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Time-evolution of the fine-structure constant in runaway dilaton models

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Abstract. We study the detailed time-evolution of the fine-structure constant α in the stringinspired runaway dilaton class of models of Damour, Piazza and Veneziano [1, 2]. We provide constraints on this scenario via the time-variations of the fine-structure constant α as measured by spectroscopic experiments and we explore ways to distinguish the dilaton runaway models from other alternative.

1. Introduction

One of the main open questions in cosmology is the acceleration of the expansion of the Universe. The simplest model, a constant energy term, the so-called cosmological constant, fits the data very well, but it is unsatisfactory from a theoretical point of view.

An alternative way to model cosmic acceleration as coming from a dynamical energy component is through a scalar field, similar in the mathematical description to the Higgs boson, recently discovered at the Large Hadronic Collider. Such scalar fields emerge quite naturally in string theory, which predicts the presence of a scalar partner of the spin-2 graviton, the dilaton. We will focus our analysis on the cosmological consequences of a particular class of string-inspired models, the runaway dilaton scenario of Damour, Piazza and Veneziano [1, 2] and assess their testability by future facilities. Specifically ELT-HIRES [3] an ultra-stable spectrograph for the E-ELT (European Extremely Large Telescope) will have two relevant capabilities: a direct measurement of the cosmic expansion performing then the so-called Sandage-Loeb test [3, 4], and tests of the stability of the fine-structure constant ($\alpha = \frac{e^2}{\hbar c}$) at up to 10^{-8} level.

2. Runaway Dilaton Cosmology

The Friedmann equation and evolution equation for the scalar field (Φ) for this class of models can be written as:

$$3H^2 = 8\pi G \sum_i \rho_i + H^2 \Phi'^2 \tag{1}$$

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

The total pressure $p = \sum_i p_i$ and the total energy density $\rho = \sum_i \rho_i$ sum over all components except the kinetic part of the scalar field, $\alpha_i(\Phi)$ are the coupling constants between the dilaton

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and each component i, so they characterize the effect of the various components of the universe on the dynamics of the field. Notice in particular that the theory does not require the coupling constant to be the same for all components. Experimental constraints impose a tiny coupling to baryonic matter:

$$\alpha_{had} \sim 40 b_F c e^{-c\Phi} \tag{3}$$

where b_F and c are constant free parameters (c is expected to be of order unity and b_F very small). Weak equivalence principle tests lead to the following bound on the present value of the coupling:

$$|\alpha_{had,0}| \le 10^{-4} \tag{4}$$

leading to the following relation between b_F and Φ_0 :

$$\Phi_0 \ge \ln \frac{|b_F|}{2 \times 10^{-6}}.$$
(5)

Using the basic definition of deceleration parameter $q = -1 - \frac{\dot{H}}{H^2}$ one can also derive the constraint:

$$\Phi_0'| \le 0.3 \tag{6}$$

where the dots represent the derivative with respect to time, and the prime with respect to the logarithm of the scale factor $\ln(a)$.

By solving the Friedmann equations for these classes of models one finds the redshift evolution of the dilaton field compared to the present value of the field (fig.1) and the evolution of the Hubble parameter for these type of model (fig.2) which should be compared to observational data. A comprehensive list of recent measurements is given in [7].



Figure 1. Redshift evolution of dilaton field compare to its present value.



Figure 2. Hubble parameter as a function of redshift of the dilaton models with experimental data from [7] in both panel, b_f had been fixed to 10^{-8}

3. Variations of fundamental constants

Recent obsevations suggest possible variations of fine-structure constant in time and/or space [8]. Our analysis is focussed on time-variations of α and some specific measurements are in Table 1, including the recent first result of the UVES Large Program for Testing Fundamental Physics [5], which is expected to be the one with a better control of possible systematics.

Object	Redshift	$\Delta \alpha / \alpha$	Spectrograph
HE0515-4414	1.15	$(-0.1 \pm 1.8) \times 10^{-6}$	UVES
HE0515-4414	1.15	$(0.5 \pm 2.4) \times 10^{-6}$	HARPS+UVES
HE0001-2340	1.58	$(-1.5 \pm 2.6) \times 10^{-6}$	UVES
HE2217-2818	1.69	$(1.3 \pm 2.6) \times 10^{-6}$	UVES
Q1101-264	1.84	$(5.7 \pm 2.7) \times 10^{-6}$	UVES

Table 1. Available specific measurements of α , with one-sigma uncertainties.

It is then interesting to study the behaviour of α in this class of models, and as it has been shown in [1], the evolution of α is given by:

$$\frac{1}{H}\frac{\dot{\alpha}}{\alpha} = \frac{b_F c e^{-c\Phi}}{1 - b_F c e^{-c\Phi}} \Phi'.$$
(7)

By integrating this equation, one finds the evolution of the variation of α :

$$\frac{\Delta\alpha}{\alpha}(z) = \frac{\alpha(z) - \alpha_0}{\alpha_0} = b_F \left(e^{-c\Phi_0} - e^{-c\Phi(z)} \right).$$
(8)

The present drift of α is locally constrained by the Rosenband bound:

$$\left(\frac{1}{\alpha}\frac{d\alpha}{dt}\right)_0 = (-1.6 \pm 2.3)^{-17} yr^{-1};$$
(9)

assuming the Planck value for the Hubble constant $H_0 = (67.4 \pm 1.4) \text{ kms}^{-1} \text{Mpc}^{-1}$, one can find:

$$|\alpha_{\text{had},0}\Phi_0'| \sim |b_F c e^{-c\Phi_0'}| \le 3 \times 10^{-5}.$$
 (10)

From here one can then predict the redshift evolution of α taking Φ_0 and Φ'_0 as free parameters and make a χ^2 analysis using both H(z) data from [7] and the α data from Table 1 (see figures (3) and (4).

4. Future tests

The drift in the spectroscopic velocity of an object following the Hubble flow can be obtained from the definition of redshift and expressed as:

$$\Delta v = \frac{c}{(1+z)} \Delta t (H_0(1+z) - H(z)).$$
(11)

Here c is the speed of light and Δt the time span of observation. The precision needed to detect this signal is expected to be reached by future facilities such as the SKA, an intensity mapping experiments, and ELT-HIRES (see [6] for the phase A study of the instrument) which will offer the unique advantage to observe this drift deep in the matter era $(z \sim 2 \rightarrow 5)$ through spectroscopic measurements in the Lymann- α forest. ELT-HIRES is expected to reach a spectroscopic velocity precision parametrized by:

$$\sigma_v = 1.35 \left(\frac{S/N}{2370}\right)^{-1} \left(\frac{N_{QSO}}{30}\right)^{-1/2} \left(\frac{1+z_{QSO}}{5}\right)^{-1.7}$$
(12)





Figure 4. Reduced- χ^2 (indicated by the color scale) using both H(z) and $\frac{\Delta \alpha}{\alpha}$ measurements, with $-10^{-8} \leq b_F \leq -10^{-9}$ (x-axis) and $-0.3 \leq \Phi'_0 \leq 0.3$ (y-axis).

Figure 3. Redshift evolution of α -variations, the data points taken from table 1.

where S/N is the signal-to-noise ratio, N_{QSO} the number of targets observed, and z_{QSO} the redshift of the observed targets.

Using the same values of the parameters as previously (b_f fixed at 10^{-8} , $H_0 = 67.4 \pm 1.4$ kms⁻¹Mpc⁻¹), one can then compute the behaviour of the redshift drift as a function of redshift for the runaway dilaton models, compare it to ΛCDM models and verify whether or not one will be precise enough to put constraints on the parameter space of the model with the ELT-HIRES. Fig.5 compares the redshift drift of the standard model of cosmology (red) to the runaway dilaton one, the error bars being the expected accuracy that ELT-HIRES can provide.



Figure 5. Redshift drift signal for the runaway dilaton class of models (blue), with model parameters in ranges allowed by observations, compared to the signal expected in ΛCDM (red) and the forecasted uncertainties for an observational time of $\Delta t = 30$ yrs, a signal-to-noise ratio of S/N=3000 for 40 uniformly spaced systems divided in 4 bins.

5. Conclusions

In this analysis, we showed that the runaway dilaton class of models remains an alternative possibility to the standard model; however, current data already places tight constraints on its free parameters. Nevertheless given these constraints, the model predicts distinctive behaviours for α and the redshift drift signal, which will be tested with future facilities such as ELT-HIRES.

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