PREPARING ESPRESSO'S FUNDAMENTAL PHYSICS TESTS

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ESPRESSO is a high-resolution ultra-stable spectrograph for the VLT, whose commissioning will start this year. One of its key science goals is to test the stability of nature's fundamental couplings with unprecedented accuracy and control of possible systematics. As the first light approaches quickly, detailed studies are being done to evaluate the optimal strategy to detect a possible variation of fine-structure constant looking into metal absorption lines produced by the intervening clouds along the line of sight of QSOs. In this paper, I present the ongoing studies and emphasise the different strategy needed for fainter targets in order to improve tests of the stability of the variation of the fine-structure constant using ESPRESSO. I will also discuss the impact that these improved measurements can have on cosmology, more specifically on a Bekenstein-type model and on three different Dynamic Dark Energy models.

1 Observing with ESPRESSO

ESPRESSO is a high-resolution ultra-stable spectrograph that will be installed at the VLT - Very Large Telescope in 2017. It will allow to observe with one Unit of Telescope (UT) of the VLT individually or to combine the light of the four telescopes. This instrument has as one of his science goals to test the stability of fundamental couplings[1]. The Fundamental Physics Guaranteed Time of Observation (GTO) for this purpose will have 27 nights and a list of 14 QSO "ideal" targets was put together.[2] In order to achieve stronger constrains on the variation of the fine-structure constant, α, an ideal quasar target should present simple and strong absorption features of transitions with high sensitivities to variations of α.

The 14 targets selected for the GTO are presented in Table 1. The selection process of the target list is presented in detail in Leite et al. 2016 [2]. The first measurement on the table is not an ideal target to test α, but is a system where the proton to electron mass ratio and the T_{CMB} relation to redshift can also be measured. This makes it an interesting target to investigate the nature of the fundamental constants variation testing different theories where a relation between these three constants is predicted.[7] The GTO sample spans redshifts 1.35 to 3 and the background quasars of the targets have very different magnitudes (M=15.9-18.8).

Since most of the targets are very faint, one needs to verify if the efficiency of the collection of photons by the CCD ensures that the number of photons from our science target is higher that the number of photons coming from the instrumentation and reading of the CCD.

The limit for which the number of photons from the target and from the instrumental noise are the same was computed for the characteristics of VLT and ESPRESSO. These limits for two different cases are plotted in Figure 1: the 1 UT with no binning - 1X1 (blue line) assuming the light collected by the area of 1 VLT UT and the currently expected specifications for the ESPRESSO efficiency and CCD noise; and the 4UT with the CCD binned by 2 in the spectral direction and by 2 in the spatial direction - 2X2 (red dashed line) assuming the light collected

Table 1: List of the best measurements of the stability of the fine structure constant considering the wavelength coverage of ESPRESSO. Column 1 gives the quasar name; the redshifts of the absorption system are given in Column 2; Column 3 gives the magnitude of the emitting quasar. Column 4 and 5 gives the value of the measurement and the corresponding uncertainty. The last Column gives the references for each measurement.

Name	z_{abs}	M	$\Delta\alpha/\alpha$ (10^{-6})	$\sigma_{\Delta\alpha/\alpha}(10^{-6})$	Ref.
J034943-381031	3.02	17.3	-27.9	34.2	[3]
J040718-441013	2.59	17.3	5.7	3.4	[4]
J043037-485523	1.35	16.5	-4.0	2.3	[4]
J053007-250329	2.14	18.8	6.7	3.5	[4]
J110325-264515	1.84	15.9	5.6	2.6	[5]
J115944+011206	1.94	17.5	5.1	4.4	[4]
J133335+164903	1.77	16.7	8.4	4.4	[4]
HE1347-2457	1.43	16.3	-21.3	3.6	[5]
J220852-194359	1.92	17.0	8.5	3.8	[4]
HE2217-2818	1.69	16.0	1.3	2.4	[6]
Q2230+0232	1.86	18.0	-9.9	4.9	[3]
J233446-090812	2.15	18.0	5.2	4.3	[4]
J233446-090812	2.28	18.0	7.5	3.7	[4]
Q2343+1232	2.43	17.5	-12.2	3.8	[3]

by the area of 4 VLT UTs and the current expected specifications for the ESPRESSO efficiency and CCD noise. The area above the each line determines the photon-dominated regime, and the area below the regime where the noise dominates.

A quick analysis of the Fig. 1 shows that for a 1 hour exposure - typical times for this scientific goal - the limiting magnitude for the 1 UT mode is of 17.4. As seen in Table 1, 5 out of the 14 targets from the GTO target list are above this limit meaning that for the observation of these targets a 4UT mode should be the best strategy. The final efficiency of the instrument will only be known in detail when ESPRESSO starts commissioning, but this exercise gives us an idea of how to plan the observation of each target.

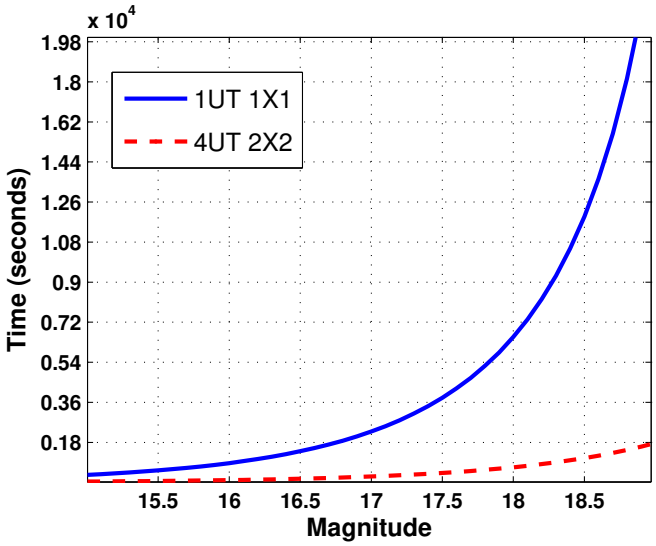

Figure 1 – The figure plots the limit for which an observation on the VLT is photon noise dominated as a function of the magnitude of a target and a given time of observation. The area above the line determines the photon-dominated regime, and the area below the regime where the noise dominates. In blue is represented this limit for the 1UT mode with no binning in the CCD, 1X1. The red dashed line represents the limit for the 4UT mode with a binning of 2X2, binned by 2 in the spectral direction and by 2 in the spatial direction of the CCD.

The instrumentation improvements that ESPRESSO will bring will allow a Baseline uncertainty per target to be of $\sigma_{\Delta\alpha/\alpha} = 0.6ppm$

2 Forecasts on Cosmology

This type of measurements are important by themselves for testing the stability of α but even a non-detection of variation can be used to constrain dark energy, as we now illustrate.

2.1 Bekenstein Type Models

The Bekenstein-Sandvik-Barrow-Magueijo [8] model assumes a variation of α that comes from the variation of the electric charge. This model can be seen as a ΛCDM-like model with an additional dynamical degree of freedom, whose dynamics is such that it leads to the aforementioned variations without having a significant impact on the Universe's dynamics. In particular, this degree of freedom can't be responsible for the dark energy (for which a cosmological constant is still invoked). In this sense, these are the simplest phenomenological models allowing for α , even if they are (arguably) less well motivated from a fundamental physics point of view.

The constraints on these kinds of models from current astrophysical and cosmological data as well as detailed forecasts for ESPRESSO are presented in Leite & Martins (2016)[9]. One important variable is the coupling ζ_α, a free parameter of the model that gives magnitude to the allowed variation on α.

Assuming the baseline uncertainties on α expected for ESPRESSO, and applying these uncertainties for the 14 targets on the GTO target list, one can expect an improvement relative to the current constraints of a factor of 5 on the coupling ζ_α. Moreover, in this type of models there are composition dependent forces which lead to a WEP violation at a level quantified by the Eotvos parameter: $\eta_\alpha \sim 3 \times 10^{-9}\zeta_\alpha$. The ESPRESSO GTO will be able to put bounds of the level of $\eta \sim 5.4 \times 10^{-15}$ to this parameter.

2.2 Dynamical Dark Energy Models

In this class of models, we consider three fiducial dynamical dark energy models where the scalar field that is responsible for dark energy also leads to α variations. In this kind of model another coupling ζ arises directly related to the variation of α.

$$\frac{\Delta\alpha}{\alpha}(z) = \zeta \int_0^z \sqrt{3\Omega_\phi(z')[1 + w_\phi(z')]}\frac{dz'}{1+z} \tag{1}$$

In Alves et al. (2017)[10], we did detailed forecasts and their analysis using Fisher matrix techniques for different scenarios. In here I will only show one specific case as an example. We considered three fiducial dynamical dark energy models:

A constant dark energy equation of state, $w_0 = const$;

A dilaton-type model where the dark energy equation of state is

$$w(z) = \frac{[1 - \Omega_\phi(1 + w_0)]w_0}{\Omega_m(1 + w_0)(1 + z)^{3[1-\Omega_\phi](1+w_0)]} - w_0}; \tag{2}$$

The Chevallier-Polarski-Linder (CPL) parametrization, where the redshift dependence of the dark energy equation of state is described by two separate parameters, w_0 and w_a, as follows:

$$w(z) = w_0 + w_a\frac{z}{1+z}; \tag{3}$$

In all cases we assumed the following fiducial values for the models: $\Omega_{m,fid}$=0.3; $w_{0,fid} = -0.9$; $w_{a,fid} = 0.3$; $\zeta_{fid} = 0$. $\zeta_{fid} = 0$ implies null results for the measurements of α. We did the analyses for the same baseline uncertainty on α expected for ESPRESSO, and applying these uncertainties on the 14 targets of GTO target list. The uncertainties retrieved for the coupling parameter ζ are presented in Table 2. This type of models also lead to a WEP violation that relates the coupling ζ with the Eotvos parameter in the following way: $\eta_\alpha \sim 10^{-3}\zeta^2$. The ESPRESSO GTO will be able to put bounds at the level of $\eta \sim 2.1 \times 10^{-16}$ to this parameter at one sigma.

Table 2: The Table shows the one sigma forecasted uncertainties on the dimensionless coupling parameter ζ, marginalizing over the remaining model parameters, for the three choices of fiducial cosmological model presented in the text.

Model	$w_0 = const$	Dilaton	CPL
$\sigma(\zeta)$	4.6×10^{-7}	3.2×10^{-7}	3.1×10^{-7}

3 Conclusion

As the first light on telescope approaches for ESPRESSO, the necessity of putting together the best observational strategy to optimize the science for the Consortium's GTO becomes more urgent. There's now a better understanding of the limitations that the instrument will face, and that not all the targets will be observed in the simple 1 UT mode. Fainter targets will gain by combining the light of several UTs even if they lose in resolution of the spectra. The definitive strategy will only be possible as the instrument becomes online and tests of efficiency are performed.

Taking conservative expectations for the ESPRESSO targets, we show that even these 14 targets for ESPRESSO GTO by themselves will be able to constraint cosmological models and put competitive bounds on the Eotvos parameter.

I emphasize that extending these forecasts with ideal uncertainties on α or with more targets would improve the output results. These are not unrealistic expectations since simply an extended Large Program on ESPRESSO, or even the future spectrograph (HIRES) planned for ELT will allow for huge improvements. More details and forecasts can be found in [2,9,10,11,12]

Acknowledgments

This work was done in the context of grant PTDC/FIS/111725/2009 from FCT (Portugal). ACL is supported by an FCT fellowship (SFRH/BD/113746/2015), under the FCT PD Program PhD::SPACE (PD/00040/2012), and by the Gulbenkian Foundation through Programa de Estímulo à Investigação 2014, grant number 2148613525. CJM. is also supported by an FCT Research Professorship, contract reference IF/00064/2012, funded by FCT/MCTES (Portugal) and POPH/FSE (EC). CSA is partially supported by grant CIAAUP-06/2017-BIC.

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