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New constraints on variations of the fine structure constant from CMB anisotropies

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We demonstrate that recent measurements of cosmic microwave background temperature and polarization anisotropy made by the ACBAR, QUAD, and BICEP experiments substantially improve the cosmological constraints on possible variations of the fine structure constant in the early universe. This data, combined with the five year observations from the WMAP mission, yield the constraint $\alpha/\alpha_0 = 0.987 \pm 0.012$ at 68% C.L. The inclusion of the new Hubble Space Telescope constraints on the Hubble constant further increases the accuracy to $\alpha/\alpha_0 = 1.001 \pm 0.007$ at 68% C.L., bringing possible deviations from the current value below the 1% level and improving previous constraints by a factor of ~ 3.

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I. INTRODUCTION

Nature is characterized by a number of physical laws and fundamental dimensionless couplings, which historically we have assumed to be spacetime invariant. For the former this assumption is a cornerstone of the scientific method (and alternatives are virtually inconceivable), but for the latter it is an assumption with no real justification. There is ample experimental evidence showing that fundamental couplings run with energy, and many particle physics and cosmology models suggest that they should also roll with time.

Searching for time variations of fundamental constants (see e.g. [1] and references therein) is a challenging but powerful probe of fundamental physics, and starts with the identification of laboratory or astrophysical environments that are so "clean" and well understood that any deviations from the expected behavior can be ascribed to new physics (as opposed to systematics or other uncertainties). The cosmic microwave background (CMB, hereafter) is one such example.

The astonishing agreement between the current measurements of and the theoretical expectations for CMB temperature and polarization anisotropies has opened the possibility of testing several aspects of fundamental physics in the early universe (see e.g. [2,3]). In particular, CMB anisotropies are sensitive to variations in fundamental constants such as the fine structure constant α (see e.g. [4–7]).

A time varying fine structure constant can leave an imprint on CMB anisotropies by changing the time of recombination and the size of the acoustic horizon at photon-electron decoupling, and the steadily improving CMB data sets have been extensively used to constrain it. Parametrizing a variation in the fine structure constant as $\Delta_\alpha = (\alpha - \alpha_0)/\alpha_0$, where $\alpha_0 = 1/137.035\,999\,07$ is the standard, local, value and α is the value during the recombination process, the authors of [8] used the first year WMAP data, finding the constraint $-0.06 < \Delta_\alpha < 0.01$ at 95% C.L. (see also [9]). This constraint was subsequently updated to $-0.039 < \Delta_\alpha < 0.01$ (see [10]) by combining the third year WMAP data with the Hubble Space Telescope key project constraint on the Hubble constant. More recently, using the five observations from the WMAP satellite, the authors of [11] found the constraint $-0.05 < \Delta_\alpha < 0.042$. It is well known (see e.g. [10]) that a variation in the fine structure constant is mostly degenerate with a variation in the Hubble constant $H_0 = 100h$ km/s/Mpc. Combining CMB data with independent measurements of H_0 can indeed improve the constraint on α.

Over the past few months substantial improvements have been reported both in measurements of CMB anisotropies and in the determination of the Hubble constant. The new results from the ACBAR [12], QUAD [13], and BICEP [14] experiments, together with the new release of the WMAP data from the five-year survey, are now sampling the CMB temperature angular spectrum with great accuracy down to arcminute angular scales and now also provide clear evidence for acoustic oscillations in the polarization channel. Moreover, the uncertainty on the Hubble constant has been reduced by more than half from the recent analysis of [15] yielding a new constraint of $h = 0.742 \pm 0.036$.

With these new experimental improvements it is therefore timely to investigate the new constraints on α, as we plan to do in this Brief Report. Our paper is therefore structured as follows: in the next section we briefly describe the data analysis method used, while in Sec. III we present our results. As we show in the Conclusion, the new data provide a significant improvement on the constraint on a time varying α.

II. ANALYSIS METHOD

We include a possible variation in the fine structure constant in the recombination process using the method adopted in [7] and modifying the publicly available RECFAST [16] routine in the CAMB [17] CMB code.

We constrain variation in the fine structure constant α/α_0 by a COSMOMC analysis of the most recent CMB data. The analysis method we adopt is based on the publicly available Markov chain Monte Carlo package COSMOMC [18] with a convergence diagnostics done through the Gelman and Rubin statistics.

We sample the following eight-dimensional set of cosmological parameters, adopting flat priors on them: the baryon and cold dark matter densities ω_b and ω_c, the Hubble constant H_0, the scalar spectral index n_s, the overall normalization of the spectrum A_s at $k = 0.05\ \mathrm{Mpc}^{-1}$, the optical depth to reionization τ and, finally, the variations in the fine structure constant α/α_0. Furthermore, we consider purely adiabatic initial conditions and we impose spatial flatness.

Our basic data set is the five-year WMAP data [2,3] (temperature and polarization) with the routine for computing the likelihood supplied by the WMAP team. Together with the WMAP data we also consider the following CMB data sets: ACBAR [12], QUAD [13], and BICEP [14]. We also include the older data sets from BOOMERanG [19] and CBI [20]. For all these experiments we marginalize over a possible contamination from the Sunyaev-Zeldovich component, rescaling the WMAP template at the corresponding experimental frequencies. Finally, we include the improved constraint on the Hubble constant of $h = 0.747 \pm 0.036$ at 68% C.L. from the recent analysis of [15].

III. CONSTRAINTS ON VARIATIONS OF THE FINE STRUCTURE CONSTANT

In Table I we report the constraints on the α/α_0 parameter obtained from the COSMOMC analysis, using the different combinations of the data sets described in the previous section.

Clearly the new CMB data at arcminute angular scales provide a substantial improvement in the determination of α. The uncertainty on α is indeed halved when the data coming from the new QUAD, BICEP, and ACBAR experiments are included in the analysis. The increase in the precision is mainly due to the effects from modified recombination on the CMB anisotropy damping tail that is more accurately measured by the QUAD and ACBAR experiments.

TABLE I. Limits on α/α_0 from WMAP data only (first row), from a larger set of CMB experiments (second row), and from CMB plus the HST prior on the Hubble constant, $h = 0.748 \pm 0.036$ (third row). We report errors at 68% and 95% confidence level.

Experiment	α/α_0	68% C.L.	95% C.L.
WMAP-5	0.998	±0.021	$^{+0.040}_{-0.041}$
All CMB	0.987	±0.012	±0.023
All CMB + HST	1.001	±0.007	±0.014

In Fig. 1 we show the 68% and 95% C.L. constraints on the α/α_0 vs the Hubble constant for different data sets. As we can see, a degeneracy is clearly present between the Hubble parameter and the fine structure constant. A change in α shifts the recombination epoch, affecting the angular diameter distance at recombination and the peak position in the CMB anisotropy angular spectra. A similar effect can be obtained by changing the value of the Hubble constant and the two parameters are therefore degenerate. Including the recent Hubble Space Telescope (HST) measurements of H_0 has therefore the important effect of breaking the α-H_0 degeneracy and thereby providing a stronger bound to α/α_0. This is clearly shown in the third row of Table I and, again, in Fig. 1. The best fit parameters for the CMB + HST run are $\Omega_b h^2 = 0.0228$, $\Omega_c h^2 = 0.112$, $\tau = 0.093$, $h = 0.720$, and $n_s = 0.964$, in agreement with the values obtained when α is not varied.

Since the age of the Universe is strongly connected with the Hubble constant, we also plot the constraints on the α/α_0 vs age of the Universe plane in Fig. 2. As we can see, including the small scale CMB experiments and the HST prior recover the standard constraint on the age of the Universe achieved assuming constant α. We indeed found that if one allows for variations in α, the WMAP five year data bound the age of the Universe changes to $t_0 = 13.9 \pm 1.1$ Gyr (at 68% C.L.), with an increase in the error of a factor ~3 with respect to the quoted standard constraint (see [2]). Including all CMB data sets improves the constraint to $t_0 = 14.3 \pm 0.6$ while combining with the HST prior yields $t_0 = 13.6 \pm 0.3$ Gyr (all at 68% C.L.).

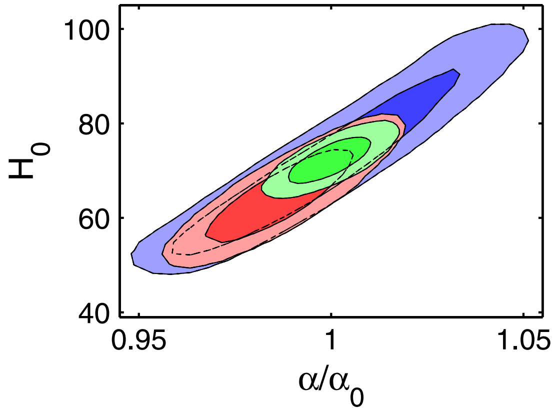

FIG. 1 (color online). 68% and 95% C.L. constraints on the α/α_0 vs the Hubble constant for different data sets. The contour regions come from the WMAP-5 data (blue, weakest contours), all current CMB data (red, middle contours), and CMB + HST (green, strongest contours).

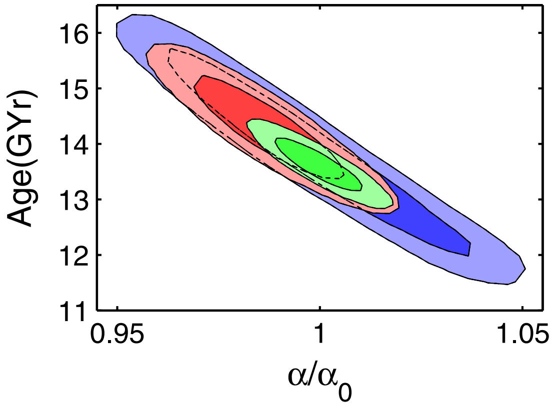

FIG. 2 (color online). 68% and 95% C.L. constraints on the α/α_0 vs the age of the Universe t_0 for different data sets. The contour regions come from the WMAP-5 data (blue, weakest contours), all current CMB data (red, middle contours), and CMB + HST (green, strongest contours).

We found no relevant degeneracies with the remaining parameters.

IV. CONCLUSIONS

In this Brief Report we have investigated the constraints on variation of the fine structure constant from current CMB observations. We have updated previous results and investigated in detail the degeneracies present between α and the remaining cosmological parameters.

We have found that the combination of the latest CMB data and HST measurement of H_0 yields the constraint $\delta\alpha/\alpha = 1.000 \pm 0.007$ at 68% C.L., providing no indications for strong variation in α in the early universe. This constraint improves by a factor ~3 previous bounds obtained by past cosmological data analysis. This bound is also competitive with big bang nucleosynthesis (BBN) bounds (see e.g. [7]) which assume the same cosmological framework, but is based on different physical mechanisms at very different energy scales. (stronger BBN bounds can be obtained by making specific model-dependent assumptions [21].)

Further improvements are expected from the Planck satellite experiment, which is now collecting data [8]: it should be able to bound variations in α at the ~0.5% level without assuming the HST prior (for comparison a cosmic variance limited experiment could improve the bound to an ~0.1% level). These ever tighter bounds, combined with local measurements using atomic clocks and with forthcoming low-redshift measurements obtained with stable high-resolution spectrographs such as PEPSI, ESPRESSO or CODEX, strongly constrain fundamental physics, particularly the dynamics of any cosmological scalar fields.

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