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The variation of the electromagnetic coupling and quintessence

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ABSTRACT

The properties of quintessence are examined through the study of the variation of the electromagnetic coupling. We consider two simple quintessence models with a modified exponential potential and study the parameter space constraints derived from the existing observational bounds on the variation of the fine structure constant and the most recent Wilkinson Microwave Anisotropy Probe observations.

1. Introduction

Over the last decade, the temporal and spatial variation of fundamental constants has become a very popular subject. The motivation partially comes from theories unifying gravity and other interactions, which suggest that fundamental constants could have indeed varied during the evolution of the universe [1]. It is therefore particularly relevant to search for these variations and try to establish correlations, if any, with other striking properties of the universe, as for instance with dark energy.

From the observational point of view, the time variation of the fine structure constant α has been widely discussed in several contexts. In particular, from the spectra of quasars (QSO), one obtains from the KecK/HIRES instrument [2]

$$\frac{\Delta\alpha}{\alpha} = (-0.57 \pm 0.11) \times 10^{-5}, \quad \text{for } 0.2 < z < 4.2, \tag{1}$$

while the Ultraviolet and Visual Echelle Spectrograph (UVES) instrument [3,4] implies

$$\frac{\Delta\alpha}{\alpha} = (-0.64 \pm 0.36) \times 10^{-5}, \quad \text{for } 0.4 < z < 2.3. \tag{2}$$

The Oklo natural reactor also provides a bound,

$$-0.9 \times 10^{-7} < \frac{\Delta\alpha}{\alpha} < 1.2 \times 10^{-7}, \quad \text{for } z < 0.14, \tag{3}$$

at 95% C.L. [5–7]. Furthermore, estimates of the age of iron meteorites, corresponding to $z \simeq 0.45$, when combined with the measurement of the Os/Re ratio resulting from the radioactive decay $^{187}\text{Re} \to {}^{187}\text{Os}$, yield [8–10]:

$$\frac{\Delta\alpha}{\alpha} = (-8 \pm 8) \times 10^{-7}, \tag{4}$$

at 1σ, and

$$-24 \times 10^{-7} < \frac{\Delta\alpha}{\alpha} < 8 \times 10^{-7}, \tag{5}$$

at 2σ.

Big bang nucleosynthesis (BBN) also places bounds on the variation of α [11]:

$$-0.05 < \frac{\Delta\alpha}{\alpha} < 0.01, \quad \text{for } 10^9 < z < 10^{10}. \tag{6}$$

Finally, the 5-year data from the Wilkinson Microwave Anisotropy Probe (WMAP) with Hubble Space Telescope (HST) prior provides the following bound at 95% C.L. [12]:

$$-0.028 < \frac{\Delta\alpha}{\alpha} < 0.026, \quad \text{for } z \sim 10^3. \tag{7}$$

Without HST prior this bound is less restrictive [12]:

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$$-0.050 < \frac{\Delta\alpha}{\alpha} < 0.042, \tag{8}$$

at 95% C.L.

On the other hand, recent observations of high redshift type Ia supernova and, more indirectly, of the CMB and galaxy clustering, indicate that the universe is undergoing a period of accelerated expansion [13]. This suggests that the universe is dominated by a form of energy density with negative pressure (dark energy). An obvious candidate for dark energy could be an uncanceled cosmological constant [14], which however would require an extremely high fine-tuning. Quintessence-type models [15] with one [16] or two [17] scalar fields, k-essence [18] and the Chaplygin gas with an exotic equation of state [19,20] are among other possibilities.

In most of the theoretical approaches, scalar fields are present in the theory. Thus, one could expect that the two observational facts, namely the variation of α and the recent acceleration of the universe, are somehow related. Indeed, the coupling of such a scalar field to electromagnetism would lead to a variation of the fine structure constant [21]. In several contexts [22], the above question has already been addressed.

In this Letter we shall consider two simple quintessence models with a modified exponential potential, proposed by Albrecht and Skordis [23,24]. Our aim is to restrict the parameter space of these models by using the observational constraints on the variation of the fine structure constant and by imposing consistency with the 5-year data from WMAP.

2. The models

2.1. Quintessence

The authors of Refs. [23,24] add a polynomial prefactor in front of the exponential potential in order to introduce a local minimum in the potential $V(\phi)$, such that the scalar field ϕ gets trapped into it. The potential can be written in the form

$$V(\phi) = V_0\left[(\phi-\phi_0)^2 + A\right]e^{-\lambda\phi}. \tag{9}$$

Since the effect of trapping is equivalent to a cosmological constant, an era of accelerated expansion is eventually reached. Notice that this model has already been analyzed in the context of the variation of the fine structure constant [25]. However, the authors consider a particular set of values for the parameters in the potential, whereas here we vary these parameters and try to find constraints on them. Recently, this potential has also been investigated in the braneworld context as a model of quintessential inflation [26]. We shall refer to this potential as the AS1 model.

Regardless of initial conditions, trapping occurs in the very early universe, when the field enters the attractor regime. The tracking properties of the AS1 potential (9) are similar to those of a pure exponential potential. Nevertheless, due to the presence of the polynomial factor, quintessence dominates near the present epoch. Furthermore, this potential can lead to both permanent and transient acceleration regimes. When $A\lambda^2 < 1$ and the field is trapped in the local minimum of the potential, permanent acceleration is achieved. On the other hand, if $A\lambda^2 < 1$ and the field arrives at the minimum with a kinetic energy sufficiently high to roll over the barrier, a transient acceleration regime is obtained [27]. Transient vacuum domination also arises for $A\lambda^2 > 1$, when the potential loses its local minimum [27]. The existence of a transient regime is interesting from the theoretical viewpoint of string theory, since it can avoid the difficulties which typically arise in the S-matrix construction at the asymptotic future in a de-Sitter space [28].

A second potential (hereafter referred as AS2 model) which can lead to the desired accelerated expansion has the form [24],

$$V(\phi) = \left[\frac{C}{(\phi-\phi_0)^2 + A} + D\right]e^{-\lambda\phi}. \tag{10}$$

The motivation of such a potential comes from brane studies, which indicate that it could arise as a Yukawa-like interaction between branes [29]. The behavior of the AS2 potential is similar to the AS1 potential during the radiation-dominated era. Nevertheless, during matter domination it retains much more density than the AS1 potential. This is due to the fact that the AS2 potential has a smoother minimum and a sharper maximum when compared to the AS1 one. Furthermore, acceleration is achieved earlier for the latter potential [24].

The evolution of the scalar field is described by the equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0, \tag{11}$$

where the dot and prime denote derivatives with respect to time and ϕ, respectively;

$$H^2 = \frac{1}{3}\rho, \quad \rho = \rho_r + \rho_m + \rho_\phi. \tag{12}$$

Here ρ_r and ρ_m are the radiation and matter energy densities, respectively, and $\rho_\phi = \dot{\phi}^2/2 + V(\phi)$. In order to integrate equations (11) and (12), it is more convenient to rewrite them in the form

$$\frac{dx}{d\mathcal{N}} = -3x + \sigma\sqrt{\frac{3}{2}}y^2 + \frac{3}{2}x\left[2x^2 + \gamma\left(1 - x^2 - y^2\right)\right],$$
$$\frac{dy}{d\mathcal{N}} = -\sigma\sqrt{\frac{3}{2}}xy + \frac{3}{2}y\left[2x^2 + \gamma\left(1 - x^2 - y^2\right)\right], \tag{13}$$

where $\gamma = w_B + 1$, w_B is the equation-of-state parameter for the background ($w_B = 0, 1/3$ for matter and radiation, respectively); $\mathcal{N} \equiv \ln a$, with a being the scale factor, and

$$x \equiv \frac{\dot{\phi}}{\sqrt{2\rho}}, \qquad y \equiv \frac{\sqrt{V}}{\sqrt{\rho}}, \qquad \sigma \equiv -\frac{V'}{V}. \tag{14}$$

The above equations are integrated from the Planck epoch ($a \simeq 10^{-30}$) to the present epoch ($a \equiv a_0 = 1$). For the fraction of radiation at present we use the central value $\Omega_r^0 h^2 = 4.3 \times 10^{-5}$, which assumes the addition of three neutrino species. The matter content is such that the correct fraction is reproduced at present, $\Omega_m^0 h^2 = 0.1369 \pm 0.0037$ [30]. Furthermore, we assume that early in the radiation era the scalar field is in its tracking regime, in which case [31]

$$\rho_\phi \simeq 3V, \qquad \Omega_\phi \simeq \frac{4}{\lambda^2}. \tag{15}$$

2.2. Coupling with electromagnetism

Due to the universality of the gravitational interactions, non-renormalizable couplings of the quintessence field ϕ to the standard model fields are expected below the Planck scale. Following Bekenstein's proposal [21], one can consider the interaction between the scalar and electromagnetic fields in the form

$$\mathcal{L}_{em} = \frac{1}{16\pi} f(\phi) F_{\mu\nu}F^{\mu\nu}, \tag{16}$$

where f is an arbitrary function. We remark that the assumption of Eq. (16) is rather arbitrary and simplistic. It is outside the framework of quantum field theory and used here only to illustrate a possible connection between quintessence and α that may help in constraining models.