Mem. S.A.It. Vol. 85, 63

Memorie della

Bounds on a change in α towards HE 2217-2818*

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Abstract. Intervening absorption systems towards distant QSOs can be used to compare the value of dimensionless fundamental constants such as the fine-structure constant, α of remote regions of the Universe to their present value on Earth. We here report on the stringent bound for $\Delta\alpha/\alpha$ obtained for the absorber at $z_{abs} = 1.6919$ towards HE 2217-2818. The absorption profile is complex and is modeled with 32 velocity components. The relative variation in α in this system is $+1.3 \pm 2.4_{stat} \pm 1.0_{sys}$ ppm (parts per million) derived by means of Al II λ 1670 Å and three Fe II transitions, and $+1.1 \pm 2.6_{stat}$ ppm whith only Fe II transitions. This bound reveals no evidence for variation in α at the 3-ppm precision level (1-σ confidence). At this sky position of the recently-reported dipolar variation of α is (3.2–5.4)$\pm$1.7 ppm. At face value this constraint is not supporting the spatial dipole model but not inconsistent with it at the 3σ level. Beside, asteroid observations revealed the presence of a possible wavelength dependent velocity drift and of inter-order distortions. A systematic error which is a serious obstacle to improve the accuracy of this kind of measurements.

Key words. Cosmology: observations– Quasars: absorption lines

1. Introduction

The standard model of particle physics depend on a number of independent numerical param-

* based on observations obtained with UVES at the the 8.2m Kueyen ESO telescope programme L185.A-0745

eters that determine the strengths of the different forces and the relative masses of all known fundamental particles. There is no theoretical prediction of these values and they are commonly referred to as the fundamental constants of Nature. A variation of the constants, at some level, is a common prediction of most modern extensions of the Standard Model (see Uzan 2003 for a review). The idea that physical constants could vary with time was suggested in the Dirac's "Large Number Hypothesis" (Dirac 1937) and it is currently of interest in the context of cosmologically relevant scalar fields, like quintessence (see **?** for a review). An attractive implication of quintessence models for the dark energy is that the rolling scalar field producing a negative pressure and therefore the acceleration of the universe may couple with other fields and be revealed by a change in the fundamental constants (Amendola et al 2013). Variation of the fundamental constants is foreseen also in other theories beyond the standard model. For instance, in theories involving more than four space-time dimension the constants we observe are merely four-dimensional shadows of the truly fundamental high dimensional constants and they may be seen to vary as the extra dimensions change slowly in size during their cosmological evolution. The fine structure constant $\alpha = e^2/\hbar c$ is dimensionless and governs the coupling between photons and electrons. By solving the Schrödinger equation for the hydrogen atom, the bound states are given by

$$E_n = -\alpha^2 \frac{mc^2}{2n^2} \tag{1}$$

where n is the principal quantum number (n=1,2,...,∞) and α is the above defined fine structure constant (Messiah 1995a, p. 354 eq. 17). When the relativistic corrections are considered the eigenvalues corresponding to angular momentum J and principal quantum number n can be approximated to

$$E_{nJ} = mc^2 \left[1 + \frac{\alpha^2}{(n - \epsilon_J)^2} \right]^{-1/2} \tag{2}$$

where ϵ_J is a function of J and α^2 (Messiah 1995b, p. 802, eq. 179) Whenever we have a fine-structure multiplet, i.e. transitions between energy levels with the same principal quantum number and different J, the relativistic corrections are proportional to α^2, to first order, as can be seen by doing a power series expansion of the term in square brackets in eq. 2.

The simplest case is that of alkali doublets such as Li I, Na I, K I, but also of the alkali ions C IV and Si IV where the splitting of the doublet, i.e. the wavelength separation of the two components is a function of α. By measuring the alkali splitting in gas at redshift z we can measure the value of α at a different instant of space-time. This means we can effectively probe the variations of α over space-time. Earth-based laboratories have so far revealed no variation in their values. For example, the constancy of the fine structure constant stability is ensured to within a few parts per 10^{-17} over a 1 yr period (Rosenband et al. 2008). Hence its status as truly constants is amply justified. Astronomy has a great potential in probing their variability at very large distances and in the early Universe.

The first attempts to measure variation of α using QSO spectra (Savedoff 1956; Bahcall et al. 1967) could only achieve an accuracy of 10^{-2} in $\Delta\alpha/\alpha$.

However, the transition frequencies of the narrow metal absorption lines observed in the spectra of distant from quasars are sensitive to α. Thus the many-multiplet (MM) method has been introduced, which allows all observed transitions to be compared, gaining access to the typically much larger dependence of the ground state energy levels on α (Dzuba et al. 1999). Overall, the MM method improves the sensitivity to the measurement of a variation of α by more than an order of magnitude over the alkali-doublet method.

The change in the rest-frame frequencies between the laboratory, $\omega_i(0)$, and in an absorber at redshift z, $\omega_i(z)$, due to a small variation in α, i.e. $\Delta\alpha/\alpha << 1$, is proportional to a q-coefficient for that transition:

$$\omega_i(z) \equiv \omega_i(0) + q_i \left[(\alpha_z/\alpha_0)^2 - 1 \right], \tag{3}$$

where α_0 and α_z are the laboratory and absorber values of α, respectively (Dzuba et al.

1999). The change in frequency is observable as a velocity shift, Δv_i, of transition i.

$$\frac{\Delta v_i}{c} \approx -2\frac{\Delta\alpha}{\alpha}\frac{q_i}{\omega_i(0)}\,. \qquad (4)$$

The MM method is based on the comparison of measured velocity shifts from several transitions having different q-coefficients to compute the best-fitting $\Delta\alpha/\alpha$.

The MM method and the advent of 8m class telescopes that could provide high resolution spectra of QSOs gave the first hints that the fine structure constant might change its value over time, being lower in the past by about 6 part per million (ppm) (Webb et al 1999, Murphy et al. 2004). With the addition of other 143 VLT-UVES absorbers Webb and collaborators arrived at the surprising conclusion that although on average there is no variation of α there are significant variations along certain directions in the sky. They have found a 4-σ evidence for a dipole-like variation in α across the sky at the 10 ppm level (Webb et al. 2011; King et al. 2012). Several other constraints from higher-quality spectra of individual absorbers exist but none directly support or strongly conflict with the α dipole evidence and a possible systematic producing opposite values in the two hemispheres is not easy to identify.

2. The UVES Large Programme

In 2010 a Large Program of optical observations dedicated to measuring α and μ in distant galaxies was approved by the ESO Observing Programmes Committee. to obtain a high-quality sample of quasar spectra, calibrated specifically for the purpose of constraining variations in α and μ to the ultimate precision allowed by current technology. For the first time the spectra were observed primarily for this purpose, with the explicit aim to keep calibration errors under control

The signal-to-noise ratio of quasar spectra is one of the main factors in the error budget. This, in turn, limits one's ability to track systematic errors. However, by careful selection of targets our Large Program focuses on 12 brightest possible quasars showing a suitable absorber with a relatively large number of absorbers along their sight-lines: 22 in total.

For each absorber we have a high enough signal-to-noise ratio to convincingly detect, model and remove any remaining systematic errors down to the level of few ppm, thereby allowing a convincing detection of any variation in α at the level seen in the Keck spectra (Murphy et al. 2003).

The measurements rely on detecting a pattern of small relative wavelength shifts between different transitions spread throughout the spectrum. Normally, quasar spectra are calibrated by comparison with spectra of a hollow cathode lamp of thorium and Argon which rich in unresolved spectral lines. However, the calibration light traverses a slightly different optical path with respect to the quasar light, so the comparison is not perfect . The Large Program adopts several innovations to ensure that we achieve the ultimate precision available:

- we systematically observed bright asteroids which reflect the sunlight with many spectral features quite well known position. These observations allow to generate a transfer function for correcting the comparison lamp wavelength scale, a technique pioneered by us Molaro et al. (2008a)
- we observed bright stars through an iodine gas absorption cell, as done for extrasolar planet searches, providing an even more precise transfer function for part of the wavelength range.
- we took a series of lamp exposures bracketing the quasar exposures to ensure the best possible starting point for this transfer function.

With the three innovative approaches above, we expect to suppress/remove the systematic errors below the 1 ppm level for individual quasar absorbers.

3. Systematic effects in the wavelength calibration

A major step forward towards the understanding the systematic effects that limit the precision of wavelength calibration has been achieved by the use of a Laser Frequency

Comb (LFC) on the HARPS spectrograph (Wilken et al. 2010; Wilken et al. 2012). These observations were capable of highlighting the presence of tiny differences in the pixel sizes of the CCD detectors, that are due to the manufacturing process. Quite interestingly the list of wavelengths of the Th-Ar lamp normally used to calibrate HARPS (Lovis & Pepe 2007), has the inaccuracies of $\pm 40\,\mathrm{m\,s^{-1}}$ due to the detector, folded in, thus when this line list is used as reference one should expect locally errors of this order of magnitude. No experiment with an LFC has been carried out so far on the spectrographs on 8m class telescopes, such as UVES or HIRES, yet pixel size differences of the same order as those found in HARPS should be expected for these detectors too. Griest et al. (2010) and Whitmore et al. (2010) compared the calibration obtained with the Th-Ar lamp with that obtained from an absorption cell of molecular iodine, for HIRES and UVES, respectively. In both cases they were able to highlight distortions of the wavelength scale with a jig-saw pattern and peak-to-peak amplitude of several hundreds $\mathrm{m\,s^{-1}}$ along the Echelle orders. Although the origin of these distortion is not completely elucidated it is likely due to the inhomogeneity in pixel size of the detectors.

3.1. Solar-asteroid comparison

Comparison of different calibration laboratory sources, like Th-Ar, LFC and I_2 cell helps to better characterize the systematics of our wavelength scale. A complementary and very interesting technique is the use of the spectrum of an astronomical object. This has the advantage that the light follows exactly the same optical path as the scientific target. A very attractive astronomical source for wavelength calibration are asteroids that reflect the solar spectrum, imprinting on it minor signatures, mainly broad and shallow absorptions, and that have radial velocities that are known, from their orbital solution, to an accuracy of a few $\mathrm{m\,s^{-1}}$. To test the accuracy of our wavelength scale one possibility is compare the measured line positions in an asteroid spectrum with those from a solar atlas obtained with a different instrument. A frequently used solar atlas for this purpose is the Kurucz solar flux spectrum (Kurucz 2005)[1]. The wavelength scale of this atlas is corrected for the gravitational redshift (~ 0.63 $\mathrm{km\,s^{-1}}$). The claimed accuracy of the absolute wavelength scale is $\sim$ 100 $\mathrm{ms^{-1}}$ (Kurucz 2005), although this should be taken as an average value, since comparison of individual lines with synthetic spectra computed from hydrodynamical models of the stellar photosphere, that take into account the convective shifts, may show deviations as large as several hundreds $\mathrm{m\,s^{-1}}$ (see e.g. Caffau et al. 2008).

Following this approach Molaro et al. (2008) compared the positions of individual lines measured in the spectra of asteroids and in the solar atlas. This is not possible in the near ultra-violet, where the line blending in the solar spectrum is so high that positions of individual lines cannot be measured. An alternative way to perform this comparison has been explored by our group in Rahmani et al (2013) where we cross-correlated the spectra of asteroids, corrected for their radial velocity, observed with UVES over several years with the solar atlas. This technique allows to highlight the presence of wavelength-dependent velocity offsets between the asteroid spectrum and the solar atlas. We reproduce in Fig. 1 the results of Rahmani et al (2013), where different spectra of the same asteroid observed at a different epoch are shown as different symbols. It is clear from the figure that the offsets increase with wavelength, but the slope is not the same at all epochs, being larger for the asteroids observed in 2012.

From our point of view it is important to asses what is the effect of these offsets on a measurement of the variation of a constant assuming that the offsets seen in the asteroid spectra are the same in the QSO spectra. It is thus crucial to detect and remove such offsets before analysing the QSO data, to avoid spurious detections.

Molaro et al. (2011) and Whitmore et al. (2013) compared solar features observed both with HARPS and UVES and found such 'intra-order distortions' in the UVES spectrum. In

[1] `http://kurucz.harvard.edu/sun/fluxatlas2005`

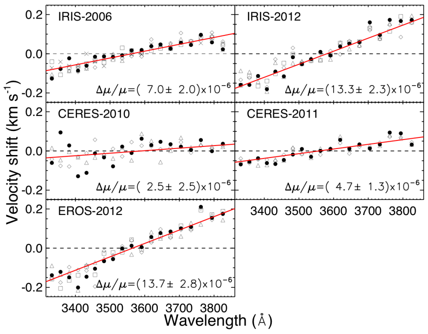

Fig. 1. The velocity shift measurements using cross-correlation analysis between solar and asteroids spectra. The solid line in each panel shows the fitted line to the velocities. The $\Delta\mu/\mu$ corresponding to the slope of the fitted straight line is also shown to provide a figure of the inpact of such drifts in the evaluation of the proton-to-electron mass ratio. Figure reproduced from Rahmani et al (2013), with permission

HARPS the offsets were measured up to 50 m s^{-1}within one order and in UVES, where the pixel size is a factor of three larger, the offsets are found a factor of three larger.

4. $\Delta\alpha/\alpha$ towards HE 2217−2818

The first result of our Large Programme is the analysis of $\Delta\alpha/\alpha$in the absorption systems towards HE 2217−2818 (Molaro et al 2013). Of the five potentially useful absorption system the one at $z_{\rm abs}$ = 1.6919 provides a tight bound on $\Delta\alpha/\alpha$. In spite of the fact that the system is complex, constituted of several sub-components that span about 250 km s^{-1}, each sub-component is narrow enough to allow a precise determination of its wavelength. A matter of concern are the telluric absorptions, that are imprinted on the spectrum and can seriously affect the intergalactic absorptions. The telluric lines were identified with the help of the spectrum of a hot, fast rotating star. No attempt was made to remove them and two different approaches were adopted. In the first case we did not consider in the analysis any intergalactic absorption affected by telluric, in the second case the portion of the spectra affected were masked and not considered in the analysis. In Fig.2, reproduced from Molaro et al (2013), the six "clean" lines that are used in the first case are shown together with the best fitting (in the χ^2 sense) model. The best fitting model shown includes as many as 32 sub-components for each transition. The number of necessary components was determined by iteratively fitting the profiles with an increasing number of components, until a reduced $\chi^2_\nu \approx 1.$ was obtained. The best-fit provides $\Delta\alpha/\alpha$= +1.3 ± 2.4$_{stat}$ ± 1.0$_{sys}$ ppm

In the second approach, in which a larger number of transitions is considered, acceptable fits can be obtained with thirty components. It is reassuring that the two approaches yield results consistent, within our estimated statistical error, supporting the robustness of the analysis: $\Delta\alpha/\alpha = -3.8 \pm 2.1_{\rm stat}$ ppm for the second approach.

One matter of concern is the use of different ions, given that ionization effects may introduce a systematic effect in the $\Delta\alpha/\alpha$ measurements (e.g. Levshakov et al. 2005). In this system we can use as many as six Fe II transitions, which have different q coefficients making it feasible to perform an analysis of $\Delta\alpha/\alpha$ based only on this ion only. Within the second approach this leads to $\Delta\alpha/\alpha = +1.14 \pm 2.58_{\rm stat}$ ppm, which is, again, statistically consistent with the other two analysis.

5. Implications for the spatial dipole in $\Delta\alpha/\alpha$

Our results are consistent with no variation in α along the line of sight to HE 2217−2818, the system at z_{abs} = 1.6919 with a very stringent bound. All the other five systems at lower redshift are consistent with this conclusion but much less stringent. It is interesting to compare this null result with the prediction of the dipole model for the spatial variation of $\Delta\alpha/\alpha$. We consider the model proposed by King et al. (2012), that stems from the analysis of nearly 200 measurements obtained both with UVES at VLT and HIRES at Keck. The combined data, at an approximate mean redshift ≥1.8, suggests a spatial variation of $\Delta\alpha/\alpha$ that can be described by the sum of a monopole and a dipole in the direction with equatorial coordinates $17.3h \pm 1.0h$, $-61^\circ \pm 10^\circ$ (King

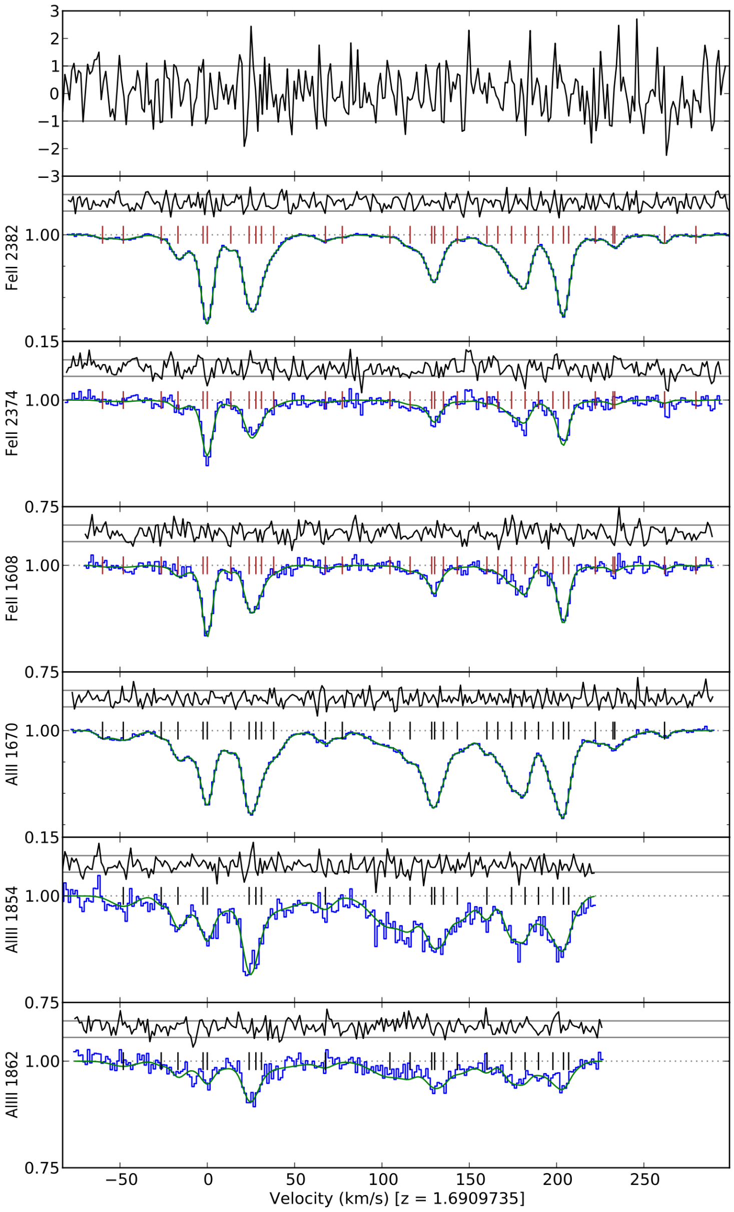

Fig. 2. Transitions in absorption system at $z_{\rm abs} = 1.6919$ used to derive $\Delta\alpha/\alpha$ in our second analysis approach. The Voigt profile model (green line) is plotted over the data (blue histogram). The velocity of each fitted component is marked with a vertical line and the residuals between the data and model, normalised by the error spectrum, are shown above each transition. The top panel shows the composite residual spectrum – the mean spectrum of the normalised residuals for all transitions shown – in units of σ. Reproduced from Molaro et al (2013) with permission, ©ESO

et al. 2012). This can also be described by a simpler model, with only the dipole term in the direction $17.4h \pm 0.9h$, $-58° \pm 9°$ (King et al. 2012). For the line of sight towards HE 2217−2818 the simple dipole-only model predicts $\Delta\alpha/\alpha = +5.4 \pm 1.7$ ppm. Thus our measurement differs from the simple dipole prediction by $1.3\,\sigma$. The corresponding prediction for the monopole plus dipole model is $\Delta\alpha/\alpha = +3.2 \pm 1.7$ ppm. Our null result does not support the existence of the dipole, yet it is not stringent enough to rule it out.

The analysis of the other absorption systems towards the remaining lines of sight is in progress. With the first analysis we have confirmed the importance of accurate observational strategy targeted to minimize the systematics. In particular the use of the solar spectrum obtained by regular asteroid observations proved to be crucial to check the wavelength accuracy of the UVES spectrograph. This analysis revealed a systematic in the UVES wavelength scale with intra-order distortions which may have an impact into a possible signal in the variability of α and μ. A full characterization of these distortions is required in order to make a significant advance in the accuracy of these measurements.

Acknowledgements. CJM is supported by an FCT Research Professorship, contract reference IF/00064/2012.

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