CONSTRAINING THE TIME VARIATION OF THE FINE STRUCTURE CONSTANT

The variation of several fundamental constants in physics can be probed by measuring wavelengths of atomic transitions in the high redshift Universe. In particular any possible variation in the electromagnetic fine-structure constant ($\alpha = e^2/\hbar c$) can be detected in the absorption spectra of distant quasars. Using a well defined sample of absorption line systems we derive a 3σ upper limit on the time variation of α of -2.5×10^{-16} yr^{-1} $\leq (\Delta\alpha/\alpha\,\Delta t) \leq +1.2 \times 10^{-16}$ yr^{-1}.

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Most of the successful physical theories rely on the constancy of few fundamental quantities (such as the speed of light *c*, the fine structure constant α, the proton-to-electron mass ratio μ, etc.). However, some of the modern theories of fundamental physics try to unify fundamental interactions. They require the existence of extra "compactified" spatial dimensions and allow for the cosmological evolution of their scale size. As a result, these theories naturally lead to the prediction of cosmological variation of fundamental constants in a four-dimensional sub-space (Uzan 2003 and reference therein). Therefore constraining the possible time variations of these fundamental physical quantities is an important step towards a complete physical theory.

One of these constants is the fine-structure constant α ($=e^2/\hbar c = 1/137.03599976(50)$ on earth), where *e* is the charge of the electron and $\hbar$ the reduced Planck constant). It characterizes the strength of the electromagnetic interaction between charged particles. The time evolution of α can be probed in the framework of standard Big-Bang models using measurements performed at different redshifts (*z*). One has to measure a quantity that is sensitive to a change in α in the remote universe and to compare to its value on Earth. The strongest constraint on α comes from the Oklo phenomenon, a natural fission reactor that operated 2 Gyrs ago, corresponding to $z \sim 0.16$ (Fujii et al. 2000). By studying the products of nuclear reactions that occurred then it is possible to constrain

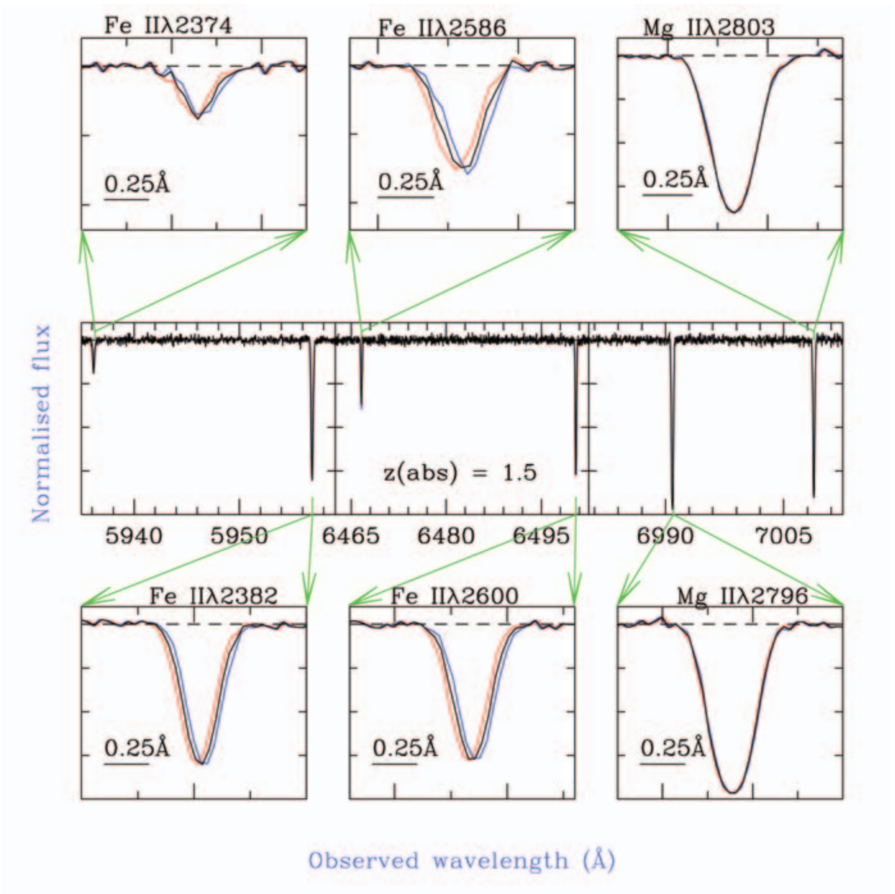

Figure 1: The figure shows a simulated spectrum of the Fe II multiplet and Mg II doublet produced by an absorbing cloud at $z_{abs}= 1.5$ for $\Delta\alpha/\alpha = 0.0$ (black), 5.0×10^{-5} (red) and -5.0×10^{-5} (blue). The zoomed-in views of different absorption lines are shown in the bottom and top panels. It can be seen that Mg ii lines are virtually insensitive to small values of Δα/α, while Fe II lines are very sensitive to these changes. Thus the position of the Mg II lines gives the absorption redshift and the relative positions of the Fe II lines probe the variation in α. This is the main idea behind the MM method. The difficulty in detecting the α variation can be appreciated from the fact that the values of Δα/α, used in this illustration are 10 times larger than the detection claimed by Webb et al. (2003).

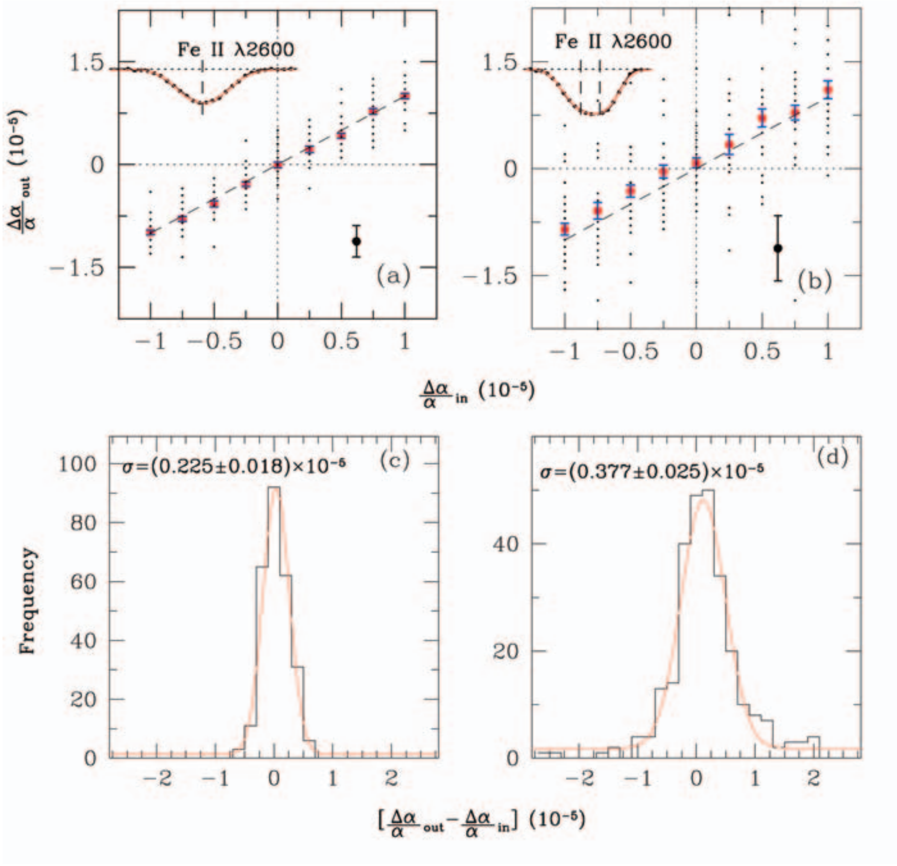

Figure 2: Absorption spectra of Mg II and Fe II are simulated using random values of the column densities, *N*, the Doppler parameter, *b*, and noise, keeping the signal-to-noise ratio, wavelength sampling and spectral resolution as in a typical UVES spectrum. Spectral shifts corresponding to a given value of Δα/α are introduced. Our procedure is applied to the simulated data and the best fitted value of Δα/α is recovered. Top panels show the relationship between the input and derived value of Δα/α in the case of a single clean component (left-hand side) and a blend of two components (right-hand side). A typical absorption profile is also shown in these panels. Dots are the values from individual realizations and the points with the error bars are the weighted mean obtained from 30 realizations. The lower panels give the distribution of the recovered Δα/α around the true one. Best fitted Gaussian distributions are overplotted.

some cross-sections that depend on α. It is found that [Δα/αΔt] = (–0.2 ± 0.8) × 10^{-17} yr^{-1}.

Constraining α with QSO absorption lines

At higher redshifts, the possible time dependence will be registered as small shifts in the absorption line spectra seen toward high redshift QSOs as the energy of the atomic transitions depend on α. One has to disentangle the contributions of the global redshift due to the expansion of the universe and the shift due to the variation in α. To do so one needs at least two transitions with different sensitivity coefficients for the variations in α. As the redshift will be the same for all transitions the relative shift will therefore constrain Δα. Initial attempts to measure the variation of α were based on alkali-doublets (e.g. Varshalovich et al. 1996) such as the well known Si IV doublet. The best constraint obtained using this method is Δα/α = (–0.5 ± 1.3) × 10^{-5} (Murphy et al. 2001). The generalization of this method, called the many-multiplet (MM) method (Dzuba et al. 1999) gives an order of magnitude improvement in the measurement of Δα/α compared to the alkali-doublet method by using not only doublets from the same species but several multiplets from different species (e.g. Webb et al. 2001). The sensitivity to variations in α of different line transitions from different multiplets were computed using many-body calculations taking into account dominant relativistic effects (Dzuba et al. 2002).

In simple terms, the MM method exploits the fact that the energy of different line transitions vary differently for a given change in α. For example rest wavelengths of Mg II λλ2797, 2803 and Mg I λ2852 transitions are fairly insensitive to small changes in α thereby providing a good anchor for measuring the systemic redshift (see Fig. 1). By comparison the rest wavelengths of Fe II multiplets are quite sensitive to small variations in α. Thus, measuring consistent relative shifts between an anchor and different Fe II lines can in principle lead to an accurate measure of Δα. The accuracy at which the variation can be measured depends very much on how well absorption profiles can be modeled. It is usual to use for this Voigt profiles that are convolved with the instrumental profile and characterized by column density (*N*), velocity dispersion (*b*) and redshift (*z*) in addition to the rest-wavelength of the species. In real data small relative shifts can be introduced due to various systematic effects such as inhomogeneities in the absorbing region, poor wavelength calibration, isotopic abundances, and atmospheric dispersion effects, etc. However most of the random systematic effects may be canceled by using a large number of measurements. The MM method applied to a large heterogeneous samples of QSO absorption lines resulted in the claim for a smaller value of α in the past, Δα/α = (–0.574 ± 0.102) × 10^{-5} for 0.2 ≤ z ≤ 3.7 (Murphy et al. 2003).

An ESO-VLT Large Programme

The data used in this new study were obtained with the *Ultra-violet and Visible Echelle Spectrograph* (UVES) mounted on the ESO KUEYEN 8.2-m telescope at the Paranal observatory for the ESO-VLT Large Programme “Cosmological evolution of the Inter Galactic Medium” (PI Jacqueline Bergeron). This programme has been devised to gather a homogeneous sample of echelle spectra of 19 QSOs, with a uniform spectral coverage, resolution and signal-to-noise ratio suitable for studying the intergalactic medium in the redshift range 1.7–4.5. Spectra were obtained in service mode observations spread over four periods (two years) covering 30 nights under good seeing conditions (≤ 0.8 arcsec).

The data were reduced using the UVES pipeline, a set of procedures implemented in a dedicated context of MIDAS, the ESO data reduction package. The main characteristics of the pipeline is to perform a precise inter-order background subtraction for science frames and master flat-fields, and to allow for an optimal extraction of the object signal rejecting cosmic ray impacts and performing sky-subtraction at the same time. The reduction is checked step by step. The extraction slit length is adjusted to optimize the sky-background subtraction. The final accuracy is better than 1%. Addition of individual exposures is performed using a sliding window and weighting the signal by the total errors in each pixel. As the error spectrum is very important for our analysis, great care was taken while combining the error spectra of individual exposures. The wavelength calibration has been carefully checked using the calibration lamp and it is better than δλ/λ ~ 7×10^{-7} rms over the full wavelength

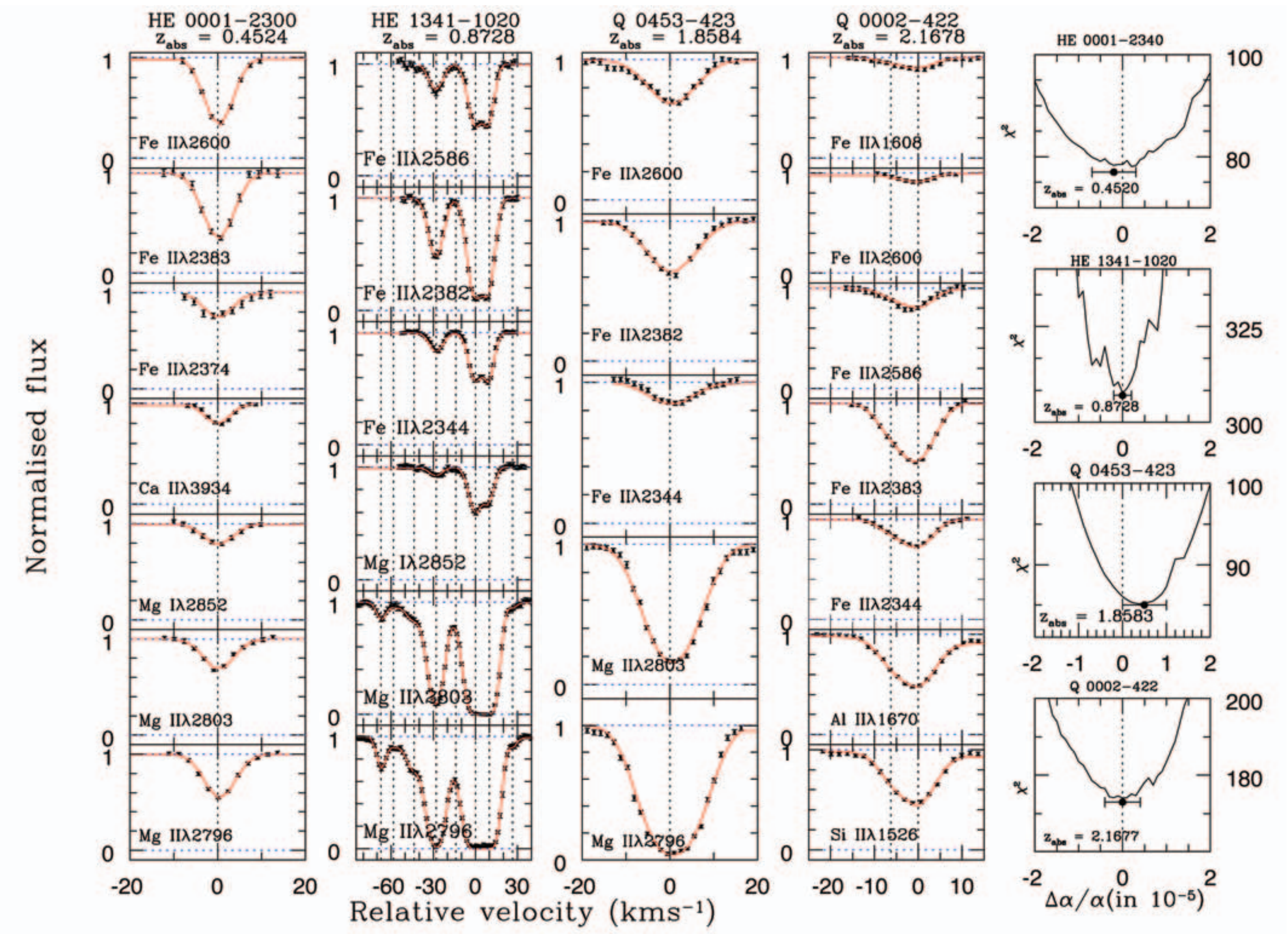

Figure 3: Example of $\Delta\alpha/\alpha$ estimation from real data: Voigt profile fits to 4 randomly chosen systems (out of 23) in our sample are shown in the first 4 columns from the left. The QSO name and absorption redshifts are given on top of the panels. The points with the error bars are the observed data and the continuous curve is the fit obtained using multicomponent Voigt profile decomposition. The locations of different components are marked with vertical dotted lines. The plots in the right most column demonstrate how $\Delta\alpha/\alpha$ is extracted from these systems. We plot χ^2 as the function of $\Delta\alpha/\alpha$. The minimum in this curve (marked with a dot) gives the best fitted value of $\Delta\alpha/\alpha$ and the error in this measurement (error bar around the dot) is based on the standard statistical method of computing errors from $\Delta\chi^2 = 1$.

range of interest, 310–540 and 545–900 nm. Details can be found in Chand et al. (2004) and Aracil et al. (2004). In our analysis we have only used absorption lines that are redshifted beyond the position of the Lyman-α emission line from the quasar. Signal-to-noise ratio of ~40 to 80 per pixel and spectral resolution ≥ 45,000 are achieved over the wavelength range of interest. This is a factor two improvement on signal-to-noise ratio at similar (or slightly higher) resolution compared to data used in earlier studies.

SIMULATIONS

As a first step we performed a detailed analysis on simulated data to have a clearer understanding of various possible systematics that can affect the analysis of real data.

The results of this exercise are used to validate our procedure and define selection criteria that will minimise systematics in our analysis. Absorption spectra of Mg II and Fe II were simulated for given column density, *N*, and Doppler parameter, *b*, at spectral resolution and signal-to-noise ratio similar to our data, introducing spectral shifts corresponding to a given value of $\Delta\alpha/\alpha$. We considered two cases: a simple single component system and a highly blended two-component system. In the highly blended case we restricted the separation between the two components to be always smaller than the velocity dispersion of one of the components. We then fitted the absorption lines in order to recover $\Delta\alpha/\alpha$ introduced in the input spectrum. This exercise allowed us to determine the precision that can be reached using our method and fitting procedure.

We used the Voigt profile fitting method and standard χ^2 statistics to fit the absorption profiles consistently and to determine the best fit value of $\Delta\alpha/\alpha$. The relationships between the input and recovered value of Δa/a are shown in Fig. 2. The method works very well in the case of simple single component systems where one expects minimum uncertainties due to systematics. The deviation of the recovered value with respect to the true one distributes like a Gaussian with $\sigma = 0.21 \times 10^{-5}$. This shows that $\Delta\alpha/\alpha$ can be constrained with an accuracy of 0.06×10^{-5} when we use 10 such systems. In the blended case one can see that a tail in the distribution appears and that the accuracy is less ($\sigma = 0.34 \times 10^{-5}$). Using strongly blended systems may therefore lead to false alarm signals. Based on detailed simulations we come up with selection criteria that will minimise the systematics in our analysis (see Chand et al., 2004 for detail).

FITTING REAL DATA

We illustrate the method in Fig. 3 using 4 randomly chosen systems from our sample. We vary $\Delta\alpha/\alpha$ ranging from -5.0×10^{-5} to 5.0×10^{-5} in step of 0.1×10^{-5}, and each time fit all the lines together. χ^2 minima obtained for each of these fits are plotted as a function of $\Delta\alpha/\alpha$ (right most panel in Fig. 3). The value of $\Delta\alpha/\alpha$ at which this $\Delta\alpha/\alpha$ is minimum is accepted as the measure of the best possible $\Delta\alpha/\alpha$ value. Following standard statistical procedure we assign a 1σ error bar to the best fitted value of $\Delta\alpha/\alpha$ by computing the change in $\Delta\alpha/\alpha$ implying

Srianand R. et al., *Time Variation of the Fine Structure Constant*

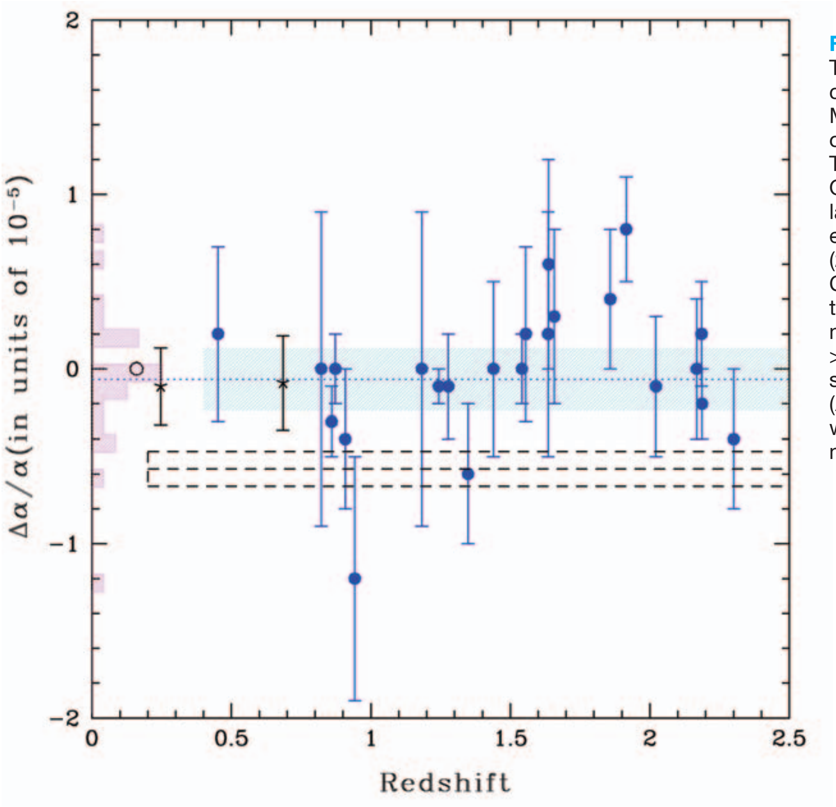

Figure 4: $\Delta\alpha/\alpha$ measurements from the UVES sample: The measured values of $\Delta\alpha/\alpha$ from our sample (filled circles) are plotted against the absorption redshifts of Mg II systems. Each point is the best fitted value obtained for individual systems using χ^2 minimization. The open circle and stars are the measurement from Oklo phenomenon (Fujii et al., 2000) and from molecular lines (Murphy et al., 2001a) respectively. The weighted mean and 1σ range measured by Murphy et al. (2003) are shown with the horizontal long dashed lines. Clearly most of our measurements are inconsistent with this range. The shadow region marks the weighted mean and its 3σ error obtained from our study [$<\Delta\alpha/\alpha>_w = (-0.06 \pm 0.06) \times 10^{-5}$]. Our data gives a 3σ constraint on the variation of $\Delta\alpha/\alpha$ to be $-2.5 \times 10^{-16}\ \mathrm{yr}^{-1} \leq (\Delta\alpha/\alpha\Delta t) \leq 1.2 \times 10^{-16}\ \mathrm{yr}^{-1}$ in the case of a flat universe with $\Omega_\lambda = 0.7$, $\Omega_m = 0.3$ and $H_0 = 68$ km/s/Mpc for the median redshift of 1.55.

$\Delta\chi^2 = \chi^2 - \chi^2_{\mathrm{min}} = 1$. We always consider two different models: (i) one in which the b parameters for all species are the same and (ii) one in which b parameters for different species are different. In all systems we notice that $\Delta\alpha/\alpha$ derived in both cases are consistent with one another within 1σ uncertainty. We use the result with lower reduced χ^2 for our final analysis.

Results obtained for the 23 systems in our sample and that from the literature are summarized in Fig. 4. The shaded region passing through most of the error bars is the weighted mean (with 1/error^2 weights) and its 3σ error from our sample. The histogram in the left hand side of the panel shows the distribution of $\Delta\alpha/\alpha$. It is clear that most of our measurements are consistent with zero within the uncertainties. The simple mean, weighted mean and standard deviation around the mean obtained for our sample are $(-0.02 \pm 0.10) \times 10^{-5}$, $(-0.06 \pm 0.06) \times 10^{-5}$ and 0.41×10^{-5} respectively. The weighted mean value is consistent with all the data points with a reduced $\chi^2 = 0.95$. Thus our study gives a more stringent 3σ constraint of $-0.24 \leq \Delta\alpha/\alpha$ (in 10^{-5}) $\leq +0.12$ over the redshift range of $0.4 \leq z \leq 2.3$. The median redshift of the whole sample is 1.55 which corresponds to a look-back time of 9.7 Gyr in the most favoured cosmological today (see caption of Fig. 4). This gives a 3σ constraint on the time variation of $\Delta\alpha/\alpha$ to be $-2.5 \times 10^{-16} \leq (\Delta\alpha/\alpha\Delta t) \leq 1.2\ 10^{-16}\ \mathrm{yr}^{-1}$. To our knowledge, this is the strongest constraint from QSO absorption line studies till date (Chand et al. 2004, Srianand et al. 2004). In addition, our study does not support the claims by previous authors of a statistically significant change in $\Delta\alpha/\alpha$ with cosmic time at $z > 0.5$.

WHAT'S NEXT?

Even though our study is consistent with no variation in α, it still does allow smaller variations in excess of what is found based on the Oklo phenomenon. Thus it is important to further improve the constraints at higher redshifts. In addition there are some shortcomings of the MM method that need to be avoided. For example, the MM method assumes that all species trace each other perfectly. However, any ionization or chemical inhomogeneity in the absorbing cloud may produce relative shifts between Mg II and Fe II lines at the level expected in the case of small variations in α. Also any peculiar isotopic abundance of Mg can mimic small variations. Thus it is important to perform detailed MM analysis using only multiplets from single species such as Ni II (or Fe II as in Quast et al. 2004) using a well defined high quality sample. It is also demonstrated that OH and other molecular lines can be used to improve limits on the variation in α (see for example Chengalur & Kanekar, 2003). In addition other constants can be constrained in a similar way. Although it is hard to make any quantitative prediction, theorists estimate that variations of the proton-to-electron mass ratio could be larger than that of the fine structure constant by a factor of 10–50. It is possible to constrain this constant by measuring the wavelengths of radiative transitions produced by the hydrogen molecule, H_2. On-going ESO programmes have been dedicated to this purpose (Ledoux et al. 2003, Ivanchik et al. 2002).

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