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# Quintessence and variation of the fine structure constant in the cosmic microwave background radiation

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We study the dependence of the CMB temperature anisotropy spectrum on the value of the fine structure constant $\alpha$ and the equation of state of the dark energy component of the total density of the universe. We find that bounds imposed on the variation of $\alpha$ from the analysis of currently available CMB data sets can be significantly relaxed if one also allows for a change in the equation of state.

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## I. INTRODUCTION

Current observations of type Ia supernovae [1] suggest that our Universe is accelerating. This has led many theorists to allow for the existence of a mysterious dark energy that permeates the universe and has negative pressure. One example is a cosmological constant $\Lambda$ with the equation of state $w_\Lambda \equiv p_\Lambda/\rho_\Lambda = -1$. More recently, it was suggested that the dark energy would not necessarily have to be of constant density at all times. The idea is to introduce a dynamical light scalar field $Q$, called quintessence, with a tracking potential $V(Q)$ chosen in such a way that $Q$ comes to dominate the expansion of the Universe only recently. The equation of state $w_Q \equiv p_Q/\rho_Q$ will now depend on the choice of $V_Q$ and will generally be time dependent. The current value of $w$ of dark energy is only loosely constrained: $w \lesssim -0.6$ [2]; however there is hope that future experiments will improve the bounds [3].

Dirac was among the first to suggest that fundamental constants, such as the fine structure constant $\alpha \equiv e^2/\hbar c$, could vary with time [4]. The interest in varying constant theories has recently risen with the increased popularity of models with both large and small extra dimensions in which four-dimensional constants are no longer fundamental. Additional motivation is provided by the fact that some of the puzzles of cosmology, such as the horizon, flatness and, arguably, other problems as well, could be resolved if the speed of light was faster in the past [5,6].

Experimental constraints on the variation in $\alpha$ come from atomic clock tests [7,8], measurements of isotope ratios [9,10] and absorption spectra in distant quasars [11,12]. While all laboratory and geophysical tests have so far failed to see any indication of $\alpha$ varying at the present epoch [13], the quasar data [12] have produced some evidence that the fine structure constant could have been smaller in the past.

The imprint of a varying fine structure constant on the cosmic microwave background radiation (CMBR) has been studied before [14,15]. It is usually assumed that the value of $\alpha$ at the time of last scattering was different from its present value but that it did not change considerably throughout the recombination epoch. It is also assumed that at any given time $\alpha$ was the same everywhere in space.[1] A change in $\alpha$ at the time of recombination would change the cross section of Thomson scattering of CMB photons and also would alter the energy levels of atoms. Thus, the main effect of varying $\alpha$ comes from the change in the redshift of the last scattering surface.

It was argued in [14] and [15] that the next generation of CMB experiments should be able to constrain the variation of $\alpha$ at redshifts $z \sim 1000$ with an accuracy $\Delta_\alpha \equiv (\alpha - \alpha_0)/\alpha_0 \sim 10^{-2} - 10^{-3}$, where $\alpha_0$ is the current value. The likelihood of a varying $\alpha$ based on the recent CMB data [16–18] was analyzed in [19–21]. While in [19] and [20] it was found that the data prefers a smaller value of $\alpha$ in the past, the combined analysis of the most recent CMB data and the big bang nucleosynthesis (BBN) constraints in [21] did not produce any evidence for a varying $\alpha$ at more than $1\sigma$ level.

In all previous studies, when looking at the effect of varying $\alpha$ on CMB spectra, it was assumed that the vacuum energy of the universe is due to a cosmological constant. Alternatively, the vacuum energy could be due to a quintessence field. One might question if the constraints on the change in $\alpha$ would be different if the variation in $\alpha$ was considered at same time with the variation in the equation of state of the dark energy component. While the change in the fine structure constant effectively changes the redshift of the CMB last-scattering surface, a change in the equation of state of quintessence changes the conformal distance to a fixed redshift. Thus, to some extent, changes in the CMBR anisotropy spectrum caused by $\Delta_\alpha \neq 0$ can be compensated for by a change in $w_Q \equiv p_Q/\rho_Q$.

We would like to emphasize that this work is an exposition of a degeneracy—not an evaluation of experimental constraints.

[1] While we employ the same assumptions in this work, we would like to stress that in many varying constant theories the change in $\alpha$ comes from the dynamics of a time- and space-dependent scalar field [29,26,28]. Fluctuations of this scalar field could potentially have a nontrivial effect on CMBR.

 

This paper is organized as follows. In Sec. II we describe our implementation of quintessence and varying $\alpha$. In Sec. III we discuss how we search for degeneracies in CMB spectra. The results are presented in Sec. IV and we finish with a discussion in Sec. V of possible theoretical frameworks in which the quintessence field and the variation in $\alpha$ may be inter-related.

## II. QUINTESSENCE, VARYING $\alpha$ AND CMBR

There is an enormous variety of quintessence models, i.e., models containing a dynamical scalar field which could drive the current accelerated expansion of the universe. While any particular choice of a model, or even a class of models, still remains a matter of personal taste, there is a relatively limited set of properties relevant to the CMBR. The effect of the $Q$ component on the CMBR spectra is primarily due to the change in the conformal distance to the last scattering surface. Somewhat less prominent is the role of the perturbations in the $Q$ component. It was shown in [22] that the main effect of including the perturbations is on very large scales due to the integrated Sachs-Wolfe (ISW) effect. For completeness, in this work we do take into account the fluctuations in the pressure and energy density of the quintessence.

We have assumed that the quintessence field (or the $Q$ component) couples to other particle species only gravitationally. The evolution of the energy density and the pressure of the $Q$ component as well as their perturbations is completely specified by the equation of state (EOS), $w(t) = p_Q/\rho_Q$, which is generally time-dependent. Equivalently, one could start with the potential $V_Q$ of the $Q$ field and deduce the EOS from it. However, many different potentials can lead to the same EOS.

We will limit ourselves to models in which the EOS of the $Q$ component remains effectively constant between the time of recombination and today. The reason for this restriction is simply the fact that none of the specific quintessence models appears to be more attractive than others. We therefore take the simplest case. The effects of several time-dependent EOS were examined in [22]. Predictions of some specific models were also studied in [23,24].

The effect of varying fine structure constant $\alpha$ on the CMBR comes from the changes in the differential optical depth $\dot{\tau}$ of photons during the time of recombination. $\dot{\tau}$ can be written as

$$\dot{\tau} = x_e n c \sigma_T, \tag{1}$$

where $x_e$ is the ionization fraction, $n$ is the electron number density and $\sigma_T$ is the Thomson scattering cross section. The dependence of $\sigma_T$ on $\alpha$ is well known:

$$\sigma_T = \frac{8\pi\alpha^2\hbar^2}{3m_e^2c^2} \tag{2}$$

where $m_e$ is the electron mass. The ionization fraction $x_e$ depends on $\alpha$ through the binding energy of hydrogen as well as through the change in the recombination rates. The correct procedure for accounting for these two effects is described in [14,15]. We have closely followed the discussion in [14,15] when incorporating the effects of varying $\alpha$ into CMBFAST [25].

We will be calculating the angular power spectrum $C_l$ of the CMB temperature anisotropy defined as follows:

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} \langle a_{lm}^* a_{lm} \rangle, \tag{3}$$

where

$$a_{lm} = \int d\hat{n} Y_{lm}^*(\hat{n}) \left( \frac{T(\hat{n}) - \overline{T}}{\overline{T}} \right), \tag{4}$$

where $T(\hat{n})$ is the CMBR temperature in a certain direction on the sky and $\overline{T}$ is the average temperature.

## III. SEARCHING FOR DEGENERACIES

The CMB anisotropy spectrum is computed by a version of CMBFAST [25], modified for simultaneous quintessence (including perturbations in quintessence) and variable fine structure constant. We have only considered flat models ($\Omega_{total}=1$) with adiabatic initial conditions. The parameter space consists of $(\Omega_m, w_Q, \Delta_\alpha, h, \Omega_B h^2, n_s, N)$, where $(\Omega_m$ is the ratio of the cold dark matter energy density to the critical density, $w_Q$ is the quintessence equation of state, $\Delta_\alpha \equiv (\alpha - \alpha_0)/(\alpha_0)$ is the fractional change in the fine structure constant, $h$ is the Hubble constant in units of 100 $\mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega_B h^2$ is the baryon density, $n_s$ is the scalar spectral index and $N$ is the overall normalization of the spectrum. The restriction to flat geometry implies that $\Omega_Q = 1 - \Omega_m$. Each point in this parameter space has a CMB anisotropy spectrum associated with it. Two points in parameter space are considered degenerate if their associated CMB spectra are indistinguishable. The degeneracy of the parameter space is surveyed by picking a point in that space to be the fiducial model, and then comparing its CMB spectrum with that of another point. To illustrate the degeneracy in the $(w_Q, \Delta_\alpha)$ plane, these parameters were gridded. A fiducial model was picked and its spectrum was compared to the least distinguishable spectrum of each grid point. The parameters $\Omega_m$ and $\Omega_Q$ were held fixed, while $h, \Omega_B h^2, n_s, N$ were allowed to vary to find the model least distinguishable from the fiducial model. It should be emphasized that the parameters of the fiducial model are chosen to suit illustrative purposes, and are not always related to experimental observations. Our results are an exposition of a degeneracy in parameter space—not an evaluation of experimental constraints.

The presence of degeneracy sensitively depends on the criteria one uses to determine distinguishability of CMB spectra. A real CMB anisotropy experiment would be limited in the following ways: a finite beam width would imply a minimum scale resolution, which we approximate as a simple truncation of the spectrum above a specific $l_{max}$. Normally the results of the experiment would be analyzed as independent ''bins''—effectively a collective range of $C_l$'s.

We consider a bin size of 1 multipole in our runs, as this illustrates the degeneracy present in an optimistic future experiment. Finally, any real experiment will have some level of error above cosmic variance—due to incomplete sky coverage, instrumentation noise, non-CMB sources in the sky, etc. Again intending to demonstrate the optimistic limit, we take the error at each $C_l$ to be 5% plus cosmic variance. To address the issue of different levels of degeneracy, some runs are done with CMB spectra being computed and compared out to a maximum multipole of $l_{max}=900$—this captures the large-angle plateau and acoustic peak structure, but not the damping scale. Alternatively, some runs are done with $l_{max}=1500$ which additionally captures the damping scale.

Note that only the scalar portion of the spectrum is considered here. The addition of a tensor component would not diminish the degeneracy—instead, as we discuss below, it might qualitatively increase it.

The chi-square from the comparison of the CMB spectrum of each point on the grid with the fiducial model is used to determine how distinguishable the points are. In the plots, solid curves mark the contours of 68.3%, 95.5% and 99.7% likelihood distinguishability. That is, points on the outer contour produce CMB spectra such that one can say with 99.7% confidence that these spectra are not produced by the fiducial model.

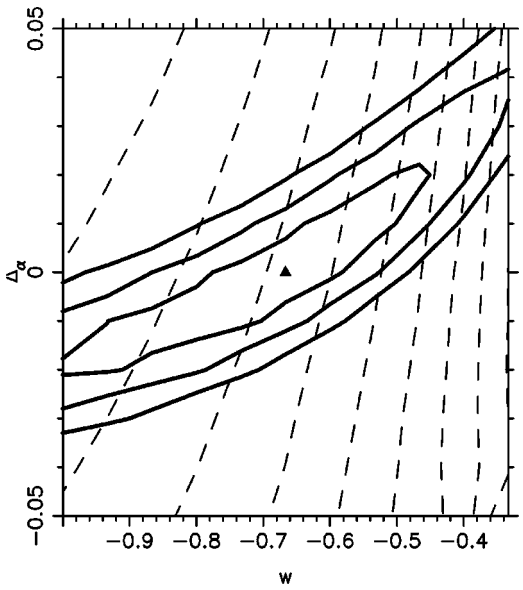


FIG. 1. Degeneracy around a quintessence fiducial model (marked with a solid triangle) in the $(w_Q,\Delta_\alpha)$ plane with $w_Q=-2/3$, $\Delta_\alpha=0$. The models are compared to the fiducial model at each $C_l$ out to $l_{max}=900$. The solid curves are 68.3%, 95.5% and 99.7% likelihood bounds, and the dashed lines are contours of constant baryon density. The fiducial model has $\Omega_B h^2=0.0200$ and $\Omega_B h^2$ changes by 0.0007 between the dashed contours.

## IV. RESULTS

We have found that effects of changing the fine structure constant and varying the equation of state of quintessence are to a large extent degenerate. This degeneracy arises because it is possible to compensate for the change in the redshift of last-scattering ($\Delta_\alpha$) by a change in the conformal distance to a given redshift ($w_Q$)—the quantity that must remain fixed is the angle on our sky subtended by the sound horizon at last scattering (i.e., the angular scale of the first Doppler peak). In addition to changing the redshift of the last scattering, a change in $\Delta_\alpha$ also changes the thickness of the last-scattering surface. Anisotropies on scales shorter than this thickness destructively interfere when projected onto the sky and, as a result, the CMB power spectrum is suppressed below a certain scale. Also, at very small scales perturbations in the primordial plasma are washed out due to the imperfect coupling of baryons and photons—the Silk damping, which further suppresses the CMBR anisotropy spectrum.

The extent of the degeneracy depends on what criteria one uses to determine which CMB spectra are in principle distinguishable and which are not. If one measures the anisotropy only on scales larger than the damping scale ($l\sim900$), compares each $C_l$ individually (rather than binning them), and considers a modest (5%) error in addition to cosmic variance, then one does find the degeneracy, as shown in Fig. 1. For the fiducial model (marked with a triangle on the plot) we have chosen $w_Q=-2/3$ and $\Delta_\alpha=0$. Similarly, we have tried using $w_Q=-1$ for the fiducial model and found that the degree of the degeneracy remains unchanged. The rest of parameters in the fiducial model were chosen to be $\Omega_{total}=1$, $\Omega_m=0.3$, $h=0.65$, $\Omega_B h^2=0.02$ and $n_s=1$.

When searching for a degeneracy in the $(w_Q,\Delta_\alpha)$ space, other parameters were allowed to vary as well. Allowed ranges for $h$, $\Omega_B h^2$ and $n_s$ were [0.5,0.9], [0.015,0.025] and [0.85,1.15] respectively. At all grid points in the $(w_Q,\Delta_\alpha)$ plane the best-fit values for $h$ and $n_s$ never varied by more than 1% from their fiducial values. Baryon density, by contrast, changed by about 4% in Fig. 1 for every 1% change in the fine structure constant. The thin dashed lines in Figs. 1 and 3 are contours of constant $\Omega_B h^2$, showing that some variation of the baryon density is required, as well as $w_Q$, to compensate for the effects of a change in the fine structure constant. However, merely varying $\Omega_B h^2$, while holding $w_Q$ fixed, is not sufficient to compensate for the change in $\Delta_\alpha$. Figure 2 shows the likelihood contours in the $(\Omega_B h^2,\Delta_\alpha)$ space with the value of $w_Q$ fixed at $-2/3$. These likelihood contours enclose a compact region, rather than an elongated, curved region as in Fig. 1. That is, if $w_Q$ is not allowed to vary, the degeneracy is not present. Though a change in the baryon density is necessary to compensate for a change in $\Delta_\alpha$, because the change in redshift of the last-scattering surface means the baryon density was different at the last scattering, a change in $w_Q$ is necessary to compensate for the change in the angular scale of the sound horizon on the last-scattering surface.

The degeneracy does not extend down to the damping scale. As shown in Fig. 3, the degeneracy is broken if the measurement of the $C_l$'s is extended to $l_{max}\sim1500$ while still assuming a precision of 5%+cosmic variance. It is worth noting that when $l_{max}\sim1500$ the spectra are very nearly identical from the 2nd acoustic peak up to and including the damping scale. The degeneracy cannot match the entire spectrum and it is the smaller scales that carry the greater statistical weight. The degeneracy is broken due to

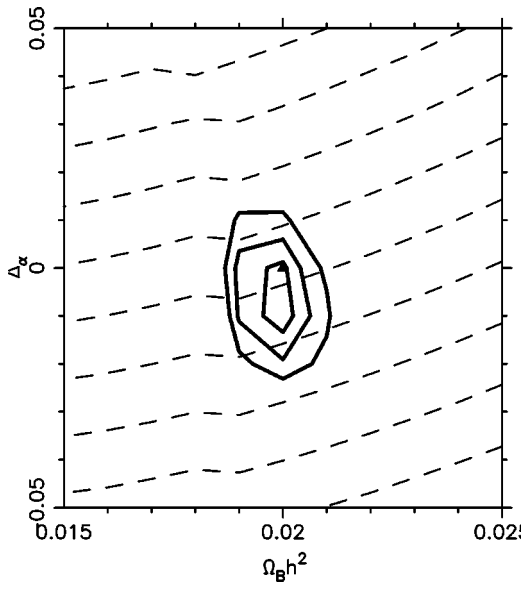


FIG. 2. Likelihood contours in the $(\Omega_B h^2, \Delta_\alpha)$ plane around a quintessence fiducial model (marked by a star) with $w_Q = -2/3$, $\Omega_B h^2 = 0.02$, $\Delta_\alpha = 0$. The models are compared to the fiducial model (marked with a solid triangle) at each $C_l$ out to $l_{max} = 900$. The solid curves are 68.3%, 95.5% and 99.7% likelihood bounds, and the dashed lines are contours of constant scalar spectral index. The value of the spectral index changes by 0.031 between each dashed line. Note the absence of the degenerate direction.

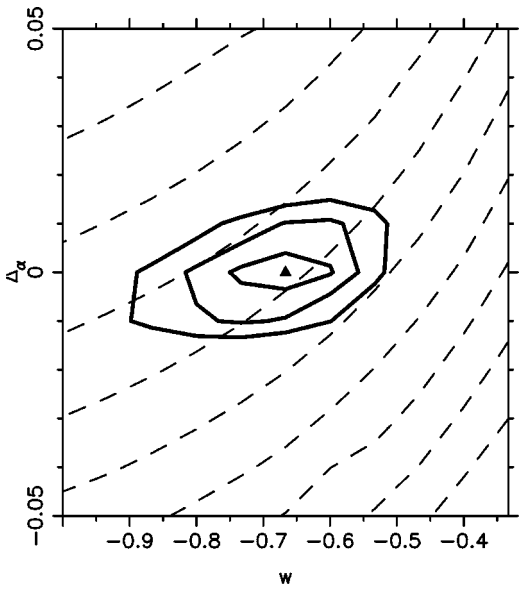


FIG. 3. Likelihood contours in the $(w_Q, \Delta_\alpha)$ plane around a fiducial model (marked with a solid triangle) with $w_Q = -2/3$, $\Delta_\alpha = 0$. The models are compared to the fiducial model at each $C_l$ out to $l_{max} = 1500$. The solid curves are 68.3%, 95.5% and 99.7%. Likelikhood bounds, and the dashed lines are contours of constant baryon density. The fiducial model has $\Omega_B h^2 = 0.0200$ and $\Omega_B h^2$ changes by 0.0008 between the dashed contours. Note the great reduction in degeneracy that occurs when one includes the damping scale into the comparison of CMB anisotropy spectra.

differences that arise at large scales (between $l = 2$ and the first Doppler peak). It is worth noting, however, that we have only considered the scalar contribution to the CMB anisotropy spectrum. The addition of the tensor contribution would affect the spectrum predominantly at large scales before the first Doppler peak, which is where the spectra discussed above differ most. Thus, it is very likely that with the addition of a tensor contribution, with a spectral index $n_t$ and a relative normalization $r$ taken as free parameters, the degeneracy would no longer be broken by the damping scale. This is a subject of ongoing work.

Other degeneracies in CMB parameters, also involving quintessence, were studied in Ref. [23]. Ways of breaking these degeneracies by other cosmological observations were discussed. In light of our current result, the extent to which, for example, $w_Q$ can be resolved by combining multiple types of observations, as discussed in [23], must be reexamined.

## V. OUTLOOK

We have shown that the effect of a varying $\alpha$ on the CMBR can be partially compensated by adjusting the value of the equation of state of the dark energy. Namely, the value of $\alpha$ at recombination decreases with the decrease in $w_Q$ along the degeneracy line. This limits the accuracy with which one could determine $\Delta_\alpha$ or the quintessence equation of state $w_Q$ from CMB observations alone.

We did not study the effects of varying $\alpha$ or $w_Q$ on other cosmological observables, such as CMBR polarization or large scale structure (LSS) spectra. In general, any new observation that measures a quantity which depends on $\alpha$ and/or $w_Q$ would reduce the degeneracy. The effect of varying $\alpha$ on the LSS power spectrum would probably be insignificant. The CDM potential wells would be unaffected, however, baryons would start falling into these potential only after the last scattering. Therefore, a change in $\alpha$ could, to some degree, affect the bias factor between CDM and luminous matter. The effect of different types of quintessence on LSS power spectrum is significant and has been considered in detail in [23].

The first polarization spectra will probably not be produced until the launch of the Planck satellite, currently scheduled in 2007. If and when it becomes available, polarization data would significantly reduce current degeneracies among cosmological models and their parameters. CMBR polarization is expected to be generated by Thompson scattering from the quadrupole moment of the temperature anisotropy. Because the temperature and the duration of recombination depend on $\alpha$, and because CMBR polarization is produced mainly during the recombination, the effect of varying $\alpha$ on the polarization spectra will be significant on all measurable scales. The effect of changing the equation of state of dark energy on the polarization spectra would be primarily due to the change in the conformal distance to the last scattering.

There is a number of additional effects that could have been taken into account. Some of them, such as the effect of a varying $\alpha$ on the helium abundance, are relatively small. However, there can be additional nontrivial effects if the dynamics and fluctuations in the field which drives the change

in $\alpha$ are also considered to a full extent. A time-dependent $w_Q$ is yet another possibility that was not considered in this paper.

Both phenomena, varying $\alpha$ and quintessence, can be modeled within Einstein's theory as a light scalar field either minimally or nonminimally coupled to gravity [26,27]. These theories closely resemble dilaton and Brans-Dicke gravities. It has also been argued that the same light scalar field which is responsible for varying $\alpha$ could give rise to quintessence [28]. Other investigations have also pointed to a possible connection between varying $\alpha$ and dark energy. Barrow, Sandvik and Magueijo have analyzed the behavior of a varying $\alpha$ cosmology during the radiation, dust, curvature and cosmological constant domination epochs [29]. In their model the value of $\alpha$ increases during the matter domination but rapidly approaches a constant when negative curvature or $\Lambda$ start to dominate. A similar effect could have been achieved if a quintessence field was used in place of a cosmological constant.

The degeneracy described in this paper suggests a need for a firmer theoretical understanding of how varying $\alpha$ and quintessence may be related to each other as already suggested by [28]. It could be that the standard computer codes, such as CMBFAST [25], for calculating the CMBR spectra will have to be modified to fully include both effects assuming that they are rooted in same underlying microphysical phenomenon. We leave this for future investigation.

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