WMAP-5yr Constraint on the Varying Fine Structure Constant

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Abstract

The constraints on the time variation of the fine structure constant at recombination epoch relative to its present value,$\Delta\alpha/\alpha \equiv (\alpha_{\rm rec} - \alpha_{\rm now})/\alpha_{\rm now}$, are obtained from the analysis of the 5-year WMAP cosmic microwave background data. As a result of Markov-Chain Monte-Carlo analysis, it is found that, contrary to the analysis based on the previous WMAP data, the mean value of $\Delta\alpha/\alpha = -0.0009$ does not change significantly whether we use the Hubble Space Telescope (HST) measurement of the Hubble parameter as a prior or not. The resultant 95% confidence ranges of $\Delta\alpha/\alpha$ are $-0.028 < \Delta\alpha/\alpha < 0.026$ with HST prior and $-0.050 < \Delta\alpha/\alpha < 0.042$ without HST prior.

1 Introduction

The variation of the fundamental physical constants is a long-standing issue. Dirac first considered such a possibility [1] and proposed that the Newton constant should be inversely proportional to time. While his claim is not compatible with the current observations, recent unification theories such as superstring theories naturally predict the variation of the fundamental constants [2]. Because of these theoretical motivations, it is important to measure their possible time variation observationally.

Among various fundamental constants, the time variation of the fine structure constant α has been most extensively discussed in observational contexts. We briefly summarize those terrestrial and celestial limits on α as follows.

- $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}\ {\rm yr}^{-1}$ from the measurement of the frequency ratio of aluminium and mercury single-ion optical clocks[3].
- $\Delta\alpha/\alpha = (-0.8 \pm 1.0) \times 10^{-8}$ or $\Delta\alpha/\alpha = (0.88 \pm 0.07) \times 10^{-7}$ from the Oklo natural reactor in Gabon ($z \sim 0.1$)[4].
- $\Delta\alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}$ ($z \sim 0.2 - 4.2$) [5] and $\Delta\alpha/\alpha = (-0.64 \pm 0.36) \times 10^{-5}$ ($z \sim 0.4 - 2.3$) [6] from spectra of quasars.
- $-5.0\times10^{-2} < \Delta\alpha/\alpha < 1.0\times10^{-2}$ (95%C.L.) from big bang nucleosynthesis (BBN, $z \sim 10^9 - 10^{10}$)[7].
- $-0.048 < \Delta\alpha/\alpha < 0.032$,[8] $-0.06 < \Delta\alpha/\alpha < 0.01$ [9] or $-0.039 < \Delta\alpha/\alpha < 0.010$ [10] (95%C.L.) from the cosmic microwave background (CMB, $z \sim 10^3$), the former two of which are based on the analysis of the 1-year WMAP data and the last one on the 3-year WMAP data.

Here, we focus on the CMB constraint on α from 5-year WMAP data, finding new limits on its value at the recombination epoch[11]. While the other physical constants may vary in time simultaneously, they are so model-dependent that we consider only the variation of α.

Both CMB and BBN are useful for obtaining the constraints of the variation of α over a cosmological time scale. Although BBN is superior in the sense that it can probe a longer timespan, it has a drawback that the effect of α in Helium abundance Y_p is model-dependent so that we cannot obtain a robust result from BBN analysis. On the other hand, the physics of the CMB is much simpler and well understood with high-precision data, so we can obtain a meaningful limit on the variation of α from the CMB data.

2 CMB and varying fine structure constant

As is well known, changing the value of the fine structure constant affects the CMB power spectrum mainly through the change of the recombination time[12]. Hence, CMB probes the value of α in this particular epoch.

The recombination process is well approximated by the evolutions of three variables: the proton fraction, the fraction of the singly ionized Helium, and the matter temperature. Their evolution equations are so complicated that we solve them numerically by public RECFAST code[13]. Incorporating the α-dependence into RECFAST code and calculating the ionization fraction (or visibility function), we can find two charastrictic signatures of changing α: the higher redshift of the last scattering surface and the narrower width of the visibility function due to the larger value of *alpha* at the recombination epoch.

Then, increasing α results in three features in the angular power spectrum of the temperature anisotropy, namely, shift of the peaks to higher multipoles, increase in the height of the peaks due to the enhanced early integrated Sachs Wolfe effect, and decrease in the small-scale diffusion damping effect.

3 Results

We constrain the variation of α using three types of CMB anisotropy spectra, namely, angular power spectrum of temperature anisotropy, C_ℓ^{TT}, that of E-mode polarization, C_ℓ^{EE}, and cross correlation of temperature and E-mode polarization C_l^{TE} of the 5-year WMAP data[14]. For this purpose, we have modified the CAMB code [15] including the RECFAST code to calculate the theoretical anisotropy spectra for different values of α at recombination and we performed the parameter estimation using Markov-Chain Monte-Carlo (MCMC) techniques implemented in the CosmoMC code[16].

We have run the CosmoMC code on four Markov chains. To check the convergence, we used the ”variance of chain means”/”mean of chain variances” R statistic and adopted the condition $R-1 < 0.03$.

First, we consider the modified version of the flat ΛCDM model, that is, as for cosmological parameters, we take $(\Omega_B h^2, \Omega_{DM} h^2, H_0, n_s, A_s, \tau, \Delta\alpha/\alpha)$, where $\Omega_B h^2$ is the normalized baryon density, $\Omega_{DM} h^2$ is the normalized cold-dark-matter density, $H_0 \equiv 100h \left[\text{km sec}^{-1}\ \text{Mpc}^{-1}\right]$ is the Hubble constant, n_s is the spectral index of the primordial curvature perturbation, A_s is its amplitude, and $\Delta\alpha/\alpha \equiv (\alpha_{\text{rec}} - \alpha_{\text{now}})/\alpha_{\text{now}}$ is the variation of the fine structure constant at recombination relative to its present value. We have also analyzed the standard flat ΛCDM model without $\Delta\alpha/\alpha$ and compared the other parameter values between these two models.

The results obtained from MCMC calculations are given in Fig. 1, which shows the one-dimensional marginalized posterior distributions of the parameters. From the result, it can be seen that the effect of the additional parameter $\Delta\alpha/\alpha$ is only to increase the errors of the other parameters, and the mean values of the other parameters in modified flat ΛCDM are practically the same as in the standard flat ΛCDM. The marginalized distributions of H_0 and Ω_B in Fig. 1 suggest the degeneracy of these parameters with $\Delta\alpha/\alpha$.

Actually, in the above calcutions, we have incorporated the result of the Hubble Key Project of the Hubble Space Telescope (HST) on the Hubble parameter H_0,[17] that is, we have imposed a prior that H_0 is a Gaussian with the mean 72 $\left[\text{km sec}^{-1}\ \text{Mpc}^{-1}\right]$ and the variance 8 $\left[\text{km sec}^{-1}\ \text{Mpc}^{-1}\right]$. If we do not use the HST prior, we can only obtain weaker constraints on the parameter values because of projection degeneracy. To check the effect of the HST prior, we show one-dimensional distributions in Fig. 2. It is confirmed that the HST prior is very important to realistically constrain the time varition of α.

The 95% confidence interval and the mean value of $\Delta\alpha/\alpha$ from 5-year WMAP data with HST prior are

$$-0.028 < \Delta\alpha/\alpha < 0.026 \quad \text{and} \quad \Delta\alpha/\alpha = -0.000894, \tag{1}$$

respectively. Without the HST prior, they read

$$-0.050 < \Delta\alpha/\alpha < 0.042 \quad \text{and} \quad \Delta\alpha/\alpha = -0.00181, \tag{2}$$

respectively. Previous results from 1-year WMAP data are $-0.048 < \Delta\alpha/\alpha < 0.032$ and $-0.107 < \Delta\alpha/\alpha < 0.043$, with and without HST prior, respectively[8], so our results from 5-year WMAP data are

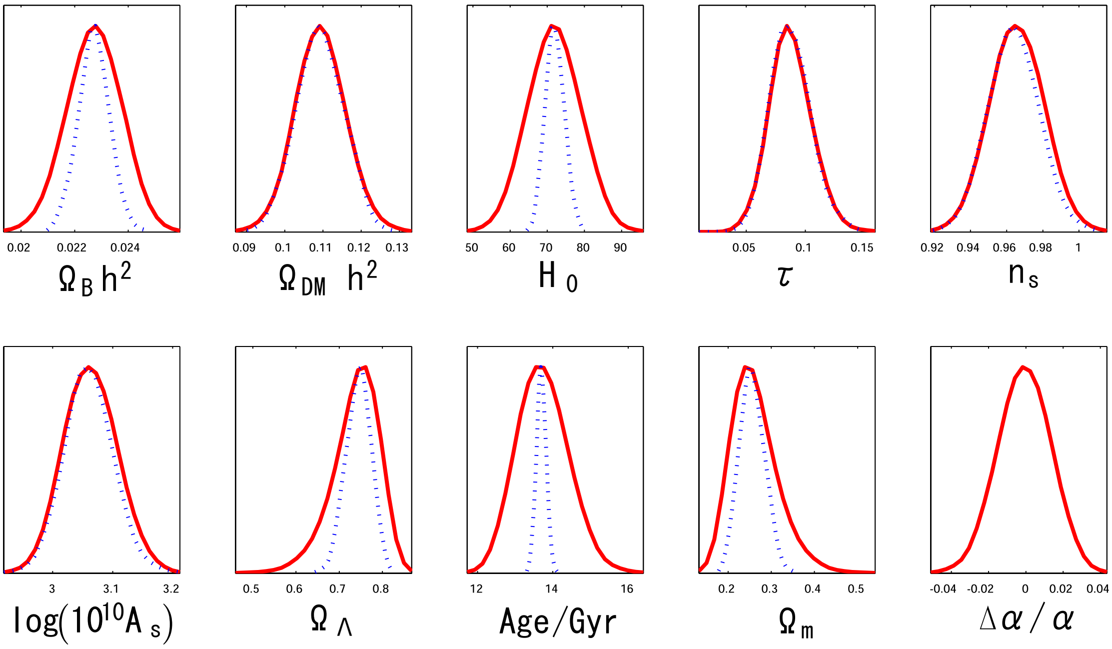

Figure 1: (colour online) One-dimensional marginalized posterior distributions for the parameters of the modified flat ΛCDM model (solid red curve), and for the standard flat ΛCDM model (dotted blue curve).

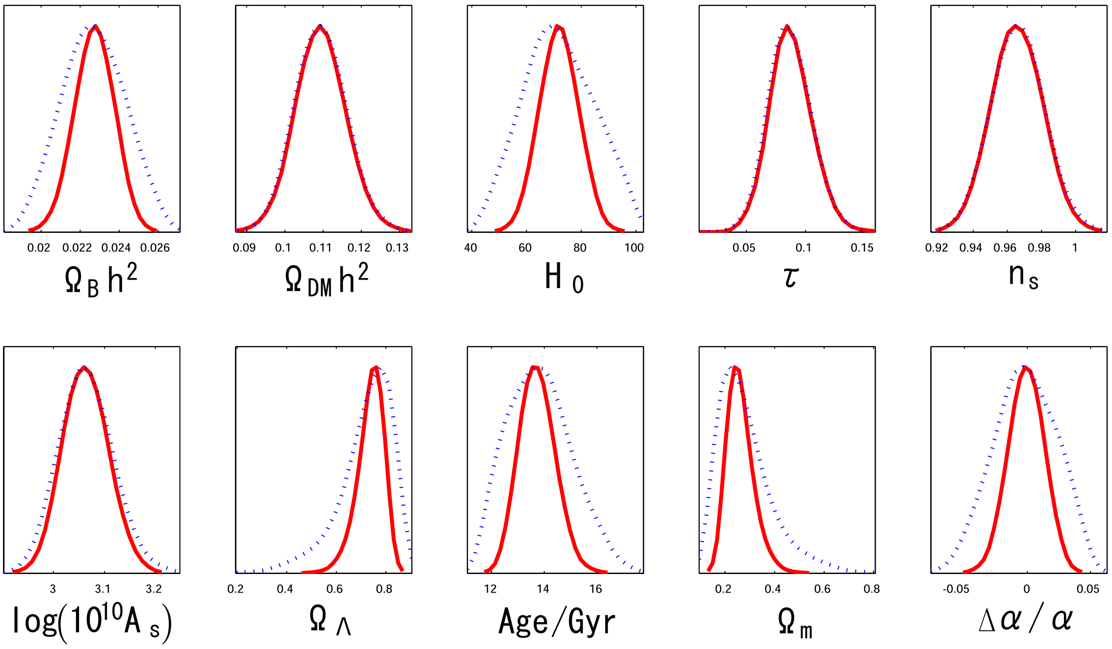

Figure 2: One-dimensional marginalized posterior distributions for the results with HST prior (solid red curve), and without it (dotted blue curve).

about 30% tighter than those from the 1-year WMAP data. We also note that for the 1-year data, the mean value of $\Delta\alpha/\alpha$ was found to be $\Delta\alpha/\alpha = -0.04$ without the HST prior although it was practically equal to 0 with it. For the 5-year data, we have found that the mean value remains practically intact whether we use the HST prior or not. This may be interpreted as an indication that the observational cosmology has made a step forward to the concordance at an even higher level.

4 Conclusion

In terms of the MCMC analysis using CosmoMC code, we have updated constraints on the time variation of the fine structure constant α based on 5-year WMAP data. We obtained tighter constraints compared with previous results from 1-year WMAP data owing to the inclusion of the polarization data and the decrease in the statistical errors. Compared with the result based on the 3-year WMAP data[10], where no comparison between the cases with and without HST prior has been made, the resultant limit is almost of the same order of magnitude but the mean value of ours is closer to 0. We have verified that the null result is favored concerning the variation of α, and the addition of this new parameter $\Delta\alpha/\alpha$ does not essentially affect the determinations of the other standard parameters contrary to the case of the analysis based on the 1-year WMAP data[8].

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