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Updated constraints on spatial variations of the fine-structure constant

A.M.M. Pinho [a,b], C.J.A.P. Martins [a,c,*]

[a] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
[b] Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal
[c] Instituto de Astrofísica e Ciências do Espaço, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal

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ABSTRACT

Recent work by Webb et al. has provided indications of spatial variations of the fine-structure constant, α, at a level of a few parts per million. Using a dataset of 293 archival measurements, they further show that a dipole provides a statistically good fit to the data, a result subsequently confirmed by other authors. Here we show that a more recent dataset of dedicated measurements further constrains these variations: although there are only 10 such measurements, their uncertainties are considerably smaller. We find that a dipolar variation is still a good fit to the combined dataset, but the amplitude of such a dipole must be somewhat smaller: 8.1 ± 1.7 ppm for the full dataset, versus 9.4 ± 2.2 ppm for the Webb et al. data alone, both at the 68.3% confidence level. Constraints on the direction on the sky of such a dipole are also significantly improved. On the other hand the data can't yet discriminate between a pure spatial dipole and one with an additional redshift dependence.

1. Introduction

Testing the stability of nature's fundamental couplings is among the most actively pursued topics in observational astrophysics [1]. In addition to the intrinsically fundamental nature of these tests, the measurements (whether they are detections of variations or null results) have deep consequences for cosmology and fundamental physics, an overview of which is provided in [2].

A recent analysis by Webb et al. of a large archival dataset has provided some evidence for spatial variations of the fine-structure constant, α, at the level of a few parts per million (ppm) [3,4]. The dataset includes a total of 293 measurements in the approximate redshift range $0.2 < z. < 4.2$, obtained with ESO's UVES spectrograph at the VLT and with the HIRES spectrograph at the Keck telescope. Both the analysis of Webb et al. and those of subsequent works [5–8] find evidence for a spatial dipole in the measurements, at a statistical level of significance of more than four standard deviations.

Meanwhile some dedicated measurements of α (that is, those where the data was specifically taken for this purpose) have been obtained and further efforts in this direction are ongoing, such as those of the UVES Large Program for Testing Fundamental Physics [9,10]. The number of currently available dedicated measurements is only a dozen or so, so they can't yet be used on their own to search for spatial variations. Nevertheless, these measurements have statistical and systematic uncertainties that are nominally smaller than those of the archival measurements. (Note that in a large sample such as that of Webb et al. the systematic uncertainties can be—and have been—estimated directly from the sample distribution, while this is not possible for individual measurements.) Here, therefore, we carry out a first joint analysis of the Webb et al. and the more recent measurements, with the aim of ascertaining whether the evidence for the dipolar variation is preserved.

2. Available data and parameterizations

Previous studies of the spatial distribution of α measurements were restricted to the data of Webb et al. [3], which is a large dataset of archival data measurements. This dataset has been extensively described elsewhere (most notably in [4]), and we refer the reader to these works for additional details. There have been recent suggestions that the level of systematics in these measurements may have been underestimated [11], but here we simply take the published values at face value, and calculate the total uncertainty for each measurement by adding in quadrature the statistical and systematic uncertainties.

* Corresponding author at: Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal.
E-mail addresses: Ana.Pinho@astro.up.pt (A.M.M. Pinho), Carlos.Martins@astro.up.pt (C.J.A.P. Martins).

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Table 1
Recent dedicated measurements of α. Listed are, respectively, the object along each line of sight, the redshift of the measurement, the measurement itself (in parts per million), the spectrograph(s), and the original reference. The recent UVES Large Program measurements are [9,10]. The quoted errors include both statistical and systematic uncertainties (to the extent that these were estimated in the original works), added in quadrature. The first measurement is the weighted average from 8 absorbers in the redshift range $0.73 < z < 1.53$ along the lines of sight of HE1104−1805A, HS1700+6416 and HS1946+7658, reported in [13] without the values for individual systems, and therefore won't be included in our analysis.

Object	z	$\Delta\alpha/\alpha$ (ppm)	Spectrograph	Ref.
3 sources	1.08	4.3 ± 3.4	HIRES	[13]
HS1549+1919	1.14	-7.5 ± 5.5	UVES/HIRES/HDS	[10]
HE0515−4414	1.15	-0.1 ± 1.8	UVES	[14]
HE0515−4414	1.15	0.5 ± 2.4	HARPS/UVES	[15]
HS1549+1919	1.34	-0.7 ± 6.6	UVES/HIRES/HDS	[10]
HE0001−2340	1.58	-1.5 ± 2.6	UVES	[16]
HE1104−1805A	1.66	-4.7 ± 5.3	HIRES	[13]
HE2217−2818	1.69	1.3 ± 2.6	UVES	[9]
HS1946+7658	1.74	-7.9 ± 6.2	HIRES	[13]
HS1549+1919	1.80	-6.4 ± 7.2	UVES/HIRES/HDS	[10]
Q1101−264	1.84	5.7 ± 2.7	UVES	[14]

In our analysis we will also consider this data on its own (to check that we recover previously published results) but, more importantly, we will for the first time combine it with the available, smaller and more recent, dataset of dedicated measurements listed in Table 1. This compilation includes the early results of the UVES Large Program for Testing Fundamental Physics [9,10], which is expected to be the one with a better control of possible systematics. The source of the data in this table is also further discussed in [12].

We note that the first measurement listed on the table is the weighted average from measurements in 8 absorption systems in the redshift range $0.73 < z < 1.53$ along lines of sight that are widely separated on the sky (HE1104−1805A, HS1700+6416 and HS1946+7658) [13]; the authors only report this average and not the individual measurements. For this reason we listed the result in Table 1 for completeness but naturally it won't be included in our analysis. Our more recent dataset therefore has 10 different measurements, all in the redshift range $1 < z < 2$.

We will fit this data to two different phenomenological parameterizations. The first is a pure spatial dipole for the relative variation of α

$$\frac{\Delta\alpha}{\alpha}(A, \Psi) = A \cos\Psi, \tag{1}$$

which depends on the orthodromic distance Ψ to the north pole of the dipole (the locus of maximal positive variation) given by

$$\cos\Psi = \sin\theta_i \sin\theta_0 + \cos\theta_i \cos\theta_0 \cos(\phi_i - \phi_0), \tag{2}$$

with (θ_i, ϕ_i) being the Declination and Right Ascension of the i-th measurement and (θ_0, ϕ_0) those of the north pole. These latter two coordinates, together with the overall amplitude A, are our free parameters. Such a parameterization has been considered in all previous analyses of the Webb et al. data [3–8] and thus serves as a simple test of our analysis. We note that we do not consider an additional monopole term, both because there is no strong statistical preference for it in previous analyses [3,4] and because physically such term would be understood as being due to the assumption of terrestrial isotopic abundances, in particular of Magnesium—we refer the interested reader to [17] for a detailed discussion of this point.

Additionally we will also consider a parameterization where there is an implicit time dependence in addition to the spatial variation. Previous analyses considered the case of a dependence on look-back time [3,4], but this has the disadvantage of requiring a specific assumption of a cosmological model, and moreover it's not clear how such a dependence would emerge from realistic varying α models. We will instead assume a logarithmic dependence on redshift

$$\frac{\Delta\alpha}{\alpha}(A, z, \Psi) = A \ln(1+z) \cos\Psi; \tag{3}$$

this has the advantage of not requiring any additional free parameters, but such dependencies are also typical of dilaton-type models [18]. As in previous analyses, this parameterization is mainly considered as a means to assess the ability of the data to discriminate between models.

Table 2
One- and three-sigma constraints on the Amplitude and coordinates of maximal variation (Right Ascension and Declination) for a pure spatial dipole variation of α. The 'all data' case corresponds to using the data of Webb et al. [3] together with the 10 individual measurements presented in Table 1. These results are also graphically displayed in Fig. 2.

Dataset & c.l.	Amplitude (ppm)	Right Ascension (h)	Declination (°)
Webb et al. (68.3%)	9.4 ± 2.2	17.2 ± 1.0	-61 ± 10
Webb et al. (99.7%)	9.4 ± 6.4	$17.2^{+4.4}_{-5.3}$	< -28
All data (68.3%)	8.1 ± 1.7	17.2 ± 0.7	-58 ± 7
All data (99.7%)	8.1 ± 5.0	17.2 ± 2.9	< -37

3. Results

We used standard likelihood techniques to fit the two parameterizations to our datasets. We considered grids of size 200^3, for the Amplitude of the dipole and the Right Ascension and Declination of its north pole. We assumed a positive value of the amplitude and uniform priors on all three parameters. It is intuitively clear (but we have nevertheless explicitly checked it, as a further test of our analysis pipeline) that allowing also for negative values of the amplitude would lead to degenerate plots, with a specific amplitude and its negative equally likely and two opposite points on the sky also equally likely as the best-fit poles.

Figs. 1 and 2 and Table 2 summarize the results of our analysis for the case of the pure spatial dipole. For the Webb et al. data alone we confirm the results of previous analyses. However, the addition of the more recent measurements has a significant impact on the results. While the statistical preference for a non-zero amplitude remains above the four-sigma level, the most likely value (and the corresponding uncertainty) for this amplitude decreases considerably, from 9.4 to 8.1 ppm. On the other hand the preferred direction of the north pole does not change significantly, but the corresponding uncertainties are reduced by about thirty percent in each coordinate.

Figs. 3 and 4 and Table 3 contain analogous results for the redshift-dependent dipole. Again the statistical preference for a non-zero dipole is at more than four standard deviations, in this case with a slightly larger value of the preferred amplitude. The uncertainties in all three fitted parameters also increase slightly, as compared to the pure spatial dipole case. In any case we find, in agreement with previous works, that current data cannot strongly discriminate between the two classes of models.

4. Outlook

We have revisited recent indications of spatial variations of the fine-structure constant, α, by considering the impact of the current set of dedicated measurements listed in Table 1 on this analysis. While this dataset is currently still small, it has already been shown that it plays a significant role in obtaining constraints on dark energy and Weak Equivalence Principle violations [19]. Here