DOI: 10.18727/0722-6691/5274

ESPRESSO Probes the Fine-structure Constant

Michael T. Murphy[1,2]
Paolo Molaro[3,2]
Tobias M. Schmidt[3,12]
Carlos J. A. P. Martins[4,6]
Vitor da Fonseca[10,11]
Dinko Milaković[2,3,9]
Guido Cupani[3,2]
Stefano Cristiani[3,2]
Valentina D'Odorico[3,2]
Tiago Barreiro[10,11]
Ricardo Génova Santos[7,8]
Ana C. O. Leite[4,5,6]
Catarina M. J. Marques[4,6]
Nelson J. Nunes[10,11]
Francesco A. Pepe[12]
Rafael Rebolo[7,8]
Nuno C. Santos[4,5]
Sérgio G. Sousa[4,5]
Maria-Rosa Zapatero Osorio[13]
Manuel Amate[7]
Vardan Adibekyan[4,5]
Yann Alibert[14]
Carlos Allende Prieto[7,8]
Veronica Baldini[3]
Willy Benz[14]
François Bouchy[12]
Alexandre Cabral[10,1]
Hans Dekker[15]
Paolo Di Marcantonio[3]
David Ehrenreich[12]
Pedro Figueira[4,15]
Jonay I. González Hernández[7,8]
Marco Landoni[16]
Christophe Lovis[12]
Gaspare Lo Curto[15]
Antonio Manescau[15]
Denis Mégevand[12]
Andrea Mehner[15]
Giuseppina Micela[17]
Luca Pasquini[15]
Ennio Poretti[16,18,19]
Marco Riva[16]
Alessandro Sozzetti[19]
Alejandro Suárez Mascareño[7,8]
Stéphane Udry[4]
Filippo Zerbi[16]

[1] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Australia
[2] Institute for Fundamental Physics of the Universe, Trieste, Italy
[3] INAF–Astronomical Observatory of Trieste, Italy
[4] Institute of Astrophysics and Space Science, University of Porto, Portugal
[5] Department of Physics and Astronomy, University of Porto, Portugal
[6] University of Porto, Centre for Astrophysics, Portugal
[7] Astrophysics Institute of the Canaries, La Laguna, Tenerife, Spain
[8] Department of Astrophysics, University of La Laguna, Tenerife, Spain
[9] National Institute for Nuclear Physics, Trieste, Italy
[10] Institute of Astrophysics and Space Science, University of Lisbon, Portugal
[11] Department of Physics, University of Lisbon, Portugal
[12] Astronomical Observatory of Geneva University, Switzerland
[13] Centre for Astrobiology (CSIC-INTA), Madrid, Spain
[14] Physics Institute, University of Bern, Switzerland
[15] ESO
[16] INAF–Astronomical Observatory of Brera, Merate, Italy
[17] INAF–Astronomical Observatory of Palermo, Italy
[18] INAF–National Galileo Observatory, Breña Baja, Spain
[19] INAF–Astrophysical Observatory of Turin, Italy

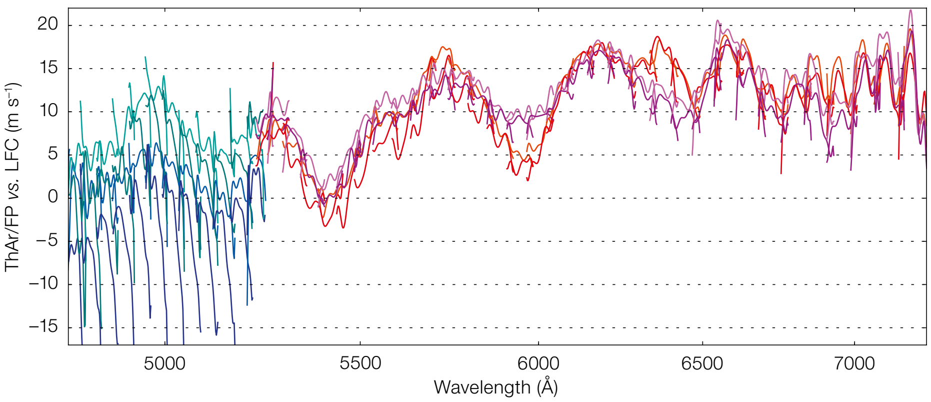

Figure 1. Comparison of the ThAr/FP and LFC calibrations. Colours indicate different fibres and slices for the Red and Blue CCDs (from Schmidt et al., 2021). Light and dark blue are slices a and b of Fibre A respectively, and light and dark green are slices a and b of Fibre B respectively, for the blue CCD. The two shades of orange are slices a and b of Fibre A, while the two shades of violet are slices a and b of Fibre B for the red CCD. For validation the sampling is reduced to 100 km s^{-1}. Traces when the blaze function drops below 25% of the peak throughput are excluded.

The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) is the new high-resolution spectrograph of ESO's Very Large Telescope. It was designed for ultra-high radial-velocity precision and extreme spectral fidelity with the aim of performing exoplanet research and fundamental astrophysical experiments with unprecedented precision and accuracy. The first precise ESPRESSO constraint on cosmological variations in the fine-structure constant has been obtained recently by using the laser frequency comb to provide a highly accurate wavelength scale. The target was the famous quasar HE 0515-4414, one of the brightest in the southern sky, with an intervening galaxy at $z = 1.15$ which imprints metal absorption lines onto the spectrum. The lack of velocity shifts between these lines is consistent with the absence of cosmological variation in the fine-structure constant at the level of about 1 part per million.

Introduction

In the Standard Model of particle physics the strengths of fundamental physical interactions are described through dimensionless couplings. Historically, these have been assumed to be constant. However, they are known to change with energy, and in many extensions of the Standard Model they will also change in time and possibly in space (Martins, 2017). The fine-structure constant, $\alpha = e^2/\hbar c$, is a dimensionless fundamental constant that can be probed directly with spectroscopic techniques because the frequencies of spectral lines depend on α in different ways. In laboratories, comparing atomic clocks based on different transitions over timescales of a few years has provided extraordinarily precise limits on local time variations in α of just 1×10^{-18} per year (Lange et al.,

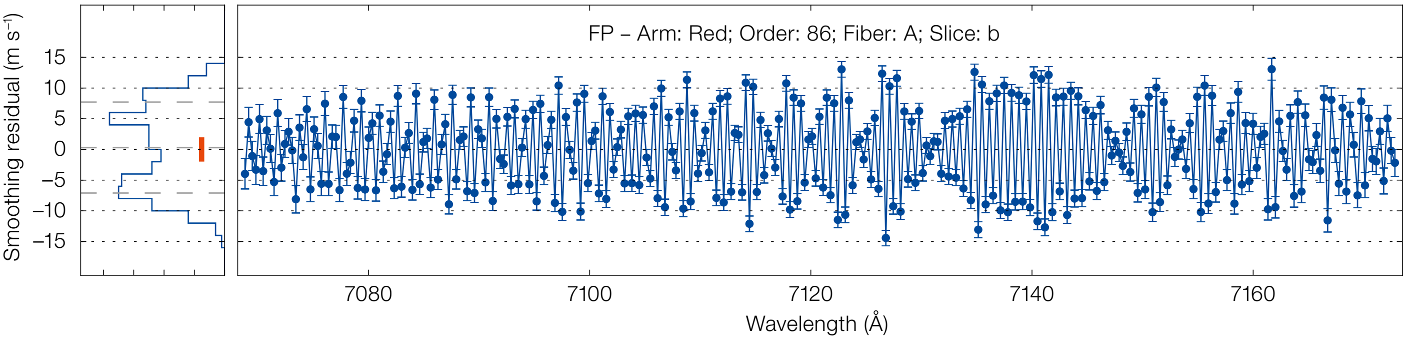

Figure 2. Alternate positional deviations up to +/– 10 m s^{-1} in the location of individual FP lines from the standard wavelength solution (from Schmidt et al., 2021). This is also seen in the LFC exposures. The effect is stable in time and it may also affect the science spectra. Thus, every individual line measurement is affected by 5–8 m s^{-1} correlated noise.

2021). While it may be tempting to extrapolate such constraints linearly to cosmological time, it should be emphasised that how the fundamental constants may vary, and on what this may depend, is entirely unknown. Instead, the variability or constancy of α must be explicitly tested over the full range of time (and distance) scales available to experiments.

The most effective way to probe cosmological variations in α is the many-multiplet (MM) method which measures the wavelength shifts of many different transitions from several atomic species produced in intervening quasar absorption systems (Dzuba, Flambaum & Webb, 1999a,b; Webb et al., 1999). Transitions from different multiplets often have very different dependencies on α. So measuring the velocity shifts between these transitions in a quasar absorption system provides a direct probe of $\Delta\alpha/\alpha$ — the relative difference between α in the absorber (α_{abs}) and its current laboratory value on Earth (α_{lab}):

$$\Delta\alpha/\alpha = (\alpha_{abs} - \alpha_{lab}) \,/\, \alpha_{lab} \cong -(\Delta v/c)\ (1/2Q)$$

where Δv is the velocity shift caused by a small variation in α (Dzuba et al., 2002). Here, Q is the sensitivity coefficient, namely the expected sensitivity of the transition's laboratory frequency to variations in α. These Q coefficients have been calculated using several different many-body quantum mechanical techniques (see, for example, Dzuba, Flambaum & Webb, 1999a,b; Murphy & Berengut, 2014). For typical values of Q (–0.03 to 0.05), a variation of one part per million (ppm) in α would produce a velocity shift Δv ~ 20 m s^{-1} between different transitions from different multiplets and atoms or ions.

The MM method has been widely used to measure $\Delta\alpha/\alpha$ at high redshifts, the largest samples being obtained with archival spectra from two high-resolution spectrographs: the Ultraviolet and Visual Echelle Spectrograph (UVES) at the Very Large Telescope (VLT) and the HIgh Resolution Echelle Spectrometer (HIRES) at the Keck Observatory (see, for example, Webb et al., 2001; Murphy, Webb & Flambaum, 2003; Webb et al., 2011). Each sample showed tentative detections of a variation in α at about the 5 ppm level, but in opposite senses. King et al. (2012) combined the sample of 143 Keck/HIRES absorption systems with a sample of 154 from VLT/UVES to produce a data set of $\Delta\alpha/\alpha$ measurements in 293 distinct absorption systems. The combined results showed a statistical preference for a dipolar spatial variation of α across the sky at about the 10 ppm level with greater than 4σ statistical significance. Note that a theoretical model which can account for a spatial dipole with such a low amplitude is more difficult to identify than one in which α varies with time (see, for example, Olive, Peloso & Uzan, 2011). As should be expected for such a surprising result, many authors have questioned the data, analysis, assumptions and potential systematic errors underpinning these measurements, and some have presented alternative data sets and analyses (for example, Chand et al., 2004; Quast, Reimers & Levshakov, 2004; Levshakov et al., 2005, 2007; Molaro et al., 2008). Constraints from higher-quality spectra of individual absorbers were also obtained, but none of them directly supported or strongly conflicted with the α dipole evidence (Molaro et al., 2013; Bainbridge & Webb, 2017; Wilczynska et al., 2020).

It now appears likely that the initial evidence for cosmological variations in α arose from a problem common to all slit-based spectrographs. Distortions in the wavelength scale of the quasar spectra were discovered when observing solar spectra reflected from asteroids with UVES, and after comparing them with an accurately calibrated solar spectrum from a Fourier-transform spectrometer (Rahmani et al., 2013). These distortions were found to be ubiquitous in slit-based echelle spectrographs (UVES, HIRES, and the High Dispersion Spectrograph [HDS] at the Subaru Telescope) and substantial enough to explain the quasar absorption results (Whitmore & Murphy, 2015; cf. Dumont & Webb, 2017). Recent quasar observations with UVES, HIRES and HDS, dedicated to measuring α and explicitly correcting for these distortions, are inconsistent with the earlier results and show no variations in α (Evans et al., 2014; Murphy, Malec & Prochaska, 2016; Murphy & Cooksey, 2017; Kotuš, Murphy & Carswell, 2017). On balance, there is currently no compelling evidence for variations in α over cosmological time or distance scales. Nevertheless, even when accurate corrections for distortions are possible, the uncertainty in the wavelength calibration of slit-based spectrographs dominates the error budget.

ESPRESSO enters the game

The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO; Pepe et al., 2021) was specifically designed to suppress wavelength calibration errors in quasar absorption measurements of α

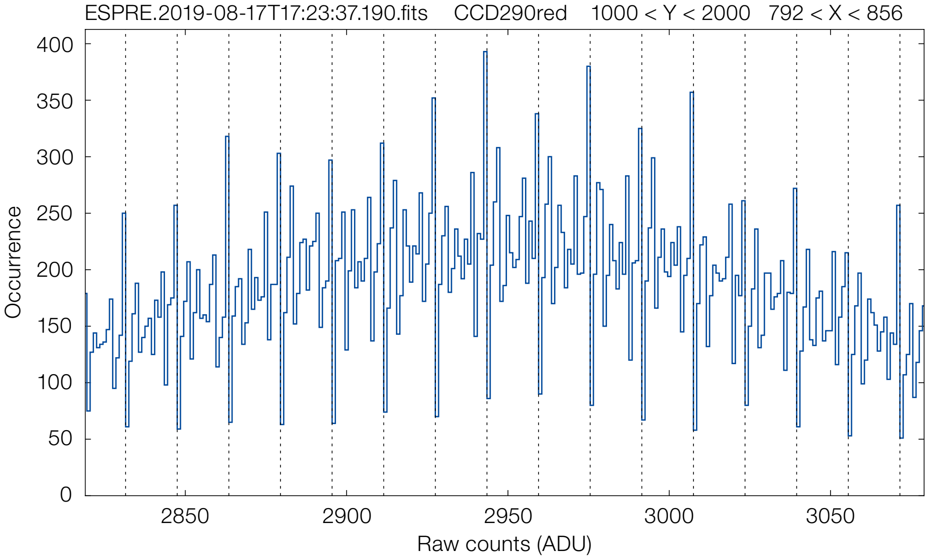

Figure 3. Example of the nonrandom occurrence of pixel values in a region of a LED frame around 7546 Å. This is probably a manifestation of the binary offset effect discovered by Boone et al. (2018) in the CCDs of several major facilities.

(Molaro, Murphy & Levshakov, 2006; Molaro, 2009). The spectrograph is located in the incoherent Combined-Coudé Laboratory underneath the four Unit Telescopes (UTs) of the VLT, and can be fed by any one UT or all four simultaneously. ESPRESSO is fed by optical fibres, is sealed in a stable vacuum vessel with temperature control at the millikelvin level, and can be calibrated with an 'astrocomb' — a femtosecond-pulsed laser frequency comb (LFC). The high frequency-space density of uniformly separated comb modes, whose individual frequencies are known *a priori* with extremely high accuracy, could enable centimetre-per-second (photon-limited) calibration precision (Murphy et al., 2007; Milaković et al., 2020). The ESPRESSO astrocomb covers the wavelength range 4850–7000 Å of ESPRESSO's full 3781–7874 Å range, and provides an accuracy of approximately 1 $\mathrm{m\,s^{-1}}$ for velocity shifts between transitions in the spectrum of the quasar HE 0515-4414. This is well below the statistical precision of the quasar absorption measurements themselves (about 30 $\mathrm{m\,s^{-1}}$), so ESPRESSO effectively removes wavelength calibration from the error budget. While only a few LFC calibration exposures could be obtained for HE 0515-4414, they were sufficient for these purposes.

In Figure 1 the comparison of ESPRESSO's LFC and standard ThAr+Fabry-Perot (FP) calibrations made by Schmidt et al. (2021) is shown, revealing a wavy structure. These distortions are most likely due to the standard ThAr+FP calibration used by the data reduction software. In principle, these could affect other measurements of $\Delta\alpha/\alpha$ with ESPRESSO if only ThAr+FP calibration were used and no corrections were made with solar twin or asteroid exposures. A further effect has also been found in the LFC and FP spectra, as shown in Figure 2. The wavelength calibration residuals of alternate, individual FP (or LFC) lines are strongly anti-correlated in ESPRESSO. The origin of this effect is unclear. Nor is it clear whether this affects the science exposures as well.

Another discovery, which we report here for the first time, concerns the flux, namely the detection of the binary offset effect (see Boone et al., 2018) on some of the amplifiers of the ESPRESSO CCDs. The example in Figure 3 shows the nonrandom occurrence of pixel values. This results in flux anomalies at the 1% level in the spectral range covered by the affected amplifiers. The underlying mechanism seems to be correlated with the number of "1" bits in the binary representation of the pixel value, just as found by Boone et al. (2018) in the CCDs of many instruments in major ground- and space-based telescopes.

Observations and data analysis

HE 0515-4414 was identified as a very bright (Gaia G = 14.9 mag) quasar at redshift z_{em} = 1.71 by Reimers et al. (1998). It was observed during the ESPRESSO Consortium's Guaranteed Time Observations (GTO) in two main runs: a visitor-mode run on 4–7 November 2018, and service-mode observations between November 2019 and March 2020. The total integration of 57 916 s (16 h) was obtained over 17 exposures. The high-resolution, single-UT mode with 2-pixel binning in the spatial direction (i.e., 'singleHR21') was selected, providing a nominal resolving power of $R \sim 145\,000$ with a 1-arcsecond-diameter fibre. All exposures were obtained with UT3-Melipal, except for those in November 2019 which were observed with UT1-Antu. Single exposures were reduced with the standard ESPRESSO data reduction software (v. 2.2.3) and combined with UVES_POPLER (v. 1.05; Murphy et al., 2019) to form a single spectrum (S/N ~ 105 per 0.4-$\mathrm{km\,s^{-1}}$ pixel at 6000 Å).

In Figure 4 the UVES and HARPS spectra for three representative transitions are compared with the new ESPRESSO spectrum. The high R and signal-to-noise ratio revealed that the z_{abs} = 1.1508 absorption system was more complex than previous studies had found: strong constraints on the relative optical depths of two different Mg I lines confirmed the presence of very narrow velocity components in the strongest absorption feature (Doppler b < 0.5 $\mathrm{km\,s^{-1}}$). A total of 129 velocity components were required to fit the approximately 720-$\mathrm{km\,s^{-1}}$-wide absorption profile, which was split into three 'regions' for simplicity, with the strongest Mg I and Fe II transitions providing the main constraints on $\Delta\alpha/\alpha$ in the reddest region.

In Figure 5 the strong lines in the reddest regions are shown to illustrate the model fitting. The entire analysis procedure was developed using a blinded approach to avoid human biases. Table 1 summarises the fiducial fitting results with the 1σ statistical and systematic uncertainties for each of the three regions. The weighted mean result for the entire absorber is:

$$\Delta\alpha/\alpha = 1.3 \pm 1.3_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}}\ \mathrm{ppm},$$

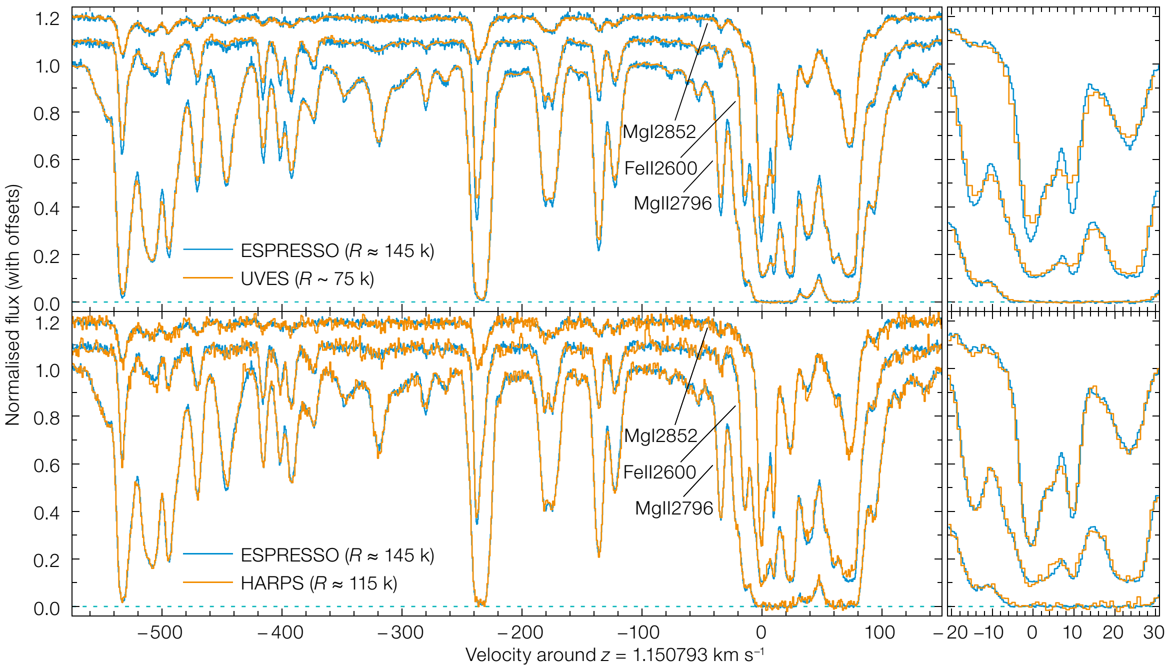

Figure 4. The upper panels compare ESPRESSO (blue) and UVES (orange) spectra, while the lower panels compare the ESPRESSO (blue) and HARPS (orange) spectra (from Murphy et al., 2022). The three spectra in each panel indicate Mg I 2852 Å, Fe II 2600 Å and Mg II 2796 Å, respectively, offset by 10% in flux for clarity. The right-hand panels zoom-in on the features near 0 and 9 km s−1.

with 1σ statistical and systematic error components. The result is consistent with no change in the fine-structure constant between the absorber at $z_{\mathrm{abs}} = 1.1508$ and the current laboratory value.

Our total uncertainty, 1.4 ppm, is similar to the ensemble precision of the previous large samples of absorbers from HIRES and UVES that indicated variations at about the 5 ppm level (Webb et al., 2001; Murphy, Webb & Flambaum, 2003; Murphy et al., 2004; Webb et al., 2011; King et al., 2012), which likely arose from long-range distortions in the wavelength scale (Rahmani et al., 2013; Whitmore & Murphy, 2015). Even the more recent results, which were corrected for these effects, had residual wavelength calibration uncertainties of 0.5–3.5 ppm, larger than our total systematic error budget (Evans et al., 2014; Murphy & Cooksey, 2017). Kotuš, Murphy & Carswell (2017) corrected the wavelength scale of their UVES spectrum of HE 0515-4414 by using the High Accuracy Radial velocity Planet Searcher (HARPS) spectrum of the same quasar. However, this still left about a 0.6 ppm wavelength calibration uncertainty which dominated their systematic error budget. The recent measurement in the same absorber by Milakovic et al. (2021) used an LFC-calibrated HARPS spectrum to measure $\Delta\alpha/\alpha$, thereby avoiding wavelength calibration uncertainties, just like our ESPRESSO measurement. Of course, the lower S/N of the HARPS spectrum (~ 58 per km s−1, cf.

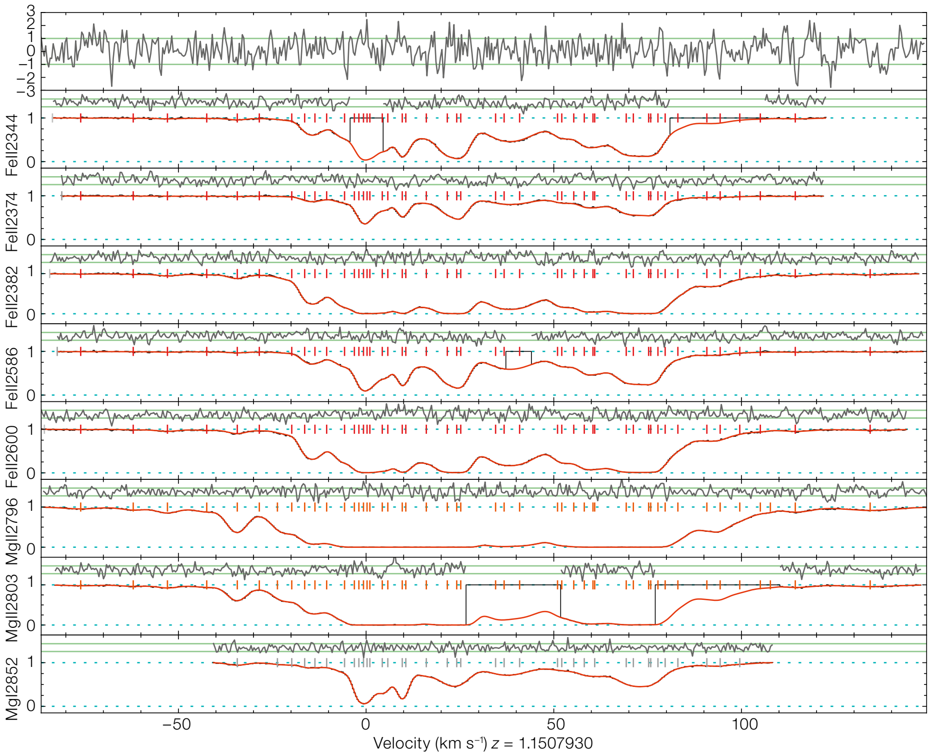

Figure 5. Example of an ESPRESSO spectrum (black histogram) for some strong transitions labelled on the vertical axis of the $z_{\mathrm{abs}} = 1.1508$ absorber (from Murphy et al., 2022). The fiducial model is shown with a red line, with individual components indicated by tick-marks. The residuals between the data and the model, normalised by the uncertainties, are shown above each transition.

Region	Left	Central	Right	Combined
$\Delta\alpha/\alpha$	2.17	1.57	1.14	1.31
1σ statistical uncertainty	3.31	5.59	1.45	1.29
Systematic uncertainty	1.35	2.37	0.45	0.43

Table 1. Results for the three different regions of the absorber with 1σ statistical uncertainties together with the likely systematic errors from several possible sources. See Murphy et al. (2022) for further details of the different entries.

170 for our ESPRESSO spectrum) limited the precision to 2.4 ppm. By contrast, our measurement is effectively free from systematic wavelength calibration errors thanks to the specific design features of ESPRESSO to suppress them (for example, the octagonal fibre feed, stable vacuum environment, and LFC calibration). This means our total systematic uncertainty is well below our photon-statistical uncertainty — a remarkable change from the pre-ESPRESSO era! Our main systematic uncertainties arise from ambiguities in fitting the absorption profile, from effects from redispersion of the spectra, and from convergence of the fitting procedure.

Our new $\Delta\alpha/\alpha$ measurement is consistent with the recent UVES and HARPS measurements in the same absorber (see above), and also the 26 other recent measurements in other absorbers with HIRES, UVES and HDS where the wavelength distortions were corrected, or had no significant impact. Combining these 28 independent measurements with low calibration error with our new ESPRESSO measurement provides a weighted mean

$$\Delta\alpha/\alpha = -0.5 \pm 0.5_{\rm stat} \pm 0.4_{\rm sys}\ \text{ppm}.$$

The above combined result is still dominated by the single UVES measurement in HE 0515-4414 by Kotuš, Murphy & Carswell (2017). However, the ESPRESSO era has arrived, and it promises to provide a larger sample of well-calibrated, high-quality quasar absorption spectra for measuring $\Delta\alpha/\alpha$ through the instrument consortium's GTO and open, competitive observing time. One important outstanding problem with improving quasar absorption measurements of $\Delta\alpha/\alpha$ is the lack of observational constraints on how the isotopic abundances in the absorbers differ from the terrestrial values. ESPRESSO's higher resolving power offers an opportunity to directly constrain or measure the Mg isotopic abundances, in particular absorption systems where the velocity structure is rather simple.

Constraints on theoretical models

The new bound on α significantly improves constraints on cosmological models with a varying α. Broadly speaking, these can be divided into two classes (Martins, 2017). In the first class, the electromagnetic sector is coupled to a scalar field which simultaneously provides the dark energy responsible for the acceleration of the Universe (Martins et al., 2022; da Fonseca et al., 2022). In the second class, dark energy and a varying α stem from different physical mechanisms, the simplest example being Bekenstein models (Martins et al., 2022). In both cases, the new constraints are consistent with a null variation of the field, i.e., compatible with ΛCDM, and we have improved previous constraints by more than a factor of ten. Although this gain is dominated by recent improvements in local atomic clock tests, the astrophysical measurements do help to break the degeneracies between cosmology and fundamental physics parameters, particularly in the first class of models. Additional ESPRESSO bounds on α will also enable improved constraints on theoretical models with spatial or environmental dependencies.

Acknowledgements

We dedicate this work to the memory of Dieter Reimers (1943–2021), discoverer of the quasar HE 0515−4414, leader in European astronomy, colleague and friend to many authors of this paper. MTM acknowledges the support of the Australian Research Council through Future Fellowship grant FT180100194. The work of CJAPM was funded by FEDER through COMPETE 2020 (POCI), and by Portuguese funds through FCT through project POCI-01-0145-FEDER-028987 and PTDC/FIS-AST/28987/2017; the author also acknowledges FCT and POCH/FSE (EC) support through Investigador FCT Contract 2021.01214.CEECIND/CP1658/CT0001. NJN was funded by projects POCI-01-0145-FEDER-028987, PTDC/FIS-AST/28987/2017, PTDC/FIS-AST/0054/2021 and EXPL/FIS-AST/1368/2021, as well as UIDB/04434/2020 & UIDP/04434/2020, CERN/FIS-PAR/0037/2019, PTDC/FIS-OUT/29048/2017.DM is also supported by the INFN PD51 INDARK grant.

References

Bainbridge, M. B. & Webb, J. K. 2017, MNRAS, 468, 1639
Boone, K. et al. 2018, PASP, 130, 064504
Chand, H. et al. 2004, A&A, 417, 853
da Fonseca, V. et al. 2022, to appear in A&A, arXiv:2204.02930
Dumont, V. & Webb, J. K. 2017, MNRAS, 468, 1568
Dzuba, V. A., Flambaum, V. V. & Webb, J. K. 1999a, Phys Rev A, 59, 230
Dzuba, V. A., Flambaum, V. V. & Webb, J. K. 1999b, Phys Rev Lett, 82, 888
Dzuba, V. A. et al. 2002, Phys Rev A, 66, 022501
Evans, T. M. et al. 2014, MNRAS, 445, 128
Lange, R. et al. 2021, Phys Rev Lett, 126, 011102
Levshakov, S. A. et al. 2005, A&A, 434, 827
Levshakov, S. A. et al. 2007, A&A, 466, 1077
King, J. A. et al. 2012, MNRAS, 422, 3370
Kotuš, S. M., Murphy, M. T. & Carswell, R. F. 2017, MNRAS, 464, 3679
Martins, C. J. A. P. 2017, Rep Prog Phys, 80, 126902
Martins, C. J. A. P. et al. 2022, Phys Rev D, 105, 123507
Milaković, D. et al. 2020, MNRAS, 493, 3997
Milaković, D. et al. 2021, MNRAS, 500, 1
Molaro, P., Murphy, M. T. & Levshakov, S. A. 2006, IAU Symp, 232, 198
Molaro, P. et al. 2008, EPJST, 163, 173
Molaro, P. 2009, in Astrophysics and Space Science Proceedings, *Science with the VLT in the ELT Era*, ed. Moorwood, A., (Dordrecht: Springer), 389
Molaro, P. et al. 2013, A&A, 555, A68
Murphy, M. T., Webb, J. K. & Flambaum, V. V. 2003, MNRAS, 345, 609
Murphy, M. T. et al. 2004, in Lecture Notes in Physics, 648, *Astrophysics, Clocks and Fundamental Constants*, ed. Karshenboim, S. G. & Peik, E., (Berlin, Heidelberg: Springer), 13
Murphy, M. T. et al. 2007, MNRAS, 380, 839
Murphy, M. T. & Berengut, J. C. 2014, MNRAS, 438, 388
Murphy, M. T., Malec, A. L. & Prochaska, J. X. 2016, MNRAS, 461, 2461
Murphy, M. T. & Cooksey, K. L. 2017, MNRAS, 471, 4930
Murphy, M. T. et al. 2019, MNRAS, 482, 3458
Murphy, M. T. et al. 2022, A&A, 658, A123
Olive, K. A., Peloso, M. & Uzan, J.-P. 2011, Phys Rev D, 83, 043509
Pepe, F. et al. 2021, A&A, 645, A96
Quast, R., Reimers, D. & Levshakov, S. A. 2004, A&A, 415, L7
Reimers, D. et al. 1998, A&A, 334, 96
Rahmani, H. et al. 2013, MNRAS, 435, 861
Schmidt, T. M. et al. 2021, A&A, 646, A144
Webb, J. K. et al. 1999, Phys Rev Lett, 82, 884
Webb, J. K. et al. 2001, Phys Rev Lett, 87, 091301
Webb, J. K. et al. 2011, Phys Rev Lett, 107, 191101
Whitmore, J. B. & Murphy, M. T. 2015, MNRAS, 447, 446
Wilczynska, M. R. et al. 2020, Science Advances, 6, 9672