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Evolution of the fine-structure constant in runaway dilaton models

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ABSTRACT

We study the detailed evolution of the fine-structure constant α in the string-inspired runaway dilaton class of models of Damour, Piazza and Veneziano. We provide constraints on this scenario using the most recent α measurements and discuss ways to distinguish it from alternative models for varying α. For model parameters which saturate bounds from current observations, the redshift drift signal can differ considerably from that of the canonical ΛCDM paradigm at high redshifts. Measurements of this signal by the forthcoming European Extremely Large Telescope (E-ELT), together with more sensitive α measurements, will thus dramatically constrain these scenarios.

1. Introduction

The observational evidence for cosmic acceleration, first inferred from the luminosity distance of type Ia supernovae in 1998 [1,2], opened a new avenue in cosmological research. The most obvious task in this endeavor is to identify the source of this acceleration—the so-called Dark Energy—and in particular to ascertain whether it is due to a cosmological constant or to a new dynamical degree of freedom. While the former option, corresponding to the canonical ΛCDM paradigm, is arguably the simplest, many alternative models have been proposed and still have to be tested [3].

The most natural way to model dynamical energy is through a scalar field, of which the recently discovered Higgs is the obvious example [4,5]. String theory predicts the presence of a scalar partner of the spin-2 graviton, the dilaton, hereafter denoted ϕ. Here, we will study the cosmological consequences of a particular class of string-inspired models, the runaway dilaton scenario of Damour, Piazza and Veneziano [6,7]. In this scenario, which among other things provides a way to reconcile a massless dilaton with experimental data, the dilaton decouples while cosmologically attracted towards infinite bare coupling, and the coupling functions have a smooth finite limit

$$B_i(\phi) = c_i + \mathcal{O}(e^{-\phi}). \quad (1)$$

As discussed in [7], provided there's a significant (order unity) coupling to the dark sector, the runaway of the dilaton towards strong coupling may yield violations of the Equivalence Principle and variations of the fine-structure constant α that are potentially measurable.

More than a decade after the original analysis the available α measurements have improved substantially [8,9], and it's therefore timely to revisit these models. Additional gains in sensitivity will be provided by forthcoming facilities such as the E-ELT: its high-resolution ultra-stable spectrograph (HIRES) will significantly improve tests of the stability of fundamental couplings and will also be sensitive enough to carry out a first measurement of the redshift drift deep in the matter-dominated era [10,11]. The combination of both types of measurements is a powerful probe of dynamical dark energy, as it can distinguish between models that are indistinguishable at low redshifts [12]. In what follows we obtain constraints on this runaway dilaton scenario using current α data, and also discuss how they may be further improved.

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2. Runaway dilaton cosmology

As discussed in [6,7], the Einstein frame Lagrangian for this class of models is

$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{8\pi G}(\nabla\phi)^2 - \frac{1}{4}B_F(\phi)F^2 + \cdots, \tag{2}$$

where R is the Ricci scalar and B_F is the gauge coupling function. From this one can show [7] that the corresponding Friedmann equation, relating the Hubble parameter, H, to the dilaton and the other components of the universe is as follows

$$3H^2 = 8\pi G\sum_i \rho_i + H^2\phi'^2, \tag{3}$$

where the sum is over the components of the universe, except the kinetic part of the dilaton field which is described by the last term (where the prime is the derivative with respect to the logarithm of the scale factor). The sum does include the potential part of the scalar field; the total energy density and pressure of the field are

$$\rho_\phi = \rho_k + \rho_v = \frac{(H\phi')^2}{8\pi G} + V(\phi), \tag{4}$$

$$p_\phi = p_k + p_v = \frac{(H\phi')^2}{8\pi G} - V(\phi); \tag{5}$$

here k and v correspond to the kinetic and potential parts of the field, with the latter providing the dark energy. On the other hand, the evolution equation for the scalar field is

$$\frac{2}{3-\phi'^2}\phi'' + \left(1 - \frac{p}{\rho}\right)\phi' = -\sum_i \alpha_i(\phi)\frac{\rho_i - 3p_i}{\rho}. \tag{6}$$

Here $p = \sum_i p_i$, $\rho = \sum_i \rho_i$, and sums are again over all components except the kinetic part of the scalar field.

The $\alpha_i(\phi)$ are the couplings of the dilaton with each component i, so they characterize the effect of the various components of the universe in the dynamics of the field. One may generically expect that the dilaton has different couplings to different components [7]. Experimental constraints impose a tiny coupling to baryonic matter, as we will discuss presently. In these models, this small coupling could naturally emerge due to a Damour–Polyakov type screening of the dilaton [13].

The relevant parameter here is the coupling of the dilaton field to hadronic matter. As discussed in [13], to a good approximation this is given by the logarithmic derivative of the QCD scale, since hadron masses are proportional to it (modulo small corrections). Assuming that all gauge fields couple, near the string cutoff, to the same $B_F(\phi)$, and in accordance with Eq. (1) which yields

$$B_F^{-1}(\phi) \propto (1 - b_F e^{-c\phi}), \tag{7}$$

we can write

$$\alpha_{had}(\phi) \sim 40\frac{\partial \ln B_F^{-1}(\phi)}{\partial\phi} \tag{8}$$

(where the numerical coefficient is further described in [7]) and we finally obtain

$$\alpha_{had}(\phi) \sim 40\, b_F\, c\, e^{-c\phi}. \tag{9}$$

Note that c and b_F are constant free parameters: the former one is expected to be of order unity and the latter one much smaller. Moreover, if we set $c = 1$ (which we will do henceforth) we can also eliminate b_F by writing

$$\frac{\alpha_{had}(\phi)}{\alpha_{had,0}} = e^{-(\phi-\phi_0)} \tag{10}$$

(where ϕ_0 is the value of the field today) and simultaneously writing the field equation in terms of $(\phi - \phi_0)$.

There are two local constraints. Firstly the Eddington parameter γ, which quantifies the amount of deflection of light by a gravitational source, has the value

$$\gamma - 1 = -2\alpha_{had,0}^2, \tag{11}$$

and is constrained by the Cassini bound, $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$ [14]. Secondly the dimensionless Eötvös parameter, quantifying violations to the Weak Equivalence Principle, has the value

$$\eta_{AB} \sim 5.2 \times 10^{-5}\alpha_{had,0}^2, \tag{12}$$

and recent torsion balance tests lead to $\eta_{AB} = (-0.7 \pm 1.3) \times 10^{-13}$ [15], while from lunar laser ranging one finds $\eta_{AB} = (-0.8 \pm 1.2) \times 10^{-13}$ [16]. From these we conservatively obtain the bound

$$|\alpha_{had,0}| \leq 10^{-4}. \tag{13}$$

Using Eq. (9), and still assuming that $c \sim 1$, this yields a bound on the product of b_F and (the exponent of) ϕ_0, namely $\phi_0 \geq \ln(|b_F|/2 \times 10^{-6})$. Nevertheless, this is not explicitly needed: the evolution of the system will be determined by α_{had} rather than by b_F or ϕ_0.

These constraints do not apply to the dark sector (*i.e.* dark matter and/or dark energy) whose couplings may be stronger. There are two possible scenarios to consider. A first possibility is that the dark sector couplings (which we will denote α_m and α_v for the dark matter and dark energy respectively) are also much smaller than unity, that is $\alpha_m, \alpha_v \ll 1$. In this case the small field velocity leads to violations of the Equivalence Principle and variations of the fine-structure constant that are quite small. Indeed, for this case to be observationally realistic the fractions of the critical density of the universe in the kinetic and potential parts of the scalar field must be

$$\Omega_k = \frac{1}{3}\phi'^2 \ll 1, \qquad \Omega_v \sim 0.7; \tag{14}$$

note that if one assumes a flat universe, then $\Omega_m + \Omega_k + \Omega_v = 1$ (do not confuse the index k, which refers to the kinetic part of the scalar field, with the curvature term in standard cosmology, which we are setting to zero throughout). A more interesting possibility is that the dark couplings (α_m and/or α_v) are of order unity. If so, violations of the Equivalence Principle and variations of the fine-structure constant are typically larger. In this case Ω_k may be more significant, and Ω_v should be correspondingly smaller [17]. Nevertheless the dark matter coupling is also constrained: during matter-domination the equation of state has the form

$$w_m(\phi) = \frac{1}{3}\phi'^2 \sim \frac{1}{3}\alpha_m^2. \tag{15}$$

The present value of the field derivative is also constrained if one assumes a spatially flat universe; in that case the deceleration parameter

$$q = -\frac{a\ddot{a}}{\dot{a}^2} = -1 - \frac{\dot{H}}{H^2} \tag{16}$$

can be written as

$$\phi_0'^2 = (1 + q_0) - \frac{3}{2}\Omega_{m0} \tag{17}$$

and using a reasonable upper limit for the deceleration parameter [18] and a lower limit for the matter density (say, from the Planck mission [19]) we obtain

$$|\phi_0'| \leq 0.3, \tag{18}$$