Current status of the problem of cosmological variability of fundamental physical constants

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Abstract

We review the current status of the problem of cosmological variability of fundamental physical constants, provided by modern laboratory experiments, Oklo phenomena analysis, and especially astronomical observations.

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1 Introduction

The problem of the talk is one of the hot point 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 constants" depend on the energy transfer in particle interactions (e.g., Ref. [1]). It is a result of radiation corrections and vacuum polarization effects. It 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 [1]. Such "running" of the constants has to be taken into account for consideration of very early Universe.

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. Multidimensional theories (Kaluza-Klein type, "p-brane" models, and others) predict variations of fundamental physical constants as a direct result of the cosmological evolution of the extra-dimensional subspace. It means that the true constants of nature are defined in higher dimensions and their three-dimensional projections we observe do not need to be constant. In several theories (e.g. Superstrings/M-theory), the variations of the constants result from the cosmological evolution of the vacuum state (a vacuum condensate of some scalar field or "Quintessence"). In addition, a possible non-uniqueness of the vacuum state in different space-time regions would allow constants to have different values in different places.

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 [2] (the counter-arguments by Moffat [3] 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 of variability of a dimensional physical parameter, one *implies* that *all* the other fundamental constants are fixed. So did Milne [4] and Dirac [5] 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. [6] and references therein). However, if we adopt the standard definition of meter [7] as the length of path traveled by light in vacuum in $1/299\,792\,458$ s, then $c = 2.997\,924\,58 \times 10^{10}$ $\mathrm{cm\,s^{-1}}$ identically. Similarly, one cannot speak of 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.

2 Tests for possible variations of fundamental constants

Various tests of the fundamental physical constants variability differ in space-time regions of the Universe which they cover (large review see e.g. [8]). In particular, *laboratory tests* infer the possible variation of certain combinations of constants "here and now" from comparison of different frequency standards. *Geophysical tests* impose constraints on combinations of fundamental constants over the past history of the Solar system, although most of these constraints are very indirect. In contrast, *astrophysical tests* (i.e. ones concerned with extragalactic observations) allows one to "measure" the values of fundamental constants in distant areas of the early Universe.

2.1 Local tests

2.1.1 Laboratory measurements

Laboratory tests are based on comparison of different frequency standards, depending on different combinations of the fundamental constants. Were these combinations changing differently, the frequency standards would eventually discord with each other. An interest in this possibility has been repeatedly excited since relative frequency drift was observed by several research groups using long term comparisons of different frequency standards. For instance, a comparison of frequencies of He-Ne/CH_4 lasers, NH_3 masers, H masers, and Hg^+ clocks with a Cs standard [9, 10, 11, 12, 13] has revealed relative drifts. Since the considered frequency standards have a different dependence on α via relativistic contributions of order α^2, the observed drift might be attributed to changing of the fine-structure constant. However, the more modern was the experiment, the smaller was the drift. Taking into account that the drift may be also related to some aging processes in experimental equipment, Prestage et al. [13] concluded that the current laboratory data provide only an upper limit $|\dot{\alpha}/\alpha| \leq 3.7 \times 10^{-14}$ yr^{-1}.

The most accurate experiment was performed recently by Sortais et al. [14]. They compared microwave clocks using laser cooled neutral atoms ^{87}Rb I and ^{133}Cs I. The frequencies of their HFS transitions of the ground states are

$$\nu_{\rm HFS}(^{87}\mathrm{Rb\,I}) = 6\ 834\ 682\ 610.904\ 343\ (17)\ \ \mathrm{Hz}$$

$$\nu_{\rm HFS}(^{133}\mathrm{Cs\,I}) = 9\ 192\ 631\ 770.000\ 000\ (0)\ \ \mathrm{Hz}$$

The error of $\nu_{\rm HFS}(^{133}\mathrm{Cs})$ equals zero by definition: it is the primary reference standard of frequency and the time unit. Measurements of the ratio $\nu_{\rm HFS}(^{87}\mathrm{Rb})/\nu_{\rm HFS}(^{133}\mathrm{Cs})$ during 24 months indicate no change at the level of 3.1×10^{-15} yr^{-1}. This gives a new upper limit for α-variation $|\dot{\alpha}/\alpha| \leq 1.8 \times 10^{-14}$ yr^{-1}, providing the gyromagnetic ratios of ^{87}Rb and ^{133}Cs are invariable, either upper limit to the gyromagnetic ratio $|\dot{g_p}/g_p| \leq 4.2 \times 10^{-15}$ yr^{-1} providing the fine-structure constant is invariable.

Some other possibilities for laboratory searches of possible variations of the physical constants suggested by Karshenboim [15].

2.1.2 Analysis of the Oklo phenomenon

The strongest limits to variation of the fine-structure constant α and the coupling constant of the strong interaction α_s have been originally inferred by Shlyakhter [16] from results of an analysis of the isotope ratio ^{149}Sm/^{147}Sm in the ore body of the Oklo site in Gabon, West Africa. This ratio turned out to be considerably lower than the standard one (instead of 0.92 it falls down to 0.006). It is believed to have occurred due to operation of the natural uranium fission reactor about 2×10^9 yr ago in those ores. One of the nuclear reactions accompanying this process was the resonance capture of neutrons by ^{149}Sm nuclei. Actually, the rate of the neutron capture reaction is sensitive to the energy of the relevant nuclear resonance level E_r, which depends on the strong and electromagnetic interaction. Since the capture has been efficient 2×10^9 yr ago, it means that the position of the resonance has not shifted by more than its width ($\Gamma = 0.066$ eV) during the elapsed time. At variable α and invariable α_s (which is just a model assumption), the shift of the resonance level would be determined by changing the difference between the Coulomb energies of the ground-state nucleus ^{149}Sm and the nucleus ^{150}Sm* excited to the level E_r. Unfortunately, there is no experimental data for the Coulomb energy of the excited ^{150}Sm* in question. Using order-of-magnitude estimates, Shlyakhter [16] concluded that $|\dot{\alpha}/\alpha| \lesssim 10^{-17}$ yr^{-1}. From an opposite model assumption that α_s is changing whereas α =constant, he derived a bound $|\dot{\alpha}_s/\alpha_s| \lesssim 10^{-19}$ yr^{-1}.

Later Damour and Dyson [17] performed a more careful analysis, which resulted in the upper bound $|\dot{\alpha}/\alpha| \lesssim 7 \times 10^{-17}$ yr^{-1} (see, also Fujii et al., [18]). They have assumed that the Coulomb energy difference between the nuclear states of ^{149}Sm and ^{150}Sm* in question is not less than that between the *ground* states of ^{149}Sm and ^{150}Sm. The latter energy difference has been estimated from isotope shifts and equals $\approx$ 1 MeV. However, it looks unnatural that a weakly bound neutron ($\approx$ 0.1 eV), captured by a ^{149}Sm nucleus to form the highly excited state ^{150}Sm*, can so strongly affect the Coulomb energy. Moreover, excited nuclei sometimes have Coulomb energies smaller than those for their ground states (e.g., Ref. [19]). This indicates the possibility of violation of the basic assumption involved in Ref. [17], and therefore this method may possess a lower actual sensitivity. Furthermore, a correlation between variations of α and α_s (which is likely in the frame of modern theory) might lead to considerable softening of the above-mentioned bound, as estimated by Sisterna and Vucetich [20].

2.1.3 Some other local tests

Geophysical, geochemical, and paleontological data impose constraints on a possible changing of various combinations of fundamental constants over the past history of the Solar system, however most of these constraints are very indirect. A number of other methods are based on stellar and planetary models. The radii of the planets and stars and the reaction rates in them are influenced by values of the fundamental constants, which offers a possibility to check variability of the constants by studying, for example, lunar and Earth's secular accelerations. This was done using satellite data, tidal records, and ancient eclipses. Another possibility is offered by analyzing the data on binary pulsars and the luminosity of faint stars. Most of these have relatively low sensitivity. Their common weak point is the dependence on a model of a fairly complex phenomenon, involving many physical effects.

An analysis of natural long-lived α- and β-decayers in geological minerals and meteorites is much more sensitive. For instance, a strong bound, $|\dot{\alpha}/\alpha| < 5 \times 10^{-15}$ yr^{-1}, was obtained by Dyson [21] from an isotopic analysis of natural α- and β-decay products in Earth's ores and meteorites.

Having critically reviewed the wealth of the local tests, taking into account possible correlated synchronous changes of different physical constants, Sisterna and Vucetich [20] derived restrictions on possible variation rates of individual physical constants for ages t less than a few billion years ago, which correspond to cosmological redshifts $z \lesssim 0.2$. In particular, they have arrived at the estimate $\dot{\alpha}/\alpha = (-1.3 \pm 6.5) \times 10^{-16}$ yr^{-1}.

The most sensitive process is $^{187}Re \rightarrow ^{187}Os + e + \bar{\nu}$ due to a very small Q-value: $\Delta\tau/\tau \simeq 1.8 \times 10^4 \cdot \Delta\alpha/\alpha$. The laboratory measurement $\tau_{1/2}(lab) = (42.3 \pm 0.7)$ Gyr can be compared with the value inferred from Re/OS measurement in ancient meteorites $\tau_{1/2}(met) = (41.6 \pm 0.4)$ Gyr, dated by means of different radioactive methods (e.g. U/Th method, which is much less weakly affected by variation of α). The agreement within errors provides a significant constraint, $\Delta\alpha/\alpha = (1 \pm 1) \times 10^{-6}$ ([22]).

All the local methods listed above give estimates for only a narrow space-time region around the Solar system. For example, the epoch of the Oklo reactor (1.8×10^9 years ago) corresponds to the cosmological redshift $z \approx 0.1$.

2.2 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 several times 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.

2.2.1 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.* [23, 24], 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 [25] 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 $|\alpha^{-1}{\rm d}\alpha/{\rm d}z| < 5.6 \times 10^{-4}$ for the epoch $0.2 \leq z \lesssim 4$. Later we (Ivanchik *et al.* [26]) 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. [27] 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 in the method based on separate measurements of fine structure of spectral lines of each species [25, 26]. 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.

2.2.2 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., [28, 29]), as well as model relations between cosmological variations of α and μ [30].

Evaluation of μ in distant space-time regions of the Universe is possible 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 [31]

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

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 these coefficients has been presented in Ref. [32]. 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.* [33] and Ivanchik *et al.* [34]; 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

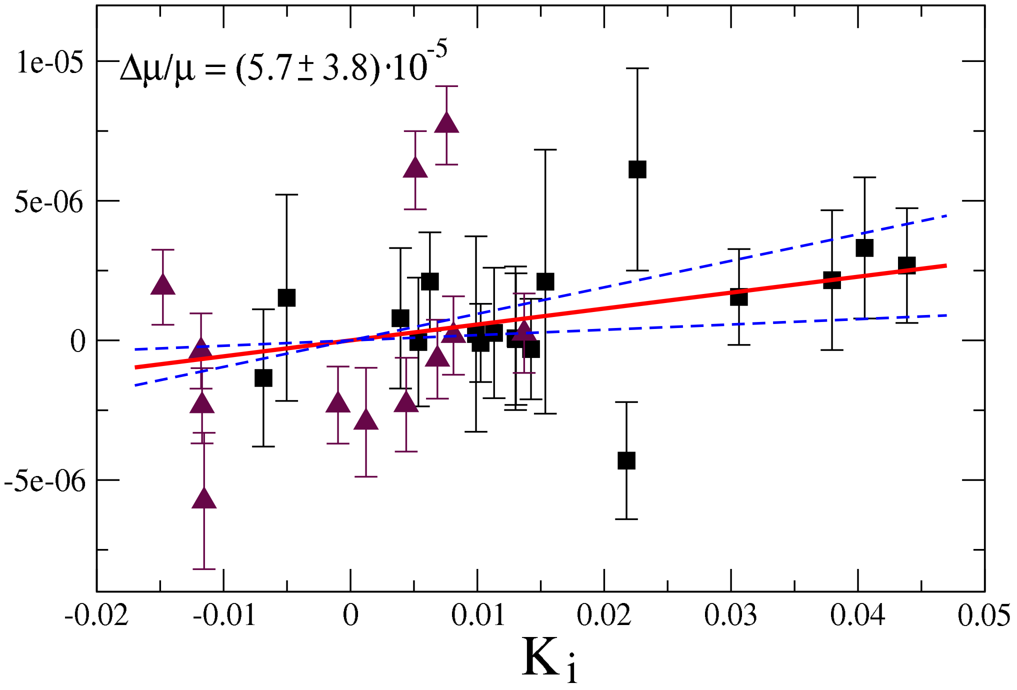

Figure 1: Regression analysis of ξ_i-to-K_i for the H_2 lines. $\xi_i = (z_i - \overline{z})/(1 + \overline{z})$

for the possible variation of μ in the past ~ 10 Gyr, obtained in Ref. [34], 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 variation of mu $|\dot{\mu}/\mu| < 6 \times 10^{-15}$ yr^{-1}.

2.3 Cosmic Microwave Background Radiation

Any time variation in the fine-structure constant (as well as m_e) alters the ionization history of the Universe and therefore changes the pattern of cosmic microwave background fluctuations. Changing α changes the energy levels of hydrogen, the Thomson cross section, and recombination rates. These changes are dominated by the change in the redshift of recombination due to the shift in the binding energy of hydrogen.

An analysis of the recently obtained data from BOOMERanG [35] and MAXIMA [36] experiments allowing for the possibility of a time-varying the fine-structure constant. This data prefers a value of α that was smaller in the past (which is in agreement with measurements of α from quasar observations). However, the strong statements about α can not be made because such a theoretical analysis involves several additional parameters (cosmological ones H_0, Ω_0, and Ω_b as well as some physical constants, e.g. the electron mass). Bounds imposed on the variation of α can be significantly relaxed if one also allows for a change in the equation of state of quintessence which mimic the cosmological Λ-term. In any case, such a analysis allows to obtained upper limit on α-variation at the recombination epoch ([37, 38, 39, 40]):

$$|\Delta\alpha/\alpha| \leq 10^{-2} \tag{3}$$

2.4 Primordial Nucleosynthesis

Temporal variations of the coupling constants can be revealed by analyzing the dependence of the primordial ^{4}He mass fraction on gravitational constant G, on fine-structure constant α, and on other constants [41]. Based on astronomical observational data for the primordial helium abundance Y_p, Kolb et al. [41] imposed constraints (2-3%) on the possible deviations of fundamental physical constants at the epoch of primordial nucleosynthesis from their current values. However, they varied different constants separately (with the remaining constants being fixed) and assumed the parameter $\eta = n_B/n_\gamma$, the baryonic-to-photon density ratio, to be also fixed.

Subsequently, modifying the standard nucleosynthesis theory, several authors imposed constraints on the relative change in fundamental physical constants by taking into account the possible simultaneous change in various constants (see, e.g., [42, 43, 44]). However, the calculations were performed for a specific fixed η (as in the pioneering study by Kolb et al. [41]).

In paper [45] a two-parameter (η, δ) model for primordial nucleosynthesis was considered, in which η is a free parameter and can depend (for a constant yield of light elements) on the deviation of constant δ. The parameter δ characterizes the relative deviation of fundamental physical constants at the epoch of primordial nucleosynthesis from their current values (in particular $\delta = \Delta\alpha/\alpha$).

Unfortunately, the Primordial Nucleosynthesis as well as Cosmic Microwave Background Radiation do not give very stringent limitation on the variation of fundamental constant because of many different parameters involved in the analysis.

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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