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The fine-structure constant: a new observational limit on its cosmological variation and some theoretical consequences

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Abstract. Endeavours of the unification of the four fundamental interactions have resulted in a development of theories having cosmological solutions in which low-energy limits of fundamental physical constants vary with time. The validity of such theoretical models should be checked by comparison of the theoretical predictions with observational and experimental bounds on possible time-dependences of the fundamental constants.

Based on high-resolution measurements of quasar spectra, we obtain the following direct limits on the average rate of the cosmological time variation of the fine-structure constant α:

$$|\,\dot{\alpha}/\alpha\,| < 1.9 \times 10^{-14}\ \mathrm{yr}^{-1}$$

is the most likely limit, and

$$|\,\dot{\alpha}/\alpha\,| < 3.1 \times 10^{-14}\ \mathrm{yr}^{-1}$$

is the most conservative limit.

Analogous estimates published previously, as well as other contemporary tests for possible variations of α (those based on the "Oklo phenomenon", on the primordial nucleosynthesis models, and others) are discussed and compared with the present upper limit. We argue that the present result is the most conservative one.

Key words: quasars: absorption lines – cosmology: theory

1. Introduction

The fine-structure constant $\alpha = e^2/\hbar c$ is the key parameter of Quantum Electrodynamics (QED). Initially it was introduced by Sommerfeld in 1916 for describing the fine structure of atomic levels and corresponding resonance lines. Later it became clear that α is important for description of the gross structure of atomic and molecular spectra as well as fine one. Moreover, now we know that *any electromagnetic phenomena may be described in terms of the powers of* α. In reality, α is not a true constant. It is established in the quantum field theory and confirmed by high-energy experiments that the coupling constants depend on distance (or momentum, or energy) because of vacuum polarization (see, e.g., Okun 1996). Here we consider the low-energy limit of α, namely, its variation in the course of the cosmological evolution of the Universe. The possibility of fundamental constants to vary arose in the discussion of Milne (1937) and Dirac (1937). (For a sketch of the history of the problem of variability of the fundamental constants, see Varshalovich & Potekhin 1995). The most important Dirac's statement was that *the constancy of the fundamental physical constants should be checked in an experiment.*

The value of the fine-structure constant is known with rather high accuracy $\sim 4 \times 10^{-9}$. The CODATA recommended value based on the 1997 adjustment of the fundamental constants of physics and chemistry is equal to $\alpha = 1/137.03599993(52)$. However, even this high precision does not exclude the possibility that the α value was different in early cosmological epochs. Moreover, some contemporary theories allow α to be different in different points of the space-time. Endeavours of unification of all fundamental interactions lead to a development of multidimensional theories like Kaluza-Klein and superstring ones which predict not only energy dependence of the constants but also dependence of their low-energy limits on cosmological time.

Superstring theories. The superstring theory is a real candidate for the theory which is able to unify gravity with all other interactions. At present this theory is the only one which treats gravity in a way consistent with quantum mechanics. In the low energy limit ($E \ll E_{\rm Planck} \equiv \sqrt{\hbar c^5/G} \simeq 1.2 \times 10^{19}$ GeV, where G is the gravitational constant, $\hbar$ is the Planck constant, and c is the speed

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of light), the superstring theory reduces to the classical General Relativity (GR) with, however, an important difference: All versions of the theory predict the existence of the dilaton which is a scalar partner of the tensorial graviton. This immediately leads to an important conclusion that all the coupling constants and masses of elementary particles, being dependent on the dilaton scalar field ϕ, should be space and time dependent. Thus, the existence of a weakly coupled massless dilaton entails small, but non-zero, observable consequences such as Jordan-Brans-Dicke-type deviations from GR and cosmological variations of the fine structure constant and other gauge coupling constants. The relative rate of the α variation is given by

$$\frac{\dot{\alpha}}{\alpha} \sim kH(\phi - \phi_m)^2 \tag{1}$$

where k is the main parameter that determines the efficiency of the cosmological relaxation of the dilaton field ϕ towards its extreme value ϕ_m, and H is the Hubble constant (Damour & Polyakov 1994). In principle, the variation of α defined by Eq. (1) depends on cosmological evolution of the dilaton field and may be non-monotonous as well as different in different space-time regions.

Kaluza-Klein theories. In superstring models the transition from $(4+D)$-dimensional string objects to the four-dimensional observed reality proceed through a compactification of the extra dimensions. Generalised Kaluza-Klein theories offer another possibility of unification of gravity and the other fundamental gauge interactions via their geometrization in a $(4+D)$-dimensional curved space. In such theories the truly fundamental constants are defined in $4+D$ dimensions and any cosmological evolution of the extra D dimensions would result in a variation of the fundamental constants measured in the observed four-dimensional world. For example, in the Kaluza-Klein theories the fine-structure constant α evolves as

$$\alpha \propto R^{-2} \tag{2}$$

where R is a geometric scaling factor which characterises the curvature of the additional D-dimensional subspace (Chodos & Detweiler 1980; Freund 1982; Marciano 1984).

There are many different versions of the theories described above and they predict various time-dependences of the fundamental constants. Thus, *bounds on the variation rates of the fundamental constants may serve as an important tool for checking the validity of different theoretical models of the Grand Unification and cosmological models related to them.*

In the next section we briefly consider the basic methods allowing one to obtain restrictions on possible variations of fundamental constants. In Sect. 3, an astrophysical method is considered in more detail. In Sect. 4, we specify the properties of observational data required to reach a high accuracy of evaluation of $\dot{\alpha}/\alpha$. In Sect. 5, we describe an observational technique employed to obtain data of the required quality. An upper bound on $|\dot{\alpha}/\alpha|$ is presented and its theoretical consequences are discussed in Sect. 6. In Sect. 7, conclusions are given.

2. Characteristic features of methods for checking possible variations of the fundamental constants

Theoretical and experimental techniques used to investigate time variation of the fundamental constants may be divided into extragalactic and local methods. The latter ones include astronomical methods related to the Galaxy and the Solar system, geophysical methods, and laboratory measurements.

An interest in the problem of changing constants has increased after an announcement of a relative frequency drift observed by several independent research groups using long term comparisons of the Cs frequency standard with the frequencies of H- and Hg^+-masers. Such drift, in principle, could arise from a time variation of α because H-maser, Cs, and Hg^+ clocks have a different dependence on α via relativistic contributions of order $(Z\alpha)^2$. A detailed description of the laboratory method based on such comparisons may be found in Prestage et al. (1995), Breakiron (1993).

Stringent limits to α variation have been presented by Shlyakhter (1976) and Damour & Dyson (1996), who have analysed the isotope ratio ^{149}Sm/^{147}Sm produced by the natural uranium fission reactor that operated about 2×10^9 yrs ago in the ore body of the Oklo site in Gabon, West Africa. This ratio turned out to be considerably lower than that in the natural samarium, which is believed to have occurred due to the neutron capture by ^{149}Sm during the uranium fission. Shlyakhter (1976) has concluded that the neutron capture cross section in ^{149}Sm has not changed significantly in the 2×10^9 yrs. However, the rate of the neutron capture reaction is sensitive to the position of the resonance level E_r, which depends on the strong and electromagnetic interactions. At variable α and invariable constant of the strong interaction (that is just a model assumption), the shift of the resonance level would be determined by changing the difference of the Coulomb energies between the ground state ^{149}Sm and the excited state of ^{150}Sm* corresponding to the resonance level E_r. Unfortunately, there are no experimental data for the excited level of ^{150}Sm* in question. Damour & Dyson (1996) have assumed that the Coulomb energy difference between the nuclear states in question is not less than one between the *ground* states of ^{149}Sm and ^{150}Sm. The latter energy difference has been estimated from isotope shifts and equals ≈ 1 MeV. However, it looks unnatural that a weakly bound neutron, captured by a ^{149}Sm nucleus to form the highly excited state ^{150}Sm*, can so strongly affect the Coulomb energy. Moreover, the data of isomer shift measurements of different nuclei indicate that the mean-square radii (and therefore the Coulomb energy) of the charge-distribution for excited states of heavy nuclei may be not only larger but also considerably *smaller* than the corresponding radius for the ground states (Kalvius & Shenoy 1974). This indicates the possibility of violation of the basic assumption involved by Damour & Dyson (1996) in the analysis of the Oklo phenomenon, and therefore this method may possess a lower actual sensibility.

Another possibility of studying the effect of changing fundamental constants is to use the standard model of the primordial nucleosynthesis. The amount of ^{4}He produced in the Big Bang is mainly determined by the neutron-to-proton number ratio at the freezing-out of n$\leftrightarrow$p reactions. The freezing-out temperature T_f is determined by the competition between the expansion rate of the Universe and the β-decay rate. A comparison of the observed primordial helium mass fraction, $Y_p = 0.24 \pm 0.01$, with a theoretical value allows to obtain restrictions on the difference between the neutron and proton masses at the epoch of the nucleosynthesis and, through it, to estimate relative variation of the curvature radius R of the extra dimensions in multidimensional Kaluza–Klein-like theories as well as the α value (Kolb et al. 1986; Barrow 1987). However one can notice that different coupling constants might change simultaneously. For example, increasing the constant of the weak interactions G_F would cause a weak freeze-out at a lower temperature, hence a decrease in the primordial ^{4}He abundance. This process would compete with the one described above, therefore, it reduces sensibility of the estimates. Finally, the restrictions would be different for different cosmological models since the expansion rate of the Universe depends on the cosmological constant Λ.

A number of other methods are based on the 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, that offers a possibility to check the variability of the constants by studying, for example, lunar and Earth's secular accelerations, which has been done using satellite data, tidal records, and ancient eclipses. Another possibility is offered by analysing the data on binary pulsars and the luminosity of faint stars. A variety of such methods has been critically reviewed by Sisterna & Vucetich (1990). All of them have relatively low sensibility.

An analysis of natural long-lived α- and β- decayers, such as ^{187}Re or ^{149}Sm in geological minerals and meteorites, is much more sensitive (e.g., Dyson 1972). A combination of these methods, reconsidered by Sisterna & Vucetich (1990), have yielded an estimate $\dot{\alpha}/\alpha = (-1.3 \pm 6.5) \times 10^{-16}$ yr^{-1}.

The following weak points are inherent to the methods described above:

(i) The derived restrictions strongly depend on model conjectures.

(ii) The "local" methods give estimates for only a narrow space-time region around the Solar system. For example, the time of the operation of the Oklo reactor corresponds to the cosmological redshift $z \approx 0.1$, while a method based on observations of quasar spectra (described below) makes it possible to bring out evolutionary effects for large span of redshifts to $z \sim 5$.

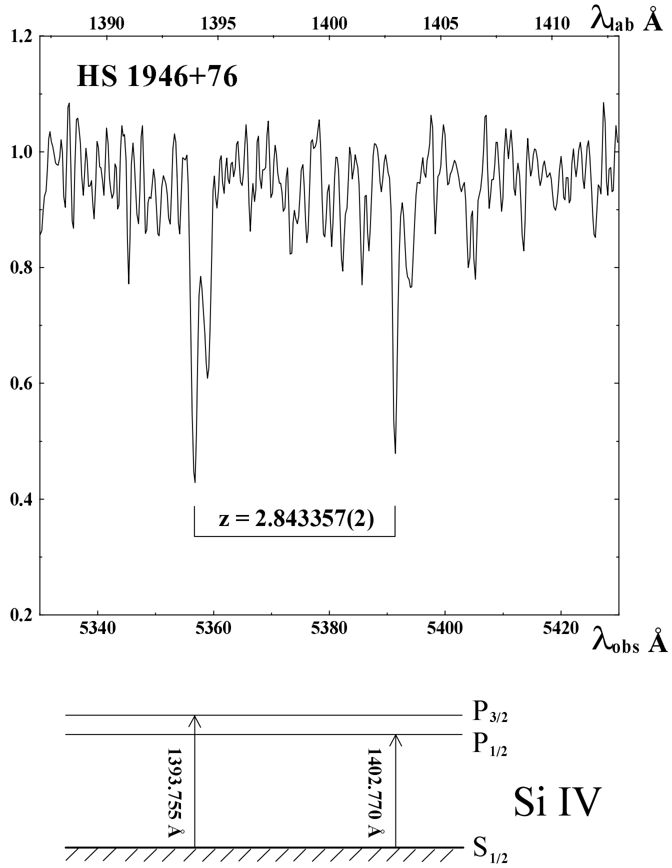

Fig. 1. Fine Doublet Splitting from Quasar Spectra

This and other problems, as we believe, can be solved by an astrophysical method which will be described in the next section.

3. The astrophysical method

An astrophysical method that allows one to estimate α value at early stages of the Universe evolution was originally proposed by Savedoff (1956). Bahcall and Schmidt (1967) were the first to apply this method to fine-splitting doublets in quasar spectra. A recent update of this method has given the result: $(-4.6 \rightarrow 4.2) \times 10^{-14}$ yr^{-1} for upper limit (95% C.L.) on a possible α variation (Cowie and Songaila 1995). A more stringent limit is presented in the paper by Varshalovich et al. (1996) and in this paper.

We adhere the conventional belief that the quasar is an object of cosmological origin. Its continual spectrum was formed at an epoch corresponding to the redshift z of main emission details specified by relationship $\lambda_{\rm obs} = \lambda_{\rm lab}(1+z)$.

Quasar spectra show the absorption resonance lines of the ions C IV, Mg II, Si IV, and others, corresponding to the $S_{1/2} \rightarrow P_{3/2}$ (λ_1) and $S_{1/2} \rightarrow P_{1/2}$ (λ_2) transitions (see Fig. 1). The difference between λ_1 and λ_2 is due to the fine splitting between the $P_{3/2}$ and $P_{1/2}$ energy levels. The relative magnitude of the fine splitting of the corresponding resonance lines is approximately proportional to the square of α,

$$\frac{\delta\lambda}{\lambda} \propto \alpha^2, \tag{3}$$

where $\delta\lambda = \lambda_2 - \lambda_1$ and $\lambda = (\lambda_2 + \lambda_1)/2$. Thus, the ratio $(\delta\lambda/\lambda)_z/(\delta\lambda/\lambda)_0$ is equal to $(\alpha_z/\alpha_0)^2$, where the subscripts z and 0 denote the fine-splitting doublet in a quasar spectrum and the laboratory value, respectively. Hence, the relative change in α can be approximately written as

$$\left(\frac{\Delta\alpha}{\alpha}\right)_z = \frac{1}{2}\left[\frac{(\delta\lambda/\lambda)_z}{(\delta\lambda/\lambda)_0} - 1\right], \tag{4}$$

provided that $(\Delta\alpha/\alpha)$ is small.

Thus, by measuring λ_1 and λ_2 in an absorption system corresponding to the redshift z and comparing the derived and laboratory values, one can directly estimate the difference between α at the epoch z and the present value.

It is to be noted that this method is the only one which provides direct values of $\Delta\alpha/\alpha$ for different space-time points of the Universe. Thus, using this method we can study not only possible deviations of the fine-structure constant from its present value but also its values in space regions which were causally disconnected at earlier evolutionary stages of the Universe (e.g. Tubbs & Wolfe 1980; Varshalovich & Potekhin 1995).

Tubbs & Wolfe (1980) (see also references therein) have used a coincidence of redshifts of optical resonant lines of ions with redshifts of the hydrogen 21 cm radio lines in distant absorption systems to derive an upper limit on the combination $\alpha^2 g_{\rm p} m_{\rm e}/m_{\rm p}$ at $z \sim 0.4 - 1.8$. Here, g_p, $m_{\rm e}$ and $m_{\rm p}$ are the proton gyromagnetic factor and the masses of electron and proton, respectively. Recently, Drinkwater et al. (1998) used a similar method of comparison of the redshifts of the HI (21 cm) and molecular radio lines at redshift $z = 0.68$ in two quasars to place a new strongest restriction on fractional variation of $g_p\alpha^2$ at the level $\sim 10^{-15}$ yr^{-1}, from which they concluded that $|\dot{\alpha}/\alpha| < 5 \times 10^{-16}$ yr^{-1}. Two drawbacks are inherent to this method of comparison: (i) It does not give direct restriction on variation of α, g_p, or electron-to-nucleon mass ratios, but only on their combination. (ii) One cannot be sure that the hydrogen and molecular absorption lines originate from the same cloud along the respective lines of sight. Since the analysed line profiles were complex and required decomposition into several contours, the perfect juxtaposition of the hydrogen and molecular lines (hence the seemingly extra high accuracy) might result from accidental coincidence of redshifts of different components of the line profiles. Only analysis of the ratios of wavelengths of the same ion species (in particular, the doublet ratios mentioned above) is free of such ambiguity.

Detailed discussion of possible sources of systematical and statystical errors of the method based on Eq. (4) has been given elsewhere (Potekhin & Varshalovich 1994). The most significant source of possible systematical error turned out to be the uncertainty in the laboratory wavelengths λ_0 (see below). Some errors which have a systematic character for one selected absorption system (e.g., the shifts of estimated line centers resulting from occasional unidentified blending of partially saturated lines) become random (statistical) for a sample of unrelated absorption systems. For this reason, Potekhin & Varshalovich have argued that one should not confide in the errorbars estimated for individual absorption systems, but derive the error from the actual scatter of the data. For example, Webb et al. (1998), using individual estimates of statistical errors of several fine-structure absorption systems, reported an unprecedented accuracy and claimed an evidence for nonmonotonic α variation: $\Delta\alpha/\alpha = (-2.64 \pm 0.35) \times 10^{-5}$ at $1.0 < z < 1.6$. However, an independent statistical treatment of the data presented in their paper, disregarding the errorbars but using the actual scatter of the data to estimate the confidence level, yields (in the same range of redshift) $\Delta\alpha/\alpha = (-3.0 \pm 1.0) \times 10^{-5} \pm \sigma_{\rm syst}$, indicating that the individual statistical errors reported by the authors significantly underestimate the actual statistical uncertainty. Here, the systematic error $\sigma_{\rm syst} \sim 10^{-4}$ is mainly due to the uncertainty in the laboratory wavelengths [see Eq. (5) below].

In this paper we apply the described method to a sample of 20 absorption systems at $2.0 < z < 3.6$, selected according to the criteria formulated in the next section.

4. Criteria of data selection

Of the available alkali-like doublets observed in quasar spectra such as C IV, Mg II, Al III, O VI, N V, Si IV, and others, we have selected for our analysis the Si IV line doublet, because it has the greatest ratio $\delta\lambda/\lambda = 6.45 \times 10^{-3}$, allowing this ratio to be measured most accurately. The abundance of silicon and its ionization state, as a rule, is such that the Si IV doublet lines occur on a linear part of the growth curve, which simplifies determination of the central wavelength of each line.

The laboratory values of the Si IV doublet wavelengths (λ_{01} = 1393.755 Å and λ_{02} = 1402.769 Å, according to Striganov & Odintsova 1982; λ_{01} = 1393.755 Å and λ_{02} = 1402.770 Å, according to Morton et al. 1988) are known with an uncertainty $\sigma_{\lambda_0} \approx 1$ mÅ. This uncertainty can introduce an appreciable systematic error in the determination of $(\Delta\alpha/\alpha)_z$ from Eq. (4). In the case of the Si IV doublet, this error can be estimated as

$$\sigma_{\rm syst}(\Delta\alpha/\alpha) \approx \sigma_{\lambda_0}/(\delta\lambda\sqrt{2}) \approx 8 \times 10^{-5}. \tag{5}$$

This value of the systematic error for Si IV is the smallest among all alkali-like ion species listed above.

Available observational data on Si IV doublets in quasar spectra have been selected taking into account the following criteria:

1. High resolution FWHM < 25 km/s.
2. Wavelength of each doublet component is measured independently (without including the a priori information on $\delta\lambda/\lambda$).
3. Any obvious blending of each component of the doublet is absent.
4. Equivalent width ($W_{1,2}$) ratio of the doublet components is limited to $1 \leq (W_1 \pm 2\sigma_{W_1})/(W_2 \pm 2\sigma_{W_2}) \leq 2$ (in conformity with the oscillator strength ratio).
5. The lines are detected at the level higher than 5σ, where σ is a noise level.
6. A dispersion curve for calibration is carefully determined – e.g., using the technique described in the next section.

Unfortunately, many of recent data found in literature do not often satisfy the necessary conditions 2, 3, and 5.

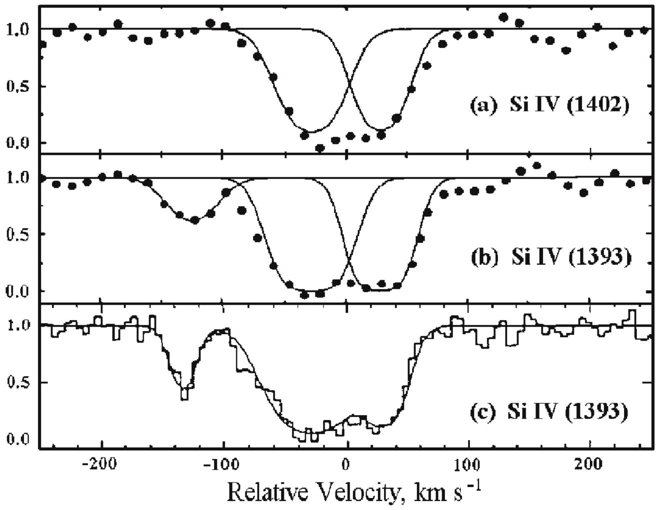

Fig. 2. The spectrum of HS 1946+76: comparison of the profiles of the Si IV doublet absorption lines with $z_{\rm abs} = 3.049$ [the $\lambda_0 = 1393$ Å (a) and 1402 Å (b) lines in our study and the $\lambda_0 = 1402$ Å line (c) in Fan and Tytler (1994)]

5. Observations and data reduction

Suitable observational data have been presented by Petitjean et al. (1994), Cowie & Songaila (1995), and Varshalovich et al. (1996). To give an idea about basic elements of observations and data reduction we describe here the main stage of the work by Varshalovich et al. (1996).

Observations were carried out in 1994 using the Main Stellar Spectrograph of the 6-m Telescope. A Schmidt camera (F:2.3), reconstructed to operate with a CCD array, was employed. In combination with a 600 lines mm^{-1} diffraction grating operating in the second order, this camera yielded a linear reciprocal dispersion of 14 Å mm^{-1} (0.24 Å pixel^{-1}). Since this study is metrological in essence, special attention was paid to wavelength calibration and check measurements. A Th+Ar lamp and the Atlas of the Th+Ar spectrum constructed from echelle data (D'Odorico et al. 1987), which gave vacuum wavelengths λ to within 0.001 Å, were employed for calibration. Ten to twenty reference lines were used to construct the dispersion curve in the form of a Chebyshev polynomial ($\lambda = a_0T_0 + a_1T_1 + a_2T_2 + ...$, where T_n is the Chebyshev polynomial of nth order) for each of the spectral segments in question. The nonlinear terms (a_2) of the dispersion curve were determined especially carefully, because the accuracy of the measured ratio $\delta\lambda/\lambda$ was particularly sensitive to the nonlinearity of the scale, contrary to the absolute calibration (i.e. a_0). For the same reason, the spectrograph was adjusted for each of the Si IV doublets in such way that both doublet components, with a separation of about 36 Å for $z \sim 3$, were in the middle of the spectral segment corresponding to one diffraction order, where the nonlinear distortions of the scale were at a minimum, while the sensitivity was at a maximum.

The wavelengths λ_1 and λ_2 were determined by gausian decomposition of the corresponding absorption lines in the observed quasar spectra. Portions of the spectrum of HS 1946+76 ($z_{\rm em} = 3.05$), one of the brightest QSOs in the sky, measured by Varshalovich et al. (1996), are shown in Figs. 1 and 2. Despite the absorption doublet shown in Fig. 1 consists of two components, it still satisfies the criteria formulated in Sect. 4, including item 3. In fact, we have checked that even total neglect of the second component of each line alters the estimate of $\Delta\alpha/\alpha$ for this absorption system by less than 2×10^{-5}, which is well below the overall statistical uncertainty reported in Eq. (6) below. On the other hand, the portion of spectrum shown in Fig. 2 requires caution, since the spectral components are close and partially saturated.

In their recent analysis of the spectrum of HS 1946+76, Fan and Tytler (1994) have detected six absorption systems, two of which contain Si IV lines. However, they presented only one of the doublet components in each of the doublets. Therefore, their high-resolution results cannot be used for measuring $\Delta\alpha$. In Fig. 2, the profiles of our measured spectral lines are compared with the profile obtained by Fan & Tytler with resolution of ~ 10 km s^{-1}. The comparison confirms that the resolution achieved in our work is equally sufficient for the profile analysis.

6. Results

6.1. Bounds on α

Results of the analysis of the Si IV fine-splitting doublet lines are presented in Table 1. The third column shows a deviation of the α value calculated according to Eq. (4) for a single doublet. The value $(\delta\lambda/\lambda)_0 = 0.0064473$ in

Eq. (4) has been adopted from Morton et al. (1988). From the data listed in Table 1, $(\Delta\alpha/\alpha)$ is estimated by standard least squares. According to the arguments given in Sect. 3, we did not involve estimates of the individual wavelength uncertainties. For example, for the profile shown in Fig. 1, the uncertainty of the gaussian decomposition yields $\sigma_\lambda \sim 0.007$ Å, and the estimate σ_λ as a function of resolution and signal-to-noise ratio, following Young et al. (1979), yields even smaller $\sigma_\lambda \sim 0.005$ Å, while the actual uncertainty may be larger. Estimating the statistical error from the scatter of $\Delta\alpha/\alpha$ measurements and taking into account the systematic error in Eq. (5), we arrive at the final estimate (for z interval $2.0 - 3.5$):

$$(\Delta\alpha/\alpha) = (-3.3 \pm 6.5\ [\mathrm{stat}] \pm 8.0\ [\mathrm{syst}]) \times 10^{-5}. \quad (6)$$

The corresponding bound at the 95% significance level is

$$|\Delta\alpha/\alpha| < \varepsilon = 2.3 \times 10^{-4}. \quad (7)$$

Since we have considered a sample of 20 absorption systems, the statistical (observational) error in Eq. (6) is $\sim \sqrt{20} \approx 4.5$ times smaller than a typical error of a single measurement. On the other hand, the statistical error and the systematic error due to the above-mentioned uncertainty of the laboratory wavelengths are of the same order of magnitude, hence any significant further improvement of the upper limit (7) would require an improvement of not only observational techniques but also the accuracy of the laboratory measurements.

According to the standard cosmological model with the cosmological constant $\Lambda = 0$, the time elapsed since the formation of the absorption spectrum with redshift z is

$$t_z = t_0[1-(1+z)^{-3/2}] \quad (\Omega = 1), \quad (8)$$
$$t_z = t_0[1-(1+z)^{-1}] \quad (\Omega \ll 1), \quad (9)$$

where Ω is the mean-to-critical density ratio. With the present age of the Universe equal to $(14 \pm 3) \times 10^9$ yr, we see that the redshifts $z = 2.8 \pm 0.7$ presented in Table 1 correspond to the elapsed time $\approx 12 \pm 4$ Gyr.

Thus, the upper limit on the time-averaged rate of change of α (with most likely values $z = 2.9$ and $t_0 = 14 \times 10^9$ yr) at the 2σ level is

$$\left|\overline{\dot{\alpha}/\alpha}\right| < 1.9 \times 10^{-14}\ \mathrm{yr}^{-1}. \quad (10)$$

And the most conservative upper limit ($z = 2.1$ and $t_0 = 11 \times 10^9$ yr) at the 2σ level is

$$\left|\overline{\dot{\alpha}/\alpha}\right| < 3.1 \times 10^{-14}\ \mathrm{yr}^{-1}. \quad (11)$$

Table 1. Variation of α values estimated from redshifted Si IV doublet line splitting according to Eq. (4)

Quasar	z	$(\Delta\alpha/\alpha)_z, 10^{-4}$	Ref.
HS 1946+76	3.050079	1.58	1
HS 1946+76	3.049312	0.34	1
HS 1946+76	2.843357	0.59	1
S4 0636+68	2.904528	1.37	1
S5 0014+81	2.801356	−1.80	1
S5 0014+81	2.800840	−1.70	1
S5 0014+81	2.800030	1.11	1
PKS 0424-13	2.100027	−4.51	2
Q 0450-13	2.230199	−1.48	2
Q 0450-13	2.104986	0.02	2
Q 0450-13	2.066646	1.03	2
Q 0302-00	2.785	2.07	3
PKS 0528-25	2.813	1.29	3
PKS 0528-25	2.810	1.03	3
PKS 0528-25	2.672	−5.43	3
Q 1206+12	3.021	−1.29	3
PKS 2000-33	3.551	−3.88	3
PKS 2000-33	3.548	2.85	3
PKS 2000-33	3.332	5.95	3
PKS 2000-33	3.191	−5.69	3

References: [1] Varshalovich et al. (1996); [2] Petitjean et al. (1994); [3] Cowie and Songaila (1995).

6.2. Consequences for theoretical models

The results obtained above make it possible to select a number of theoretical models for dependence of α on cosmological time t (the time elapsed since the Universe creation). Consider some of them:

a. The hypothesis of the logarithmic dependence

$$\alpha^{-1} \approx \ln\left(\frac{t}{8\pi\tau_{\mathrm{Planck}}}\right). \quad (12)$$

Here, $\tau_{\mathrm{Planck}} \equiv \sqrt{\hbar G/c^5} = 5.4 \times 10^{-44}$ sec is the Planck time. Teller (1948) suggested this dependence on the basis of the striking concurrence of the value $\alpha^{-1} = 137.036$ and value $\ln(t_0/8\pi\tau_{\mathrm{Planck}}) \approx 137$ (note that the form of the dependence and t_0 value is presented in the modern interpretation). Later Dyson (1972) showed that it could be supported by considerations that follow from the method of renormalization in the QED. In the standard cosmological model with $\Lambda = 0$ and $\Omega = 1$, this hypothesis gives rise to the following dependence

$$\alpha_z = \frac{\alpha_0}{1 - \frac{3}{2}\alpha_0 \ln(1+z)} \quad (13)$$

For $z = 2.8$, this yields $\alpha_z = 1.015\,\alpha_0$, in obvious contradiction with inequality (7). Thus, the logarithmic dependence can be excluded. Note that a more general dependence $\alpha^{-1} = C\ln(t/\tau)$ with arbitrary C and $\tau \geq \tau_{\mathrm{Planck}}$

has been ruled out already by Varshalovich & Potekhin (1995).
b. The power-law dependence (for standard model)

$$\alpha \propto t^n \tag{14}$$

in the standard flat Universe this leads to the dependence $\alpha = \alpha_0(1+z)^{-3n/2}$, from which, using Eq. (7), we obtain the bound

$$|n| < 2\varepsilon/[3\ln(1+z)] = 1.1 \times 10^{-4} \tag{15}$$

c. The Kaluza-Klein-like models often assume that compactification was occurring at the very early stages of Universe evolution and now the additional D dimensions of the subspace have radius of curvature $R \sim l_{\rm Planck} \equiv \sqrt{\hbar G/c^3} = 1.6 \times 10^{-33}$ cm. Thus, determining of variations at such level is impossible at present. On the other hand, there are theories in which the process of the compactification can develop even now. The information about R for such theories may be obtained from measurements of the α variation. According to Eq. (2), the restriction on the changing of the subspace scaling factor is

$$\frac{\Delta R}{R_0} \approx \frac{1}{2}\frac{\Delta\alpha}{\alpha} \lesssim 10^{-4} \tag{16}$$

d. The recent version of the dilaton evolution proposed by Damour & Polyakov (1994) in the frame of the string model has provided an expression connecting the variation of the fundamental constants:

$$\frac{\dot G}{G} = \Theta k \frac{\dot\alpha}{\alpha} \simeq 3332.5 k \frac{\dot\alpha}{\alpha}. \tag{17}$$

Here, k is a parameter of the theory, which fixes a type and speed of the evolution of the scalar field (i.e. dilaton field), $\Theta = 2(\ln(\Lambda_s/mc^2))^2$ is a numerical coefficient, $\Lambda_s \simeq 5 \times 10^{17}$ GeV is a string mass scale, and $m = 1.661 \times 10^{-24}$ g is the atomic mass unit ($mc^2 = 931.5$ MeV). The parameter k regulates the character of the time variation: G and α oscillate for $k \geq 1$, whereas for $k \ll 1$, these constants change monotonously. For the models with $k \geq 1$ discussed by Damour & Polyakov (1994), a measured bound on $\dot G/G$ enables one to obtain a bound on $\dot\alpha/\alpha$. For models with $k \ll 1$, we can obtain the bound on $\dot G/G$ from Eq. (11): $\left|\dot G/G\right| \ll 3332.5\,|\dot\alpha/\alpha| < 1 \times 10^{-10}$ yr^{-1}.

7. Conclusions

We have formulated criteria for selection of high-quality doublet lines in quasar spectra, most suitable for the analysis of the large-scale space-time variation of the fine-structure constant. We have also described the calibration technique capable to provide the necessary metrological quality.

Using the formulated criteria and described technique, we have performed the Si IV doublet analysis of quasar spectra, that has enabled us to set an upper bound on the rate of the possible cosmological time variation of the fine-structure constant. This limit is much more model-independent and hence more robust than those provided by the local tests, including the analysis of the Oklo phenomenon.

One may anticipate that with development of observational spectroscopy the portion of material which satisfies the formulated criteria will rapidly increase in the near future. However, as shows the discussion in Sect. 6.1, this will not allow one to further tighten the bound on $\dot\alpha/\alpha$ until an improvement of the laboratory wavelength accuracy. On the other hand, in frames of the hypothesis that α does *not* change at the present stage of the cosmological evolution, the progress of the observational spectroscopy offers an exciting opportunity to improve the accuracy of determination of the fine splitting $\delta\lambda/\lambda$ against that available in the laboratory experiments.

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