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New spectrographs for the VLT and E-ELT suited for the measurement of fundamental constants variability

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Abstract. An ideal instrument to probe fundamental constants such as the fine structure constant and the electron-to-proton mass ratio by means of absorption lines in QSOs spectra is a spectrograph which combine high throughput, high resolution and high stability and is compulsorily attached to a telescope with a large photon collecting area. Both the ESPRESSO proposal for the incoherent combined VLT focus and CODEX for the E-ELT keep these recipes and, although they are not optimized for this purpose, they hold the promise to improve the present limits by about two orders of magnitude. Thus either these physical constants are varying within this range or they would likely escape astronomical detection.

Key words. Cosmology: observations – Cosmology: dark energy – Instruments: spectrographs

1. Introduction

The fundamental dimensionless physical constants cannot be predicted by theory but can only be measured experimentally. And the same for their possible variations. There are several theoretical predictions that coupling constants should change, but unfortunately with little theoretical guidance on the expected rate of change. The role of fundamental constants in the representation of nature and the implications of their variability for the Equivalence Principle and for cosmology have been highlighted in many contributions at this conference (cfr K. Olive and J.P Uzan, these proceedings). In astronomy, the most effective way to measure a variability of the fine structure constant and of the electron-to-proton mass ratio is by means of absorption lines in quasar spectra mainly in the optical range. Radio or sub-millimiter observations are more sporadic and are reviewed in Combes (2009). The ammonia method recently suggested to probe electron-to-proton mass ratio is even more effective but is hampered by the scarcity of sources. Applied to the Milky Way, where ammonia sources are numerous among the dark clouds, this method provides stringent limits and an unexpected detection (Levshakov et al 2009). Measuring the variability of the fine structure constant α or the electron-to-proton ratio μ by means of absorption lines implies the measurement of a tiny variation of the position of one or a few lines compared to other

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reference lines. For the fine structure constant the relation between its change and the doppler velocity shift is:

$$\frac{\Delta\alpha}{\alpha} \approx \frac{\Delta v}{2c}\Delta Q \qquad (1)$$

where Q are the coefficients which describe the relativistic sensitivity of the transition to α change. Q values are theoretically derived by means of Hartree-Fock calculations and typical values are in the of order ≈ 0.02(Dzuba et al 2008). Given these sensitivities, for revealing changes of 1 ppm (one part per million) in α we need to be able to detect relative shifts of about 20 m s^{-1} . A similar relation holds for the Lyman and Werner lines of molecular hydrogen. Their sensitivity to a change of μ are encoded in the K coefficients

$$\frac{\delta\mu}{\mu} \approx \frac{\delta\lambda_i}{\lambda_i}K_i \qquad (2)$$

With the most sensitive K_i coefficients of $\approx$ 0.05 (Thompson et al 2009).

The precision with which the wavelength of a spectral transition can be determined from an absorption line depends on the signal-to-noise of the spectrum, the intrinsic width of the absorption line, the spectrograph resolution and pixel size. The wavelength error decreases with signal-to-noise, with the decreasing intrinsic line width and with increasing spectrograph resolving power until the intrinsic line width is resolved. QSOs are rather faint targets and intervening metal absorbers have intrinsic line widths of few km s^{-1} which explain why high resolution spectrographs and large collecting areas are needed for this purpose. Landman et al. 1982 provided a convenient expression for the wavelength error of a gaussian line:

$$\sigma_0 = \frac{1}{(2\pi \ln 2)^{1/4}}\frac{1}{S/N}\sqrt{\Delta_{\rm pixel}\mathrm{FWHM}}.$$

The real case could be more complex with a line profile consisting of a blend of subcomponents which make errors somewhat larger (Bohlin et al. 1983).

However, in addition to photon noise errors there are those of instrumental origin and those coming from wavelength calibration. These are much more subtle and difficult to quantify and is rather questionable if they can be smaller than 50 m s^{-1} , thus becoming the dominant source of uncertainty for measures of $\delta\alpha/\alpha$ with the ambition to reach 1 ppm level accuracy.

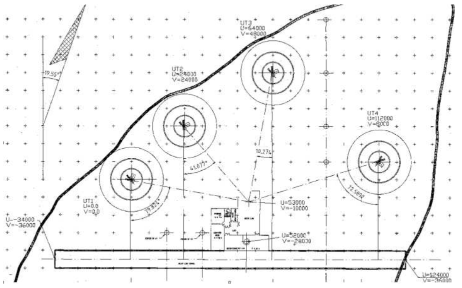

Fig. 1. VLT and the incoherent combined Coude' Lab

2. Laser Comb

Current wavelength calibration sources are based on ThAr lamps and for some applications on I_2 cells. Both methods are not ideal in several respects, their non-uniformity and lack of long-term stability being among the main concerns. The precision of the ThAr wavelength lines used for the wavelength calibration is varying between 15 m s^{-1} for the strongest lines to 80 m s^{-1} for the weaker, thus setting a ultimate precision in the reference scale on which the spectra are calibrated. A novel concept for wavelength calibration has recently been proposed, which makes use of frequency laser comb. A laser frequency comb system provides a series of uniformly spaced, very narrow lines whose absolute positions are known a priori with relative precision of $\sim 10^{-12}$ (Murphy et al 2007). The first Laser Comb Wavelength calibration test in the optical range was performed on HARPS at La Silla, ESO Chile, in January 2009 and the results reported in Wilken et al 2009.

The test performed only on a single order showed structured residuals with regular jumps every 512 pixels. These are likely originated in the CCD manufacturing process where a 512 pixel mask is applied. The ThAr wavelength calibration adapts to these defects becoming

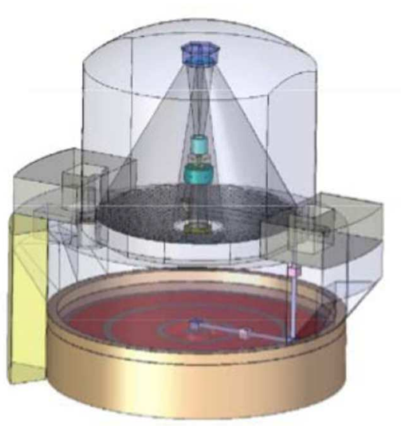

Fig. 2. E-ELT 42m telescope with the Coud focus

locally unreliable with maximum deviations of up to 100 m s^{-1} within one order range. It is rather interesting to note that the same instrument is delivering an overall 1 m s^{-1} accuracy when the whole order spectrum available is considered. In terms of α a deviation of 100 m s^{-1} would correspond to $\delta\alpha/\alpha \approx 7 \cdot 10^{-6}$ for a Fe II-Mg II pair. Centurion et al (2009) tested the presence of possible local wavelength calibration errors from the comparison of Fe II lines with almost identical sensitivity to fine structure constant changes. They found that deviations reaching 200 m s^{-1} or higher are present (or $\delta\alpha/\alpha \geq 10^{-5}$) . Griest et al 2009 compared HIRES-Keck observations calibrated with ThAr with similar ones with a I_2 self-calibration spectrum and found significant and not reproducible deviations up to several hundreds m s^{-1} . All these results show that the wavelength calibration issue could be more serious than what previously generally assumed. The implementation of a reference system such as the Laser Comb calibration will be probably a first important step towards a precise measurement of $\delta\alpha/\alpha$.

3. ESPRESSO

The HARPS spectrograph at the 3.6m telescope in La Silla holds the observations with the highest precision along a fairly large temporal baseline. In the detection of the 3 Neptune-like planets Lovis et al (2006) obtained residuals on the orbital solutions of 0.64 m s^{-1} over a period of 500 days. From the HARPS experience we know that a number of properties a spectrograph must feature in order to deliver accurate radial velocities. The spectrograph should be a passive instrument located inside a stable environment with no human access, enclosed inside a vacuum tank with controlled temperature and pressure. ESPRESSO, which stems for Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, is a high-efficiency, high-resolution, fiber-fed spectrograph of high mechanical and thermal stability which will implement the Laser Comb reference technique when available. ESPRESSO is conceived for the incoherent combined Coude' focus of the 4 VLT and is in phase A study by a consortium formed by the Observatoire of Geneve, INAF-Observatories of Trieste and Milano, the Instituto de Astrofisica de Canarias, the University of Porto and ESO. ESPRESSO has many scientific drivers such as the search for exo-planet search, the chemical analysis of stars in Local galaxies and the physical constants variability with the exciting possibility of using a 16 m equivalent, but effectively somewhat smaller telescope due to the fiber-link losses, telescope, in advance of the E-ELT and of the other future extremely large telescopes. It is placed at the incoherent Combined Coude' room, but the distances from each telescope to the combined focus are considerable ranging from the 48 m of UT2 to the 69 m of UT1, and slightly different for each UT. A Coude' train brings the light from the B Nasmyth platform to the Coude' room, where the instrument acquisition and guide system collects it into a fiber which then feeds the spectrograph. The Coude' train has a FoV of 5 arcsec radius and it will be coated for high response in the 300-750 nm wavelength range. Full optical components, long fibres and even hybrid solutions are under investigations and will provide transmissions of about 80% along most of the optical range.

To limit the size of the echelle and of the other optical components the optical design makes use of anamorphism and pupil slicing. In this way a compact design is obtained, and a 20 cm optical beam and a 20x160 cm echelle provides the resolving power of an un-sliced 40 cm beam spectrograph. The resolving power while working with i UT is of R=120000, while for the 4 UT mode is till to be defined depending on the configuration adopted on the CCD. The basic concept of the spectrograph is a cross dispersed echelle with two arms. A dual fiber system allows to record the sky or to monitor the spectrograph drifts with a simultaneous calibration source.

High spectrograph optomechanical stability is obtained through a controlled environment in vacuum and by avoiding movable components. In UVES a thermal change of 0.1K or a variation in the ambient pressure of 0.1 mBar induces a radial velocity shift of about 20 m s^{-1} , and the precise value depends on the settings. Thus for reaching the cm^{-2} precision the required stability is of the order of 10^{-3} K or mBar or better.

One critical item is the light input system, which must scramble the signal to ensure that the variability at the fiber input does not degrade the stability of the spectrograph, still keeping an excellent transmission. A stabilization system in the fiber head will compensate for seeing and tracking instabilities to ensure that a photon's position on the CCD only depends on its wavelength but not on its position on the entrance aperture. This component is rather critical, because at a resolution of 150 000 a typical pointing accuracy of ~ 0.05 arcsec corresponds to an error of 100 m s^{-1} which requires a scrambling gain of ~ 5000 in order to reach 2 cm s^{-1} accuracy. This is a 50 times more stringent requirement than in HARPS. In the 4-UT case there are 4 independent pupils and the scrambling shall occur after combining the light from the sub-pupils.

4. CODEX

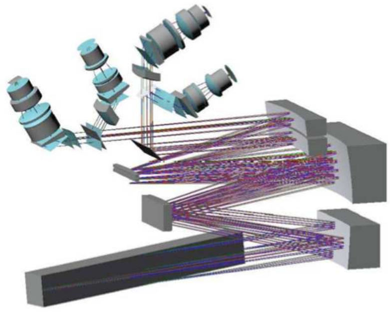

Fig. 3. CODEX multi camera optical layout

CODEX (COsmic Dynamics EXperiment) is a concept for an extremely stable, high-resolution optical spectrograph for the European Extremely Large Telescope (E-ELT). The science case for CODEX encompasses a large range of topics, including the search for exo-planets down to earth-like masses, primordial nucleosynthesis and the possible variation of fundamental constants. However, its prime science driver is the exploration of the universal expansion history by detecting and measuring the cosmological redshift drift using QSO absorption lines (Pasquini et al 2005).

CODEX will represent a major development in high-resolution optical spectrographs compared to existing instruments such as UVES and HARPS. In order to achieve its science goals CODEX will have to deliver an exceptional radial velocity accuracy and stability, i.e. 2 cm s^{-1} over a timescale of ~ 20 yr. The spectrograph design contains several novel concepts, and makes use of pupil splitting and anamorphism in order to keep the dimensions of the optics and of the echelle grating reasonable. Several of the sub-systems will be implemented or the first time in ESPRESSO f which is a sort of CODEX precursor instrument. The camera largest lens is 35 cm in diameter and the echelle grating is only twice the UVES size: 20*160 cm. The two arms design optimizes the efficiency and slanted VPHs are used as cross-dispersers. They produce an anamorphism of a factor 1.5 to 2.5 perpendicular to the main dispersion allowing to keep each detector limited in size;

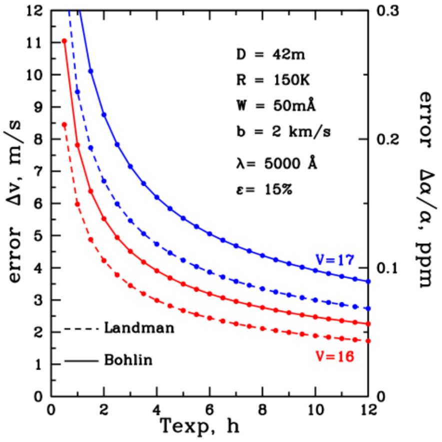

Fig. 4. Expected wavelength accuracy for a single absorption line with EW =0.050 Å and a Doppler parameter b= 2 km s^{-1} as a function of the exposure time. The dotted curves show the idealized case of a Gaussian line shape (Landmann et al. 1982) for QSOs with apparent magnitudes of V=16 and V=17, respectively. The solid curve take into account also uncertainties of continuum fitting (Bohlin et al. 1983).

Two possible designs for the spectrograph are presently considered. One possibility is a multi-spectrograph concept where the light at the E-ELT Coude' focus is sliced into several identical spectrographs. The second is a multi-camera concept which envisages only one spectrograph, but with four cameras. There is no pupil splitting before the spectrograph entrance and there is only one 500 microns at F/3 fibre entering the spectrograph and a second dedicated to record the sky. The pupil is splitted in 6 parts grouped into 2 slits. Each of the two slits is separated by a dichroic in a red and in a blue spectrum and the image is collected by four cameras as shown in Fig. 3. This design has some very attractive parts, in particular it is compact and the costs are of relatively moderate. At the moment the latter design is preferred.

Careful study of HARPS performances have also revealed a correlation between detector temperature and radial velocity variations probably due to the expansion of the detector along the attachments of the mosaic of CCDs to the support. CCD differential movements in the detector are very small, of the order of 0.02 pixel/K or 0.10 m s^{-1} for 10 mK and the actual thermal instabilities are about half as much, thus inducing instabilities at the level of few cm s^{-1} . The development of a new temperature control of the CCD with a new super stable cryostat is required to eliminate these tiny effects.

Another E-ELT instrument under study which can be interesting for fundamental constants studies is the high resolution (R=130000) InfraRed SIMPLE spectrograph. It is working from $\lambda \geq 08\mu m$ up to 2.5 μm and in a vacuum, cooled at cryogenic temperatures and in a gravity invariant location. The rather small entrance aperture of 0.04 arcsec requires AO but it should be able to deliver radial velocity accuracies better than 1 m s^{-1} and it will be particularly useful for high redshift systems where the most used absorption lines fall into the infrared region.

5. Conclusions

The current measurements of α and μ are performed at the limit of about 2 ppm which is likely the best of what can be done with current spectrographs.

The novel calibration technique based on the Laser Comb, when available, will significantly improve this situation. The improved wavelength calibration and specifically designed spectrographs should thereby enable photon noise limited measurements so that unlike for presently available spectrographs systematic uncertainties of the wavelength calibration and slit off-centering would not be the dominant error source.

The large collecting power of the combined VLT or of the E-ELT will thus be essential to reduce the photon noise of these measurements which are necessarily performed on rather faint targets.

Fig. 4 shows the expected wavelength accuracy of CODEX at the E-ELT in the photon noise limit for the two cases. A wavelength accuracy of 3 m s^{-1} is within reach and corresponds to an error of $\sigma_{\Delta\alpha/\alpha}$ of 0.1 -0.2 ppm for α, with the precise value depending on the sensitivity coefficients ΔQ of the spectral lines used.

CODEX at the E-ELT should thus decrease the error in measurements of the variability of α and μ by one and possibly two orders of magnitude and should thus definitively resolve the current controversies on the variability of α and μ and open a new domain to this research. A convincing detection of variability would have far reaching implications revealing new physics beyond the Standard Model of Physics, and possibly providing insights into the nature of dark energy. Alternatively if the constants are found not varying with CODEX explorations, their variability, if any, will fall in a regime not accessible to astronomical observations.

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