High-Precision Measurements of $\Delta \alpha/\alpha$ from QSO Absorption Spectra

Sergei A. Levshakov\textsuperscript{1}, Paolo Molaro\textsuperscript{2}, Sebastian Lopez\textsuperscript{3}, Sandro D’Odorico\textsuperscript{4}, Miriam Centurión\textsuperscript{2}, Piercarlo Bonifacio\textsuperscript{2,5}, Irina I. Agafonova\textsuperscript{1}, and Dieter Reimers\textsuperscript{6}

\textsuperscript{1} Department of Theoretical Astrophysics, Ioffe Physico-Technical Institute, Politekhnicheskaya Str. 26, 194021 St. Petersburg, Russia
\textsuperscript{2} Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy
\textsuperscript{3} Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
\textsuperscript{4} European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany
\textsuperscript{5} Observatoire de Paris 61, avenue de l’Observatoire, 75014 Paris, France
\textsuperscript{6} Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany

Summary. Precise radial velocity measurements ($\delta v/c \sim 10^{-7}$) of Fe\textsc{ii} lines in damped Ly$\alpha$ systems from very high quality VLT/UVES spectra of quasars HE 0515–4414 and Q 1101–264 are used to probe cosmological time dependence of the fine structure constant, $\alpha$. It is found that between two redshifts $z_1 = 1.15$ and $z_2 = 1.84$ the value of $\Delta \alpha/\alpha$ changes at the level of a few ppm: $(\alpha_{z_2} - \alpha_{z_1})/\alpha_0 = 5.43 \pm 2.52$ ppm. Variations of $\alpha$ can be considered as one of the most reliable method to constrain the dark energy equation of state and improvements on the accuracy of the wavelength calibration of QSO spectra are of great importance.

1 Introduction

The late-time acceleration of the universe discovered from the luminosity distance measurements of high-redshift SNe Ia is now regarded as evidence for the existence of dark energy. In many models, the cosmological evolution of dark energy is accompanied by variations in coupling constants as, e.g., the fine-structure constant $\alpha$ [1]. Since theories predict different behavior of dark energy, from slow-rolling to oscillating, to study its dynamics the coupling constants must be measured with highest accuracy at each redshift.

In order to fulfill this requirement we developed a method called ‘Single Ion Differential $\alpha$ Measurement, SIDAM’ [2, 3, 4, 5]. Based on the measurements of the relative line position of only one element Fe\textsc{ii}, it is free from many systematics which affect other methods, e.g., [6, 7]. It has been shown that SIDAM can provide a sub-ppm precision at a single redshift and that this level of accuracy is mainly caused by systematic errors inherited from the uncertainties of the wavelength scale calibration [5] (ppm stands for parts per million, $10^{-6}$).
Fig. 1. Histograms are the combined Fe\textsc{ii} profiles from the $z = 1.84$ damped Lyα system towards Q 1101–264 [8]. The zero radial velocity is fixed at $z_{\text{abs}} = 1.838911$. The synthetic profiles are over-plotted by the smooth curves. The normalized residuals, $(F_{\text{cal}} - F_{\text{obs}})/\sigma_i$, are shown by dots (horizontal dotted lines restrict the 1σ errors). The dotted vertical lines mark positions of the sub-components. Bold horizontal lines mark pixels used to minimize $\chi^2$. The ranges at $v < -50$ km s$^{-1}$ and at $v \simeq -30$ km s$^{-1}$ in the Fe\textsc{ii} λ2600 profile are blended with weak telluric lines.

In this presentation we consider our recent results [8] with the SIDAM procedure obtained from the analysis of very high resolution (FWHM $\simeq 3.8$ km s$^{-1}$, slit width 0.5 arcsec) and high signal-to-noise (S/N = 100-120 per pixel) spectra of Q 1101–264 ($z_{\text{em}} = 2.15$, $V = 16.0$). The observations were performed at the VLT Kueyen telescope on 21-23 February, 2006 under the ESO programme No. 076.A-0463. The total exposure time was 15.4 hours.

2 Results

The spectroscopic measurability of $\Delta \alpha/\alpha \equiv (\alpha_z - \alpha_0)/\alpha_0$ at redshift $z$ ($\alpha_0$ refers to the $z = 0$ value) is based on the fact that the energy of each line transition depends individually on a change in $\alpha$ [9]. It means that the relative change of the frequency $\omega_0$ due to varying $\alpha$ is proportional to the so-called sensitivity coefficient $Q = q/\omega_0$ [4]. The $q$-values for the resonance UV transitions in Fe\textsc{ii} are taken from [10], and their rest frame wavelengths — from [8, 11].

The value of $\Delta \alpha/\alpha$ can be measured from the relative radial velocity shifts between lines with different sensitivity coefficients. In linear approximation
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Fig. 2. $\chi^2$ as a function of the velocity difference $\Delta v$ between the Fe\,II $\lambda 1608$ and $\lambda 2382/2600$ lines [8]. The number of data points $M = 305$, the number of degrees of freedom $\nu = 257$. The minimum of the curve at $\Delta v = -0.18$ km s$^{-1}$ gives the most probable value of $\Delta \alpha/\alpha = 5.36$ ppm. The 1σ confidence level is determined by $\Delta \chi^2 = 1$ (dashed line) which gives $\sigma_{\Delta v} = 0.08$ km s$^{-1}$ or $\sigma_{\Delta \alpha/\alpha} = 2.38$ ppm.

(|$\Delta \alpha/\alpha| \ll 1$) we have [5]:

$$\frac{\Delta \alpha}{\alpha} = \frac{(v_2 - v_1)}{2c(Q_1 - Q_2)} = \frac{\Delta v}{2c \Delta Q},$$

where index ‘1’ is assigned to the line $\lambda 1608$, and index ‘2’ marks one of the other Fe\,II lines ($\lambda 2382$ or $\lambda 2600$).

The resulting normalized, vacuum-barycentric, and co-added spectra are shown in Fig. 1. Two independent data reduction procedures (1D and 2D) resulted in almost identical co-added spectra. We found a perfect fit of the Fe\,II profiles to a 16-component model (shown by the smooth curves in Fig. 1): the normalized $\chi^2$ per degree of freedom equals $\chi^2_{\nu} = 0.901$ ($\nu = 257$). The computational procedure was the same as in [5]. Since the $Q$ values for the $\lambda 2382$ and $\lambda 2600$ lines are equal, their relative velocity shift, $\Delta v_{2600-2382}$, characterizes the goodness of wavelength calibrations, $\sigma_{\text{scale}}$, of the corresponding echelle orders. We found that the value of $\Delta v_{2600-2382} = 20$ m s$^{-1}$ is comparable with $\sigma_{\text{scale}} \leq 20$ m s$^{-1}$ estimated from the ThAr lines. So, in what follows we consider the $\lambda 2382$ and $\lambda 2600$ lines as having the same radial velocity, and calculate $\Delta v$ between this velocity and that of the line $\lambda 1608$.

The radial velocity shift between the $\lambda 1608$ and $\lambda 2382/2600$ lines was derived by comparing synthetic profiles with their observed profiles and minimizing $\chi^2$. To find the most probable value of $\Delta v$, we fit the absorption lines with a fixed $\Delta v$, changing $\Delta v$ in the interval from $-270$ m s$^{-1}$ to $-90$ m s$^{-1}$ in steps of $10$ m s$^{-1}$ (see Fig. 2). For each $\Delta v$, the strengths of the subcomponents, their broadening parameters and relative velocity positions were allowed to vary in order to optimize the fit and thus minimize $\chi^2(\Delta v)$. The most probable value of $\Delta v$ corresponds to the minimum of the curve $\chi^2(\Delta v)$. 

$$\Delta \alpha \approx \frac{(v_2 - v_1)}{2c(Q_1 - Q_2)} = \frac{\Delta v}{2c \Delta Q},$$

where index ‘1’ is assigned to the line $\lambda 1608$, and index ‘2’ marks one of the other Fe\,II lines ($\lambda 2382$ or $\lambda 2600$).

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In our case it is $-180 \text{ m s}^{-1}$. The 1$\sigma$ confidence interval to this value is given by the condition $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} = 1$ (the horizontal dashed line in Fig. 2. It is seen from the figure that $\sigma_{\Delta v} = 80 \text{ m s}^{-1}$, or $\Delta \alpha/\alpha = 5.36 \pm 2.38 \text{ ppm}$.

We have specifically investigated those systematic effects which could introduce a non-zero difference between the blue and the red lines ($\lambda_{1608}$ and $\lambda_{2382}/2600$, respectively) and thus simulate a variation of $\Delta \alpha/\alpha$ at the ppm level: (1) possible isotopic shifts caused by unknown isotope abundances, (2) effects of the unresolved components, and (3) possible blends. We also compared our previous results [8], where Fe II lines falling in both UVES arms were used, with the present measurements to check up possible shifts caused by different changes of isophote onto the slit during integration and did not reveal any of them. We found that the largest systematic error does not exceed $30 \text{ m s}^{-1}$, i.e. $\sigma_{\Delta \alpha/\alpha, \text{sys}} \leq 0.89 \text{ ppm}$ [8].

We note that the accuracy of $\sigma_{\Delta \alpha/\alpha} = 2.38 \text{ ppm}$ represents a factor of 1.5 improvement with respect to our previous result $\sigma_{\Delta \alpha/\alpha} = 3.8 \text{ ppm}$ [4] obtained from the archive data of lower resolution ($\text{FWHM} \approx 6 \text{ km s}^{-1}$) but the same S/N ratio. Thus the higher spectral resolution is shown to significantly contribute to higher accuracy in the $\Delta \alpha/\alpha$ measurements.

The comparison of $\Delta \alpha/\alpha = -0.07 \pm 0.84 \text{ ppm}$ at $z_1 = 1.15$ towards HE 0515–4414 [5] with the measured quantity $\Delta \alpha/\alpha = 5.36 \pm 2.38 \text{ ppm}$ at $z_2 = 1.84$ shows a tentative change of the value of $\Delta \alpha/\alpha$ between these two redshifts: $(\alpha_{z_2} - \alpha_{z_1})/\alpha_0 = 5.43 \pm 2.52 \text{ ppm}$.

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