Search for α variation in UVES spectra: Analysis of C IV and Si IV doublets towards QSO 1101-264

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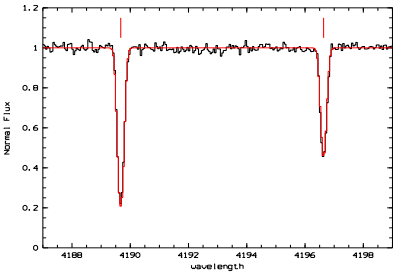

Figure 1. Absorption of C IV at $z = 1.7061$. Black: observed spectrum. Red: fitted spectrum. The sharpness of the components allows us to determine the centroid accurately.

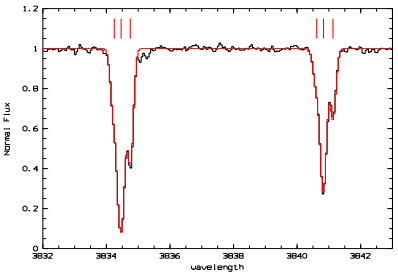

Figure 2. Absorption of C IV at $z = 1.4767$. The leftmost line in both absorptions correspond to the blended and discarded line. Black: observed spectrum. Red: fitted spectrum.

Introduction

Modern theories in physics (Super Symmetry Grand Unification Theory, Superstring and others) predict the dependence of fundamental physical constants on energy, a prediction supported by high energy experiments (Okun 1998), and have cosmological solutions where low-energy values of these constants vary with the cosmological time (Varshalovich 2000). Such variations could provide evidence for the existence of compact dimensions, at least qualitatively (Carilli et al. 2000, Levshakov 1994).

Recent measurements of absorption lines in high resolution QSO spectra suggest the variation of the fine structure constant α throughout cosmological time (e.g. Webb et al. 2002 and refs. therein). The use of QSO spectra to search for an α variability takes advantage of the many absorption lines originated in clouds lying at various redshifts along the line of sight to the QSO. The measurements are performed by comparing wavelength separations of transitions observed at various redshifts with their corresponding laboratory values at $z = 0$. Two approaches exist for this study of $\Delta\alpha/\alpha$: the "Alkali Doublet" (AD) method and the "Many Multiplet" (MM) method. The former, first applied by Bahcall et al. (1967), considers alkaline-like ions to compare the wavelength separation of its doublets. The latter, developed by Dzuba et al. (1999a; 1999b; 2001), uses wavelengths of various transitions from different multiplets and ions. In the AD method it is common to use doublets of ions like C IV and Si IV, which are routinely detected in QSO metal absorbers. For these ions the wavelength separation between λ_1 and λ_2, corresponding to the transitions $^2S_{1/2} \rightarrow {}^2P_{3/2}$ and $^2S_{1/2} \rightarrow {}^2P_{1/2}$ respectively, is proportional to α^2.

From a MM method analysis based on 128 systems, Webb et al. (2002) find $\Delta\alpha/\alpha = (-0.57 \pm 0.10) \times 10^{-5}$ over the redshift range $0.2 < z < 3.7$, indicating a smaller value of α in the past. From an AD method analysis of 21 Si IV doublets Murphy et al. (2002) obtain a weighted mean $\Delta\alpha/\alpha = (-0.5 \pm 1.3) \times 10^{-5}$ at $\langle z_{abs} \rangle = 2.8$.

Also other methods of analysis give some indication, yet to be confirmed, of a decrease of α at high redshift. Recently, Bahcall et al. (2003) find $\Delta\alpha/\alpha = (-2 \pm 1.2) \times 10^{-4}$ from an analysis of strong nebular emission lines of [O III] (5007 Å and 4959 Å) in a QSO sample over $0.16 < z < 0.80$.

We have conducted a search for C IV and Si IV doublets in the absorption spectrum toward QSO 1101-264, obtained by VLT-UVES during the Science Verification. Seven C IV and two Si IV systems were identified and accurate measurements of wavelengths over the redshift range $1.1862 < z < 1.8377$ were performed. After a careful selection of pairs of lines, we applied the AD method, with an original expression for the error analysis, to compute the α variation. Here we present the results of this work.

Observations, Measurements and Analysis

QSO 1101-264 ($z_{em} = 2.145$) was observed for five nights between February 9 and 17, 2000 for the Science Verification of the UV-Visual Echelle Spectrograph (UVES) installed at the second VLT Unit (Kueyen). Twelve exposures of 3600 and 5400 seconds were made using the dichroic settings: Dic1 (B3460Å + R5800Å) and Dic2 (B4370Å + R8600Å) to cover the spectral range 3000Å - 10000Å, with slit width of 0.8 arcseconds (red), 0.9 arcseconds (blue) and 1 arcsecond (when seeing was mediocre) providing $R = 50.000 - 43000$. The binning of the CCD was 2x2 or 2x1, depending on the seeing conditions. The S/N given per spectral bin of the extracted spectrum across the spectral range is: 15 for $\sim$ 3150Å, 50 for $\sim$ 3400Å and 50 - 60 for $\sim$ 3800Å-6000Å.

All the work done on the spectrum was performed under the MIDAS package. Data reduction was carried out by the Science Verification Team and for the present work, the reduced spectrum was converted from air wavelengths to vacuum wavelengths. A total of nine systems among the C IV (1548Å, 1550Å) and Si IV (1393Å, 1402Å) ions were identified. A code for line fitting considering Voigt profiles and based on the reduced χ^2 test as parameter of goodness of the fit was used. The laboratory wavelengths considered in the present analysis are: C IV (1548.204Å, 1550.781Å) and Si IV (1393.76018Å, 1402.77291Å) measured by Griesmann & Kling (2000), the best available up to date. The AD method for doublet comparison was employed together with an analitic expression for the error analysis.

Systems identified

The absorptions are located in the near UV band, aproximately from 3100Å to 4400Å, presented from increasing redshift as follows:

The C IV system at $z = 1.1862$, shows a complicated profile unfortunately contaminated, inside the Lyman forest.

An interesting system in which there are C IV and Si IV absorptions at the same redshift $z = 1.2022$, inside the Lyman forest.

Two C IV systems, at $z = 1.4767$ (Figure 2) and $z = 1.6527$ respectively, present a similar shape with three pairs of lines, one of them blended.

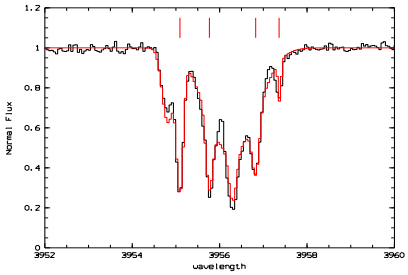

Figure 3. Absorption of Si IV 1393Å at $z = 1.8377$, with the lines selected to compute $\Delta\alpha/\alpha$. Black: observed spectrum. Red: fitted spectrum.

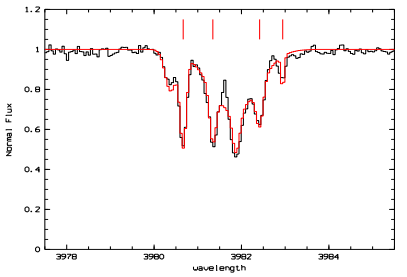

Figure 4. Absorption of Si IV 1402Å at $z = 1.8377$, showing the selected lines. Black: observed spectrum. Red: fitted spectrum.

A C IV system at $z = 1.7061$ is the ideal doublet to measure, a fortunate case because it is a simple pair of strong lines (see Figure 1). It is a very good example of the available high quality instruments displaying a spectrum with $R \approx 45000$ and $S/N \approx 60$.

The C IV system at $z = 1.7513$ is a not very strong absorption.

A system in which there are present absorptions of C IV and Si IV at the same redshift, is found at $z = 1.8377$, these are specially clear and strong but some appear blended (see Figures 3 and 4).

Line fitting and line selection

The synthetic spectrum for every doublet was constructed basically by using the minimum number of components, until a very good shape reproducing the real spectrum was reached.

The $z = 1.4767$ system in Figure 2 helps to illustrate the fitting procedure: the first wavelengths guess values, correspond to the two lines in the obvious absorption minima, it is a possible system with two pairs of lines.

After several line fitting runs with different starting guess values around the minima, a poor synthetic spectrum was obtained. To improve it, new lines were added, bearing in mind the slightly asymmetric shape of the spectrum toward the left side. In this manner the new model considers three pairs of lines, the first not very well resolved but useful to describe the system and determine better the other wavelengths centroids.

The addition of a new couple of lines, helps to get a good synthetic spectrum and a better determination of the strong absorption lines, but not represent a useful doublet to perform the calculations of interest because it does not show an explicit minimum to think of a reliable absorption.

The sample contains a total of 47 doublets, not all suitable for the desired measure of $\Delta\alpha/\alpha$ due to complicated profiles, some of them contaminated or blended. For that reason a rigorous selection of lines was made, choosing the best resolved profiles, outside the Lyman forest to avoid contaminations, discarding asymmetric shapes, focusing on small Doppler broadening (b parameter), bearing in mind that in narrower absorptions the centroids are better determined than in broader ones.

The selection of appropriate centroid wavelengths was based on the profile given by the system C IV at $z = 1.7061$ (Figure 1) where the line fitting provided wavelengths uncertainties of $\sigma_{\lambda_1} = 0.0015$Å and $\sigma_{\lambda_2} = 0.0021$Å. Because, somehow, a complex velocity structure is present in all systems, the most symmetric shapes were selected qualitatively and the corresponding σ_{λ_1} and σ_{λ_2} values served as quantitative criterion to ensure the best wavelengths to be included in the calculations. Almost all the selected lines are below these values excepting two particular cases in wich σ_{λ_2} was 0.0025Å and 0.0031Å. The more accurate measurements correspond to 6 doublets of C IV and 4 doublets of Si IV, to compute $\Delta\alpha/\alpha$ over a redshift range $1.4767 < z < 1.8393$.

The Alkali Doublet Method

Considering a possible small variation of α, Varshalovich et al. (2000) use the approximate formula

$$\frac{\alpha_z - \alpha}{\alpha} = \frac{\Delta\alpha}{\alpha} = \frac{c_r}{2}\left[\frac{(\Delta\lambda/\lambda)_z}{(\Delta\lambda/\lambda)_0} - 1\right] \qquad \text{with} \qquad c_r \approx \frac{\delta q_1 - \delta q_2}{\delta q_1 - 2\delta q_2}, \tag{1}$$

where $\lambda = \frac{1}{2}(\lambda_1 + \lambda_2)$; $(\Delta\lambda/\lambda)_z$ and $(\Delta\lambda/\lambda)_0$ represent the doublet separation for the absorption at redshift z and at the laboratory, respectively; c_r is a correction term given by Murphy et al. (2001), with q_1 and q_2 coefficients representing the relativistic correction to the energy for a particular transition, calculated for many elements by Dzuba et al. (1999b). The correction coefficients c_r are: 1.1758 for C IV and 0.8914 for Si IV.

An analitic expression for the error analysis can be obtained through an aproximation for the standard deviation of $\Delta\alpha/\alpha$ as

$$\frac{\Delta\alpha}{\alpha} = f(\lambda_{z1}, \lambda_{z2}) \qquad \sigma_f^2 \approx \sigma_{\lambda_{z1}}^2 \left(\frac{\partial f}{\partial \lambda_{z1}}\right)^2 + \sigma_{\lambda_{z2}}^2 \left(\frac{\partial f}{\partial \lambda_{z2}}\right)^2 + \cdots \tag{2}$$

and with the derivatives of eq. (1) yields the error propagation equation for the AD method. Results appear in Table 1 and are plotted in Figure 5.

The behaviour of $\Delta\alpha/\alpha$ shows a scatter plot along the redshift interval and due to the few points available, separated by great redshift intervals, a rank correlation analysis does not provide any clue about a particular trend.

The results corresponding to Si IV are more accurate than those for C IV and it is evident in the error bars smaller by one order of magnitude. Moreover the Si IV laboratory wavelengths are determined with an error factor of 10^{-5}Å, whereas the C IV wavelengths with an error factor of 10^{-3}Å (Griesmann & Kling 2000).

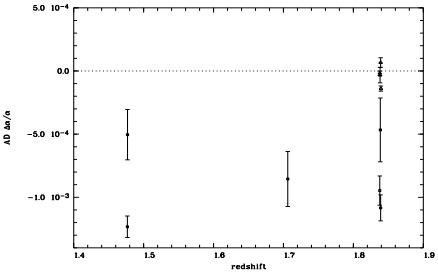

Figure 5. Results from the AD method. Squares indicate values for C IV and triangles for Si IV.

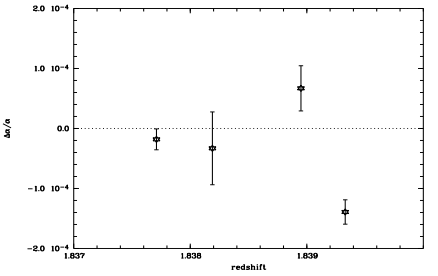

Figure 6. Zoom of Fig. 5 for the 4 Si IV components.

A particular plot is showed for Si IV (see Figure 6) and averaging the four values lead to: $\Delta\alpha/\alpha = (-3.09 \pm 8.46) \times 10^{-5}$, where the error is the standard deviation around the mean.

Table 1. $\Delta\alpha/\alpha$ calculations with their corresponding standard deviations.

Ion, z	$\frac{\Delta\alpha}{\alpha}$	$\sigma_{\Delta\alpha/\alpha}$
C IV, 1.4767	-1.2330×10^{-3}	8.4913×10^{-5}
C IV, 1.4769	-5.0416×10^{-4}	1.9919×10^{-4}
C IV, 1.7061	-8.5510×10^{-4}	2.1750×10^{-4}
C IV, 1.8377	-9.4692×10^{-4}	1.1591×10^{-4}
C IV, 1.8385	-4.6644×10^{-4}	2.5231×10^{-4}
C IV, 1.8389	-1.0835×10^{-3}	1.0289×10^{-4}
Si IV, 1.8377	-1.8157×10^{-5}	1.7412×10^{-5}
Si IV, 1.8381	-3.3109×10^{-5}	6.0675×10^{-5}
Si IV, 1.8389	6.6867×10^{-5}	3.7639×10^{-5}
Si IV, 1.8393	-1.3921×10^{-4}	2.0282×10^{-5}

Conclusions

For the first time, UVES data have been employed to compute $\Delta\alpha/\alpha$ with the AD method. As shown in the figures, the spectrum under study has a very good quality, comparable, or better, than spectra used in previous work. Despite the stringent selection criteria applied to find suitable absorption profiles for measuring central wavelengths, an acceptable number of doublets was obtained to carry out the desired calculations.

Even if the absorption profiles of C IV have very high quality, the measurements errors obtained from this ion are bigger by one order of magnitude than those obtained from Si IV. In addition, the $\Delta\alpha/\alpha$ values provided by the C IV doublets disagree in order of magnitude with those provided by Si IV, that appear to be consistent with previous determinations (Murphy et al. 2002). These differences between C IV and Si IV data are probably due to the better determination of Si IV laboratory wavelengths in comparison to C IV wavelengths. Until better laboratory data for C IV are obtained, we consider only the result obtained from the multiple components of the Si IV system at $z \simeq 1.84$. The resulting $\Delta\alpha/\alpha = (-3.09 \pm 8.46) \times 10^{-5}$ does not support a change of α at such redshift. However, despite the result consistent with zero, our $\Delta\alpha/\alpha$ values show a negative sign, which is consistent with the findings of all previous determinations of $\Delta\alpha/\alpha$ (Varshalovich et al. 2000, Webb et al. 2002, Murphy et al. 2002, Bahcall et al. 2003). This remarkably consistent indication for a possible negative variation of α certainly deserves further investigation on a large number of systems, aimed at reducing the final error bar. The selection process of the best absorption lines, made to improve the $\Delta\alpha/\alpha$ determination, reduces the quantity of doublet systems available in a single QSO spectrum in a sensitive way. This is a motivation to study many more QSO's spectra to enhance the data sample, concentrating the analysis on the Si IV transitions, which have well determined laboratory data.

REFERENCES

Bahcall J. N., Sargent W. L. W., Schmidt M., 1967, ApJ 149, L11

Bahcall J. N., Steinhardt C. L., Schlegel D., 2003. Preprint astro-ph/0301507

Carilli C. L., Menten K. M., Stocke J. T. et.al., 2000, Phys. Rev. Lett. 85, 5511

Dzuba V. A., Flambaum V. V., Webb J. K., 1999a Phys. Rev. Lett. 82, 888

Dzuba V. A., Flambaum V. V., Webb J. K., 1999b Phys. Rev. A 59, 230

Dzuba V. A., Flambaum V. V., Webb J. K., 2001, Phys. Rev. A 63, 042509

Griesmann U., Kling R., 2000, ApJ 536, L113

Levshakov S. A., 1994 MNRAS 269, 339

Murphy M. T., Webb J. K., Flambaum V. V., Prochaska J. X., Wolfe A. M. 2001 MNRAS 327, 1237

Murphy M. T., Webb J. K., Flambaum V. V., Curran S. J. 2002. Invited Review at the XXII Physics in Collision Conference (PIC02) Stanford CA, USA. Preprint astro-ph/0209488

Okun L. B., 1998, Physics-Uspeki 41, 553

Varshalovich D. A., Potekhin A. Y., Ivanchik A. V., 2000. Comments At. Mol. Phys. (to appear) Preprint physics/0004068

Webb J. K., Murphy M. T., Flambaum V. V. et al., 2002, Invited talk presented at JENAM 2002 workshop on the Cosmology of extra dimensions and varying fundamental constants, to appear in the proceedings. Preprint astro-ph/0210531

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