АСТРОФИЗИКА

ТОМ 58 ФЕВРАЛЬ, 2015 ВЫПУСК 1

NEW LIMIT ON THE SPATIAL AND TEMPORAL VARIATIONS OF THE FINE-STRUCTURE CONSTANT USING HIGH REDSHIFTS OF QUASAR SPECTRA

T.D.LE

Received 8 September 2014
Accepted 5 December 2014

High precise measurements on the light from distant quasars can be served as a powerful tool to test the possible spatial and temporal variations of the fine-structure constant $\alpha = e^2/\hbar c$ during the evolution of the Universe. Here we set a limit on a possible cosmological space-time variations of α by comparying transitions in the absorption lines of the SiIV doublet observed in the early Universe with those mesured in the laboratory. The weighted mean value of the α-variation derived from our analysis over the redshift range $2.0 \leq z \leq 3.7$ is $\Delta\alpha/\alpha = (-0.53 \pm 0.72) \times 10^{-5}$. This result improves the constraint on $\Delta\alpha/\alpha$ by a factor ~ seven compared to the published results in the literature.

Key words: *quasars: spectra: fine-structure constant*

1. *Introduction.* One of the most important questions of modern physics concerns the possibility that fundamental constants such as the fine-structure constant $\alpha = e^2/\hbar c$ vary across space and time during the history of the Universe. However, if there is a change in the fine-structure constant over cosmological space and time, the effect will be very small. Most studies on this effect has been done and reported in [1-10] from the analysis of the astrophysical data. Astrophysical methods used to aquire constraints on this quantity is based on comapring the differences between the observed line centers of emission or absorption lines from astrophysical sources to their expected values in a laboratory on Earth. One of the earliest to measure α at high redshifts was based on the relative separate of Alkali-Doublet (AD method) lines [11-12]. The results of this method determined $\Delta\alpha/\alpha \equiv (\alpha_z - \alpha_0)/\alpha_0 = (-2 \pm 5) \times 10^{-2}$ at a redshift $z \sim 1.95$ and $\Delta\alpha/\alpha = (-2 \pm 1.2) \times 10^{-4}$ from an analysis of strong nebular OIII emission lines in the SDSS quasars over the redshift range $0.16 \leq z \leq 0.80$. Here α_0 is the value of the fine-structure constant on the Earth and α_z its value at reshift z. In 2005, applying the same method to analyze the NeIII, NeV, OIII, OI and SII doublets in a sample of 14 Seyfert 1.5 galaxies up to redshift 0.281, Grupe, Pradhan & Frank found $\Delta\alpha/\alpha = (1.5 \pm 0.7) \times 10^{-3}$ [13]. Recently, Gutierrez and Corredoira applied this method to the analysis of the OIII emission lines in the SDSS quasars spectra and obtained $\Delta\alpha/\alpha = (2.4 \pm 2.5) \times 10^{-5}$ [14]. Such studies at higher redshifts, that

can be achieved using Many-Multiplet (MM method) correlates different multiplets from several ions difference with AD method [15-17]. It is implied from MM method that the wavelengths of fine structure transitions in different species have different dependences on α. Thus, by comparing the measured wavelengths of absorption (not emission) lines seen in quasar spectra with the measured or computed laboratory wavelengths of the same lines one can place upper limits on any variation in α. The MM method makes use of a combination of transitions from different species [18-20] and gives an order of magnitude better precision in the measurement of $\Delta\alpha/\alpha$ than the AD method. The best constraints obtained by applying the MM method to KECK/HIRES data were $\Delta\alpha/\alpha=(-0.57\pm0.10)\times10^{-5}$ over the range $0.2\leq z\leq3.7$; $\Delta\alpha/\alpha=(-0.5\pm1.3)\times10^{-5}$ by analyzing a KECK/HIRES sample of 21 SiIV doublets observed along 8 QSO sight lines and $\Delta\alpha/\alpha=(-0.5\pm0.11)\times10^{-5}$ over the range $0.2\leq z\leq4.2$ by combining data from 143 absorption systems [21-24].

The important points should be noted that the AD method can be applied to emission as well as absorption lines. However, emission lines are usually broader than absorption lines, thus inducing larger errors on individual measurements which require large statistics to cancel. Therefore, the constraints on time variability on α obtained from emission lines are not as strong as those derived from absorption lines. As regard the MM method, it can be used for a large number of transitions to constrain the variation of α. Usually, at least five transitions from different species are used. The transitions are chosen so that their sensitivities to a change in α are different. The most significant sources of systematic errors in the MM method are induced by the assumption that all species have the same kinematic structure and by the fact that lines from multiplet isotopes are blended for most species. It is difficult to identify the central line wavelength due to the possibilities of line blends and line misidentifications. Moreover, it is suspected that there could be some unnoticed systematic effects that might challenge the claim for a variation in α. Recently, this problem has gained much interest in astrophysics and cosmology. Possible spatial and temporal variations of the fine structure constant at the cosmological scale are discussed extensively [25].

Very recently, a new method has been proposed to search for spatial and temporal variations in α [26]. This method based on the emission and absorption lines of alkalilike atoms and compared the wavelengths of transitions ${}^1D_2-{}^3P_1$, ${}^1D_2-{}^3P_2$, for a set of OIII strong nebular seen in SDSS quasars. Basing on this method, the relative change in α could be approximately written as

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

provided that $\Delta\alpha/\alpha$ is a small value in the past. Where $\lambda_1(0)$ and $\lambda_2(0)$ are the laboratory wavelengths, $\lambda_1(t)$ and $\lambda_2(t)$ are observed wavelengths from quasars. According to this method, the change in the emission or absorption spectra caused by redshifts and that caused by any change in α will be resulted in a corresponding change in the energy separation of the doublets from quasars and laboratory. Therefore, it provides a direct check on the values of $\Delta\alpha/\alpha$ for different epochs and different regions in the Universe. The analysis method not only allows us to use more than one line pair per object and gives a more secure result, but also opens the possibility of observing objects of higher redshifts in the optical wavelength range and has the advantage that it is more transparent and less suffers from systematic errors.

In this paper, we are to extract the most reliable information on the value of the finestructure constant at high redshifts of quasars by applying the new method in [26] to the SiIV doublet absorption lines (which correspond to the $^2S_{1/2}-^2P_{3/2}$ and $^2S_{1/2}-^2P_{1/2}$ transitions) in the quasars over the range $2.0 \le z \le 3.7$. We also make a comparison of our result with previously published results using the same data.

2. *Data sample and analysis.* QSOs spectra from astronomical observations contains many absorption lines which correspond to the $^2S_{1/2}-^2P_{3/2}$ and $^2S_{1/2}-^2P_{1/2}$ transitions from the ground stages of alkalilike ions. We have used the data from the work of [19-21] for our analysis as the SiIV line doublet has the greatest ratio $\delta\lambda/\lambda = 6.45\times10^{-3}$, allowing this ratio to be measured most accurately. Besides, the SiIV system is a simple pair of strong lines which occur on a linear part of the ground curve, making the determination of the central wavelength of each line simplified.

It is indicated from the Eq. (1) that the most significant source of possible systematical error lies in the uncertainty in the laboratory wavelengths λ_0. It thus represents a good alternative for determining the line centers and line blending. The laboratory values of the SiIV doublet wavelengths ($\lambda_1(0) = 1393.755$ Å and $\lambda_2(0) = 1402.769$ Å) are known to a certain error $\sigma_\lambda \approx 1$ mÅ. This uncertainty can be used to estimate systematic errors in the determination of $\Delta\alpha/\alpha$. The discussion of possible sources of systematical and statistical errors of the method based on Eq. (1) and the analysis method used in the present work is as described in [26]. Note that the analysis in this work is based on the fine-splitting doublets of the same element and same level of ionization and both lines originate in the same upper energy level. Furthermore, the line ratios are independent of α. Accordingly, our analysis is quite independent of the physical conditions of the gas from which the SiIV lines originate. Therefore, our approach eliminates the largest systematic errors present in other determinations of α using the same data and provides good estimation of the remaining statistical and systematic errors.

3. ***Results.*** We have a sample of 20 SiIV absorption systems in high-z quasars (covering the range $2.0 \le z \le 3.7$), all suitable for the desired obtainable of $\Delta\alpha/\alpha$. Results of the analysis of the SiIV fine-splitting doublet lines are presented and compared to the results of the works in [19-21] in Table 1. A plot for $\Delta\alpha/\alpha$ as a function of absorption redshift of the SiIV systems is shown in Fig.1.

It can be seen from Table 1 that in most of the cases the absolute deviations from zero of individual $\Delta\alpha/\alpha$ values determined from our analysis are smaller than those determined from other analyses. Averaging our results out, we obtained $\Delta\alpha/\alpha = (-0.53 \pm 0.72)\times 10^{-5}$. This result is consistent with the results derived by Murphy [17], who applied the MM method to the KECK/HIRES data to an analytic sample of 21 SiIV doublets observed along 8 QSO sight lines and found $\Delta\alpha/\alpha = (-0.57 \pm 0.10)\times 10^{-5}$ over the redshift range $0.2 \le z \le 3.7$ and $\Delta\alpha/\alpha = (-0.5 \pm 1.3)\times 10^{-5}$ and $\Delta\alpha/\alpha = (-0.5 \pm 0.11)\times 10^{-5}$ over redshift range $0.2 \le z \le 4.2$.

As depicted in Fig.1, the distribution of $\Delta\alpha/\alpha$ in our study is a similar

Table 1

VARIATION OF α VALUES ESTIMATED FROM REDSHIFTED SiIV DOUBLET LINE SPLITTING ACCORDING TO Eq (1)

Quasar	z	$\Delta\alpha/\alpha$ (in units of 10^{-4})	Ref.	$\Delta\alpha/\alpha$ (in units of 10^{-5})
Q 0302-00	2.785	2.07	19	1.778
PKS 0528-25	2.813	1.29	19	-2.050
PKS 0528-25	2.810	1.03	19	-1.500
PKS 0528-25	2.672	-5.43	19	-3.005
Q 1206+12	3.021	-1.29	19	-3.094
PKS 2000-33	3.551	-3.88	19	1.604
PKS 2000-33	3.548	2.85	19	0.008
PKS 2000-33	3.332	5.95	19	-1.380
PKS 2000-33	3.191	-5.69	19	-2.526
HS 1946+76	3.050079	1.58	20	0.085
HS 1946+76	3.049312	0.34	20	0.004
HS 1946+76	2.843357	0.59	20	0.071
S4 0636+68	2.904528	1.37	20	0.020
S5 0014+81	2.801356	-1.80	20	-0.135
S5 0014+81	2.800840	-1.70	20	-0.129
S5 0014+81	2.800030	1.11	20	0.055
PKS 0424-13	2.100027	-4.51	21	-0.312
Q 0424-13	2.230199	-1.48	21	-0.112
Q 0424-13	2.104986	0.02	21	-0.017
Q 0450-13	2.066646	1.03	21	0.050

References: [19] Cowie & Songaila (1995); [20] Varshalovich et al. (1996); [21] Petitjean et al. (1994).

comparison to the distribution of $\Delta\alpha/\alpha$ in the AD, MM, SIDAM methods. Our result corresponds to a factor of seven improvements on the constraint based on SiIV doublets compared to the previous study by Ivanchik, Potekhin & Varshalovich, who obtained $\Delta\alpha/\alpha = (-3.3 \pm 6.5) \times 10^{-5}$ [3-4].

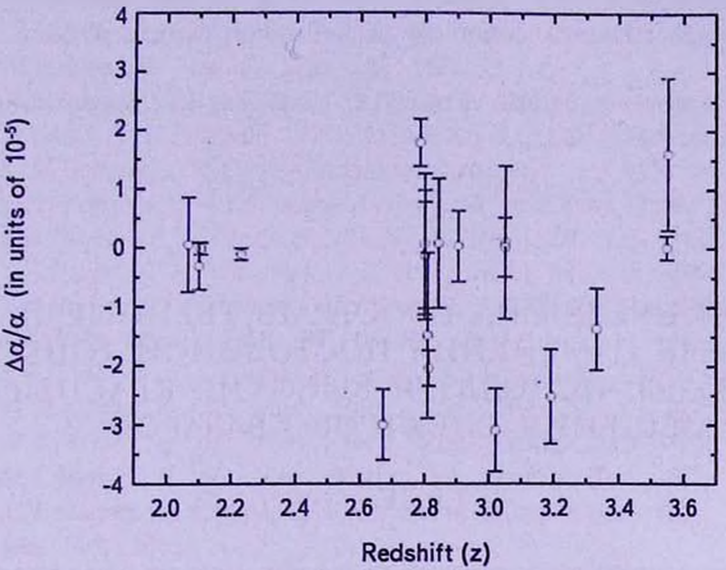

Fig.1. Plot of the high-redshift vs. $\Delta\alpha/\alpha$ for SiIV doublet absorption lines.

4. *Conclusions*. In.this work, we have made use of an appropriate chosen sample of 20 SiIV absorption systems in high-z quasars to contraint the possible spatial and temporal variations of the finestructure consatnt. We have analyzed these data to place an upper limit on a hypothetical dependence of the fine-structure constant α on cosmic space-time. We find $\Delta\alpha/\alpha = (-0.53 \pm 0.72) \times 10^{-5}$ at mean redshift redshift ranges $2.0 \le z \le 3.7$. This is roughly a factor ~ seven compared to the existing measurements that described by [11,12,27-31], by the AD method [31-35] and by the many-multiplet emission-line method [12]. This improvement is due to the fact that our approach includes only α-independent line ratios which can be used to identify the true size of statistical and systematic errors.

It should be emphasized that our study is consistent with small variations in α and also allows smaller variations in excess of what is found based on the Oklo phenomenon. So, it is important at higher redshifts-z. In addition, our methodology can be applied not only for low redshifts but also for high redshifts of quasars and for both absorption and emission lines. It can also be extended to a study of possible spatial anisotropy of fine splitting values at lager z. Our result can be directly used to estimate the difference between α at the epochs z and the present value, because it refers to an earlier cosmology epoch and to more different distant regions of the Universe that were causally unconnected at the epoch of the information of the observed spectra.

Study the spatial and temporal variation of the fundamental constants such as the fine structure constant is motivated by theories unifying the fundamental interactions and regarded as an important tool to open a new window to new physics with implications on cosmology as well as on particle physics.

Department of physics, CNS, Vietnam 128 Ly Thuong Kiet Street, I Ward, VT, Vietnam, e-mail:

НОВЫЙ ПРЕДЕЛ НА ПРОСТРАНСТВЕННЫЕ И ВРЕМЕННЫЕ ИЗМЕНЕНИЯ ПОСТОЯННОЙ ТОНКОЙ СТРУКТУРЫ, ИСПОЛЬЗУЯ ВЫСОКИЕ КРАСНЫЕ СМЕЩЕНИЯ СПЕКТРОВ КВАЗАРОВ

Т.Д.ЛЕ

Измерения высокой точности света от далеких квазаров могут служить сильным средством для проверки возможных пространственных и временных изменений постоянной тонкой структуры $\alpha = e^2/\hbar c$ в процессе эволюции Вселенной. Здесь мы ставим ограничения на возможные космологические пространственно-временные изменения α посредством сравнения переходов линий поглощения дублета SiIV, наблюдаемых в ранней Вселенной с лабораторными измерениями. Весомое среднее значение α-изменения, согласно нашим анализам, в пределах использованных красных смещений $2.0 \le z \le 3.7$, равно $\Delta\alpha/\alpha = (-0.53 \pm 0.72) \times 10^{-5}$. Этот результат улучшает ограничения на $\Delta\alpha/\alpha$ с фактором примерно семь по сравнению с опубликованными результатами в литературе.

Ключевые слова: *квазары: спектры: постоянная тонкой структуры*

REFERENCES

1. *H.Chand*, *R.Srianand*, *P.Petitjean*, *B.Aracil*, Astron. Astrophys., **417**, 871, 2004.
2. *R.Srianand*, *H.Chand*, *P.Petitjean*, *B.Aracil*, PRL, **92**, 121302, 2004.
3. *A.V.Ivanchik*, *Y.A.Potekhin*, *D.A.Varsharlovich*, Astron. Astrophys., **343**, 439, 1999.

4. *D.A.Varshalovich, A.V.Ivanchik, Y.A.Potekhin*, Z. Tek. Fiz, **69**, 1001, 1999.
5. *J.D.Prestage, L.R.Tjoelker, L.Maleki*, PRL, **74**, 3511, 1995.
6. *J.P.Uzan*, Rev. Mod. Phys., **75**, 403, 2003.
7. *T.Damour, F.Dyson*, Nucl. Phys. B, **480**, 37, 1996.
8. *T.Damour, F.Dyson*, Nucl. Phys. B, **423**, 532, 1994.
9. *N.Kolachevsky*, Physics-Uspekhi, **47**, 1101, 2004.
10. *M.P.Savedoff*, Nature, **178**, 688, 1956.
11. *J.N.Bahcall, C.L.Steinhardt, D.Schlegel*, Astrophys. J., **600**, 520, 2004.
12. *D.Grupe, A.K.Pradhan, S.Frank*, Astron. J., **130**, 255, 2005.
13. *C.M.Gutierrez, M.Lopez-Corredoira*, Astrophys. J., **713**, 46, 2010.
14. *D.A.Varshalovich, A.Y.Potekhin, A.V.Ivanchik*, AIP Conf. Proc., **506**, 503, 2000.
15. *V.A.Dzuba, V.V.Flambaum, J.K.Webb*, PRA, **59**, 230, 1999.
16. *V.A.Dzuba, V.V.Flambaum, J.K.Webb*, PRL, **82**, 888, 1999.
17. *V.A.Dzuba, V.V.Flambaum, M.T.Murphy, J.K.Webb*, PRA, **63**, 042509, 2001.
18. *J.K.Webb et. al.*, PRL, **87**, 091301, 2011.
19. *J.K.Webb et. al.*, Astrophys. Space Sci., **283**, 565, 2003.
20. *M.T.Murphy et. al.*, Mon. Notic. Roy. Astron. Soc., **327**, 1208, 2001.
21. *M.T.Murphy et. al.*, Mon. Notic. Roy. Astron. Soc., **327**, 1223, 2001.
22. *M.T.Murphy et. al.*, Mon. Notic. Roy. Astron. Soc., **327**, 1244, 2001.
23. *M.T.Murphy, J.K.Webb, V.V.Flambaum*, Mon. Notic. Roy. Astron. Soc., **345**, 609, 2003.
24. *M.T.Murphy, V.V.Flambaum, S.Muller, C.Henkel*, Science, **320**, 1611, 2008.
25. *J.K.Webb et. al.*, PRL, **107**, 191101, 2011.
26. *T.D.Le*, AIP Conf. Proc, **1594**, 23, 2014.
27. *L.L.Cowie, A.Songaila*, Astron. J., **453**, 596, 1995.
28. *L.L.Cowie*, Nature, **428**, 132, 2004.
29. *D.A.Varshalovich, A.Y.Potekhin*, Astron. Letter, **20**, 771, 1994.
30. *P.Petitjean, M.Rauch, R.F.Carswell*, Astron. Astrophys., **291**, 29, 1994.
31. *A.M.Wolfe, R.L.Brown, M.S.Roberts*, PRL, **37**, 179, 1976.
32. *A.Y.Potekhin, D.A.Varshalovich*, Astron. Astrophys. Suppl. Ser., **104**, 89, 1994.
33. *A.F.Martinez, G.Vladilo, P.Bonifacio*, Mem. S. A. It. Suppl., **3**, 252, 2003.
34. *P.Molaro, D.Reimers, I.I.Agafonova, S.A.Levshakov*, EJST, **126**, 173, 2008.
35. *P.Molaro et. al.*, Astron. Astrophys., **481**, 559, 2008.