variations of these constants, when both constants are allowed to vary, and in the case that only one of them is variable. In particular, we have found that $-0.019 < \Delta\alpha/\alpha_0 < 0.017$ (95% c.l.), in our joint estimation of α and cosmological parameters. Finally, we analyze how the constraints depends on the recombination scenario.

1. Introduction

Time variation of fundamental constants is a prediction of theories that attempt to unify the four interactions in nature. Many observational and experimental efforts have been made to put constraints on such variations. Cosmic microwave background radiation (CMB) is one of the most powerful tools to study the early universe and in particular, to put bounds on possible variations of the fundamental constants between early times and the present.

Previous analysis of CMB data (earlier than the WMAP five-year release) including a possible variation of α have been performed by Martins et al. (2002); Rocha et al. (2003); Ichikawa et al. (2006); Stefanescu (2007); Mosquera et al. (2008); Landau et al. (2008) and including a possible variation of m_e have been performed by Ichikawa et al. (2006); Scóccola et al. (2008b); Landau et al. (2008); Yoo & Scherrer (2003).

In the last years, the process of recombination has been revised in great detail (Chluba & Sunyaev 2009a,b; Hirata & Forbes 2009), and in particular, helium recombination has been calculated very precisely, revealing the importance of considering new physical processes in the calculation of the recombination history (Dubrovich & Grachev 2005; Switzer & Hirata 2008a; Hirata & Switzer 2008; Switzer & Hirata 2008b; Kholupenko et al. 2007).

In a previous paper (Scóccola et al. 2008a), we have analized the variation of α and m_e in an improved recombination scenario. Moreover, we have put bounds on the possible variation of these constants using CMB data and the power spectrum of the 2dFGRS.

In Section 2, we review the dependences on α and m_e in the recombination scenario. In section 3 we present bounds on the possible variation of α and m_e using the 5-yr data release of WMAP (Hinshaw et al. 2009) together with other CMB experiments and the power spectrum of the 2dFGRS (Cole et al. 2005). In addition to the results of our previous work (Scóccola et al. 2008a), here we also present bounds considering only variation of one fundamental constant (α or m_e) alone. A comparison with similar analyses by other authors is presented in Section 4.

2. The detailed recombination scenario

The equations to solve the detailed recombination scenario can be found for example in Wong et al. (2008), as they are coded in Recfast. In the equation for helium recombination, a term which accounts for the semi-forbidden transition 2^3p–1^1s is added. Furthermore, the continuum opacity of HI is taken into account by a modification in the escape probability of the photons that excite helium atoms.

The cosmological redshifting of a transition line photon K and the Sobolev escape probability $p_{\rm S}$ are related through the following equation (taking He I as an example):

$$K_{\rm HeI} = \frac{g_{\rm HeI,1^1s}}{g_{\rm HeI,2^1p}} \frac{1}{n_{\rm HeI,1^1s} A^{\rm HeI}_{2^1p-1^1s} p_{\rm S}} \tag{1}$$

where $A_{\rm HeI,2^1p-1^1s}$ is the A Einstein coefficient of the He I 2^1p–1^1s transition. To include the effect of the continuum opacity due to HI, based on the approximate formula suggested by Kholupenko et al. (2007), $p_{\rm S}$ is replaced by the new escape probability $p_{esc} = p_s + p_{\rm con,H}$ with

$$p_{\rm con,H} = \frac{1}{1 + a_{\rm He}\gamma^{b_{\rm He}}}, \tag{2}$$

and

$$\gamma = \frac{\frac{g_{\rm HeI,1^1s}}{g_{\rm HeI,2^1p}} A^{\rm HeI}_{2^1p-1^1s}(f_{\rm He} - x_{\rm HeII})c^2}{8\pi^{3/2}\sigma_{\rm H,1s}(\nu_{\rm HeI,2^1p})\nu^2_{\rm HeI,2^1p}\Delta\nu_{\rm D,2^1p}(1-x_{\rm p})} \tag{3}$$

where $\sigma_{{\rm H},1s}(\nu_{\rm HeI,2^1p})$ is the H ionization cross-section at frequency $\nu_{\rm HeI,2^1p}$ and $\Delta\nu_{\rm D,2^1p} = \nu_{\rm HeI,2^1p}\sqrt{2k_{\rm B}T_{\rm M}/m_{\rm He}c^2}$ is the thermal width of the He I 2^1p–1^1s line.

The transition probability rates $A_{\rm HeI,2^1p-1^1s}$ and $A_{\rm HeI,2^3p-1^1s}$ can be expressed as follows (Drake & Morton 2007):

$$A^{\rm HeI}_{i-j} = \frac{4\alpha}{3c^2}\omega^3_{ij}\left|\left\langle\psi_i|r_1 + r_2|\psi_j\right\rangle\right|^2 \tag{4}$$

where ω_{ij} is the frequency of the transition, and $i(j)$ refers to the initial (final) state of the atom. It can be shown (Scóccola et al. 2008a) that to first order in perturbation theory, the dependence of the bracket goes as the Bohr radius a_0. On the other hand, ω_{ij} is proportional to the difference of energy levels and thus its dependence on the fundamental constants is $\omega_{ij} \simeq m_e\alpha^2$. Consequently, the dependence of the transition probabilities of HeI on α and m_e can be expressed as

$$A^{\rm HeI}_{i-j} \simeq m_e\alpha^5. \tag{5}$$

The dependences on α and m_e of all the physical quantities relevant at recombination are summarized in Table 1.

Fig. 1 shows the ionization history for different values of α. Recombination occurs at higher redshift if α is larger. On the other hand, there is little change when considering different recombination scenarios, for a given value of α. Something similar happens when varying m_e.

With regards to the fitting parameters $a_{\rm He}$ and $b_{\rm He}$, it is not possible to determine yet the effect that a variation of α or m_e would have on them. However, we have shown in Scóccola et al. (2008a) that for the precision of WMAP data, there is no need to know these dependences.

In Table 2 we show the results of our statistical analysis, and compare them with the ones we have presented in

3. Results

We performed our statistical analysis by exploring the parameter space with Monte Carlo Markov chains generated with the CosmoMC

Description	Physical Quantity	Dependence
Binding Energy of Hydrogen	B_1	$\alpha^2 m_e$
Transition frequencies	$\nu_{\mathrm{H2s}}, \nu_{\mathrm{HeI},2^1\mathrm{s}}, \nu_{\mathrm{HeI},2^3\mathrm{s}}$	$\alpha^2 m_e$
Photoionization cross section n	$\sigma_n(Z, h\nu)$	$\alpha^{-1} m_e^{-2}$
Thomson scattering cross section	σ_T	$\alpha^2 m_e^{-2}$
Recombination Coefficients Case B	α_{H}, α_{HeI}, α^t_{HeI}	$\alpha^3 m_e^{-3/2}$
Ionization Coefficients	$\beta_{\mathrm{H}}, \beta_{\mathrm{HeI}}$	α^3
Cosmological redshift of photons	K_{H}, K_{HeI}, K^t_{HeI}	$\alpha^{-6} m_e^{-3}$
Einstein A Coefficients	A^{HeI}_{i-j}	$\alpha^5 m_e$
Decay rate 2s → 1s	Λ_{H}, Λ_{HeI}	$\alpha^8 m_e$

Table 1. Dependence on α and m_e of the physical quantities relevant during recombination.

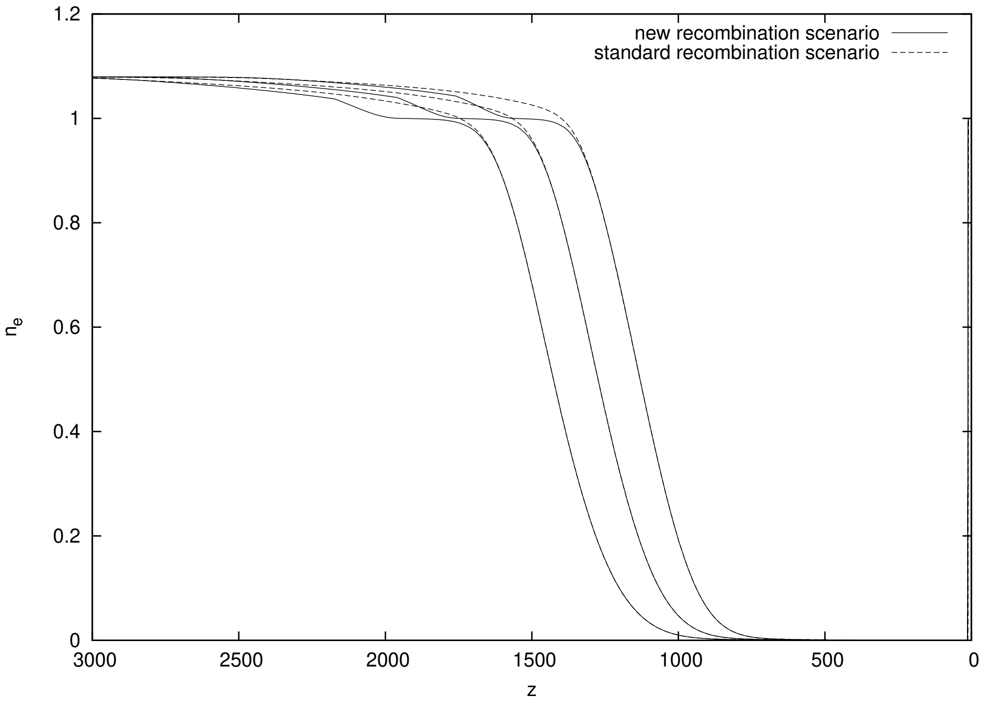

Fig. 1. Ionization history allowing α to vary with time. From left to right, the values of $\frac{\alpha}{\alpha_0}$ are 1.05, 1.00, and 0.95, respectively. The dotted lines correspond to the standard recombination scenario, and the solid lines correspond to the updated one.

code (Lewis & Bridle 2002) which uses the Boltzmann code CAMB (Lewis et al. 2000) and RECFAST to compute the CMB power spectra. We modified them in order to include the possible variation of α and m_e at recombination. Results are shown in Table 2.

We use data from the WMAP 5-year temperature and temperature-polarization power

parameter	wmap5 + NS	wmap5 + PS	wmap3 + PS
$\Omega_b h^2$	$0.02241^{+0.00084}_{-0.00084}$	$0.02242^{+0.00086}_{-0.00085}$	$0.0218^{+0.0010}_{-0.0010}$
$\Omega_{CDM} h^2$	$0.1070^{+0.0078}_{-0.0078}$	$0.1071^{+0.0080}_{-0.0080}$	$0.106^{+0.011}_{-0.011}$
Θ	$1.033^{+0.023}_{-0.023}$	$1.03261^{+0.024}_{-0.023}$	$1.033^{+0.028}_{-0.029}$
τ	$0.0870^{+0.0073}_{-0.0081}$	$0.0863^{+0.0077}_{-0.0084}$	$0.090^{+0.014}_{-0.014}$
$\Delta\alpha/\alpha_0$	$0.004^{+0.015}_{-0.015}$	$0.003^{+0.015}_{-0.015}$	$-0.023^{+0.025}_{-0.025}$
$\Delta m_e/(m_e)_0$	$-0.019^{+0.049}_{-0.049}$	$-0.017^{+0.051}_{-0.051}$	$0.036^{+0.078}_{-0.078}$
n_s	$0.962^{+0.014}_{-0.014}$	$0.963^{+0.015}_{-0.015}$	$0.970^{+0.019}_{-0.019}$
A_s	$3.053^{+0.042}_{-0.041}$	$3.05203^{+0.04269}_{-0.04257}$	$3.054^{+0.073}_{-0.073}$
H_0	$70.3^{+5.9}_{-5.8}$	$70.3^{+6.1}_{-6.0}$	$70.4^{+6.6}_{-6.8}$

Table 2. Mean values and 1σ errors for the parameters including α and m_e variations. NS stands for the new recombination scenario, and PS stands for the previous one.

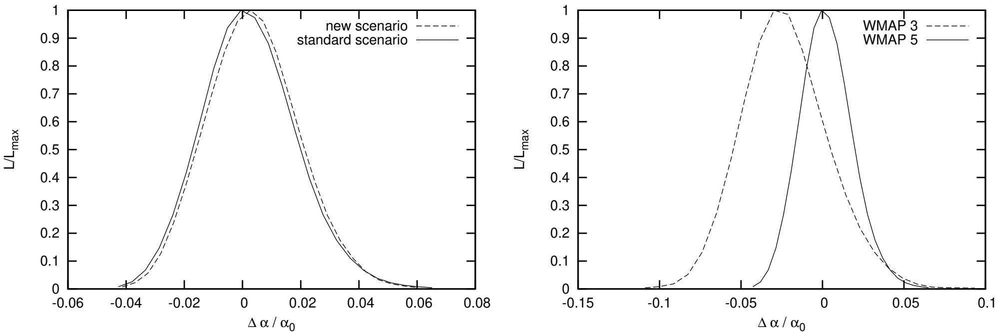

Fig. 2. One dimensional likelihood for $\frac{\Delta\alpha}{\alpha_0}$. Left figure: for WMAP5 data and two different recombination scenarios. Right figure: comparison for the standard recombination scenario, between the WMAP3 and WMAP5 data sets.

spectrum (Nolta et al. 2009), and other CMB experiments such as CBI (Readhead et al. 2004), ACBAR (Kuo et al. 2004), and BOOMERANG (Piacentini et al. 2006; Jones et al. 2006), and the power spectrum of the 2dFGRS (Cole et al. 2005). We have considered a spatially-flat cosmological model with adiabatic density fluctuations, and the following parameters:

$$P = \left(\Omega_B h^2, \Omega_{CDM} h^2, \Theta, \tau, \frac{\Delta\alpha}{\alpha_0}, \frac{\Delta m_e}{(m_e)_0}, n_s, A_s\right) \quad (6)$$

where $\Omega_{CDM} h^2$ is the dark matter density in units of the critical density, Θ gives the ratio of the comoving sound horizon at decoupling to the angular diameter distance to the surface of last scattering, τ is the reionization optical depth, n_s the scalar spectral index and A_s is the amplitude of the density fluctuations.

In Table 2 we show the results of our statistical analysis, and compare them with the ones we have presented in Landau et al. (2008), which were obtained in the standard recombination scenario (i.e. the one described in (Seager et al. 2000), which we denote PS), and using WMAP3 (Hinshaw et al. 2007; Page et al. 2007) data. The constraints are tighter in the current analysis, which is

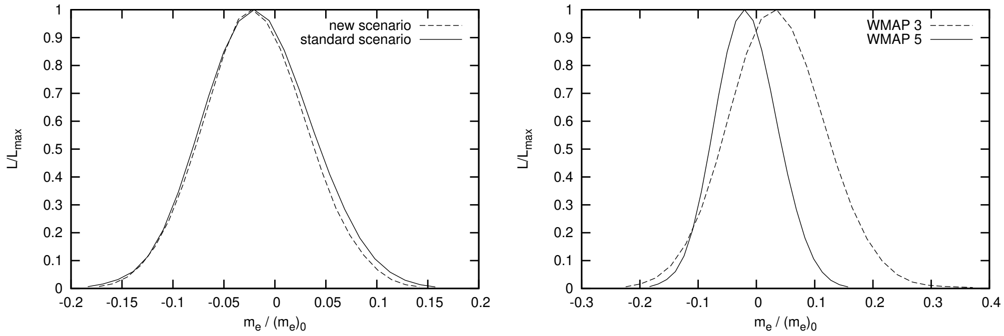

Fig. 3. One dimensional likelihood for $\frac{\Delta m_e}{(m_e)_0}$. Left figure: for WMAP5 data and two different recombination scenarios. Right figure: comparison between the WMAP3 and WMAP5 data sets for the standard recombination scenario.

an expectable fact since we are working with more accurate data from WMAP. The bounds obtained are consistent with null variation, for both α and m_e, but in the present analysis, the 68% confidence limits on the variation of both constants have changed. In the case of α, the present limit is more consistent with null variation than the previous one, while in the case of m_e the single parameters limits have moved toward lower values. To study the origin of this difference, we perform another statistical analysis, namely the analysis of the standard recombination scenario (PS) together with WMAP5 data and the other CMB data sets and the 2dFGRS power spectrum. The results are also shown in Table 2. We see that the change in the obtained results is due to the new WMAP data set, and not to the new recombination scenario. In Fig. 2 we compare the probability distribution for $\Delta\alpha/\alpha_0$ in different scenarios and with different data sets. In Fig. 3, we do the same for $\Delta m_e/(m_e)_0$. Bounds on the fundamental constants are shifted to a region of the parameter space closer to that of null variation in the case of α. On the other hand, limits on the variation of m_e are shifted to negative values, but still consistent with null variation. The bound on $\Omega_b h^2$ is also shifted to higher values.

We present here the results of our statistical analysis when only one fundamental constant is allowed to vary together with a set of cosmological parameters. We obtained these results using data from WMAP5, CBI, ACBAR, BOOMERANG, and the $P(k)$ of the 2dFGRS. The constraints (with 1-σ errors) on the variation of α are $\Delta\alpha/\alpha_0 = -0.002 \pm 0.009$ in the standard recombination scenario, and $\Delta\alpha/\alpha_0 = -0.001 \pm 0.009$ in the detailed recombination scenario. For m_e, both bounds are $\Delta m_e/(m_e)_0 = -0.01 \pm 0.03$. The limits are more stringent than in the case of joint variation of the constants. This is to be expected since the parameter space has higher dimension in the later case. The values for the cosmological parameters are consistent with those from the joint variation analysis.

4. Discussion

The obtained results for the cosmological parameters are in agreement within 1σ with the ones obtained by the WMAP collaboration (Dunkley et al. 2008), without considering variation of fundamental constants. It is also interesting to compare our results with the works of Nakashima et al. (2008) and Menegoni et al. (2009) where only the variation of α was analized using WMAP 5 year release and the Hubble Space Telescope (HST) prior on the H_0. In these works, the HST prior on H_0 is used to reduce the large degeneration between H_0 and α and find more stringent constraints on α variation. However, we have shown in Mosquera et al. (2008) (where the variation of α was analysed using the WMAP

3 year release), that more stringent constraints on α can be found using the power spectrum of the 2dFGRS. Indeed, our constraints on α alone are more stringent than those reported by Nakashima et al. (2008). On the other hand, our constraints are of the same order than those presented by Menegoni et al. (2009), using data from higher multipoles reported by recent CMB experiments, such as QUAD (QUaD collaboration: M. L. Brown et al. 2009) and BICEP (Chiang et al. 2009). Finally, it is important to stress, that when using the HST prior on H_0, the correct value to be used is the value obtained using only the closest objects, since bounds obtained using other objects could be affected by a possible α variation.

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