



Research article

Stringent limit on space-time variation of fine-structure constant using high-resolution of quasar spectra

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ABSTRACT

We have obtained a new limit on the space-time variation of the fine-structure constant ($\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$) using the observations of Mg II line in quasar J110325-264515 spectra with redshift $z_{\text{abs}} = 1.8389$. The obtained parameter is $\Delta\alpha/\alpha = (-0.155 \pm 0.728) \times 10^{-6}$. It was derived from the comparison between the quasar J110325-264515 spectra and the laboratory sample spectra. The obtained result appears as a new highly sensitive probe of the cosmological variability of the fine-structure constant. From the relative spectra of the Mg II, we found the most stringent constraint up today on $\Delta\alpha/\alpha$ comparing to the previously published results.

1. Introduction

Searching for space-time variations of dimensionless nature constants, such as the fine-structure constant $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$, and the ratio of electron to proton mass, $\mu = m_e/m_p$, is an essential topic in contemporary physics [1, 2, 3, 4, 5]. The standard model (SM) of particle physics does not explain the qualities of α and μ , and their dependence on the parameters. These variations violate the Einstein Equivalence Principle (EEP). The study on this topic could open a new window to physics beyond the SM [6, 7, 8]. Consequently, if these constants change with cosmological space-time, they would be violated by the EEP, which is well-known as the basic hypothesis of General Relativity (GR). The gravity theory is currently almost well-tested relative to scalar fields and it plays an important role in astrophysical and cosmological epochs. However, GR does not consist of quantum mechanics because it is only an effective field theory indicating some energy thresholds. Based on energy or length scales, we can expect to predict the GR deviations, since GR passed all tests with flying colors [9, 10, 11]. Hence, we can explain and search for the effects of non-GR with a critical relation using current and future newly detected sources. Consequently, it is the most important motivation for related studies in astrophysics and cosmology beyond GR, which does not include dark matter or dark energy. It is also used to explain the accelerating expansion of our Universe at present and the missing-mass problem in galaxies. One of the most significant studies indicated the orbital effects of spatial variations of fundamental

couplings [12, 13]. Furthermore, these effects would also provide us a motivation to evaluate other observational data in order to determine such variations more accurately. It should be noted that the search for these variations is conducted in laboratories using spectral observational data of distant quasars. These studies will open new physical phenomena beyond the SM in the context of GUTs; string and superstring theory. Such observations and laboratory measurements would indicate the variations of these fundamental physical constants; that are important frameworks for general relativity, modified gravity and theories with extra-dimensions. Simultaneously, it is an essential way to check variations from GR in future constraints [14, 15, 16, 17, 18]. The most recent studies use the observations to detect the change rates of $\Delta\alpha/\alpha$ with high precision. This could motivate many experimental and theoretical frameworks that will allow to test the fundamental physical constants for the variations over cosmological timescales. Numerous studies related to this subject have been testing spatial and temporal variations in the fine-structure constant using the absorption lines in quasar spectra with wide-spanning redshifts by applying Many-Multiplet (MM) technique [19, 20]. Application of this method for the analysis of 30 absorption systems with spanning redshifts $0.2 \leq z_{\text{abs}} \leq 4.2$ from the Keck telescope showed that the α -value was smaller in the past compared to that obtained in the present case [20]. Other results from the analysis of 140 absorption systems yield $\Delta\alpha/\alpha = (-5.7 \pm 1.1) \times 10^{-5}$ [21, 22]. Based on the Very Large Telescope (VLT) data, the obtained results included 154 measurements of α and $\Delta\alpha/\alpha = 2.1 \pm 1.2$ ppm [23]. Data achieved from

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two different observations (Keck and VLT) suggests that the fine-structure constant may vary with the spatial dipole [23, 24]. However, the result should be examined in more detail considering statistical and systematic effects. One of the most significant challenges of the MM method is to establish the effects that could be used to identify the spatial variation of α with the distorted wavelengths. The first study that revealed the difficulties associated with this approach related to wavelength calibration was localized in small-scale intra-orders. They were pointed out by Griest et al. [25]. A calibration technique using Echelle and asteroids was first applied to study the distorted wavelength. These studies indicated that the distortion effects were approximately linear on large scales [26, 27]. Using different telescopes and identifying the distorted wavelength, Evans et al. completed this analysis and concluded that the effects depend on long-range scales. Weak evidence for variations in α came from a simple type of distorted wavelength simulation. Whitmore and Murphy determined it from the analysis of Quasar Stellar Object (QSO) absorption systems. Based on this indication, the application could only be used as a single wavelength and not for most of the observed quasar spectra, such as multiplet lines. Therefore, this model brought different conclusions from what was found previously by other scientists [28, 29, 30]. Thus, it could not be included in our present analysis. Therefore, an innovative technique to test the space-time variation in α was proposed and accomplished with high accuracy [31]. A new approach was used to check spatial and temporal variations in the fine-structure constant over cosmological timescales. This method could estimate $\Delta\alpha/\alpha$ with high accuracy over a wide-range of redshifts and it is orders sensitive than the other methods [32]. This method includes α -independent line ratios, and it was implemented by atomic/molecule spectra calculations using the many-body perturbation theory and the Fock-space coupled-cluster method. Thus, the effect of space-time variations in α could be observed by calculating the relativistic energy shifts of the atomic and molecular spectra from quasars and comparing it to the laboratory sample values. It allowed us to identify statistical and systematic errors with higher accuracy [31, 32, 33]. The best determined connection using this procedure inferred an alteration with the cosmological space-time of $\Delta\alpha/\alpha = (1.56 \pm 1.78) \times 10^{-6}$ over redshift range: $z = 1.8389$ [31, 32, 33]. Therefore, we tested space-time variation in α over wide-spanning redshifts for doublet and multiplet lines with high accuracy while subject to low systematic effects, leading to a higher level accuracy of $\Delta\alpha/\alpha$ determination [34]. Based on the observed spectra, one can apply this procedure to estimate the rate of $\Delta\alpha/\alpha$ change rate below 10^{-6} .

In this work, we applied the method to analyze Mg II lines in quasar J110325-264515 spectra. We combined the spectra with Ritz laboratory data to check the α -variation over cosmic timescales [31, 32, 33, 34]. Obtained result yield better limit on $\Delta\alpha/\alpha$ [24].

2. $\Delta\alpha/\alpha$ from quasar spectra J110325-264515

Cosmological observations suggest a way to determine any variations in α . In the previous studies, one could derive the observed change in α as follows [31, 32, 33]:

$$\frac{\Delta\alpha}{\alpha} \approx \frac{1}{2} \left(\frac{\frac{\lambda_2(t)}{\lambda_1(t)} - 1}{\frac{\lambda_2(0)}{\lambda_1(0)} - 1} - 1 \right), \text{ which provides a small change in } \alpha. \text{ Hence,}$$

by comparing $\lambda_1(t)$ and $\lambda_2(t)$ wavelengths measured from QSO and the relative laboratory, it is easy to infer a change in α at different epochs and regions of the Universe. This study uses spectra from the archive of observational data and Ritz laboratory [31, 32, 33, 34, 35, 36]. The estimation of statistical and systematic errors is explained in [31, 32, 33, 34, 35, 36]. Mg II spectra that were used have a good quantity and only a several $m\text{\AA}$ uncertainty errors. Based on this uncertainty, we could identify the systematic error of $\Delta\alpha/\alpha$ with high accuracy. $\Delta\alpha/\alpha$ is obtained using the non-linear least-squares algorithm for each QSO

absorber [34, 35, 36]. This fitting algorithm could be applied well to available absorption systems with a minimal number of parameters for detailed profiles to find the value of $\Delta\alpha/\alpha$ with high accuracy. By minimizing χ^2 simultaneously, we could measure $\Delta\alpha/\alpha$ and the error associated with the wavelength separation $\Delta\lambda$ for each QSO system. The main error contribution in our studies depends on the width-separation ratio, which would be determined from quasars and the laboratory with small separations. We achieved the best relative positions of Mg II lines and estimated them for each absorption system in quasar J110325-264515. Moreover, physically related parameters, such as redshift and b parameters, were fixed for each line system to reduce the expected number of input free-parameters. Therefore, line broadening is mostly influenced by turbulent than thermal motion. For this reason, two cases should be considered: the system includes a simple single-component and the system includes two highly blended components. In this way, two components separation to be limited to one component with small velocity dispersion. Then, the Mg II lines were fitted in the input spectrum to obtain $\Delta\alpha/\alpha$. In this way, we could estimate $\Delta\alpha/\alpha$ with high precision that was achieved using our approach and fitting procedure. Therefore, the previous fitting program's application follows the reduced variation of χ^2 for each fitting absorber as a general function of $\Delta\alpha/\alpha$. We included free parameters and fixed values describing the properties of absorbing system properties, and the atomic and molecular properties in our analysis procedure. Detailed examination of the spectral data and its relationship for each line is the best way to fit the absorption systems. After that it is used to check for the relevant transitions of Mg II by estimating the value of $\Delta\alpha/\alpha$. Moreover, all transitions have been checked in blended cases, which are rejected if detected during the procedure examination of spectral data. The fitting procedure of Mg II absorption lines is the same as used and described in [31, 32, 33, 34, 35, 36]. The α -variation was identified for the first time for each line. Then, it was applied to all lines taking into account the relative parameters: N -column density, z_{abs} -absorption redshift, Doppler, and b -line width. These parameters were deduced from the function that is equivalent for the all transitions. Analysis of $\Delta\alpha/\alpha$ indicated a variation in the range of $[-1.2 \times 10^{-6} - 1.2 \times 10^{-6}]$ with the step of -0.1×10^{-6} for the analyzed lines of Mg II. The analysis only included (χ^2) minimum (χ_{min}^2) for the measurement of $\Delta\alpha/\alpha$ for the system with reduced fitting $\chi^2 \simeq 1$. In a statistical process with standard quality, 1σ error is assigned to the best practical value of $\Delta\alpha/\alpha$ to make sure that $\Delta\chi^2 = \chi^2 - \chi_{\text{min}}^2 = 1$ is computed as required for variations in $\Delta\alpha/\alpha$. Then, the absolute maximum changes of $\Delta\alpha/\alpha$ are based on $\Delta\chi^2 = 1$ for the estimation of $\Delta\alpha/\alpha$ errors. Minimal χ^2 are obtained to fit each line listed in Table 1. Figure 1 shows $\Delta\alpha/\alpha$ as a function of redshift values. Finally, we obtain $\Delta\alpha/\alpha = (-0.155 \pm 0.728) \times 10^{-6}$. We calculated statistical and systematic errors as $\sigma_{\text{tot}}^2 = \sigma_{\Delta\alpha/\alpha}^2 + \sigma_{\text{sys}}^2$. Subsequently, it includes systematic and statistical errors in the individual determination of $\Delta\alpha/\alpha$, such as homogeneity at 10^{-6} .

Figure 1 presents the variation of $\Delta\alpha/\alpha$ from Mg II absorption systems. Each point is plotted with χ^2 minimization along the redshift. As a result, $\Delta\alpha/\alpha$ has a negative or positive value depending on the statistical significance of how deep one looks back into the Universe (Table 1). In the analysis, we created multiple velocity components for each absorption system with parameters (N , z_{abs} , Doppler, b) and considering $\Delta\alpha/\alpha$ for each transition of the rest-wavelength as a free parameter. In this way, we also concert the connection between $\Delta\alpha/\alpha$ with redshift, different transitions and the shifted velocity components. This allows to reduce the motion in the individual systems with numerous ion samples from absorbing systems with the $\chi^2 = 2762.3$ for the $\Delta\alpha/\alpha$ fitting.

Previous studies attempted to determine alternative descriptions of the observable line structures or systematic errors. However, these results might be broken down into well blended and multi-cloud systems. The potential systematic error involves velocity structure and blended lines or it may be known as inconsistencies of the spectrograph and inhomogeneity of the cloud itself. The previous studies had inconsistency

Table 1. Atomic Data Availability-Wavelength Table [34] for our analysis. The redshift order of $\Delta\alpha/\alpha$ was calculated from the input lines of Mg II. The averaged estimation of all Mg II lines is $\Delta\alpha/\alpha = (-0.155 \pm 0.728) \times 10^{-6}$.

Species	Trans	A	Wavenumber [cm ⁻¹]	$\lambda_{vac}[A]$	z	$\Delta\alpha/\alpha (10^{-6})$	$\sigma_{\Delta\alpha/\alpha}(10^{-6})$
Mg II	2796		35760.85414 (6)	2796.353789 (5)	1.83704	-2.41148	0.550
		26	35760.9403866 (53)	2796.34704565 (42)	1.83743	0.60081	0.970
		25	35760.9189011 (53)	2796.34872573 (42)	1.83752	0.04110	0.860
		25	35760.9174313 (53)	2796.34884066 (42)	1.83881	0.05286	0.420
		25	35760.9155410 (53)	2796.34898848 (42)	1.83886	0.04939	2.700
		25	35760.9137747 (53)	2796.34912660 (42)	1.83888	1.52514	0.710
		25	35760.8592344 (53)	2796.35339142 (42)	1.83890	0.04110	3.860
		25	35760.8577646 (53)	2796.35350635 (42)	1.83893	0.05286	0.700
		25	35760.8558742 (53)	2796.35365416 (42)	1.83896	0.04939	0.600
		25	35760.8541079 (53)	2796.35379228 (42)	1.83896	0.46731	0.790
		24	35760.8373967 (5)	2796.35509903 (42)	1.83905	-0.40375	0.587
		2803	35669.30440 (6)	2803.530982 (5)	1.83947	-2.41574	1.900
	26	35669.3905712 (53)	2803.52420938 (42)	1.83954	0.79181	1.680	
	25	35669.3725048 (53)	2803.52642924 (42)	1.83955	-0.28532	1.410	
	25	35669.3623278 (53)	2803.52562935 (42)	1.83957	1.95809	1.003	
	25	35669.3128381 (53)	2803.53111891 (42)	1.83957	-0.28532	0.610	
	25	35669.3026610 (53)	2803.53031902 (42)	1.83965	0.70560	0.930	
	24	35669.2876697 (53)	2803.530982 (5)	1.83970	-0.39493	1.605	

because the measurements were influenced by the different approach in systematic effects determination. It leads to depreciation in error estimations. The wavelength calibration is one of the key problems, while the systematic effect has been widely obtained from the methods of investigations and models that were used in the studies. Previous analysis had a significant estimated errors and inconsistencies. As a result, most of the results could not be used to detect the errors in α when applying them to the high redshift systems [23, 24].

Our analysis indicates the possible sources of the errors that arise from observed systems or caused by the errors of laboratory spectra calibration. The calibration errors were determined to estimate the change rate of α from observations with high precision. This study used a wide sample of Mg II spectra from HST/STIS Echelle observational data. The Mg II lines were measured with the accuracy of 1 km s⁻¹ and uncertainty order of 1:10⁶, laboratory uncertainty was order of 1:10⁷, and the Gaussian distribution that provided a possible way to estimate the errors in α . The error estimation was performed for the observed lines independently. It allowed to compare the distribution with the standard statistical error. The Mg II doublet lines were checked for scattering

before proceeding with the fitting procedure leading to a more accurate result [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34].

3. Discussions and conclusions

Quasar J110325-264515 has an absorption redshift of 1.8389. It includes weakly and highly ionized samples such as Mg II because they normally come from different gas phases. Moreover, Mg II lines are the most unaffected by blending from the transitions of strong atomic require very high signal-to-noise ratio. Therefore, the use of velocity component structures such as Mg II can be an example of these weakly ionized species. This should be useful for estimation of absorption components with small separation in absolute positions in the fitting process because it cannot be possibly fit all of them. However, the same ion multiplets could allow to fit and determine the fitting parameters with high precision simultaneously. As a result, our study provides the best way to estimate the statistical and systematic errors. Therefore, we determine a strong limit of $\Delta\alpha/\alpha = (-0.155 \pm 0.728) \times 10^{-6}$, which consists of dipole variation [33, 34]. Our result improves high accuracy determination of $\Delta\alpha/\alpha$ compared with reported results in the studies of Bainbridge and Webb. They obtained $\Delta\alpha/\alpha = (3.3 \pm 2.9) \times 10^{-6}$ using the same data associated with quasar J110325-264515 [34]. Our method provides a benefit that could determine $\Delta\alpha/\alpha$ with higher precision than previous results. The obtained results indicate the existence of known conflicts [35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. Moreover, the use of a fitting parameter for $\Delta\alpha/\alpha$ analysis is an explicitly asymmetric approach. Almost all of these works used χ^2 against the $\Delta\alpha/\alpha$ curve to procure the mainly useful fitted estimation of $\Delta\alpha/\alpha$. The best result came from analyses that would only provide the cosmic variation in α at a level of parts per million. By searching for α -variation over cosmic timescales, the present analysis is based on the width-line ratios, total errors, and α -independence. In this way, we could demonstrate the exact size of error estimation from the split wavelengths with small separations of all lines. Moreover, it could also be utilized for a wide-redshifts with high accurate estimation of the statistical and systematic errors.

Based on a combination of the Ritz laboratory data and Mg II lines from the quasar J110325-264515, we showed a useful way to check the α -variation over cosmological space-time. The obtained result provides one of the tightest space-time variation effects in α based on the individual absorber. In this analysis procedure, data-reduction, calibration is required to consider the possible systematic effect in α . It is systematic

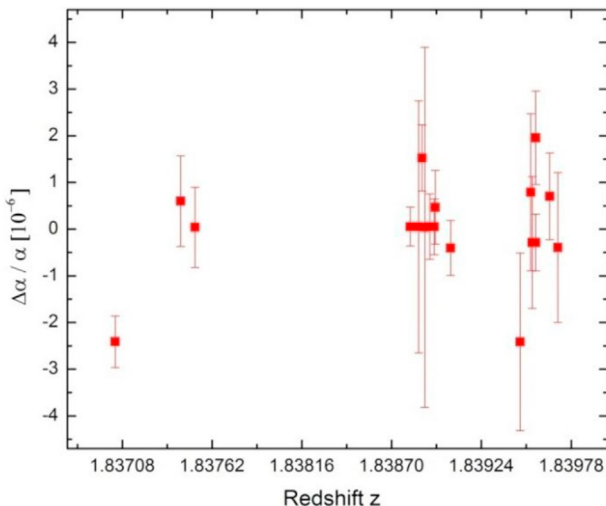


Figure 1. $\Delta\alpha/\alpha$ as a function of redshifts.

and statistically used to estimate the remaining errors. Additionally, the available analysis used for the estimation of line ratios independently of α that should be precisely for the estimation of $\Delta\alpha/\alpha$, including statistical and systematic errors. The obtained limit on $\Delta\alpha/\alpha$ is more stringent than Bainbridge and Webb's results for the similar data [34]. The determination of $\Delta\alpha/\alpha$ is highly accurate and more sensitive than that of previous studies [37, 38, 39, 40, 41, 42, 43, 44]. Our estimate matches the currently available constraints on the spatial and temporal effects in α using high-resolution spectra from astrophysical observations [31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. Accordingly, at present great attempt has been placed on improving the laboratory wavelength of transitions, which is employed in our analysis from the Mg II multiplet line. This process provides the most robust constraint to determine the setup of α -variation on cosmological space or time, and the additional estimation of various systems. It should be applied to the systems in order to reduce the errors and uncertainties.

The present study provides an important question of how spatial or temporal effects variation of α with cosmological space-time. Using the available data it makes possible to estimate the value of $\Delta\alpha/\alpha$ with higher accuracy comparing to the previous studies. We believe that this study will activate further achievements and clarify interesting hypothesis on this question. As a result, the variation of the fundamental physical constants like the fine-structure constant with cosmological space-time will open new areas in astrophysics and cosmology. This provides valuable mystery phenomena in early cosmic time. The present study analyzes the effect of space-time-varying in α utilizing the high-resolution of quasar J110325-264515 with redshift $z_{\text{abs}} = 1.8389$. We found that the upper limit for the α change rate improved to $\Delta\alpha/\alpha = (-0.155 \pm 0.728) \times 10^{-6}$ comparing with the previous studies. Moreover, the present technique could be applied to a wide-range redshift systems, which should yield stronger results. Therefore, any spatial and temporal variations in the fundamental physics constants would violate the EEP and to discover the deviations in GR.

Improving the observational techniques and further laboratory tests, this research would expand a progressive window into parameters from the GUTs.

Declarations

Author contribution statement

T. D. Le: Conceived and designed the analysis; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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