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Current status of astronomical observations on possible cosmological variations of the proton-to-electron mass ratio $\mu = m_{\mathrm{p}}/m_{\mathrm{e}}$

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Abstract. Astronomical constraints on a possible cosmological variation of the proton-to-electron mass ratio $\mu = m_{\mathrm{p}}/m_{\mathrm{e}}$ are discussed. The analysis of H_2 lines observed in the spectra of distant quasars Q 0405-443 ($z_{\mathrm{em}} = 3.02$) and Q 0347-383 ($z_{\mathrm{em}} = 3.22$) is performed [1] using, partly, very precise values of H_2 frequencies from new laboratory measurements [2] and sensitivity coefficients from new accurate calculations [2,3]. A possible μ-variation of $\Delta\mu/\mu = (2.0 \pm 0.6) \times 10^{-5}$ over 12 Gyr is not excluded. However, the discussion of systematic errors show that some may well be underestimated. Thus, the above value should be treated as the most stringent limit the cosmological variation of μ at $z \approx 2.6 - 3.0$ (12 Gyr ago).

1 Introduction

Whether the fundamental constants of nature are changing with time or not? This question has been attracting much attention since Dirac formulated his famous "Large Numbers Hypothesis" [4]. At first it was a phenomenologically motivated problem which sounds as "Why in the evolving and changing Universe the physical parameters that people call "fundamental constants" should be unvarying?". More serious interest appeared when a theoretical motivation came from advances in multidimensional (Kaluza-Klein gravity, [5]) and Superstring theories [6,7] which predict variations of the fundamental constants with changing extra dimensions and varying fundamental scalar fields. Moreover, the researches of high-redshift Type Ia supernovae led us to conclude that the Universe expansion is accelerated by dominated energy form with vacuum-like equation of state (so called "Dark Energy", $p = w\epsilon$, where $w \approx -1$) [8]. This equation of state is naturally generated by scalar fields which as well may be related with fundamental constants. So, the discovery of fundamental constant variability would be a great step towards our understanding of Nature as well as a powerful tool for studying evolution of scalar fields concerned with Dark Energy [9–12] and for testing different versions of Grand Unified Theories that establish relations between fundamental constants such as the fine-structure constants α and the proton-to-electron mass ratio μ [13–17].

A few years ago it was claimed by Webb et al. [18] that the fine-structure constant α could be smaller in the past. It has induced a great interest for experimental tests of the possible variations of fundamental constants. Some of such results [1,2,19–31] are presented in Table 1. One can see there are disagreements between results obtained by different authors. So, now the problem becomes even more intriguing. The data in the table are divided into three subgroups according to a time interval. The first set, so-called "Now and Here", corresponds to measurements performed during a short time interval (<10 years) at Earth laboratories.

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Table 1. The experimental results on possible temporal variations of the fundamental constants. (The bold font marks more than 1σ-results.)

Epoch	Reference	Constant	$\Delta x/x$	$\dot{x}/x$, yr^{-1}
"Now and Here"	2007 Fortier et al.	α	$(3.6 \pm 6.0) \times 10^{-15}$	$(-0.6 \pm 1.0) \times 10^{-15}$
	2006 Peik et al.	α	$(1.6 \pm 2.3) \times 10^{-15}$	$(-0.3 \pm 0.4) \times 10^{-15}$
	2003 Bize et al.	α	$< 2.4 \times 10^{-15}$	$< 1.2 \times 10^{-15}$
	1995 Prestage et al.	α	$< 3.7 \times 10^{-14}$	$< 3.7 \times 10^{-14}$
"Oklo"	2006 Petrov et al.	α	$(0.1 \pm 0.7) \times 10^{-7}$	$(-0.5 \pm 3.5) \times 10^{-17}$
	2004 Lamoreaux et al.	α	$\mathbf{(4.5 \pm 0.2) \times 10^{-8}}$	$(-2.3 \pm 0.1) \times 10^{-17}$
	2000 Fujii et al.	α	$\mathbf{(8.8 \pm 0.7) \times 10^{-8}}$	$(-4.4 \pm 0.4) \times 10^{-17}$
QSO	2007 Levshakov et al.	α	$\mathbf{(5.4 \pm 2.5) \times 10^{-6}}$	$(-5.4 \pm 2.5) \times 10^{-16}$
	2004 Chand et al.	α	$(-0.6 \pm 0.6) \times 10^{-6}$	$(0.6 \pm 0.6) \times 10^{-16}$
	2003 Murphy et al.	α	$\mathbf{(-0.5 \pm 0.1) \times 10^{-5}}$	$(6.4 \pm 1.4) \times 10^{-16}$
	1999 Webb et al.	α	$\mathbf{(-1.1 \pm 0.4) \times 10^{-5}}$	$(2.2 \pm 5.1) \times 10^{-16}$
	2006 Reinhold et al.	μ	$\mathbf{(2.0 \pm 0.6) \times 10^{-5}}$	$(2.0 \pm 0.6) \times 10^{-15}$
	2005 Ivanchik et al.	μ	$\mathbf{(1.7 \pm 0.7) \times 10^{-5}}$	$(1.7 \pm 0.7) \times 10^{-15}$
	2005 Kanekar et al.	μ	$< 1.4 \times 10^{-5}$	$< 2.1 \times 10^{-15}$
	1995 Cowie & Songaila	μ	$(0.8 \pm 6.3) \times 10^{-4}$	$(0.8 \pm 6.3) \times 10^{-14}$
	2007 Tzanavaris et al.	$\alpha^2 g_p \mu^{-1}$	$(0.6 \pm 2.0) \times 10^{-5}$	$(0.6 \pm 2.0) \times 10^{-15}$
	1995 Cowie & Songaila	$\alpha^2 g_p \mu^{-1}$	$(0.7 \pm 1.1) \times 10^{-5}$	$(0.7 \pm 1.1) \times 10^{-15}$

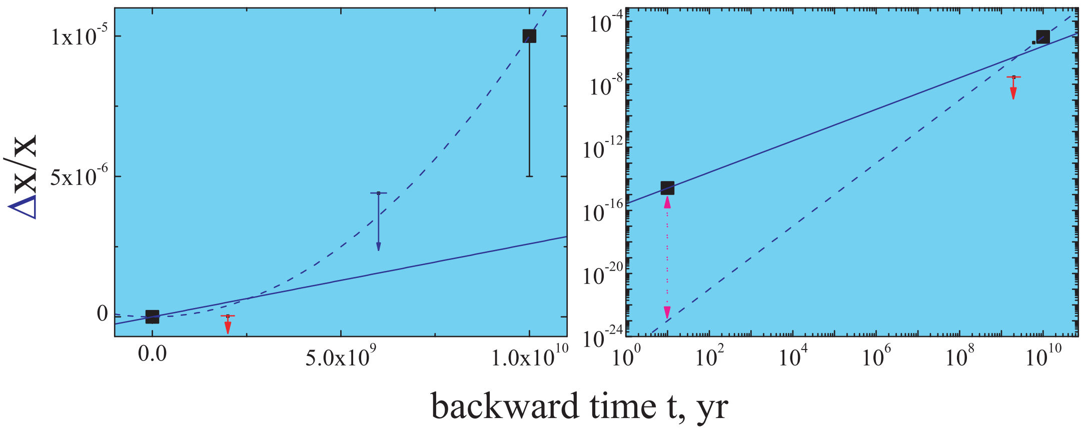

Fig. 1. Comparison of different experimental limits on deviation of fundamental constants $\Delta x/x$ with the linear dependence corresponding to the best laboratory-based experiments [19,20] (solid line) and the simple non-linear (quadratic) dependence corresponding to $\Delta x/x = 10^{-5}$ at $t = 10^{10}$ yr (dotted line) is presented on linear (left panel) and logarithmic (right panel) scales. It is easy to see that to detect such a dependence on a 10 years scale, the accuracy of laboratory experiments have to be better than 8 orders of magnitude. The blue and red arrows are limits by Tzanavaris et al. [31] and from "Oklo" respectively. The first and second black squares correspond to laboratory and QSO data, respectively.

The second one corresponds to the "Oklo" phenomenon (Gabon, West Africa) which occurred 1.8–2 Gyr ago. The third set of data obtained from studies of QSO spectra which give us an information about early stages of the Universe evolution up to 13 Gyrs ago. Despite the high accuracy ($\sim 10^{-15}$) achieved by laboratory experiments, the results from QSO spectra have important advantages. It is illustrated in Fig. 1.

2 Testing possible cosmological variation of μ from QSO spectrum analysis

At present the proton-to-electron mass ratio has been measured with a relative accuracy of 4×10^{-10} and equals $\mu_0 = 1836.15267247(80)$ [32]. Laboratory metrological measurements rule out a large variation of μ on a short time scale but do not exclude its change over the cosmological scale, $\sim 10^{10}$ years. Moreover, one can not reject the possibility that μ (as well as other constants) could be different in widely separated regions of the Universe.

Quasars are the most luminous and distant visible objects in the Universe. Therefore, the light traveling from the QSO to the observer carries information from the early epochs of the Universe (2–14 Gyr ago). Studies of absorption systems in QSO spectra give information about physical conditions at the epochs of the spectrum formation.

The real possibility of experimentally testing the cosmological variation of μ appeared only after the discovery of H_2 molecule clouds at high redshift by Levshakov and Varshalovich (1985) [33]. It should be noted that more than 100 000 quasars are identified today but H_2 absorptions are observed in only 12 of them [34] because to detect such systems one needs large optical telescopes and high-resolution spectrographs (e.g. 8 m VLT or 10 m Keck). Out of these 12 systems, only 2 have the characteristics suitable for our analysis (see [1] for more details).

Astrophysical methods to constrain possible fundamental constant changes are based on the comparison of wavelengths measured in quasar spectra with ones measured in laboratory (see Fig. 2). We use QSO absorption lines to constrain $\Delta\mu/\mu$ with $\Delta\mu = \mu - \mu_0$, where μ is the proton-to-electron mass ratio at the epoch of the QSO absorption spectrum formation and μ_0 is its contemporary value.

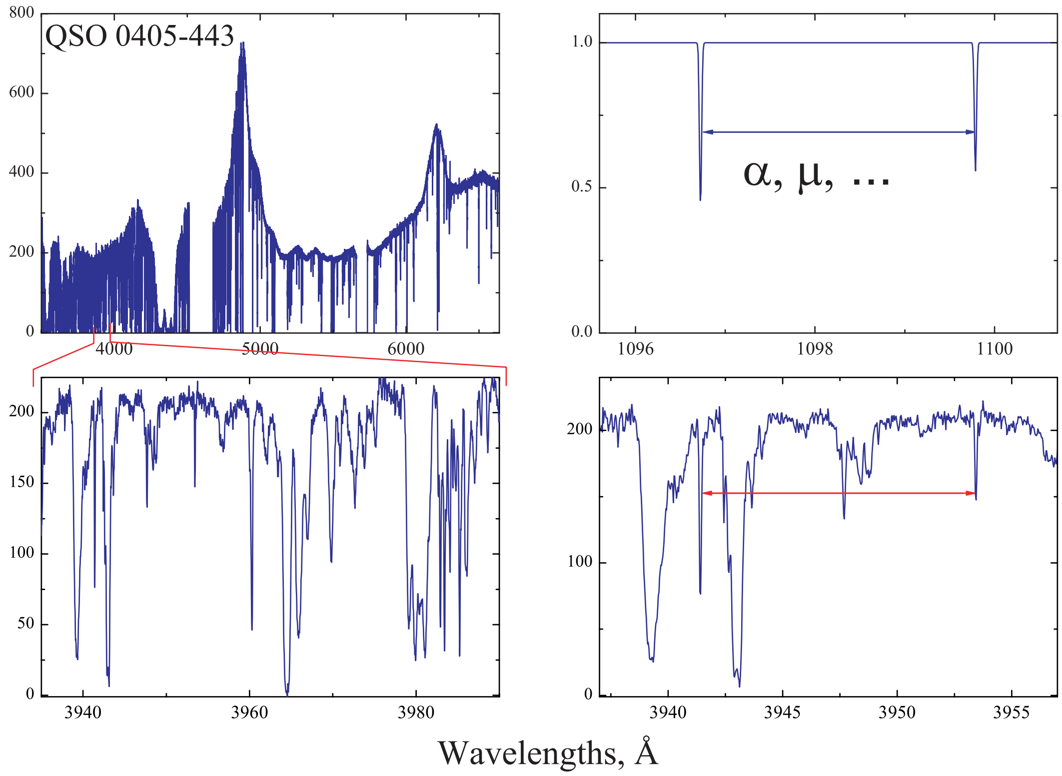

Fig. 2. Parts of an optical QSO spectrum and a UV-laboratory spectrum (top right panel). Astrophysical methods to constrain possible fundamental constant changes are based on the comparison of wavelengths measured in quasar spectra with ones measured in laboratory.

The method used here to constrain the possible variations of μ was proposed by Varshalovich and Levshakov [35]. It is based on the fact that wavelengths of electron-vibro-rotational lines depend on the reduced mass of the molecule, with the dependence being different for different transitions. It enables us to distinguish the cosmological redshift of a line from the shift caused by a possible variation of μ.

Thus, the measured wavelength λ_i of a line formed in the absorption system at the redshift z_abs can be written as

$$\lambda_\mathrm{i} = \lambda_\mathrm{i}^0 (1 + z_\mathrm{abs})(1 + K_\mathrm{i} \Delta\mu/\mu) \tag{1}$$

where λ_i^0 is the laboratory (vacuum) wavelength of the transition, and $K_\mathrm{i} = \mathrm{d}\ln\lambda_\mathrm{i}^0/\mathrm{d}\ln\mu$ is the sensitivity coefficient for the Lyman and Werner bands of molecular hydrogen. This expression can be represented in terms of the individual line redshift $z_\mathrm{i} \equiv \lambda_\mathrm{i}/\lambda_\mathrm{i}^0 - 1$ as

$$z_\mathrm{i} = z_\mathrm{abs} + bK_\mathrm{i} \tag{2}$$

where $b = (1 + z_\mathrm{abs})\Delta\mu/\mu$.

In reality, z_i is measured with some uncertainty which is caused by statistical errors of the astronomical measurements λ_i, by errors of the laboratory measurements of λ_i^0, and by possible systematic errors. Nevertheless, if $\Delta\mu/\mu$ is nonzero, there must be a correlation between z_i and K_i values. Thus, a linear regression analysis of these quantities yields z_abs and b (as well as their statistical significance), consequently an estimate of $\Delta\mu/\mu$.

2.1 Observations

We used the UVES echelle spectrograph mounted on the Very Large Telescope of the European Southern Observatory to obtain new and better quality data (compared to what was available in the UVES data base) on two bright high-redshift quasars, Q 0347-383 ($z_\mathrm{em} = 3.22$) and Q 0405-443 ($z_\mathrm{em} = 3.02$). Spectra were extracted using procedures implemented in MIDAS, the ESO data reduction package.

In each of the quasar spectra there is a damped Lyman-α system in which H_2 has been well studied, at $z_\mathrm{abs} = 3.0249$ and 2.5947 for Q 0347-383 and Q 0405-443, respectively. A crucial advantage of these H_2 absorption systems is that numerous unsaturated lines with narrow simple profiles are seen. A single component profile is sufficient to fit the lines on the line of sight toward Q 0347-383 and profiles of two well separated ($\Delta V = 13\,\mathrm{km\,s^{-1}}$) components are fitted in the case of Q 0405-443 (for more details see [1]).

2.2 New laboratory measurements of wavelengths λ_i^0

Previously for our analysis we used Abgrall's atlas (1993) of H_2 laboratory wavelengths with errors $\sigma_\lambda \sim 1.5\,\mathrm{m\AA}$ [36]. In the work [1], observational accuracy became comparable with the laboratory one. This pointed out towards more precise H_2 laboratory wavelengths. Very recently, new extremely accurate wavelengths ($\sigma_\lambda \sim 0.07\,\mathrm{m\AA}$, i.e. more than 20 times better) were measured using ultraviolet laser spectroscopy [37,2] for a number of the lines.

2.3 New calculations of sensitivity coefficients K_i

In previous work we used standard adiabatic approximation with energy level represented by Dunham formula [38]. Now *ab initio* non-adiabatic calculations of the H_2 wavelengths λ_i of the individual lines of the Lyman and Werner series and corresponding sensitivity coefficients K_i (with accuracy better than 1%) have been performed [3].

3 Results

Using 76 H_2 absorption lines observed at $z_\mathrm{abs} = 2.59473$ and 3.02490 in the spectra of two quasars, respectively, Q 0405-443 and Q 0347-383, we have searched for any correlation

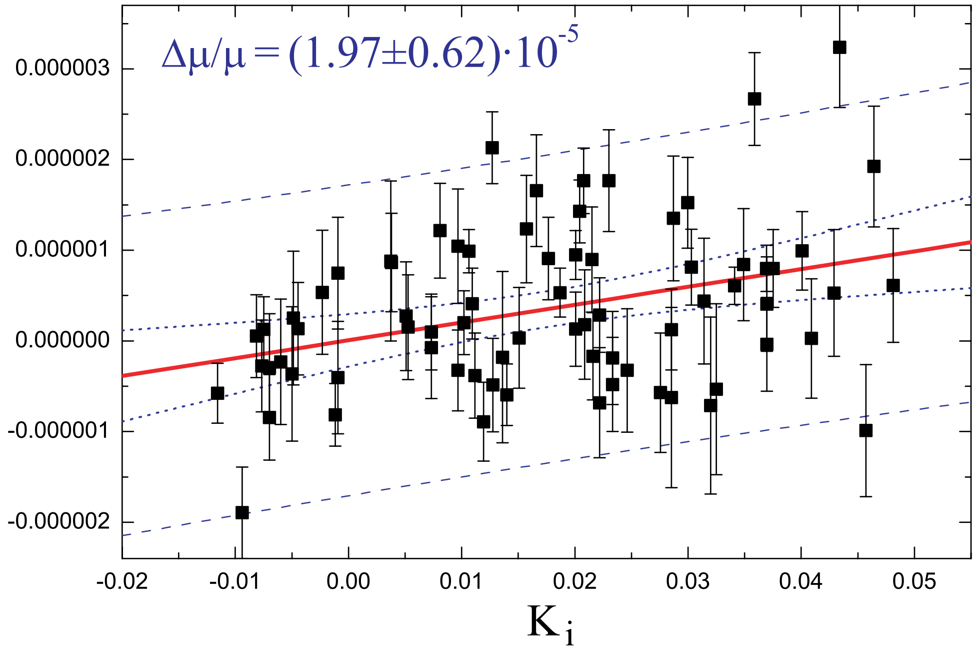

Fig. 3. Regression analysis of reduced redshift ζ_i (as defined by Eq. (3)) as a function of K_i for both quasars.

between the relative positions of H_2 absorption lines measured as

$$\zeta_\mathrm{i} = \frac{z_\mathrm{i}^\mathrm{obs} - z_\mathrm{abs}}{1 + z_\mathrm{abs}} \tag{3}$$

and the sensitivity coefficients K_i of the corresponding lines (Fig. 3). A positive correlation could be interpreted as a variation of the proton-to-electron mass ratio, $\Delta\mu/\mu$. We find such a correlation that could be interpreted as a variation of μ over 12 Gyr at the following level:

$$\Delta\mu/\mu = (1.97 \pm 0.62) \times 10^{-5}. \tag{4}$$

However, the large scatter in the measurements is suspicious. Indeed, some systematic error could be underestimated and could produce a shift monotonically increasing (or decreasing) with increasing wavelength. Such effects could lead to a slope of the regression line, i.e. mimic μ-variation. In fact, we could distinguish in principle such effects from a real μ-variation if the individual errors were small enough (more detail explanations see in [1]) but at the moment, unfortunately, the large dispersion of the points (Fig. 3) prevents us to do so. Therefore, the estimate (4) should be treated as the most stringent limit on a possible cosmological μ-variation at $z \approx 2.6 - 3.0$ (12 Gyr ago).

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