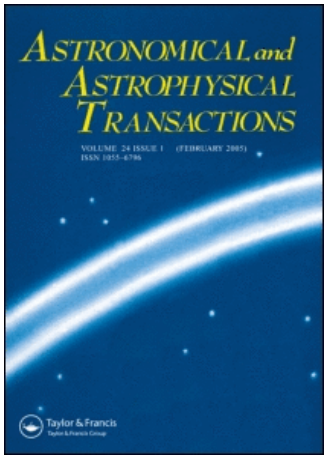

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AN UPPER LIMIT ON POSSIBLE TIME VARIATION OF THE FINE-STRUCTURE CONSTANT FROM QSO ABSORPTION SPECTRA

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A statistical analysis of 1185 fine splittings of CIV, NV, OVI, MgII, AlIII and SiIV doublet absorption lines with redshifts $z = 0.2$–3.7 in QSO spectra is carried out in order to estimate a possible time variation of the fine-structure constant $\alpha = e^2/\hbar c$ at cosmological time scales $t \sim 10^{10}$ yr. Robust statistical estimates like the "trimmed mean" are used as well as least squares.

No statistically significantly time variations of α is found. The estimate $\alpha^{-1}\, d\alpha/dz = (-1.2 \pm 2.9) \times 10^{-4}$ is obtained. For the 95% confidence level, the upper limit on the rate of a relative variation of the fine-structure constant is $|\alpha^{-1}\, d\alpha/dz| < 6.4 \times 10^{-4}$, which approximately corresponds to $|\alpha^{-1}\, d\alpha/dt| < 4 \times 10^{-14}\,\mathrm{yr}^{-1}$. This limit reprents the strongest up-to-date restriction on the possible time variation of α for the epoch $0.2 \le z \le 4$.

KEY WORDS Quasar spectra, cosmology, physical constants.

1. INTRODUCTION

The problem of a possible time variation of fundamental constants has attracted attention since Dirac (1937) formulated his "large number hypothesis". In the 80s, it was realized that the Kaluza–Klein and "superstring" theories may produce variations of fundamental constants (e.g., Marciano, 1984, Wu and Wang, 1986). Here we consider possible variations of the electromagnetic coupling constant $\alpha = e^2/\hbar c$.

Sisterna and Vucetich (1990) obtained limits on the possible variation rates of fundamental constants at the present epoch. The most stringent result for earlier stages of the Universe evolution was obtained by Wolfe *et al.* (1976) who considered the MgII doublet absorption and used the relation

$$Y(z) = \left(\frac{(\lambda_2 - \lambda_1)_z}{(\lambda_2 - \lambda_1)_0}\frac{\bar{\lambda}_0}{\bar{\lambda}_z}\right)^{1/2} - 1 = \frac{\Delta\alpha}{\alpha}(1 + O(\alpha^2)), \qquad (1)$$

where λ_1 and λ_2 are the doublet wavelengths, $\bar{\lambda}$ is their weighted mean with the statistical weights of the excited states, and $\Delta\alpha = \alpha_z - \alpha_0$ is the difference between the values of α at a given redshift z and at present. The authors found that $\Delta\alpha/\alpha = (0.3 \pm 2.0) \times 10^{-2}$ at $z = 0.52$ (hereafter we use the form $y \pm \sigma(y)$, where $\sigma(y)$ is the root-mean-square deviation of an estimate y).

The disadvantage of the estimate of Wolfe *et al.* (1976) was that they used an observation of a single absorption system, thus being unable to eliminate a possible error caused by shifting an observed line center due to occasional

superimposing of spectral lines of other clouds of interstellar matter. This uncertainty might be eliminated by a statistical analysis of observations of various absorption systems. This became possible in the recent years after obtaining many QSO spectra. Levshakov (1992) carried out such an analysis basing on ~500 pairs of lines with resolution $10 \sim 150\,\mathrm{km \cdot s^{-1}}$. However, his analysis suffered from some methodical shortcomings pointed out by Potekhin and Varshalovich (1992) (hereafter Paper I). In particular, he removed all the data which could give $|\Delta\alpha/\alpha| > 0.01$ but did not account for this in his least-squares estimates. Hence, his estimate, $d \ln \alpha/dz = (2 \pm 1) \times 10^{-4}$, cannot be regarded as fully correct.

We have carried out a more representative statistical analysis, which has enabled us to eliminate the above-mentioned uncertainty and obtain the strongest up-to-date restriction $|d \ln \alpha/dt| < 6.4 \times 10^{-4}$ for $0.2 \lesssim z \lesssim 4$ at the 95% significance level.

2. DATA PROCESSING

Any experimental value Y_i of $Y(z_i)$ calculated according to (1) includes an unknown random error determined by random statistical errors in λ_1 and λ_2 due to finite spectral resolution, spectral noise and blending. The laboratory splitting is also known with an error which can be taken into account if to include into the processing the laboratory point $Y_0 = 0$ ($z_0 = 0$) with a finite relative weight $w_0/w_i \sim 100$ ($i > 0$) (in the case when different ions are processed separately, see Paper I).

We have investigated the z-dependence of α with the aid of a simple linear regression,

$$Y(z) = a + b \cdot (z - \bar{z}), \tag{2}$$

where $\bar{z}$ is the weighted mean of z_i and $z_0 = 0$.

The other method which has been used consists in estimating the center of the distribution of the subset $\{Y_i : z_i > z_{\min}\}$ for different $z_{\min} > 0$.

If the error distribution were Gaussian, the least-squares (LS) regression analysis would be most efficient. In practice, however, the existing data are essentially non-uniform, and their distribution is not Gaussian. In this case "trimmed mean" (TM) estimates are efficient (e.g. Lehmann 1983). These robust estimates were originally applied to the location problem. They were extended to the linear regression analysis by Ruppert and Carroll (1980). We have slightly modified their method in order to ensure that the laboratory point $Y_0 = 0$ is not removed.

Let the trimming level β vary in the interval $0 \le \beta_1 \le \beta \le \beta_2 < 0.5$, and let the minimum of the variance estimate $\hat{\sigma}^2$ be at some β_0. As shown by Jaeckel (1971) for the location problem, the TM estimate with $\beta = \beta_0$ is asymptotically the best for the (unknown) real distribution of errors. Following him, we have taken $\beta_1 = 0$, $\beta_2 = 0.25$.

3. RESULTS

Our analysis is based on confidently identified resonant doublet lines of CIV, NV, OVI, MgII, AlIII and SiIV with $z > 0.2$, taken from the processed QSO absorption spectra published in 1980–1992. The lines selected were observed with

Table 1 Least-squares estimates of regression parameters.

Ion	*N*	$\bar{z}$	$a(\times 10^{-4})$	$b(\times 10^{-4})$
CIV	655	2.2	27 ± 14	24 ± 16
NV	35	2.4	-20 ± 29	-37 ± 28
OVI	9	2.6	0 ± 30	-8 ± 41
MgII	306	1.1	11 ± 19	-13 ± 30
AlIII	33	2.0	7 ± 24	21 ± 27
SiIV	147	2.4	-10 ± 11	-4.2 ± 8.3

the effective spectral resolution FWHM = 0.5–6 Å and the signal-to-noise ratio $S/N = 10$–100; typically, $S/N \approx 20$. Altogether, we have considered 1185 pairs of lines, listed in Paper I.

We have adopted laboratory standards of λ_1 and λ_2 given by Striganov and Odintsova (1982). The differences from the standards of Morton *et al.* (1988) are too small to affect noticeably our main results and conclusions.

The observational data have been analysed with the LS and TM methods. Estimates of linear regression parameters have been used as well as estimates of the data distribution center. The formulae used are given in Paper I.

The LS estimates and root-mean-square errors of the parameters a and b of the regression (2) are given in the last two columns of Table 1. The second column presents the numbers N of the doublets considered to each ion while the third column lists their mean redshifts. The overall estimate of the slope b is $(-0.2 \pm 6.6) \times 10^{-4}$ for all the data. Analogous estimates for more uniform data subsets with FWHM < 2.5 Å and FWHM < 1 Å are $b = (-7.2 \pm 6.6) \times 10^{-4}$ and $(-6 \pm 12) \times 10^{-4}$, respectively.

Table 2 gives the results of the TM analysis of the regression parameters with the trimming level β which minimizes the estimate of the slope variance, $\hat{\sigma}^2(\hat{b})$, in the interval $0 < \beta < 0.25$. The overall estimate of b is $(-1.2 \pm 2.9) \times 10^{-4}$ yielding the 95%-level restriction $|dY/dz| < 6.4 \times 10^{-4}$.

The numbers N of doublet data for the ions NV, OVI and AlIII (in contrast to CIV, MgII and SiIV) are insufficient to estimate accurately $\sigma^2(\hat{b})$: adding or removing one or several doublets causes variations of $\hat{b}$ and $\hat{\sigma}(\hat{b})$ up to 50% with respect to the tabulated values. However this uncertainty does not affect the overall estimations since they are mainly determined by the SiIV data (see Tables 1 and 2).

To test the applicability of our regression model we have obtained the TM estimates (again optimizing β) for the data with $z_i \geq z_{\min}$. The results for each ion

Table 2 Trimmed-mean estimates of regression parameters.

Ion	*N*	$\bar{z}$	$a(\times 10^{-4})$	$b(\times 10^{-4})$
CIV	655	2.2	13.8 ± 9.0	11.5 ± 8.4
NV	35	2.4	-14 ± 12	-33 ± 13
OVI	9	2.6	0 ± 30	-8 ± 41
MgII	306	1.1	18 ± 15	1 ± 22
AlIII	33	2.0	5.2 ± 7.8	14 ± 11
SiIV	147	2.4	-2.1 ± 4.3	-2.5 ± 3.4

at each z_{min} are given in Paper I. No statistically significant deviation of α_z from α_0 has been obtained for any z_{min}. In particular, for $N = 1068$, 528 and 93 systems with $z > 1.0$, 2.0 and 3.0 we have $\Delta\alpha/\alpha = (2.0 \pm 6.3) \times 10^{-4}$, $(7.0 \pm 9.2) \times 10^{-4}$ and $(1.3 \pm 2.1) \times 10^{-3}$ at $\bar{z} = 2.1$, 2.6 and 3.2, respectively.

4. CONCLUSIONS

Our statistical analysis of doublet fine splitting in the QSO absorption spectra at cosmological redshifts z reveals no statistically significant variation of the fine-structure constant α with z. Our estimate $\alpha^{-1} d\alpha/dz = (-1.2 \pm 2.9) \times 10^{-4}$ and the 95%-significance restriction $|\alpha^{-1} d\alpha/dz| < 6.4 \times 10^{-4}$ are more stringent than the corresponding results of Wolfe *et al.* (1976) by more than one order of magnitude. Large numbers of absorbing systems considered minimize an uncertainty caused by a possible unidentified occasional blending.

In the standard cosmological model with the average density of matter in the Universe close to the critical value, age t is related to z as $t = \frac{2}{3} H_0^{-1} \times [1 - (1 + z)^{-3/2}]$. For the Hubble constant $H_0 = 60\ \mathrm{km\ s^{-1}\ Mpc^{-1}} = 6 \times 10^{-11}\ \mathrm{yr^{-1}}$, the above limit yields $|d \ln \alpha/dt| < 4 \times 10^{-14}\ \mathrm{yr^{-1}}$ at small redshifts z. This limit is less restrictive than the limit $|d \ln \alpha/dt| < 1.4 \times 10^{-15}\ \mathrm{yr^{-1}}$ obtained by Sisterna and Vucetich (1990) for the present epoch ($z \ll 1$). However, our restriction has an independent importance because it covers earlier evolutionary stages and more distant regions of the Universe.

Estimates of the center of the distribution of empirical values $\Delta\alpha/\alpha$ at z/z_{min} (where z_{min} is a parameter) also show no statistically significant difference between α_z and α_0. This indicates that the absence of any significant trend of α is not caused by the choice of the linear regression model. In particular, from observations of 93 absorption systems with redshifts $3.0 \le z \le 3.7$ we have obtained $\Delta\alpha/\alpha = (1.3 \pm 2.1) \times 10^{-3}$ at $\bar{z} = 3.2$.

The methods used in our estimates are robust and adaptive (Lehmann, 1983). Therefore, it is unlikely that our upper limit on the variation rate of the fine-structure constant can be significantly improved without involving new (and more precise) observational data.

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