Fundamental constants and high resolution spectroscopy

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Absorption-line systems detected in high resolution quasar spectra can be used to compare the value of dimensionless fundamental constants such as the fine-structure constant, $\alpha$, and the proton-to-electron mass ratio, $\mu = m_p/m_e$, as measured in remote regions of the Universe to their value today on Earth. In recent years, some evidence has emerged of small temporal and also spatial variations in $\alpha$ on cosmological scales which may reach a fractional level of $\approx 10$ ppm (parts per million). We are conducting a Large Programme of observations with the Very Large Telescope’s Ultraviolet and Visual Echelle Spectrograph (UVES), and are obtaining high-resolution ($R \approx 6000$) and high signal-to-noise ratio (S/N $\approx 100$) spectra calibrated specifically to study the variations of the fundamental constants. We here provide a general overview of the Large Programme and report on the first results for these two constants, discussed in detail in Molaro et al. and Rahmani et al. A stringent bound for $\Delta \alpha/\alpha$ is obtained for the absorber at $z_{abs} = 1.6919$ towards HE 2217-2818. The absorption profile is complex with several very narrow features, and is modeled with 32 velocity components. The relative variation in $\alpha$ in this system is $+1.3 \pm 2.4_{\text{stat}} \pm 1.0_{\text{sys}}$ ppm if Al ii $\lambda$ 1670 $\AA$ and three Fe ii transitions are used, and $+1.1 \pm 2.6_{\text{stat}}$ ppm in a slightly different analysis with only Fe ii transitions used. This is one of the tightest bounds on $\alpha$-variation from an individual absorber and reveals no evidence for variation in $\alpha$ at the 3-ppm precision level ($1\sigma$ confidence). The expectation at this sky position of the recently-reported dipolar variation of $\alpha$ is $(3.2\pm 5.4)$ $\pm 1.7$ ppm depending on dipole model used and this constraint of $\Delta \alpha/\alpha$ at face value is not supporting this expectation but not inconsistent with it at the 3$\sigma$ level. For the proton-to-electron mass ratio the analysis of the H$_2$ absorption lines of the $z_{abs} \approx 2.4018$ damped Ly$\alpha$ system towards HE 0027-1836 provides $\Delta \mu/\mu = (-7.6 \pm 8.1_{\text{stat}} \pm 6.3_{\text{sys}})$ ppm which is also consistent with a null variation. The cross-correlation analysis between individual exposures taken over three years and comparison with almost simultaneous asteroid observations revealed the presence of a possible wavelength dependent velocity drift as well as of inter-order distortions which probably dominate the systematic error and are a significant obstacle to achieve more accurate measurements.

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1 Introduction

General relativity and the standard model of particle physics depend on a number of independent numerical parameters that determine the strengths of the different forces and the relative masses of all known fundamental particles. There is no theoretical explanation of why they have the values they have but they determine the properties of atoms, cells, stars and the whole Universe. They are commonly referred to as the fundamental constants of Nature, but 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). That physical constants could vary over cosmological time is an idea that has been around ever since Dirac’s “Large Number Hypothesis” (Dirac 1937). It is currently of great interest in the context of cosmologically relevant scalar fields, like quintessence...
mological evolution. The fine structure constant 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

$$E_n = -\frac{\alpha^2 mc^2}{2n^2},$$  \hspace{1cm} (1)

where \(n\) is the principal quantum number (\(n=1,2,\ldots,\infty\)) and \(\alpha\) 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

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

where \(\epsilon_J\) is a function of \(J\) and \(\alpha^2\) (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 \(\alpha^2\), 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 \(\text{I}\), Na \(\text{I}\), K \(\text{I}\), but also of the alkali ions C \(\text{I}\) \(\text{IV}\) and Si \(\text{I}\) \(\text{IV}\) where the splitting of the doublet, i.e. the wavelength separation of the two components is a function of \(\alpha\). By measuring the alkali splitting in gas at redshift \(z\) we can measure the value of \(\alpha\) at a different instant of space-time. This means we can effectively probe the variations of \(\alpha\) 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\(^{-15}\) 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 \(\alpha\) using QSO spectra (Bahcall et al. 1967; Savedoff 1956) 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 quasars are sensitive to \(\alpha\). 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 \(\alpha\) (Dzuba et al. 1999). Overall, the MM method improves the sensitivity to the measurement of a variation of \(\alpha\) 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 \(\alpha\), i.e. \(\Delta\alpha/\alpha \ll 1\), is proportional to a \(q\)-coefficient for that transition:

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

where \(\alpha_0\) and \(\alpha_z\) are the laboratory and absorber values of \(\alpha\), respectively (Dzuba et al. 1999). The change in frequency is observable as a velocity shift, \(\Delta v_i\), of the \(i\)th transition.

$$\frac{\Delta v_i}{c} \approx -2 \frac{\Delta \alpha}{\alpha} \frac{q_i}{\omega_i(0)}. \hspace{1cm} (4)$$

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 \(\alpha\) there are significant variations along certain directions in the sky. They have found a 4-\(\sigma\) evidence for a dipole-like variation in \(\alpha\) across the sky at the 10 ppm level (Webb et al. 2011; King et al. 2012). Several other constraints from high-quality spectra of individual absorbers exist (Chand et al. 2006; Levshakov et al. 2007) but none directly support or strongly conflict with the \(\alpha\) dipole evidence and a possible systematic producing opposite values in the two hemispheres is not easy to identify.

The proton-to-electron mass ratio, \(\mu\), is also a dimensionless constant which can be probed experimentally. It is known that the wavelengths of the rovibronic molecular transitions are sensitive to \(\mu\). In a diatomic molecule the energy of the rotational transitions is proportional to the reduced mass of the molecule, \(M\), and that of vibrational transitions is proportional to \(\sqrt{M}\), in the first order approximation. The frequency of the rovibronic transitions in Born-Oppenheimer approximation can be written as

$$\nu = \nu_{\text{elec}} + \nu_{\text{vib}}/\sqrt{\mu} + \nu_{\text{rot}}/\mu$$ \hspace{1cm} (5)

where \(\nu_{\text{elec}}, \nu_{\text{vib}},\) and \(\nu_{\text{rot}}\) are some numerical coefficients related, respectively, to electronic, vibrational and rotational transitions. Therefore, by comparing the wavelength of the molecular transitions detected in quasar spectra with their laboratory values one can measure the variation in \(\mu\) (i.e. \(\Delta \mu/\mu \equiv (\mu_z - \mu_0)/\mu_0\) where \(\mu_z\) and \(\mu_0\) are the values of proton-to-electron mass ratio at redshift \(z\) and today) over...
cosmological time scales. Using intervening molecular absorption lines seen in the high-z quasar spectra for measuring $\Delta \mu/\mu$ in the distant universe was first proposed by Thompson (1975). As H$_2$ is the most abundant molecule its Lyman and Werner absorption lines seen in the quasar absorption spectra have been frequently used to constrain the variation of $\mu$. However, H$_2$ molecules are detected in only a few percent of the high redshift damped Lyman-alpha (DLA) systems (Srianand et al. 2012) with only a handful of them being suitable for probing the variation of $\mu$.

If $\mu$ varies, the observed wavelengths of different H$_2$ lines will shift differently with respect to their expected wavelengths based on laboratory measurements and the absorption redshift. The sensitivity of the wavelength of the i’th H$_2$ transition to the variation of $\mu$ is generally parametrised as

$$\lambda_i = \lambda_0^i (1 + z_{abs}) (1 + K_i \frac{\Delta \mu}{\mu}),$$

(6)

where $\lambda_0^i$ is the rest frame wavelength of the transition, $\lambda_i$ is the observed wavelength, $K_i$ is the sensitivity coefficient of i’th transition, and $z_{abs}$ is the redshift of the H$_2$ absorber. Alternatively Eq. [6] can be written as

$$z_i = z_{abs} + CK_i, \quad C = (1 + z_{abs}) \frac{\Delta \mu}{\mu}$$

(7)

which clearly shows that $z_{abs}$ is only the mean redshift of transitions with $K_i = 0$. Eq. [7] is sometimes presented as

$$z_{red} = \frac{(z_i - z_{abs})}{(1 + z_{abs})} = K_i \frac{\Delta \mu}{\mu}$$

(8)

that shows the value of $\Delta \mu/\mu$ can be determined using a linear regression analysis of reduced redshift ($z_{red}$) vs $K_i$. This method has been frequently used in the literature for constraining the variation of $\mu$ (see Cowie & Songaila 1995; Levshakov et al. 2002, Malec et al. 2010, van Weerdenburg et al. 2011; Varshalovich & Levshakov 1993, Wendt & Molaro 2011b, 2012). However, at present measurements of $\Delta \mu/\mu$ using H$_2$ is limited to 6 H$_2$-bearing DLAs at $z \geq 2$. All of these analyses suggest that $|\Delta \mu/\mu| \leq 10^{-5}$ at $2 \leq z \leq 3$. The best reported constraints based on a single system being $\Delta \mu/\mu = (0.3 \pm 3.7) \times 10^{-6}$ reported by King et al. (2011) towards Q 0528–250. Among the developments in the field since then we must signal a number of high precision measurements of $\Delta \mu/\mu$ both using UV lines (Malec et al. 2010, van Weerdenburg et al. 2011, Wendt & Molaro 2011b, 2012).

At $z \leq 1.0$ a stringent constraint on $\Delta \mu/\mu$ is obtained using inversion transitions of NH$_3$ and rotational molecular transitions (Henkel et al. 2009, Kanekar 2011, Murphy et al. 2008). The best reported limit using this technique is $\Delta \mu/\mu = -(3.5 \pm 1.2) \times 10^{-7}$ (Kanekar 2011). Bagdonaite et al. (2013) obtained the strongest constraint to date of $\Delta \mu/\mu = (0.0 \pm 1.0) \times 10^{-7}$ at $z = 0.89$ using methanol transitions. In the Galaxy stringent bounds have been obtained in the millimetre and sub-millimetre domain by (Levshakov et al. 2010a,b,c).

However, $\Delta \mu/\mu$ measurements using NH$_3$ and CH$_3$OH are restricted to only two specific systems at $z \leq 1$. Alternatively one can place good constraints using 21-cm absorption in conjunction with metal lines and assuming all other constants have not changed. Rahmani et al. (2012) have obtained $\Delta \mu/\mu = (0.0 \pm 1.50) \times 10^{-6}$ using a well selected sample of four 21-cm absorbers at $z_{abs} \sim 1.3$. Srianand et al. (2010) have obtained $\Delta \mu/\mu = (-1.7 \pm 1.7) \times 10^{-6}$ at $z \sim 3.17$ using the 21-cm absorber towards J1337+3152. However, one of the main systematic uncertainties in this method comes from how one associates 21-cm and optical absorption components.

An ESO Large Programme (LP) has been undertaken in the last four semesters to address the case of constant variability. We shall here briefly describe the programme, and show some of its first results.

### 2 The UVES Large Programme

The main drawback of the sample assembled by Webb et al. (2011) is that the observations where mainly acquired with scientific objectives other than the measurement of $\Delta \alpha/\alpha$ thus systematic errors are not monitored and minimised. In 2010 our Large Program of optical observations dedicated to measuring $\alpha$ and $\mu$ in distant galaxies was approved by the ESO Observing Programmes Committee. The Large Program was granted 42 nights beginning mid 2010 at UVES at the ESO VLT to obtain a high-quality sample of quasar spectra, calibrated specifically for the purpose of constraining variations in $\alpha$ and $\mu$ 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 fundamental physical questions being addressed demand a level of rigour in quasar absorption studies well beyond the norm previously adopted.

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
– 15 among the brightest known quasars showing a suitable absorber
– a relatively large number of absorbers along their sightlines: 22 in total.

The coordinates and magnitude of the target QSOs are given in Table 1. This means we have observed each absorber for more than three nights on average, which allowed us to build for many absorbers a much higher signal-to-noise ratio than achieved in all previous studies except the two “test case” absorbers studied in Molaro et al. (2008b). In these cases the photon statistical noise was reduced well below that from systematic errors. Our Large Programme achieved this for all relevant absorbers. 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 $\alpha$ 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 (normally thorium) rich in unresolved spectral lines. These observations allow to generate a transfer function for correcting the comparison lamp wavelength scale. This technique was recently 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, important for varying constants;
– we took a series of lamp exposures bracketing the quasar exposures to ensure the best possible starting point for this transfer function.

Previous estimates of wavelength calibration errors in varying measurements are at the 3 - 5 ppm level (Molaro et al. 2008b). With the three innovative approaches above, we expect to suppress/remove them below the 1 ppm level for individual quasar absorbers.

### 2.1 Systematic effects in the wavelength calibration

A major step forward towards the understanding of 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, 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 $\pm 40 \text{ m s}^{-1}$ 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 $\text{ m s}^{-1}$ along the echelle orders. Although the origin of these distortion is not completely elucidated it is likely due to a combination of inhomogeneity in pixel size of the detectors and errors in the reference line positions of the Th-Ar lamps.

### 2.2 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 (Zwitter et al. 2007), that reflect the solar spectrum, imprinted 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 $\text{ m s}^{-1}$. To test the accuracy of our wavelength scale one possibility is to 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). The wavelength scale of this atlas is corrected for the gravitational redshift ($\sim 0.63 \text{ km s}^{-1}$). The claimed accuracy of the absolute wavelength scale is $\sim 100 \text{ m} \text{s}^{-1}$ (Kurucz 2005). However, 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 $\text{ m s}^{-1}$ (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 show in Fig. 1 the results of the analysis of [Rahmani et al. (2013)], where different spectra of the same asteroid observed at a different epochs 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 assess the effect of these offsets on a measurement of the variation of a constant, such as $\Delta \alpha / \alpha$ or $\Delta \mu / \mu$, assuming that the offsets seen in the asteroid spectra are the same in the QSO spectra.

In Fig. 1 taken from [Rahmani et al. (2013)], an intrinsic $\Delta \mu / \mu = 0$ is assumed and the H$_2$ lines are assumed to be imprinted on the spectrum, displaying the measured velocity offset. The estimated $\Delta \mu / \mu$, assuming all the velocity differences to be due to a variation in $\mu$ is then given in each panel. It is striking that at least in two cases one would conclude on the existence of a variation in $\mu$ at a level of 4.5 \sigma. 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 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.

3 $\Delta \alpha / \alpha$ 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 and has been presented in [Molaro et al. (2013)]. We refer the reader to that paper for all the details of this analysis, that is here summarized. Of the five potentially useful absorption systems only the one at $z_{abs} = 1.6919$ 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 measured wavelength of 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 the telluric absorptions, two different approaches were adopted to deal with them. In the first case any intergalactic absorption affected by telluric lines was removed from the analysis, 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 $\chi^2$ sense) model. The best fitting model shown includes as many as 32 sub-components for each transition. The number of components was determined by iteratively fitting the profiles with an increasing number of components, until a minimum in the reduced $\chi^2$ was obtained.

The best-fit provides $\Delta \alpha / \alpha = +1.3 \pm 2.4_{\text{stat}} \pm 1.0_{\text{sys}}$ ppm

In the second approach, in which a larger number of transitions is considered, acceptable fits can be obtained with a slightly smaller number of components, thirty, rather than thirty-two. It is nevertheless reassuring that the two approaches yield consistent results, within our estimated statistical error, supporting the robustness of our analysis: $\Delta \alpha / \alpha = -3.8 \pm 2.1_{\text{stat}}$ 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 on this ion only. Within the second approach this leads to $\Delta \alpha / \alpha = +1.14 \pm 2.5_{\text{stat}}$ ppm, which is, again, statistically consistent with the other two analysis.

3.1 Implications for the spatial dipole in $\Delta \alpha / \alpha$

Our results are consistent with no variation in $\alpha$ along the line of sight to HE 2217–2818, the system at $z_{abs} = 1.6919$ with a very stringent bound, but the other five systems at
Fig. 2 Transitions in absorption system at $z_{\text{abs}} = 1.6919$ 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 $\sigma$. Credit: Molaro et al. A&A 555, 68, 2013 reproduced with permission, ©ESO
The normalized residual (i.e., \( \text{[data] - [model]} / [\text{error}] \)) for each fit is also shown in the top of each panel along with the 1σ line. We identify the clean absorption lines by using the letter “C” in the right bottom of these transitions. The vertical ticks mark the positions of fitted contamination. Reproduced from Rahmani et al. (2013), with permission.

The model with two components accounts better for the multi phase nature of the absorbing gas. In this case \( z \) and \( b \) of the two components are forced to be the same for different \( J \)-levels. The best-fit values is \( \Delta \mu/\mu = (-7.6 \pm 8.3_{\text{stat}} \pm 6.3_{\text{sys}}) \) ppm, after correction for the velocity drift. The reduced \( \chi^2 \) is 1.177, that is slightly lower than the corresponding single component fit. The two component model is marginally favored by the statistical indicators with respect to the single component and provides our favoured value for \( \Delta \mu/\mu \).

Our measurement is consistent with a constant \( \mu \) over the last \( \approx 11 \) Gyr within one part in \( 10^5 \). This is consistent with \( \Delta \mu/\mu \) measurements in literature as reported in Table 2. The measurement towards Q0528 – 250 has the smallest estimated error, there is however some concern on this measurement, due to the fact that King et al. (2011) and Noterdaeme et al. (2008) derive molecular hydrogen column densities that differ by a factor of 50. Further investigation of this system is highly desirable. We note that three out of four UVES based measurements show positive values of \( \Delta \mu/\mu \). However, since wavelength dependent drift, as observed by us, could bias \( \Delta \mu/\mu \) measurements towards positive values so this cannot be taken as evidence of variation until the origin of the UVES velocity drifts is fully elucidated.
Table 2  
Selected values of $\Delta \mu/\mu$ from the literature

| $\Delta \mu/\mu$ | Ref. | absorber | $z$    | QSO       |
|-----------------|------|----------|-------|-----------|
| $10^{-6}$       |      |          |       |           |
| 4.3 ± 7.2       | Wendt & Molaro (2012) | H$_2$ | 3.025 | Q0347–383 |
| 0.3 ± 3.2$_{\text{stat}}$ $\pm$ 1.9$_{\text{sys}}$ | King et al. (2011) | H$_2$ and HD | 2.811 | Q0528–250 |
| 8.5 ± 4.2       | van Weerdenburg et al. (2011) | H$_2$ and HD | 2.059 | J2123–005 |
| 10.9 ± 7.1      | King et al. (2008) | H$_2$ | 2.595 | Q0405–443 |
| 3.7 ± 14        | Thompson et al. (2009) | H$_2$ | 2.595 | Q0405–443 |

Fig. 4  Reduced redshift vs the $K_i$ for all the fitted $H_2$ lines. Lines from different $J$-levels are plotted with different symbols. The best fitted linear line for different $J$-levels with the constraint that the slope should be same is also shown. This analysis provides $\Delta \mu/\mu = 20.0 \pm 9.3$ ppm, without any correction for the velocity drift.

5 Conclusions and future prospects

The analysis of the first two lines of sight of the ESO Large Program dedicated to the study of the variability of the fundamental constants provided results which are consistent with a null variation of the fine structure constant $\alpha$ and of the proton-to-electron mass ratio $\mu$. Namely:

$$\Delta \alpha/\alpha = +1.3 \pm 2.4_{\text{stat}} \pm 1.0_{\text{sys}} \text{ ppm}$$

and

$$\Delta \mu/\mu = -7.6 \pm 8.1_{\text{stat}} \pm 6.3_{\text{sys}} \text{ ppm}$$

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 $\alpha$ and $\mu$. A full characterization of these distortions is required in order to make a significant advance in the accuracy of these measurements.
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