ASTROPHYSICAL TESTING COSMOLOGICAL VARIABILITY OF FUNDAMENTAL PHYSICAL CONSTANTS

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We review the current status of the problem of cosmological variability of fundamental physical constants, in particular, the fine-structure constant $\alpha = e^2/\hbar c$ and the proton-to-electron mass ratio $\mu = m_p/m_e$, with emphasis on the recent results provided by astronomical observations.

1 Introduction

The problem of the talk is one of the hot points of contemporary physics and cosmology. Current theories of fundamental interactions (e.g., SUSY GUT, Superstring theory) predict two kinds of variations of fundamental constants. First, they state that the fundamental constants are "running" – that is, depend on the energy of particle interaction (e.g., Ref. [1]). This effect has been reliably confirmed in high-energy accelerator experiments. For example, the fine-structure constant $\alpha = e^2/\hbar c$ equals 1/137.036 at low energies ($E \to 0$) and 1/128.896 at energy 90 GeV [2]. Second, the current theories predict that the *low-energy limits* of the fundamental constants can vary in the course of cosmological evolution and take on different values at different points of space-time. Here we focus on the latter kind of their possible variability.

Clearly, experimental detection of a space-time variability of the fundamental constants would be a great step forward in understanding Nature. Note, however, that a numerical value of any dimensional physical parameter depends on arbitrary choice of physical units. In turn, there is no way to determine the units in a remote space-time region other than through the fundamental constants. Therefore it is meaningless to speak of a variation of a dimensional physical constant without specifying which of the other physical parameters are *defined* to be invariable. This point has been recently emphasized by Duff [3] (the counter-arguments by Moffat [4] are actually based on the unjustified implicit assumption that one can measure absolute time intervals in distant space-time regions without specifying the clock used). Usually, while speaking on variability of a dimensional physical parameter, one *implies* that *all* the other fundamental constants are fixed. So did Milne [5] and Dirac [6] in their pioneering papers devoted to a possible change of the gravitational constant G. More recently, a number of authors considered cosmological theories with a time varying speed of light c (e.g., Ref. [7] and references therein). However, if we adopt the standard definition of meter as the length of path traveled by light in vacuum in $1/299\,792\,458$ s, then $c = 2.997\,924\,58 \times 10^8$ m s^{-1} identically. Similarly, one cannot speak on variability of the electron mass m_e or charge e while using the Hartree units ($\hbar = e = m_e = 1$), most natural in atomic physics.

Thus, only *dimensionless* combinations of the physical parameters are truly fundamental, and only such combinations will be considered hereafter. We shall review the current status of the problem of space-time variability of the low-energy limits of the fundamental constants, paying main attention to two constants which are of paramount importance for atomic and molecular spectroscopy: (i) the fine-structure constant $\alpha = e^2/\hbar c$, and (ii) the proton-to-electron mass ratio $\mu = m_p/m_e$, which characterize the strengths of electromagnetic and strong interactions.

2 Quasar spectra

Values of the physical constants in the early epochs are estimated directly from observations of quasars (the most powerful sources of radiation) whose spectra were formed when the Universe was several times younger than now. The wavelengths of the spectral lines observed in radiation from these objects ($\lambda_{\rm obs}$) increase compared with the laboratory values ($\lambda_{\rm lab}$) in proportion $\lambda_{\rm obs} = \lambda_{\rm lab}(1+z)$, where z is the *cosmological redshift* which can be used to determine the age of the Universe at the line-formation epoch. Analyzing these spectra we can study the epochs when the Universe was younger than now.

At present, the extragalactic spectroscopy enables one to probe the physical conditions in the Universe up to cosmological redshifts $z \lesssim 6$, which correspond, by order of magnitude, to the scales $\lesssim 15$ Gyr in time and $\lesssim 5$ Gpc in space. The large time span enables us to obtain quite stringent estimates of the rate of possible time variations, even though the astronomical wavelength measurements are not so accurate as the precision metrological experiments. Moreover, such analysis allows us to study the physical conditions in distant regions of the Universe, which were causally disconnected at the line-formation epoch.

In general, the dependence of wavelengths of resonant lines in quasar spectra on fundamental constants is not the same for different transitions. This makes it possible to distinguish the cosmological redshift (common for all lines in a given absorption system) from the shift due to the possible variation of fundamental constants.

2.1 Fine-structure constant

Quasar spectra were used for setting bounds on possible variation rates of fundamental physical constants by many authors. The first ones were Bahcall *et al.* [8, 9], who compared the observed redshifts z of the components of fine-structure doublets in spectra of distant quasars, and derived the estimates $\Delta\alpha/\alpha = (-2 \pm 5) \times 10^{-2}$ at $z = 1.95$ and $\Delta\alpha/\alpha = (-1 \pm 2) \times 10^{-3}$ at $z = 0.2$. Afterwards this and similar methods were used for setting stronger bounds on $\Delta\alpha/\alpha$ at different z. In particular, Potekhin and Varshalovich [10] applied modern statistical methods to analysis of ≈ 1400 pairs of wavelengths of the fine-splitted doublet absorption lines in quasar spectra and obtained an upper bound on the rate of a relative variation of the fine-structure constant $|\alpha^{-1}\mathrm{d}\alpha/\mathrm{d}z| < 5.6 \times 10^{-4}$ for the epoch $0.2 \leq z \lesssim 4$. Later we (Ivanchik *et al.* [11]) optimized the strategy of studying the time-dependence of α. As a result, a new constraint on the possible deviation of the fine-structure constant at $z = 2.8$–3.1 from its present ($z = 0$) value was obtained: $|\Delta\alpha/\alpha| < 1.6 \times 10^{-4}$. The corresponding upper limit of the α variation rate averaged over $\sim 10^{10}$ yr is $|\dot{\alpha}/\alpha| < 2 \times 10^{-14}$ yr^{-1}.

In a recent series of papers, Webb *et al.* (e.g., Ref. [12] and references therein) reported a possible detection of variation of the fine-structure constant, $\Delta\alpha/\alpha = (-0.72 \pm 0.18) \times 10^{-5}$, averaged over the cosmological redshifts $z = 0.5$–3.5. However, it is difficult to evaluate systematic errors which might simulate this result. In particular, the method used by the authors, which is based on simultaneous measurements of wavelengths of a large number of transitions for various ions, depends more sensitively on poorly known factors (e.g., isotope variations, instrumental calibration errors, etc.) than the method based on separate measurements of fine structure of spectral lines of each species [10, 11]. On the other hand, the latter method has a larger statistical error than the method of Webb *et al.* Therefore, it is especially important to check possible variations of different fundamental constants, using different techniques, applied to different stages of the cosmological evolution.

2.2 Proton-to-electron mass ratio

Since any interaction inherent in a given particle contributes to its observed mass, a variation in α suggests a variation in the proton-to-electron mass ratio $\mu = m_p/m_e$. The functional dependence $\mu(\alpha)$ is currently unknown, but there are several theoretical models which allow one to estimate the electromagnetic contribution to μ (e.g., [13, 14]), as well as model relations between cosmological variations of α and μ based on Grand Unification [15].

Evaluation of μ in distant space-time regions of the Universe is possible due to observations of H_2 molecular lines in quasar spectra. The wavelengths of these lines depend on μ through the reduced mass of the molecule. The method is based on the relation [16]

$$\frac{1+z_i}{1+z_k} = \frac{(\lambda_i/\lambda_k)_z}{(\lambda_i/\lambda_k)_0} \simeq 1 + (K_i - K_k)\left(\frac{\Delta\mu}{\mu}\right), \tag{1}$$

where z_i is the observed redshift of an individual line, the subscripts 'z' and '0' mark the wavelength ratios in the quasar spectrum and the terrestrial laboratory, respectively, and $K_i \equiv \partial \ln \lambda_i / \partial \ln \mu$ are the *sensitivity coefficients*. A method for calculation of these coefficients has been presented in Ref. [17]. The authors have applied a linear regression (z as a linear function of K) analysis to the H_2 absorption lines in the spectrum of quasar PKS 0528−250 at $z = 2.8108$ and obtained an estimate of the fractional variation of $|\Delta\mu/\mu| = (11.5 \pm 7.6) \times 10^{-5}$. Thus, no statistically significant variation was found. The above estimate approximately corresponds to the upper bound $|\dot{\mu}/\mu| < 1.5 \times 10^{-14}$ yr^{-1}.

Recently, similar analyses of the H_2 absorption system in the spectrum of quasar Q 0347−382 at $z = 3.0249$ have been performed by Levshakov *et al.* [18] and Ivanchik *et al.* [19]; the latter authors analyzed also the H_2 absorption system in the spectrum of quasar Q 1232+082 at $z = 2.3377$. The most conservative estimate for the possible variation of μ in the past ~ 10 Gyr, obtained in Ref. [19], reads

$$\Delta\mu/\mu = (5.7 \pm 3.8) \times 10^{-5}. \tag{2}$$

The corresponding linear regression is illustrated in Fig. 1. Thus, we have obtained the most stringent estimate on a possible cosmological μ-variation

$$|\dot{\mu}/\mu| < 1 \times 10^{-14} \ \ \mathrm{yr}^{-1}. \tag{3}$$

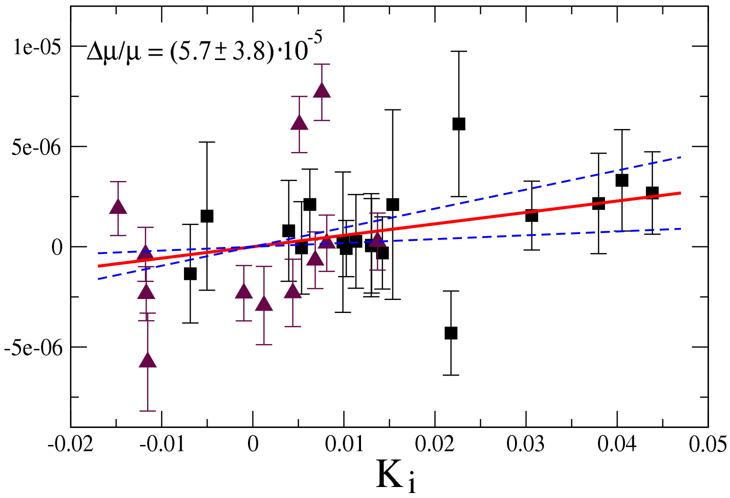

Figure 1: Regression analysis of ξ_i-to-K_i for the H_2 lines; $\xi_i = (z_i - \overline{z})/(1+\overline{z})$.

3 Conclusions

We have discussed the current status of the problem of cosmological variability of fundamental physical constants, making emphasis on the studies of the space-time variability of two basic parameters of atomic and molecular physics: the fine-structure constant α and the proton-to-electron mass ratio μ. A variation of these parameters is not firmly established. More precise measurements and observations and their accurate statistical analyses are required in order to detect the expected variations of the fundamental constants.

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