АСТРОФИЗИКА

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CONSTRAINING THE COSMOLOGICAL TIME VARIATION OF THE FINE - STRUCTURE CONSTANT

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The variation of the fine-structure constant $\alpha = e^2/\hbar c$ can be probed by comparing wavelength of atomic transitions from redshift of quasars in Universe and laboratory over cosmological time scales $t \sim 10^{10}$ yr. After a careful selection of pairs of lines, the Thong method with a derived analytical expression for the error analysis was applied to compute the α variation. We report a new constraint on the variation of the fine-structure constant based on the analysis of the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} doublet absorption lines. The weighted mean value of the variation in α derived from our analysis over the redshift range $0.4939 \le z \le 3.7$ is $\Delta\alpha/\alpha = (-0.09 \pm 0.07) \times 10^{-5}$. This result presents 3 orders of magnitude better than the results obtained by earlier analysis of the same data on the constraint on $\Delta\alpha/\alpha$.

Key words: *Cosmology:observations - line:profiles - quasars:absorption lines*

1. *Introduction*. The interested idea that certain fundamental constants are not constant at all, but have a certain cosmological time dependence, is not new. In the 1930s, this idea was discussed by Paul Dirac and Milne [1,2], but with respect to the gravitational constant. Some of the modern theories of fundamental physics, like SUSY GUT, String and Super-String theories, motivate experimental searches of possible variations in the fine structure constant. Such theories require the existence of extra "compactified" spatial dimensions and allow for the cosmological evolution of their time and space scale sizes. As a result, these theories naturally predict the cosmological time and space variation of fundamental constants in a 4-dimensional sub-space [3,4]. The strongest constraint on time variation of the fine-structure constant comes from the Oklo phenomenon, a natural fission reactor that operated 2 Gyrs ago, corresponding to $z \sim 0.16$ [5]. By studying the products of this nuclear reactions that occurred then it is possible to constrain some cross-sections that depend on α. It is found that $\Delta\alpha/\alpha\,\Delta t = (-0.2 \pm 0.8) \times 10^{-17}$ yr [6]. Since 1967, there have been many important studies of the cosmic time dependence of α using quasar absorption lines [7]. Some of the most comprehensive and detailed investigations were described in [8-14]. The results reported in all of these papers are consistent with a fine structure constant that does not vary with cosmological time and epoch. At higher redshifts, a possible time dependence will be registered in the form of small shifts

in the absorption line spectra seen toward distant quasars as the energy of the atomic transitions depend on α. Initial attempts to measure the variation of α were based on the absorption lines of Alkali-Doublets [6]. The best constraint obtained using this method is $\Delta\alpha/\alpha = (-0.5 \pm 1.3)\times 10^{-5}$ [15]. Other methods such as the one using OIII emission lines [7,8,14,15], though more robust, are not sensitive enough to detect small variations in $\Delta\alpha/\alpha$. Investigations based on molecular lines [12] detected in two systems give $\Delta\alpha/\alpha = (-0.10 \pm 0.22)\times 10^{-5}$ and $\Delta\alpha/\alpha = (-0.08 \pm 0.27)\times 10^{-5}$ at $z_{abs} = 0.2467$ and 0.6847 respectively. Such studies at high-z are elusive due to lack of molecular systems. The generalization of Alkali-Doublet method, called Many-Multiplet (MM) method, gives an order of magnitude improvement in the measurement of $\Delta\alpha/\alpha$ compared to AD method [8] by using not only doublets but several multiplets from different species. The sensitivity of different line transitions from different multiplets to variations in α were computed using many-body calculations taking into account dominant relativistic effects [8].

Recently, the subject has become of great interest for both physicists and astronomers because of the suggestion that a significant time dependence has been found using absorption lines from many different multiplets in different ions, the width separate ratio between two lines from quasars and laboratory and Many-Multiplet methods [8,16-20].

In this paper, we conducted a search for cosmological time variation of the fine structure constant from the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} doublet absorption lines in the works published in 1994, 1995 and 1996 [11,12,15,21]. The C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} systems were identified. After a careful selection of pairs of lines, we applied the width separate ratio between two lines from quasars and laboratory method, with an orginal expression for the error analysis, to compute the α variation.

2. *Data Analysis.* We have used the data from the works published in 1994, 1995 and 1996 [11,12,15,21] for our analysis, because the C_{IV}, N_V, Mg_{II}, Al_{III} and SiI_V line doublets have the greatest ratio $\delta\lambda/\lambda = 6.54\times 10^{-3}$, allowing this ratio to be measured most accurately. The abundance of silicon and its ionization state, as a rule, is that the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} doublet lines occur on a linear part of the ground curve, which simplifies determination of the central wavelength of each line. Considering a possible small variation in [16] used the approximate formula.

$$\frac{\Delta E_Z}{\Delta E_0} = \frac{\alpha^2(t)}{\alpha^2(0)} = \frac{\frac{1}{2}\left(\frac{\lambda_2(t)}{\lambda_1(t)}\right) - 1}{\frac{1}{2}\left(\frac{\lambda_2(0)}{\lambda_1(0)}\right) - 1}, \qquad (1)$$

We may write

$$\frac{\Delta\alpha}{\alpha} \approx \frac{1}{2}\left(\frac{\frac{1}{2}\left(\frac{\lambda_2(t)}{\lambda_1(t)}\right)-1}{\frac{1}{2}\left(\frac{\lambda_2(0)}{\lambda_1(0)}\right)-1}-1\right), \tag{2}$$

where $\lambda_1(0)$ and $\lambda_2(0)$ are the laboratory wavelengths, $\lambda_1(t)$ and $\lambda_2(t)$ are observed wavelengths from quasars. The advantage of absorption lines is that they are usually considerably narrower than emission lines. In addition, the merit of the above transition is that they originate from the same level, and consequently, λ_1 and λ_2 undoubtedly originate in the same regions of the interstellar medium. The wavelength values of these transitions given in Table 1.

Table 1

LABORATORY WAVELENGTH STANDARDS

Ion	λ_1(Å)	λ_2(Å)
C_{IV}	1548.202	1550.774
N_V	1238.821	1242.804
Mg_{II}	2796.352	2803.530
Al_{III}	1854.716	1862.790
Si_{IV}	1393.755	1402.769

The laboratory values of the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} doublet wavelengths are known with an uncertainty $\sigma_\lambda \approx 1$mÅ. This uncertainty can introduce an appreciable systematic error in the determination of $\Delta\alpha/\alpha$. The analysis methods used in the present work are as described in [16]. An analytic expression for the error analysis can be obtained thought an approximation for the standard deviation as $\Delta\alpha/\alpha = f(\lambda_1(t), \lambda_2(t))$:

$$\sigma_f^2 \approx \sigma_{\lambda_1(t)}^2\left(\frac{\partial f}{\partial\lambda_1(t)}\right) + \sigma_{\lambda_2(t)}^2\left(\frac{\partial f}{\partial\lambda_2(t)}\right) + \ldots, \tag{3}$$

which, with the derivatives of Eq. (3), yields the error propagation equation for width separate ratio method. In the analysis performed in our paper, this shift was small compared to rms errors in the derived estimates. However, the systematic shift due to nonlinearity could be significant when analyzing lower resolution data. Therefore, it seems reasonable to minimize it by making use of relation Eq. (3). Another possible source of systematic error is related to the fact that we know the laboratory wavelengths λ_1 and λ_2 with insufficient (possible errors of laboratory wavelengths λ_1 and λ_2 are about several mÅ [22], whereas typical errors $\sigma(\lambda)$ of astrophysical measurements vary from tens to hundreds of mÅ) accuracy. If different types of ions are handled in a separate way, these systematic errors are eliminated by including the laboratory point with a relative weight of ~100 in the set of analyzed data points. Errors

due to possible variations in isotope composition are negligible. The energy of the $^2S_{1/2}$ and $^2P_{3/2}$ levels are virtually identical for all isotopes of a given ion. Therefore, when going to another isotope, the relative change in Eq. (3) is equal to relative change in energy of the $^2S_{1/2}$ level, which does not exceed 10^{-6} for the ions in question. Collision broadening and shifts in the measured absorption and emission lines produce even smaller errors, because the lines are formed in a tenuous interstellar medium with a number density of less than $1\,cm^{-1}$, so that the probability for a collision with an ion over the lifetime in the $^2P_{1/2}$ and $^2P_{3/2}$ states is negligible. When observing a single absorption and emission system, the most important sources of possible systematic errors may be blending of the observed doublet lines with other absorption and emission lines and possible λ-calibration inaccuracies. However, the random orientation of absorbing clouds with respect to the line of sight makes both the increase and decrease in the measured λ due to blending equally probable. Taking into account the fact that absorption and emission system with different z are observed in different spectra regions, one may conclude that the errors resulting from blending and calibration inaccuracies cease to be systematic when a fairly large number of observations of different absorption and emission system are processed.

Results appear in Table 2, a plot for C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} absorption systems are shown in Fig.1 and a sample average is $\Delta\alpha/\alpha = (-0.09 \pm 0.07)\times 10^{-5}$, where the error is the standard deviation around the mean.

3. *Results.* Results of the analysis of the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} fine-splitting doublet lines are presented and compared to the results of the works of published in 1994, 1995 and 1996 [11,12,15,21] in Table 1, a plot for components of the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} is shown in Fig.1.

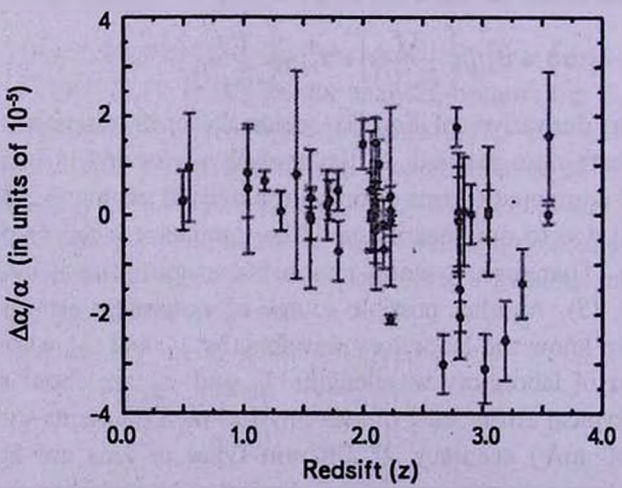

Fig.1. Plot of the high-redshift vs. $\Delta\alpha/\alpha$ for C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} doublet absorption lines.

Table 2

THONG METHOD ANALYSIS COMPARE TO THE WORKS PUBLISHED IN 1994, 1995 and 1996 [11,12,15,21]. A SAMPLE AVERAGE IS $\Delta\alpha/\alpha = (-0.09 \pm 0.07) \times 10^{-5}$

Ion	Quasar	z	$\Delta\alpha/\alpha$ (in units of 10^{-5})	Ref.	$\Delta\alpha/\alpha$ (in units of 10^{-5})
1	2	3	4	5	6
Si_{IV}	HS 1946+76	3.050079	0.158	[15]	0.085
Si_{IV}	HS 1946+76	3.049312	0.034	[15]	0.004
Si_{IV}	HS 1946+76	2.843357	0.059	[15]	0.071
Si_{IV}	S4 0636+68	2.904528	0.137	[15]	0.020
Si_{IV}	S5 0014+81	2.801356	-0.180	[15]	-0.135
Si_{IV}	S5 0014+81	2.800840	-0.170	[15]	-0.129
Si_{IV}	S5 0014+81	2.800030	0.111	[15]	0.055
C_{IV}	PKS 0424-13	1.5544	0.000	[11]	-0.002
C_{IV}	PKS 0424-13	1.5557	0.500	[11]	-0.084
C_{IV}	PKS 0424-13	1.5613	-2.100	[11]	0.350
C_{IV}	PKS 0424-13	1.5632	0.600	[11]	-0.096
C_{IV}	PKS 0424-13	1.7157	-1.800	[11]	0.29514
C_{IV}	PKS 0424-13	1.7885	-2.900	[11]	0.488
C_{IV}	PKS 0424-13	1.7904	4.400	[11]	-0.733
C_{IV}	PKS 0424-13	2.1000	1.700	[11]	-0.279
C_{IV}	PKS 0424-13	2.1329	-6.100	[11]	1.012
C_{IV}	PKS 0424-13	2.1728	1.200	[11]	-0.199
C_{IV}	PKS 0424-13	1.0341	-2.000	[11]	0.842
C_{IV}	PKS 0424-13	1.0348	-1.200	[11]	0.517
Si_{IV}	PKS 0424-13	2.1000	-0.400	[11]	0.276
Si_{IV}	PKS 0424-13	2.1728	1.000	[11]	-0.684
C_{IV}	Q 0450-13	1.4422	-4.900	[11]	0.814
C_{IV}	Q 0450-13	1.6967	-1.200	[11]	0.192
C_{IV}	Q 0450-13	1.9985	-8.600	[11]	1.427
C_{IV}	Q 0450-13	2.0666	-3.000	[11]	0.500
C_{IV}	Q 0450-13	2.1050	-1.000	[11]	0.168
C_{IV}	Q 0450-13	2.1066	1.200	[11]	-0.207
C_{IV}	Q 0450-13	2.2311	12.600	[11]	-2.101
N_V	Q 0450-13	2.2312	-1.100	[11]	0.373
Mg_{II}	Q 0450-13	0.4939	-1.100	[11]	0.282
Mg_{II}	Q 0450-13	0.5481	-3.700	[11]	0.950
Al_{III}	Q 0450-13	1.1742	-1.600	[11]	0.679
Al_{III}	Q 0450-13	1.3107	-0.200	[11]	0.073
Si_{IV}	Q 0450-13	2.0666	0.100	[11]	-0.684
Si_{IV}	Q 0450-13	2.1050	0.000	[11]	-0.086
Si_{IV}	Q 0450-13	2.1068	-2.200	[11]	-0.019
Si_{IV}	Q 0450-13	2.2302	-0.100	[11]	1.455
Si_{IV}	PKS 0424-13	2.100027	-4.510	[21]	-0.312
Si_{IV}	Q 0424-13	2.230199	-1.480	[21]	-0.112
Si_{IV}	Q 0424-13	2.104986	0.020	[21]	-0.017
Si_{IV}	Q 0450-13	2.066646	1.030	[21]	0.079
Si_{IV}	Q 0302-00	2.785	2.070	[12]	1.778

Table 2 (the end)

1	2	3	4	5	6
Si_{IV}	PKS 0528-25	2.813	1.290	[12]	-2.050
Si_{IV}	PKS 0528-25	2.810	1.030	[12]	-1.500
Si_{IV}	PKS 0528-25	2.672	-5.430	[12]	-3.005
Si_{IV}	Q 1206+12	3.021	-1.290	[12]	-3.094
Si_{IV}	PKS 2000-33	3.551	-3.880	[12]	1.604
Si_{IV}	PKS 2000-33	3.548	2.850	[12]	0.008
Si_{IV}	PKS 2000-33	3.332	5.950	[12]	-1.380
Si_{IV}	PKS 2000-33	3.191	-5.690	[12]	-2.526

4. *Conclusions.* In this study we have present the Thong method for deriving $\Delta\alpha/\alpha$ by means of the C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} doublet lines from the works published in 1994, 1995 and 1996 [11,12,15,21]. Our statistical analysis based on a catalog of C_{IV}, N_V, Mg_{II}, Al_{III} and Si_{IV} absorption doublets in quasar with cosmological redshift covering range $0.4939 \le z \le 3.7$ is $\Delta\alpha/\alpha = (-0.09 \pm 0.07) \times 10^{-5}$. Our result presents 3 orders of magnitude better than the results obtained by earlier analysis of the same data on the constraint on $\Delta\alpha/\alpha$ and more sensitive than that described by AD method [7-9,11,14,15] and SIDAM method [23,24]. This improvement consistent indication for a possible variation of α certainly deserves further investigation on a large number of systems, aimed at reducing the final error bar. This approach eliminates the largest systematic errors present in other determinations of α and provides estimation of the remaining statistical and systematic errors. Our analysis includes α-independent line ratios which can be used to identify the true size of statistical and systematic errors. This method can be applied not only for low redshifts but also for high redshifts of quasars and for both absorption and emission lines.

The key insight of this methodology, as well as other models of variable α, is that variation of α provides a new window into the parameters of the underlying theory that unifies gravity and the Standard Model (SM) of particle physics.

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ОГРАНИЧЕНИЕ ИЗМЕНЕНИЯ ПОСТОЯННОЙ ТОНКОЙ СТРУКТУРЫ В ТЕЧЕНИЕ КОСМОЛОГИЧЕСКОГО ВРЕМЕНИ

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Изменение постоянной тонкой структуры $\alpha = e^2/\hbar c$ можно исследовать, сравнивая длину волны атомных переходов от красных смещений квазаров во Вселенной и лаборатории в космологической шкале времени $t \sim 10^{10}$ лет. После тщательного отбора пар линий, для определения измения α, был применен метод Тонга с аналитическим выражением для анализа ошибок. Мы представляем новое ограничение к изменению постоянной тонкой структуры, основанное на анализе дублетных линий поглощения C_{IV}, N_V, Mg_{II}, Al_{III} и Si_{IV}. Взвешенное среднее значение изменения α, полученное из наших анализов при красных смещениях $0.4939 \le z \le 3.7$, равняется $\Delta\alpha/\alpha = (-0.09 \pm 0.07) \times 10^{-5}$. Этот результат на три порядка лучше, чем были получены ранее при анализе тех же данных о $\Delta\alpha/\alpha$ ограничениях.

Ключевые слова: *космология:наблюдения - линии:профили - квазары: линии поглощения*

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