**EUROPEAN SOUTHERN OBSERVATORY**

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME LARGE PROGRAMME PERIOD: **85A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title Category: **A–7**

THE UVES LARGE PROGRAM FOR TESTING FUNDAMENTAL PHYSICS

2. Abstract / Total Time Requested

Total Amount of Time: Total Number of Semesters:

Astronomical observations represent a unique way to probe possible cosmological variations of dimensionless constants ($\alpha$, $\mu = m_e/m_p$). A variability of these constants violates Einstein's Equivalence Principle and could be related to the presence of light scalar fields, such as quintessence. The observational status is controversial for both constants and calls for an urgent clarification. Analysis of 143 absorption systems (HIRES-Keck) provided $\Delta\alpha/\alpha = -5.7\pm$ 1.1 ppm, (1 ppm $= 10^{-6}$), whereas 23 systems (UVES-VLT) yielded $\Delta\alpha/\alpha= -6.4\pm$ 3.6 ppm or $\Delta\alpha/\alpha= 0.1\pm$ 1.5 ppm once two deviating systems are excluded from the mean. Measurements of $\mu$ from the same UVES data were used to claim a variability with $\Delta\mu/\mu = -24 \pm 6$ ppm, and no variability with $\Delta\mu/\mu = -2.6 \pm 3.0$ ppm. The measurement of fundamental constants requires very high signal-to-noise and observing procedures beyond what is done in standard observations. Data available so far were generally taken for other purposes and do not have the necessary quality to fully exploit UVES capabilities. Here we are proposing new observations of a selected sample taken with a specifically studied methodology. For the first time, a series of attached calibration frames to each science observation to estimate drifts due to temperature and pressure changes will be implemented. We estimate that an accuracy of $\approx$ 2 ppm for each system (and $\approx$ 0.5 ppm for the mean of a sample with 22 systems) is within reach.

3.

| Run | Period | Instrument | Time | Month | Moon | Seeing | Sky Trans. | Obs.Mode |
|---|---|---|---|---|---|---|---|---|
| A | 85 | UVES | 5n | jun | g | $\leq 0.8''$ | CLR | v |
| B | 85 | UVES | 36h | sep | g | $\leq 0.8''$ | CLR | s |
| C | 86 | UVES | 5n | nov | g | $\leq 0.8''$ | CLR | v |
| D | 86 | UVES | 5n | mar | g | $\leq 0.8''$ | CLR | v |
| E | 87 | UVES | 36h | apr | g | $\leq 0.8''$ | CLR | s |
| F | 87 | UVES | 36h | sep | g | $\leq 0.8''$ | CLR | s |
| G | 88 | UVES | 5n | nov | g | $\leq 0.8''$ | CLR | v |
| H | 88 | UVES | 5n | mar | g | $\leq 0.8''$ | CLR | v |

4. Principal Investigator: MOLARO

4a. Co-investigators:

| | | |
|---|---|---|
| P. | Petitjean | 1361 |
| M. | Murphy | 2009 |
| S. | Levshakov | 1403 |
| D. | Reimers | 1311 |
| A. | Srianand | 1402 |
| S. | Lopez | 1823 |

*Following CoIs moved to the end of the document ...*

5. Description of the proposed programme

A) Scientific Rationale:

**Theoretical motivation**

Over the past few years there has been great interest in the possibility that the Nature's fundamental constants might show temporal variations over cosmological time scales. The Standard Model (SM) of particle physics needs several ($\approx 26$) dimensionless physical constants for the description of the natural world, and some of these are directly related to the strength of fundamental forces. Among them the fine-structure constant, $\alpha = e^2/\hbar c$, and the electron-to-proton mass ratio, $\mu = m_e/m_p$, are of particular interest for astronomy since they can be measured accurately by observations of intervening absorption systems towards distant QSOs. The fine structure constant $\alpha$ is related to the strength of the electromagnetic force; $m_e$ is related to the vacuum expectation value of the Higgs field, namely the scale of the weak nuclear force, and $m_p$ is related to the Quantum Chromodynamics energy scale or the strong nuclear force. Therefore, $\mu$ is related to the ratio between weak and strong nuclear forces.

A variability of the coupling constants is not foreseen in the Standard Model but appears naturally in fundamental theories like string theory and supergravity, as well as in more phenomenological approaches such as quintessence models for Dark Energy. However, these theories have no predictive power and the issue is purely experimental. Varying constants could provide insights into the existence of scalar fields and the nature of dark energy (Martins 2007). A precise detection of the variability of a constant could be used for reconstructing the quintessence potential and the equation of state of Dark Energy, providing a breakthrough in cosmology (Avelino et al 2006). However, also a stringent limit on the absence of a variability is used to constrain theories and to limit the strength of the coupling between quintessence and ordinary matter (Garcia-Berro et al. 2007). GUT theories provide predictions on how $\alpha$ and $\mu$ should vary and the simultaneous measurement of their variations would give important information on different Grand Unification scenarios.

Recent laboratory experiments with atomic clocks improved by two orders of magnitude previous limits on changes in $\alpha$ of $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}$ yr$^{-1}$ (Rosenband et al 2008). If we make a linear extrapolation of this limit at a lookback time of 10 Gyr (or z$\approx$ 1.8) we obtain $\Delta\alpha/\alpha = -0.16 \pm 0.23$ ppm, which contrasts with the astronomical claim of a variability at the level of $\approx$ -6 ppm (Murphy et al 2004, see below). Thus, if present, the temporal variation needs to be non linear. In some theories a damping of the temporal variation is expected when entering into the dark energy dominated era, i.e for z$\leq$ 1. This rather complicated pattern has to be firmly established by accurate astronomical observations at different redshifts and cannot rely on average values obtained from large samples. At present the best laboratory limit for $\mu$ is $\dot{\mu}/\mu = (1.6 \pm 1.7) \times 10^{-15} yr^{-1}$ from Blatt et al. (2008), and astronomical bounds at high redshift are providing the most stringent bounds to this constant.

**Observational status: the controversy**

At the moment of writing there are claims for a variability of both $\alpha$ and $\mu$ at 5 $\sigma$ and 4 $\sigma$ of confidence respectively, although they are contrasted by null results and the whole issue is highly controversial.

*The $\alpha$ controversy.* Fine structure variability can be probed in the most effective way through the analysis of metal lines of intervening absorption systems observed in the spectra of distant QSOs. The energy levels of high mass nuclei are subject to relativistic corrections which are sensitive to a change in the $\alpha$ value. The sensitivity of each transition to $\alpha$ is expressed in terms of $q$-factors which were carefully calculated for the most frequently observed resonance lines (Dzuba et al 1999, 2002). Thus comparing a minimum of 2 lines with different sensitivities to an $\alpha$ change, it is possible to measure $\Delta\alpha/\alpha$. This measure is purely a measure of the radial velocity difference, $\Delta v$, of two lines with different sensitivity coefficients $\mathcal{Q} = q/\omega_0$, with $\omega_0$ being the rest frequency, and can be written in the form:

$$\frac{\Delta\alpha}{\alpha} = \frac{(v_2 - v_1)}{2\,c\,(\mathcal{Q}_1 - \mathcal{Q}_2)} = \frac{\Delta v}{2\,c\,\Delta\mathcal{Q}} \,. \tag{1}$$

The sensitivity coefficients range between $\mathcal{Q} \approx 0$ for lines which are not sensitive to changes in $\alpha$ and $\mathcal{Q} \approx 0.02$ - 0.05 for the most sensitive ones. Thus to measure a change in $\alpha$ of 1- 3 ppm we need to be able to measure a very small velocity shift of $\approx 30$ m s$^{-1}$, which well illustrates the difficulty of the measurement. The popular Many-Multiplet method applies the concept to the several components of a metal absorption system and to the several multiplets available to maximize the available information. The observational status is summarized in Fig 1 (from Murphy et al 2008). From the measurements of the relative radial velocity shifts between different metal absorption lines (MgII, SiII, FeII, ZnII etc) of 143 QSO absorption systems with redshifts $0.2 < z < 4.2$ Murphy et al (2004) claimed $\Delta\alpha/\alpha = -5.7 \pm 1.1$ ppm. We emphasize that this effort would correspond approximately to about 150 nights of observing time at the Keck telescope, probably one of the major observing programs ever conducted at any 10 m telescope. On the other hand, Chand et al. (2004), Srianand et al (2008) using the data of the Large Program (PI J. Bergeron) on bright QSOs analyzed 23 absorption systems, which are not in common with the Murphy's ones, failed to reproduce Murphy et al.'s result. At first they claimed a very stringent result of $0.6 \pm 0.6$ ppm, but Murphy et al (2008) have convincingly shown that the error estimate of Chand et al 2004 are underestimated by at least a factor of $\approx 3$. When these errors are properly accounted for, the new weighted mean becomes $\Delta\alpha/\alpha = -6.4 \pm 3.6$ ppm. As can be seen in Fig 2, the new values show a scatter

5. Description of the proposed programme (continued)

larger than the quoted errors implying the presence of systematic errors which are comparable or even larger than the statistical ones. However, Srianand et al. (2008) have shown that excluding two systems deviating at the 3 $\sigma$ level in the reanalysis using VPFIT leads to $\Delta\alpha/\alpha = 0.1 \pm 1.5$ ppm. These authors admitted that the errors were underestimated, and it is of at least $> 6$ ppm for individual system. An additional systematic error is also required to explain the scatter, bringing to a total error exceeding 10 ppm. The origin of this additional systematic error is not clear yet, but we argue here that it is likely due to the way UVES data have been acquired (see below).

**What is the UVES limit for an individual absorption system?**

The level at which possible variations are investigated today sets high demands on all steps involved to gain a better understanding of systematics behind the observed transitions. On a concentrated observational effort into the absorption system at $z_{abs} = 1.15$ towards the brightest QSO available, HE 0515–4414 (V=15), Molaro et al (2007) found $\Delta\alpha/\alpha = -0.12 \pm 1.79$ ppm. Three independent analyses agree on this value as it is possible to see from the blue squares of Fig 1 (Chand et al 2004, Levshakov et al 2005, 2006, Chand et al 2006, Molaro et al 2007). We recall here that this result should not be extrapolated at higher redshift, given the possibility of the damping of the $\alpha$ variability at relatively low redshift. A second system at $z = 1.84$ towards Q 1101–264 has provided $\Delta\alpha/\alpha = 5.66 \pm 2.67$ ppm again, with a relatively small error. (Levshakov et al. 2007 A&A 466,1077). We emphasize that the accuracy achieved in these two systems ($\approx$ 2ppm) with large integration times ad hoc observations is comparable to that obtained for much larger samples ($\sigma_\alpha = 1.1$ ppm and 3.6 ppm for 143 and 23 systems, respectively) where the observations were taken for other purposes. These two cases show that the potential for UVES accuracy is around 1-2 ppm, i.e. where photon noise and wavelength accuracy errors are comparable. Based on this experience we ask for new observations with the aim of achieving a similar accuracy also for other 22 systems. The weighted mean of this sample will place new limits or detection at a sub-ppm accuracy.

*The $\mu$ controversy.* Bounds on $\mu$ variations are best obtained from observations of the Werner and Lyman series of the molecular hydrogen in Damped Ly$\alpha$ galaxies (DLA). The electron-vibro-rotational transitions have different dependence from the reduced mass and can be used to constrain a variability of $\mu$. The handful of systems investigated depends on the few absorption systems showing $H_2$ and $z_{abs} \geq 2.5$. This redshift is necessary because the restframe $H_2$ lines are at $\approx 1000$ Å , which makes them falling in the Lyman forest. The measurement of $\mu$ relies on the $H_2$ molecular lines and the same UVES data have been used to claim a variability of $\Delta\mu/\mu = 24 \pm 6$ ppm (Reinhold et al. 2006) or no variability with $\Delta\mu/\mu = 2.6 \pm 3$ ppm (King et al 2008, see also Wendt and Reimers 2008).

**The need for new accurate observations**

Measuring the variability of $\alpha$ or $\mu$ implies the measurement of a tiny variation of the position of one or few lines with respect to other reference lines. It is not much different from revealing exoplanets, but with the limitations that only few lines can be used and QSOs are much fainter than stellar sources. These observations are challenging the instrumental performances of UVES-VLT or HIRES-Keck telescopes. They require excellent wavelength calibration and control of instrumental performances.

*Wavelength Calibration.* The laboratory ThAr lines are known with a precision of 20-100 $ms^{-1}$, which has been recently improved with HARPS to the level of about 10 $ms^{-1}$ (Lovis &Pepe 2007). This will set the ultimate limit in the accuracy and show that the wavelength calibration is the crucial factor, providing we can reach spectra with S/N higher than 100. Calibration frames must be taken immediately before and after the science frame to minimize the influence of changing ambient weather conditions which cause different velocity offsets. The estimations for UVES are of 50 $ms^{-1}$ for $\Delta T = 0.3$ K or a $\Delta P = 1$ mbar (Kaufer et al. 2004), which are rather frequent in Paranal. These thermal-pressure drifts differ in the different cross dispersers thus introducing relative shifts between the different spectral ranges. Moreover, since Dec 2001 UVES has implemented an automatic resetting of the Cross Disperser encoder positions at the start of each exposure ( $www.eso.org/observing/dfo/quality/UVES/pipeline/pipe_reduc.html$, see also the UVES pipeline user manual p. 78). This implementation has been done to have the possibility to use daytime ThAr calibration frames for saving night time. If this is excellent for standard observations, it is not for the measurement of fundamental constants which require the best possible wavelength calibration. We emphasize that this has not been taken into account for all the available archive data of the LP Bergeron used for measuring $\alpha$ variability. To our knowledge only the calibration frames for QSO 1011 -264 were taken close to the QSO frames avoiding automatic resetting (see Levshakov et al 2007). In summary, the calibration frames have been rarely taken close to the science frames and in the attached mode, which prevents from obtaining an accurate measurement from available data. It is very likely that some of the systematic revealed by the recent analysis is due to this problem.

Here we are therefore proposing a new set of observations with several important improvements with respect to the existing observations: a) Several calibration lamps taken immediately after and immediately before the QSO to produce a median image of high S/N free of cosmic events. The time pacing of the calibration images will allow us to track instrumental drifts due to any contributing factor. b) The Calibration lamps of ThAr will be **attached** to the science exposures, i.e. both must be included in the same Observing Block to avoid the automatic resetting of the spectrograph. We will also check out the spectrograph response by means of

5. Description of the proposed programme (continued)

observations of well known asteroids which are ideal radial velocity standards at the level of 1 m $s^{-1}$ (Molaro et al 2007). In particular, when comparing lines which fall in the red and blue two spectral regions of UVES, it is important to check the optical alignment of the two slits since after the dicroic the beam is splitted into two different optical paths. In addition observation of a bright star being taken through the I2 cell would provide a transfer function between the ThAr wavelength scale and the I2 one, and would tell us about the systematics involved with blindly applying the ThAr wavelength scale to an object.

*Spectrograph and CCD configuration.* The precision in the measure of a line position increases with the spectrograph resolving power, until the intrinsic broadening of the metal lines is resolved, the signal-to-noise and with the decreasing size of the pixels ($\Delta\lambda^{3/2}$, see Bohlin et al (1983) for a precise relation). According to this we require a) the highest resolution b) best line sampling along the dispersion direction and c) S/N $\geq$ 100 not to be photon noise limited

All QSO observations from the LP, PI J. Bergeron, used both by Chand et al (2004) and by Murphy et al (2008) as well as data used for $\mu$ analysis by Reinhold et al (2006), Wendt and Reimers (2008), King et al (2008) have been taken with binning 2x2. Thus the data usually used in this field lack the required calibration lamps and the high sampling which are mandatory for this kind of analysis. The 1x1 binning implementation will result a factor sqr of 2 increase in the accuracy compared to the present analysis for a comparable S/N. The High Resolution of **R=60000, slit 0.8 arcsec** will be used to resolve narrow absorption lines ( $\approx$ 4 km $s^{-1}$ ).

B) Immediate Objective: The objective of the LP is to obtain a set of very high quality data to provide the most accurate $\Delta\alpha/\alpha$ measurements to date. The proposed observational strategy contains a series of implementations which considerably reduce the calibration errors and provide a better control of the systematic.

**The sample**. From a careful analysis of the extant samples we selected 11 QSOs as the best targets for this achievement. Two targets are for $\mu$ and 9 targets for $\alpha$. For $\alpha$ we selected 7 QSOs from the Chand et al 2004 sample and two from the Murphy et al Keck/HIRES sample. The selection criteria were: 1) Presence of **multiple absorption systems** along the same line of sight. Along the 9 targets we have a total of 22 absorption systems suitable for $\alpha$ analysis. 2) **Brightness**. The QSOs are the brighest available. 3) **Redshift**. High redshift is preferred given theoretical arguments that suggest that the variability may be larger at higher redshift. In addition a high redshift allows to measure the Fe II 1608 Å. FeII 1608 has a sensitivity to $\alpha$ of opposite sign of the other FeII lines and the comparison of their velocities allows a direct measurement of $\alpha$ free from isotopic systematic. There is an intrinsic uncertainty in the Many-Multiplet method inherent to the assumed isotopic abundances of Mg. Murphy et al (2001) and Ashenfelter et al (2004) have shown that assuming pure $^{24}$Mg (i.e. no $^{25}$Mg) a significant variation would have been obtained also from Chand et al measures. 4) **Simplicity**. Systems with simpler structure to minimize uncertainties due to the profile modelling. The selected systems exhibit very simple line profiles or narrow and resolved components. 5) **Line broadening**. The broadening of the components making the absorption profile needs to be narrow ( $\leq$ 4 km $s^{-1}$ ). 6) **Line saturation**. Systems which show unsaturated lines of Mg II have been preferred.

We are still few years ahead of the implementation of an astronomical Laser Frequency Comb on UVES, which justifies taking new and more careful observations now. These observations will also pave the way for a follow up investigation with next generation of high resolution, high stability spectrographs which may be available at the 16m combined VLT focus, such as ESPRESSO, or to the E-ELT, such as CODEX.

The feasibility of the approach proposed here has been demonstrated by Levshakov et al (2007) where a total error of 2 ppm has been achieved for $\Delta\alpha/\alpha$ in a system towards a 16 mag QSO. Fig 3 shows a small portion of the spectrum of Q 0347-383 resulting from the co-addition of 11 individual spectra taken during the recent run, 19-23 Sep, for comparison with a similar plot given in Fig 5 of King et al. (2008). In spite of the lower signal to noise, the narrow $H_2$ lines are deeper and better resolved, note the relative strength of the $H_2$ and Ly$\alpha$ lines at 4226 $\AA$. This results into a better determination of the line position. Accurate measurement of the position of few lines show that the error is of $\approx$ 2 mÅ while in Thompson et al (2009, cfr their Table 4) the errors are always greater than 4 $m\AA$ (for example our and Thompson errors for some lines are: for 4280.2765 $\pm$ 0.0018 (our) and 0.0042 mÅ (Thompson), for 4284.8965 are $\pm$ 0.0024, and $\pm$ 0.0059, for 4296.4480 $\pm$ 0.0027, and $\pm$ 0.0042, for 4398.096 $\pm$ 0.0023 and $\pm$ 0.0052.

C) Telescope Justification: Only the large collecting power of VLT and the unique capabilities of UVES make possible to reach high S/N together with the required spectral resolution and wavelength coverage for our objects.

D) Observing Mode Justification (visitor or service): We are flexible to ESO wishes for a mix of service and visitor mode. Considering the special calibration plan we prefer visitor, but also service is feasible for a fraction of the program requiring very good seeing and this mode is requested for about 30% of the program.

## 5. Attachments (Figures)

| Instrument | $N_{abs}$ | $z_{abs}$ | $\Delta\alpha/\alpha$ [$10^{-5}$] | Reference |
|---|---|---|---|---|
| HIRES | 30 | 0.5–1.6 | −1.100 ± 0.400 | Webb et al. (1999) |
| HIRES | 49 | 0.5–3.5 | −0.720 ± 0.180 | Murphy et al. (2001a) |
| HIRES | 128 | 0.2–3.7 | −0.543 ± 0.116 | Murphy et al. (2003) |
| HIRES | 143 | 0.2–4.2 | −0.573 ± 0.113 | Murphy et al. (2004) |
| UVES | 23 | 0.4–2.3 | −0.060 ± 0.060 | Chand et al. (2004) |
| UVES | 1 | 1.151 | −0.040 ± 0.190 ± 0.270 | Quast et al. (2004) |
| UVES | 1 | 1.839 | +0.240 ± 0.380 | Levshakov et al. (2005) |
| UVES | 1 | 1.151 | +0.040 ± 0.150 | Levshakov et al. (2005) |
| UVES | 1 | 1.151 | +0.100 ± 0.220 | Chand et al. (2006) |
| HARPS | 1 | 1.151 | +0.050 ± 0.240 | Chand et al. (2006) |
| UVES | 1 | 1.151 | −0.007 ± 0.084 (± 0.100) | Levshakov et al. (2006) |
| UVES | 1 | 1.839 | +0.540 ± 0.250 | Levshakov et al. (2007) |
| UVES | 23 | 0.4–2.3 | −0.640 ± 0.360 | This work |

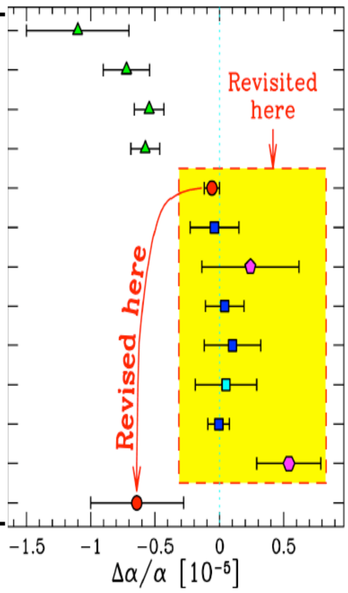



Fig. 1: Summary of all the $\Delta\alpha/\alpha$ from the compilation of Murphy et al (2008). It illustrates the present controversy. The green triangles are the Murphy et al sample with 30, 49, 128 and 143 systems. The red circle is the Chand et al result with 23 systems together with the revision by Murphy et al (2008). The blue squares are HE 0515-4414, the violet pentagons QSO 1101 -264.

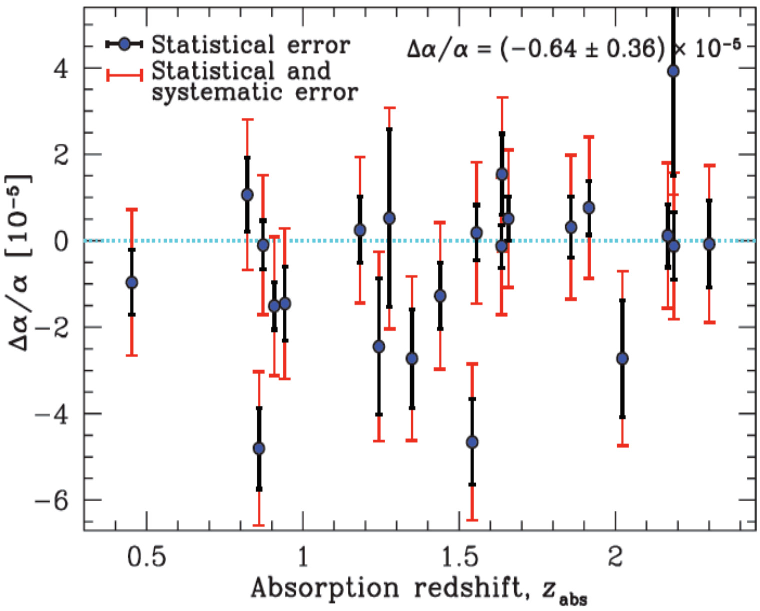
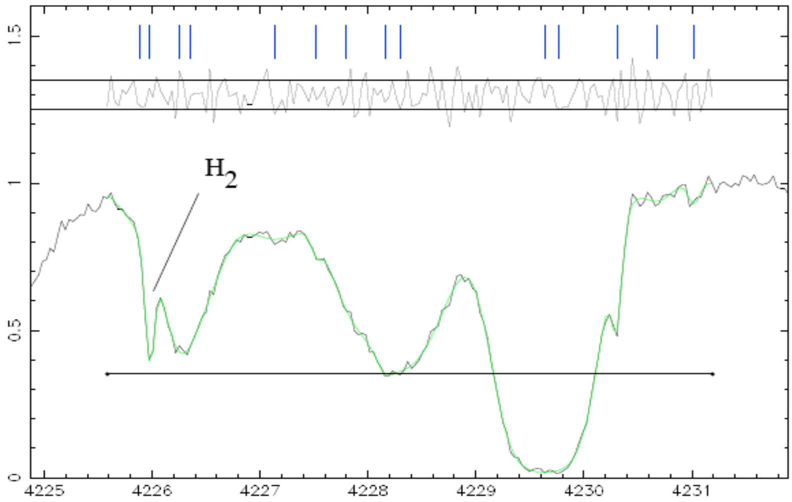



Fig. 2: Murphy et al (2008) re-analysis of the 23 systems of Chand et al. 2004. The weighted mean is $\Delta\alpha/\alpha = -6.4 \pm 3.6$ ppm (see however Srianand et al 2008). The statistical error is of $\geq 6$ ppm for an individual system, but the scatter requires a remaining large systematic error. The total error budget is of about 15 ppm for each system. We are proposing new observations which should provide a total error of 2-3 ppm for each system.

## 5. Attachments (Figures)



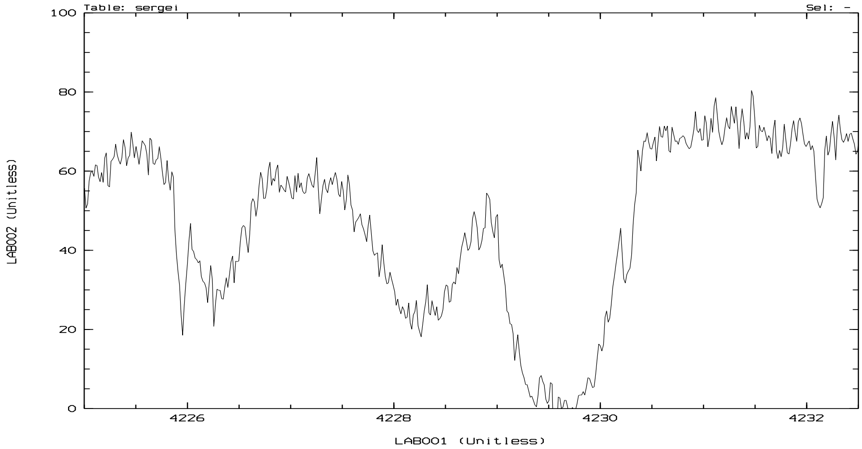




Fig 3. Top panel: Portion of the spectrum of Q 0347-383 from King et al (2008, their Fig 4). Bottom panel: about the same region from the combined spectrum taken in the September 2009 run. In spite of the lower S/N the higher resolution and higher sampling allow a better resolution of the narrow $H_2$ lines. Typical error in line positioning in these lines is estimated in $\approx$ 2 mÅ which has to be compared with the figure of 4-8 mÅ error reported in the recent measurements of Thompson et al (2009), as discussed in the text. We therefore demonstrate that our procedure leads to an improvement by at least a factor of two in the measurement precision thus answering to the OPC concern expressed by the OPC after first submission.


**References** Avelino, P.P. et al. 2006, Phys. Rev. D, 74, 083508; Blatt et al 2008, PhRvL 100, 8101 Bohlin, R.C. et al. 1983, ApJS, 51, 277; Chand, H. et al. 2006, A&A, 451, 45; Chand, H. et al. 2004, A&A, 417, 853; Dzuba, V.A. et al. 1999, Phys. Rev. A, 59, 230; Dzuba, V.A. et al. 2002, Phys. Rev. A, 66, 022501; Garcia-Berro, Isern, J. Kubyshin 2007, AAR 14,113; Kaufer, A. et al. 2004, UV-Visual Echelle Spectrograph. User Manual, p.40; King, L. et al. 2008, arXiv: astro-ph/0807.4366, PRL101,251305 Levshakov, S.A. et al. 2007, A&A, 466, 1077; Levshakov, S.A. et al. 2006, A&A, 449, 879; Levshakov, S.A. et al. 2005, A&A, 434, 827; Lovis, C., & Pepe, F. 2007, A&A, 468, 1115; Martins, C.J.A.P. 2007, arXiv: astro-ph/0610665; Molaro, P. et al. 2008, A&A, 481, 559; Molaro, P. et al. 2007, arXiv: astro-ph/0712.4380; Murphy, M.T. et al. 2008, MNRAS, 384, 1053; Murphy, M.T. et al. 2004, LNP, 648, 131 (astro-ph/0310318); Reinhold, E. et al. 2006, Phys, Rev. Lett., 96, 151101; Rosenband, D.B. et al. 2008, Sciencexpress Report, 6 March, 1; Srianand, R. et al. 2007, Phys. Rev. Lett., 99, 239002; Thompson, R. et al 2009, ApJ 703, 1648 Wendt, M., & Reimers, D. 2008, arXiv: astro-ph/0802.1160

## 6. Experience of the applicants with telescopes, instruments and data reduction

Our team gather together the world most active teams in the observational variability of fundamental constants, often arguing for opposite claims and giving rise to the well known controversy. Thus, the team is highly experienced and with publications relating to all scientific aspects of the proposed research. Murphy et al produced the first hints of variation of the fine structure constant bringing the subject to the attention of the world wide scientific community. Quast et al (2004 A&A 415, L7 ) was the first group to provide some evidence at variance with Murphy et al claim of a variability for $\alpha$ followed closely by Chand et al (2004). Levshakov et al 2007 and Molaro et al 2007 have provided the more stringent bound to $\alpha$ by means of individual absorption systems. Levshakov et al have been the first to use UVES commissioning data to provide a bound to a $\mu$ change by means of $H_2$ molecular lines. We are familiar with the reduction procedure for UVES data but we will adopt our own software, in particular for the process of fitting absorption lines. We are well provided with all required technical facilities.

## 7. Resources available to the team, such as: computing facilities, research assistants, etc.

The wavelength calibration will be performed with spectra keeping their original pixel size in wavelength. For precise measurements it is more appropriate to work with individual exposures in this format. Special care will be adopted to prevent small non-zero offsets between individual exposures which may be smeared out in the co-added spectra obtained with the rebinned individual spectra with the same starting wavelength and step size.

## 8. Special remarks:

This proposal was first submitted in P83. The feedback was: *It was considered very important science by the Cosmology panels and by the OPC. However, it was decided that it is not adequate yet for recommendation as a large programme. The problems associated with the calibration of UVES data can be first addressed with a normal programme.* The program was converted into normal and carried on in 19- 23 Sep 2009. The preliminary results show that indeed the methodology adopted allow to cut down the errors by a factor 2, (cfr Fig 3 and section 5B) with a corresponding increase in the accuracy of the measurements. We stress that this LP will offer a data base of exquisite quality to all groups working in the field of varying constants to ensure a complete and reliable scientific analysis. The different groups have the first opportunity to apply their own techniques onto the same shared set of high quality observations. This comparison will represent a good premise for the solution of the present controversy which we have to provide to the community of physicists given the profound implications of this topic on many aspects of theoretical physics.

## 9. Justification of requested observing time and lunar phase

Lunar Phase Justification: Our targets have $V \approx 17$ which must be observed with resolution $R = 60000$ (narrow slit, 0.8 arcsec). To reach the required S/N $\sim 100$ in the co-added spectrum and with binning 1x1 we need relatively long integrations. Almost dark sky is required.

Time Justification: (including seeing overhead) The estimation of the required nights has been performed with version 3.2.2 of the UVES ETC. We considered average seeing conditions of 0.8 arcsec and a slit width of 0.7 arcsec to achieve a spectral resolution $R = 60000$. For a typical QSO of V=16.6, with one 1.5h exposure we get a S/N $\approx 30$ at $\approx 5000$ $\mathring{A}$ where several crucial lines fall. According to the Bohlin et al formula and as also shown by the measurements reported in Fig 3 of this proposal this S/N is providing a precision in line position of $\approx 120$ m/s . Thus we need to obtain a S/N of 120 to have an error in the line positioning of $\approx 30$ m/s, which corresponds to the best wavelength calibration available. With such a high signal-to-noise we are limited by the wavelength calibration and not by photon noise. Therefore, we need about 16 such exposures, or about 24 hours, for our typical magnitude QSO. We need a series attached ThAr to bracket the observations. Overheads are of 5.25 minutes for each exposure and about 3 hours in total per target. Together with the attached calibrations, we estimate a total of $\sim$ 27h, (or about 3 nights) for target. For the two fainter objects of the sample (17.3 and 17.6), about 7 nights each will be necessary to reach an acceptable S/N, which is anyway below the desirable. The setting is DIC-2 437+760 for systems with z$\approx$ 2, and DIC-2 390+580 for systems with lower redshift, sometimes both settings are required according to the absorption systems of the QSO. The total program is thus estimated in (9x3) + (2x7)= 41 nights in total, of which 4 already obtained in P83, so that the request is for 37 over 4 Periods. At twilight we plan to observe bright asteroids (9-11 mag) to monitor the radial velocity accuracy of UVES and the optical alignment into the two arm slits. In case of poor weather conditions during visitor mode IS will be also used.

## 9b. Convert to a normal programme?

Yes: a minimum of 4 nights in Period 85, RunA

## 10. Report on the use of ESO facilities during the last 2 years

Programme 076.A-0463 (PI Lopez): Results are Levshakov et al (2007) A&A, 466, 1077, Molaro et al (2007 arXiv: astro-ph/0712.4380)). 381.A-0634, PI Petitjean, 4h UVES: Spatial distribution of metals around galaxies in the center of the D4 CFHTLS. data reduced, paper in preparation. 383.A-0272, PI Petitjean, 6h on UVES: Probing early galactic chemical enrichment: the most metal poor Damped Lyman-$\alpha$ system, data reduced. 083.A-0733(A). (PI Molaro) : Measuring Dimensionless Constants with UVES. Observations carried on between 19-23 Sep 2009. Two targets observed. preliminary results discussed in the text and Fig 3.

## 11. Applicant's publications related to the subject of this application during the last 2 years


Levshakov S. A., Molaro P., Lopez, S., D'Odorico S., Bonifacio, P., Agafonova, I. I., & Reimers D. 2007, A&A, 466, 1077 : A new measure of $\Delta\alpha/\alpha$ at redshift $z = 1.84$ from very high resolution spectra of Q 1101–264.

Levshakov, S. A.; Reimers, D.; Kozlov, M. G.; Porsev, S. G.; Molaro, P. A new approach for testing variations of fundamental constants over cosmic epochs using FIR fine-structure lines 2008 A&A 479, 719

Molaro, Paolo; Reimers, Dieter; Agafonova, Irina I.; Levshakov, Sergei A. Bounds on the fine structure constant variability from FeII absorption lines in QSO spectra 2007 ,arXiv07124380

Petitjean, P.; Srianand, R.; Chand, H.; Ivanchik, A.; Noterdaeme, P.; Gupta, N. 2009, Space Science Review, astroph/0905.1516: Constraining Fundamental Constants of Physics with Quasar Absorption Line Systems

Srianand, R.; Chand, H.; Petitjean, P.; Aracil, B. 2007, PhysRevLett.99.239002: In response to the comments by Murphy et al.

King, J.A., Webb, J.K., Murphy, M.T., Carswell, R.F., 2008, Phys. Rev. Lett., 101, 251304: Stringent null constraint on the cosmological evolution of the proton-to-electron mass ratio

Murphy, M.T. et al., 2008, Science, 320, 1611: Strong limit on a variable proton-to-electron mass ratio from molecules in the distant Universe

Murphy, M.T. et al., 2008, MNRAS, 384, 1053: Revision of VLT/UVES constraints on a varying fine-structure constant

Murphy, M.T. et al., 2007, Phys. Rev. Lett., 99, 239001: Comment on "Limits on the Time Variation of the Electromagnetic Fine-Structure Constant...'

Murphy, M.T. et al., 2007, MNRAS, 378, 221: Selection of ThAr lines for wavelength calibration of echelle spectra and implications for variations in the fine-structure constant'

## 12. List of targets proposed in this programme

| Run | Target/Field | $\alpha$(J2000) | $\delta$(J2000) | ToT | Mag. | Diam. | Additional info | Reference star |
|---|---|---|---|---|---|---|---|---|
| A | HE 1347-2457 | 13 50 38.88 | -25 12 16.7 | 20 | 16.3 | | 1.439 | |
| A | HE 2217 -2818 | 22 20 06.77 | -28 03 23.4 | 20 | 16.0 | | 0.94,1.555 | |
| B | HE 0001 -234 | 00 03 45.0 | -23 23 55 | 25 | 16.6 | | 0.45, 2.185, 2.187 | |
| B | Q 0117 +2118 | 01 20 17.26 | 21 33 46.4 | 20 | 16.1 | | 0.72,1.04, 1.32, 1.34, Keck | |
| C | Q 0347-383 | 03 25 27.61 | -43 01 08.8 | 30 | 17.3 | | 3.0, for $\mu$ | |
| D | HE 1341-1020 | 13 44 27.10 | -10 35 42.0 | 30 | 17.1 | | 0.87,1.27,1.91 | |
| E | Q 1213 -0017 | 12 15 49.81 | -00 34 32.2 | 30 | 17.0 | | 1.31, 1.55 | |
| F | PKS 0237-23 | 02 40 08.17 | -23 09 15.73 | 25 | 16.6 | | 1.635, 1.637, 1.65 | |
| F | Q 0405-443 | 04 07 17.99 | -44 10 13.4 | 30 | 17.6 | | 2.4, for $\mu$ | |
| G | Q 0002-422 | 00 04 48.20 | -41 57 28.0 | 30 | 17.4 | | 1.54,2.167, 2.30, Keck | |
| H | Q 1331 +1704 | 13 33 35.78 | +16 49 04.0 | 25 | 16.7 | | 1.77 | |
| B | Q 0453-423 | 04 55 22.90 | -42 16 16.9 | 25 | 17.3 | | 1.85,backup | |
| B | Q 0109-3518 | 01 11 43.60 | -35 03 00.5 | 25 | 16.9 | | 1.18, 1.34, backup | |
| C | Q 0122-380 | 01 24 17.40 | -37 44 22.6 | 25 | 17.1 | | 0.8, 0.85, 1.24, backup | |
| B | HE 0027-1836 | 00 33 23.63 | -18 19 56.0 | 30 | 17.6 | | 2.55, for $\mu$ alternative to 0405-443 | |

Target Notes: The additional info column specifies: the redshift of absorption systems, whether the target is asked for $\mu$ variability, and whether the target is drawn from the Murphy-Keck sample. The strategy is to observe one or two targets for each run in order to be able to complete a measurement. However, observations could be planned onto two or more close runs to optimize the observations according to the general observing conditions. Priorities will be given according to the object brightness. Three QSOs drawn from the Chand et al 2004 sample are taken as backup downwind targets.

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

9 out of the 11 targets have already been observed with UVES but not with the necessary integration time, calibration frames and CCD binning. In particular, the observations have been taken with binning of 2 pixels along the dispersion direction, and often without close TrAr Lamps. When calibration frames were close to the science the automatic resetting of the spectrograph produced a loss of the ambient conditions (T, p) thus introducing a systematics in the radial velocity of the spectrum (cfr UVES user manual Kaufer et al). For $\mu$ the observations of Q0347-383 and Q0405-443 were taken on Jan 7-9 2002 and January 4-6 2003. Calibration spectra were taken each night immediately after or before the object spectra. However, also in this case they were not taken in the attached mode as can be verified checking the Cross Disperser encoder position stored in the header files of the images.

13. Scheduling requirements

14. Instrument configuration

| Period | Instrument | Run ID | Parameter | Value or list |
|---|---|---|---|---|
| 85 | UVES | A | DIC-1 | Standard setting: 390+580 |
| 85 | UVES | A | DIC-2 | Standard setting: 437+760 |
| 85 | UVES | B | DIC-1 | Standard setting: 390+580 |
| 85 | UVES | B | DIC-2 | Standard setting: 437+760 |
| 86 | UVES | C | DIC-2 | Standard setting: 437+760 |
| 86 | UVES | C | DIC-1 | Standard setting: 390+580 |
| 86 | UVES | C | DIC-2 | Standard setting: 437+860 |
| 86 | UVES | D | DIC-2 | Standard setting: 437+760 |
| 87 | UVES | E | DIC-2 | Standard setting: 437+760 |
| 87 | UVES | F | DIC-1 | Standard setting: 390+580 |
| 87 | UVES | F | DIC-2 | Standard setting: 437+760 |
| 87 | UVES | F | DIC-2 | Standard setting: 437+860 |
| 88 | UVES | G | DIC-2 | Standard setting: 437+760 |
| 88 | UVES | G | DIC-1 | Standard setting: 390+580 |
| 88 | UVES | H | DIC-2 | Standard setting: 437+760 |
| 88 | UVES | H | DIC-1 | Standard setting: 390+580 |

4b. Co-investigators:

*...continued from page 1*

| | | |
|---|---|---|
| C. | Martins | 1200 |
| P. | Bonifacio | 1347 |
| M. | Centurión | 1347 |
| M | Wendt | 1311 |
| S. | D'Odorico | 1258 |
| A. | Malec | 2009 |
| G | Vladilo | 1347 |
| S | Monai | 1347 |