Revisiting VLT/UVES constraints on a varying fine-structure constant

M. T. Murphy\textsuperscript{1}, J. K. Webb\textsuperscript{2}, and V. V. Flambaum\textsuperscript{2}

\textsuperscript{1} Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK; mim@ast.cam.ac.uk
\textsuperscript{2} School of Physics, University of New South Wales, Sydney, NSW 2052, Australia; jkw@phys.unsw.edu.au, flambaum@phys.unsw.edu.au

Summary. Current analyses of VLT/UVES quasar spectra disagree with the Keck/HIRES evidence for a varying fine-structure constant, \( \alpha \). To investigate this we introduce a simple method for calculating the minimum possible uncertainty on \( \Delta \alpha/\alpha \) for a given quasar absorber. For many absorbers in Chand et al. (2004) and for the single-absorber constraint of Levshakov et al. (2006) the quoted uncertainties are smaller than the minimum allowed by the UVES data. Failure of this basic consistency test prevents reliable comparison of the UVES and HIRES results.

1 Introduction
The ‘many-multiplet’ (MM) method is the most precise technique for constraining cosmological changes in the fine-structure constant, \( \alpha \), from QSO absorption spectra [1]. We have previously described self-consistent MM evidence from 143 Keck/HIRES absorbers for a smaller \( \alpha \) over the redshift range \( 0.2 \leq z_{\text{abs}} \leq 4.2 \) at the fractional level \( \Delta \alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5} \) [2]. Clearly, independent analyses of spectra from different spectrographs are desirable to refute/confirm this. First attempts with VLT/UVES spectra, e.g. [3, 4], generally found null results with quoted uncertainties < \( 0.1 \times 10^{-5} \). To investigate these claims, we introduce a simple method for calculating the minimum possible uncertainty on \( \Delta \alpha/\alpha \) from a given absorption system.

2 A simple measure of the limiting precision on \( \Delta \alpha/\alpha \)
The velocity shift, \( v_j \), of transition \( j \) due to a small relative variation in \( \alpha \), \( \Delta \alpha/\alpha \ll 1 \), is determined by the \( q \)-coefficient for that transition,

\[
\omega_{z,j} \equiv \omega_{0,j} + q_j \left[ (\alpha_z/\alpha_0)^2 - 1 \right] \Rightarrow \frac{v_j}{c} \approx -2 \frac{\Delta \alpha}{\alpha} \frac{q_j}{\omega_{0,j}},
\]

where \( \omega_{0,j} \) & \( \omega_{z,j} \) are the rest-frequencies in the lab and at redshift \( z \), \( \alpha_0 \) is the lab value of \( \alpha \) and \( \alpha_z \) is the shifted value measured from an absorber at \( z \). The MM method is the comparison of measured velocity shifts from several transitions (with different \( q \)-coefficients) to compute the best-fit \( \Delta \alpha/\alpha \). The linear equation (1) implies that the error in \( \Delta \alpha/\alpha \) is determined only by the \( q \)-coefficients (assumed to have negligible errors) and the total velocity uncertainty, integrated over the absorption profile, from each transition, \( \sigma_{v,j} \).
\[ \delta(\Delta \alpha/\alpha)_{\text{lim}} = \sqrt{S/D}, \]  
(2)

for \( S = \sum_j \left( \frac{\sigma_{v,j}}{c} \right)^{-2} \) and \( D = S \sum_j \left( \frac{2q_j}{\omega_0,j} \right)^2 \left( \frac{\sigma_{v,j}}{c} \right)^{-2} - \left[ \sum_j \frac{2q_j}{\omega_0,j} \left( \frac{\sigma_{v,j}}{c} \right)^{-2} \right]^2. \)

This expression is just the solution to a least-squares fit of \( y = a + bx \) to data \((x_i, y_i)\), with errors only on the \( y_i \), where the intercept \( a \) is also allowed to vary; this mimics the real situation in fitting absorption lines where the absorption redshift and \( \Delta \alpha/\alpha \) must be determined simultaneously.

The quantity \( \sigma_{v,j} \) is commonly used in radial-velocity searches for extrasolar planets, e.g. [5], but is not normally useful in QSO absorption-line studies. Most metal-line QSO absorption profiles display a complicated velocity structure and one usually focuses on the properties of individual velocity components, each of which is typically modelled by a Voigt profile. However, it is important to realize that \( \Delta \alpha/\alpha \) and its uncertainty are integrated quantities determined by the entire absorption profile. Thus, \( \sigma_{v,j} \) should incorporate all the velocity-centroiding information available from a given profile shape.

From a spectrum \( F(i) \) with 1-\( \sigma \) error array \( \sigma_F(i) \), the minimum possible velocity uncertainty contributed by pixel \( i \) is given by [5]

\[ \frac{\sigma_v(i)}{c} = \frac{\sigma_F(i)}{\lambda(i) \left| \partial F(i)/\partial \lambda(i) \right|}. \]  
(3)

That is, a more precise velocity measurement is available from those pixels where the flux has a large gradient and/or a small uncertainty. This quantity can be used as an optimal weight, \( W(i) \equiv [\sigma_v(i)/c]^{-2} \), to derive the total velocity precision available from all pixels in a (portion of) spectrum,

\[ \sigma_v = c \left[ \sum_i W(i) \right]^{-1/2}. \]  
(4)

For each transition in an absorber, \( \sigma_{v,j} \) is calculated from (3) & (4); the only requirements are the 1-\( \sigma \) error spectrum and the multi-component Voigt profile fit to the transition’s absorption profile. The latter allows the derivative in (3) to be calculated without the influence of noise. Once \( \sigma_{v,j} \) has been calculated for all transitions, the uncertainty in \( \Delta \alpha/\alpha \) follows from (2).

It is important to realize that the uncertainty calculated with the above method represents the absolute minimum possible 1-\( \sigma \) error on \( \Delta \alpha/\alpha \); the real error – as derived from a simultaneous \( \chi^2 \)-minimization of all parameters comprising the Voigt profile fits to all transitions – will always be larger than \( \delta(\Delta \alpha/\alpha)_{\text{lim}} \) from (2). The main reason for this is that absorption systems usually have several velocity components which have different optical depths in different transitions. Equation (2) assumes that the velocity information integrated over all components in one transition can be combined with the same integrated quantity from another transition to yield an uncertainty on \( \Delta \alpha/\alpha \). However, in a real determination of \( \Delta \alpha/\alpha \), each velocity component (or group of components which define a sharp spectral feature) in one transition is, effectively, compared with only the same component (or group) in another transition. Fig. 1 illustrates this point.
3 Application to existing constraints on $\Delta\alpha/\alpha$

We have calculated $\delta(\Delta\alpha/\alpha)_{\text{lim}}$ for the absorbers from the three independent data-sets which constitute the strongest current constraints on $\Delta\alpha/\alpha$: (i) The 143 absorbers in our Keck/HIRES sample [2]; (ii) The 23 Mg/Fe II systems from UVES studied by [3]; (iii) The UVES exposures of the $z_{\text{abs}} = 1.1508$ absorber towards HE 0515$-4414$ studied by [4]. For sample (ii), the spectra were kindly provided by B. Aracil who confirmed that they have the same wavelength and flux arrays as those used in [3]. The main difference is the error arrays: our error array is generally a factor $\approx 1.4$ smaller than that used by [3] (H. Chand, B. Aracil, 2006, priv. comm.). We have confirmed this by digitizing the absorption profiles plotted in [3]. Thus, $\delta(\Delta\alpha/\alpha)_{\text{lim}}$ calculated using our spectra will be smaller than the value [3] would derive. The continuum normalization will also be slightly different, but this has negligible effects on the analysis here. For sample (iii), the exposures were reduced using a modified version of the UVES pipeline and their $S/N$ matches very well those quoted by [4]. For samples (ii) & (iii) we use the Voigt profile models published in [3] & [4] to calculate $\delta(\Delta\alpha/\alpha)_{\text{lim}}$. For all samples, the atomic data for the transitions (including $q$-coefficients) were the same as used by the original authors. In practice, when applying (3) and (4) we sub-divide the absorption profile of each transition into 15 km s$^{-1}$ chunks to mitigate the effects illustrated in Fig. 1. This provides a value of $\delta(\Delta\alpha/\alpha)_{\text{lim},k}$ for each chunk $k$. The final value of $\delta(\Delta\alpha/\alpha)_{\text{lim}}$ is simply $\left\{ \sum_k 1/\delta(\Delta\alpha/\alpha)_{\text{lim},k}^2 \right\}^{1/2}$; in all cases this is $\leq 1.4$ times the value obtained without sub-divisions.

Figure 2 shows the $1\sigma$ error on $\Delta\alpha/\alpha$ quoted by the original authors versus the limiting precision, $\delta(\Delta\alpha/\alpha)_{\text{lim}}$. The main results are clear. Firstly, the $1\sigma$ errors quoted for the HIRES sample in [2] always exceed $\delta(\Delta\alpha/\alpha)_{\text{lim}}$, as expected if the former are robustly estimated. Secondly, for at least 11 of their 23 absorbers, Chand et al. [3] quote errors which are smaller than $\delta(\Delta\alpha/\alpha)_{\text{lim}}$. Recall that since their error arrays are larger than ours, 11 out of 23 is a conservative estimate. Finally, the very small error quoted by [4] for HE 0515$-4414$, $0.084 \times 10^{-5}$, disagrees significantly with the limiting preci-
4 Murphy et al.

Fig. 2. Quoted errors vs. limiting precision for current samples. The Chand et al. and Levshakov et al. samples fail the basic requirement $\delta(\Delta \alpha/\alpha) > \delta(\Delta \alpha/\alpha)_{\text{lim}}$.

Thus, the (supposedly) strong current UVES constraints on $\Delta \alpha/\alpha$ fail a basic consistency test which not only challenges the precision claimed by [3] and [4] but which must bring into question the robustness and validity of their analysis and final $\Delta \alpha/\alpha$ values.

4 Conclusion

We have introduced a very simple method of determining the limiting precision on $\Delta \alpha/\alpha$ obtainable from a set of transitions in a QSO absorption system, $\delta(\Delta \alpha/\alpha)_{\text{lim}}$. Only the 1-σ error spectrum and the model absorption profile (generally constructed from Voigt profiles) are required to calculate $\delta(\Delta \alpha/\alpha)_{\text{lim}}$. The method simply equates the total velocity information contained in the absorption profile of a transition with the expected error on $\Delta \alpha/\alpha$ via that transition’s sensitivity to $\alpha$-variation. All absorption systems in our HIRES data-set have quoted uncertainties in $\Delta \alpha/\alpha$ which exceed $\delta(\Delta \alpha/\alpha)_{\text{lim}}$, as expected. However, the uncertainties on $\Delta \alpha/\alpha$ currently quoted by [3] and [4] from UVES spectra are, in many cases, smaller than $\delta(\Delta \alpha/\alpha)_{\text{lim}}$. Clearly, the UVES and HIRES results cannot be reliably compared until more rigorous analyses of the UVES spectra are completed.

References

1. J. K. Webb, V. V. Flambaum, C. W. Churchill, M. J. Drinkwater, J. D. Barrow: Phys. Rev. Lett. 82, 884 (1999)
2. M. T. Murphy, V. V. Flambaum, J. K. Webb, V. V. Dzuba, J. X. Prochaska, A. M. Wolfe: Lecture Notes Phys. 648, 131 (2004)
3. H. Chand, R. Srianand, P. Petitjean, B. Aracil: Astron. Astrophys. 417, 853 (2004)
4. S. A. Levshakov, M. Centurión, P. Molaro, S’D’Odorico, D. Reimers, R. Quast, M. Pollmann: Astron. Astrophys. 449, 879 (2006)
5. F. Bouchy, F. Pepe, D. Queloz: Astron. Astrophys. 374, 733 (2001)