

Indications of a Spatial Variation of the Fine Structure Constant

J. K. Webb,¹ J. A. King,¹ M. T. Murphy,² V. V. Flambaum,¹ R. F. Carswell,³ and M. B. Bainbridge¹

¹*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*

²*Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H30, PO Box 218, Victoria 3122, Australia*

³*Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, United Kingdom*

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We previously reported Keck telescope observations suggesting a smaller value of the fine structure constant α at high redshift. New Very Large Telescope (VLT) data, probing a different direction in the Universe, shows an inverse evolution; α increases at high redshift. Although the pattern could be due to as yet undetected systematic effects, with the systematics as presently understood the combined data set fits a spatial dipole, significant at the 4.2σ level, in the direction right ascension 17.5 ± 0.9 h, declination -58 ± 9 deg. The independent VLT and Keck samples give consistent dipole directions and amplitudes, as do high and low redshift samples. A search for systematics, using observations duplicated at both telescopes, reveals none so far which emulate this result.

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Quasar spectroscopy as a test of fundamental physics.—The vast light-travel times to distant quasars allow us to probe physics at high redshift. The relative wave numbers ω_z of atomic transitions detected at redshift $z = \lambda_{\text{obs}}/\lambda_{\text{lab}} - 1$, can be compared with laboratory values ω_0 via the relationship $\omega_z = \omega_0 + Q(\alpha_z^2 - \alpha_0^2)/\alpha_0^2$ where the coefficient Q measures the sensitivity of a given transition to a change in α . The variation in both magnitude and sign of Q for different transitions is a significant advantage of the many multiplet method [1,2], helping to combat potential systematics.

The first application of this method, 30 measurements of $\Delta\alpha/\alpha = (\alpha_z - \alpha_0)/\alpha_0$, indicated a smaller α at high redshift at the 3σ significance level. By 2004 we had made 143 measurements of α covering a wide redshift range, using further data from the Keck telescope obtained by 3 separate groups, supporting our earlier findings, that towards that general direction in the Universe at least, α may have been smaller at high redshift, at the 5σ level [3–5]. The constant factor at that point was (undesirably) the telescope and spectrograph.

New data from the VLT.—We have now analyzed a large dataset from a different observatory, the Very Large Telescope (VLT). Full details and searches for systematic errors will be given elsewhere [6,7]. Here we summarize the evidence for spatial variation in α emerging from the combined Keck + VLT samples. Quasar spectra, obtained from the ESO Science Archive, were selected, prioritizing primarily by expected signal to noise but with some preference given to higher redshift objects and to objects giving more extensive sky coverage. The ESO MIDAS pipeline was used for the first data reduction step, including wavelength calibration, although enhancements were made to derive a more robust and accurate wavelength solution from an improved selection of thorium-argon calibration lamp emission lines [8]. Echelle spectral orders from several exposures of a

given quasar were combined using UVES_POPLER [9]. A total of 60 quasar spectra from the VLT have been used for the present work, yielding 153 absorption systems. Absorption systems were identified via a careful visual search of each spectrum, using RDGEN [10], scanning for commonly detected transitions at the same redshift, hence aligned in velocity coordinates. Several transition matches were required for acceptance and, given the high spectral resolution, chance matches were eliminated.

Absorption system modeling.—As in our previous studies, VPFIT was used to model the profiles in each absorption system [11] with some enhancements, described in [6]. A comprehensive list of the transitions used, their laboratory wavelengths, oscillator strengths, and Q coefficients are compiled in [4,6].

The following general procedures were adhered to: (i) For each absorption system, physically related parameters (redshifts and b parameters) are tied, in order to minimize the required number of free parameters and derive the strongest possible constraints on line positions, and hence $\Delta\alpha/\alpha$. (ii) Parameters were tied only for species with similar ionization potentials, to minimize possible introduction of random effects on α , mimicked by spatial (and hence velocity) segregation effects. (iii) Line broadening is typically dominated by turbulent rather than thermal motion. Both limiting-case models were applied and $\Delta\alpha/\alpha$ determined for each. The final $\Delta\alpha/\alpha$ was derived from a likelihood-weighted average. (iv) Where appropriate and available, isotopic shifts and hyperfine structure are included in the fitting procedure. (v) Velocity structures were determined initially choosing the strongest unsaturated transitions in each system. Normalized residuals across each transition fitted were examined and the fit progressively refined with the introduction of each additional transition to the fit. (vi) Transitions falling in spectral regions contaminated by telluric features or atmospheric

absorption were discarded. Any data regions contaminated by cosmic rays, faulty CCD pixels, or any other unidentified noise effects, were also discarded. (vii) A few gravitational lenses were identified by being difficult or impossible to model successfully. The spatially extended quasar image and the resultant complex line-of-sight geometry can significantly alter apparent relative line strengths. These systems were discarded. (viii) In all cases we derived the final model without solving for $\Delta\alpha/\alpha$. The introduction of $\Delta\alpha/\alpha$ as an additional free parameter was only done once the profile velocity structure had been finalized, eliminating any possible bias towards a “preferred” $\Delta\alpha/\alpha$. One potential consequence of this approach might conceivably be a small bias on $\Delta\alpha/\alpha$ towards zero, should some “fitting away” of $\Delta\alpha/\alpha$ occur by column density adjustments or velocity structure decisions. The reverse is not true; it cannot bias towards a nonzero $\Delta\alpha/\alpha$. For details of all the points above see [6].

VPFIT [11] minimizes χ^2 simultaneously over all species. While the strongest components may appear in all species, weaker components can sometimes fall below the detection threshold and hence are excluded, such that a component which appears in MgII, for example, does not appear in FeII. There is no solution to this (known) problem but its effect merely adds an additional random scatter on $\Delta\alpha/\alpha$ for an ensemble of observations.

Spatially dependent α .—An initial inspection of $\Delta\alpha/\alpha$ vs redshift for the new VLT data set reveals a redshift trend, opposite in sign compared to the earlier Keck data. Splitting each sample at $z = 1.8$, our 2004 Keck sample [5] gave $\langle\Delta\alpha/\alpha\rangle_{z<1.8} = -0.54 \pm 0.12 \times 10^{-5}$ and $\langle\Delta\alpha/\alpha\rangle_{z>1.8} = -0.74 \pm 0.17 \times 10^{-5}$. The present VLT sample, discussed in detail in [6], gives $\langle\Delta\alpha/\alpha\rangle_{z<1.8} = -0.06 \pm 0.16 \times 10^{-5}$ and $\langle\Delta\alpha/\alpha\rangle_{z>1.8} = +0.61 \pm 0.20 \times 10^{-5}$. Errors here and throughout this Letter are 1σ estimates. Our VLT result above for $z < 1.8$ agrees with the VLT data presented in [12].

Errors on individual $\Delta\alpha/\alpha$ values for our VLT sample are $\sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{rand}}^2$, where σ_{rand}^2 was derived empirically by fitting a constant $\Delta\alpha/\alpha$ to the sample, i.e., monopole only, using a modification of the least trimmed squares (LTS) method, where only 85% of data, those points with the smallest squared residuals, are fitted. σ_{rand} was assumed constant for all absorbers and found to be $\approx 0.9 \times 10^{-5}$, showing that the scatter in the VLT $\Delta\alpha/\alpha$ is greater than expected on the basis of statistical errors alone. Errors on $\Delta\alpha/\alpha$ for the Keck sample are discussed in [4], although we derive a new estimate of $\sigma_{\text{rand}} = 1.74$ for the Keck points using the LTS method, again relative to a monopole-only fit to the Keck sample.

The Keck (Mauna Kea, Hawaii) and VLT (Paranal, Chile) locations on Earth are separated by 45° in latitude and hence, on average, observe different directions on the sky. The $\langle\Delta\alpha/\alpha\rangle$ results above suggest exploring a simple spatial dependence using the combined data set.

The Keck sample we use is as presented in [5] with minor modifications: three points were removed. Two had been included erroneously (from a spectrum known to have calibration problems) and one further point was clipped, having a residual greater than 3σ against a modified LTS fit to the Keck data.

We fit three different models to the three datasets (i.e., Keck, VLT, and combined samples). Initially we try a dipole + monopole model, $\Delta\alpha/\alpha = A \cos\Theta + m$, where m allows an offset from the terrestrial value, Θ is the angle on the sky between quasar sight line and best-fit dipole position, and A is the dipole amplitude. Noting the theoretical interpretation of the monopole term is unclear, we fit a second model, without the monopole, $\Delta\alpha/\alpha = A \cos\Theta$. Third, in order to explore a possible spatial gradient in α , we assign a distance to each $\Delta\alpha/\alpha$ measurement of $r(z) = ct(z)$ where c is the speed of light and $t(z)$ is the look-back time at redshift z . The model is then $\Delta\alpha/\alpha = Ar \cos\Theta$.

To estimate the dipole significance we bootstrap the sample, repeatedly randomizing the association between $\Delta\alpha/\alpha$ and the absorption system location in space (i.e., quasar sight line and absorption redshift). A dipole is fitted and its χ^2 derived at each realization, to obtain a χ^2 probability distribution. This gives the probability of fitting a dipole to the data and obtaining a value of χ^2 less than or equal to that observed for the real sample by chance alone, i.e., the statistical significance of a dipole model compared to a monopole, and hence an uncertainty estimate for the dipole amplitude A .

All three models give a detection significance in the range $4.1\text{--}4.2\sigma$ and the best-fit parameters and associated errors (given in the figure captions) vary only slightly.

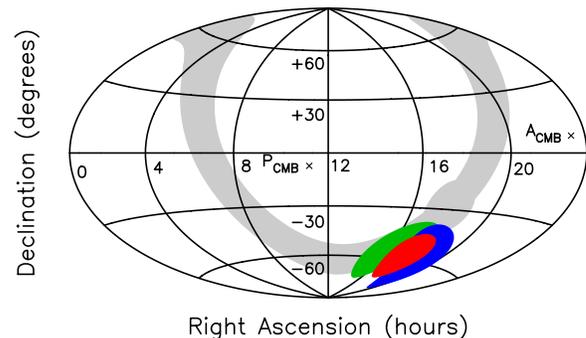


FIG. 1 (color online). All-sky plot in equatorial coordinates showing the independent Keck (green, leftmost) and VLT (blue, rightmost) best-fit dipoles, and the combined sample (red, center), for the dipole model, $\Delta\alpha/\alpha = A \cos\Theta$, with $A = (1.02 \pm 0.21) \times 10^{-5}$. Approximate 1σ confidence contours are from the covariance matrix. The best-fit dipole is at right ascension 17.4 ± 0.9 h, declination -58 ± 9 deg and is statistically preferred over a monopole-only model at the 4.1σ level. For this model, a bootstrap analysis shows the chance probability of the dipole alignments being as good or closer than observed is 6%. For a dipole + monopole model this increases to 14%. The cosmic microwave background dipole and antipole are illustrated for comparison.

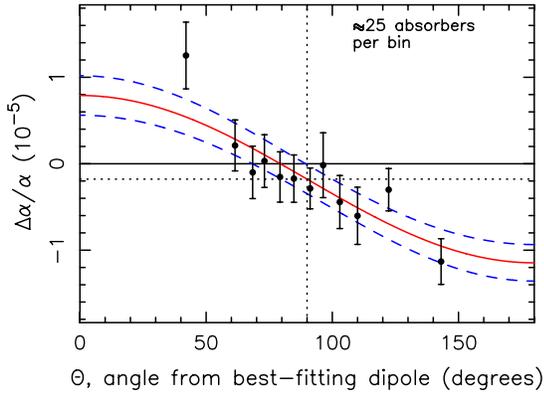


FIG. 2 (color online). $\Delta\alpha/\alpha$ for the combined Keck and VLT data vs angle Θ from the best-fit dipole position (best-fit parameters given in Fig. 1 caption). Dashed lines illustrate $\pm 1\sigma$ errors. For a discussion on the monopole term, see [6].

Figure 1 illustrates an all-sky map for the best-fit no-monopole model, using equatorial coordinates. Approximate 1σ error contours are derived from the covariance matrix. Figure 2 illustrates the $\Delta\alpha/\alpha$ binned data and the best-fit dipole + monopole model. Figure 3 illustrates $\Delta\alpha/\alpha$ vs look-back time distance projected onto the dipole axis, $r \cos\Theta$, using the best-fit dipole parameters for this model. This model seems to represent the data reasonably well and $\Delta\alpha/\alpha$ appears distance dependent, the correlation being significant at the 4.2σ level.

An alternative to the LTS method described above, to allow for any unknown additional contribution to the errors on individual $\Delta\alpha/\alpha$ measurements, one can assume $\sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2$ and iteratively trim the sample during model fitting. This provides a further test of whether the apparent spatial gradient in α is dominated by a subset of the data, perhaps more prone to some unknown systematic than the remainder. Adopting $\sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2$ will tend to result in higher

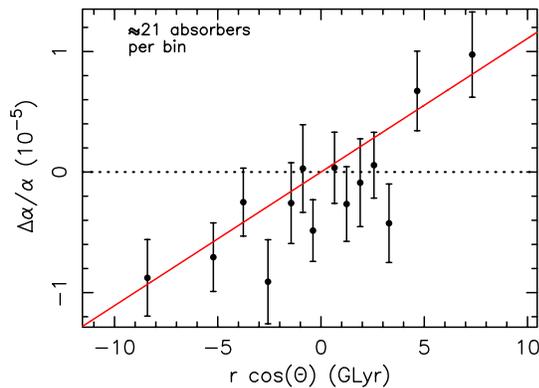


FIG. 3 (color online). $\Delta\alpha/\alpha$ vs $Ar \cos\Theta$ showing an apparent gradient in α along the best-fit dipole. The best-fit direction is at right ascension 17.5 ± 0.9 h, declination -58 ± 9 deg, for which $A = (1.1 \pm 0.25) \times 10^{-6}$ GLy $^{-1}$. A spatial gradient is statistically preferred over a monopole-only model at the 4.2σ level. A cosmology with parameters $(H_0, \Omega_M, \Omega_\Lambda) = (70.5, 0.2736, 0.726)$ was used [18].

significance levels. Figure 4 illustrates this test and shows that the apparent dipole seems robust to data trimming.

Empirical test for systematics.—One potential systematic in the data could arise if there were slight mechanical misalignments of the slits for the two arms of the UVES spectrograph on the VLT. This could cause wavelength shifts between spectral features falling in the blue and red arms. However, this specific effect appears to be substantially smaller than required to explain values of $\Delta\alpha/\alpha \sim 10^{-5}$ seen in the present work [13].

A more subtle but related effect may be slight off-center placement of the quasar image in the spectrograph slit, by different amounts for different exposures, at different wavelength settings. This may apply to either or both Keck and VLT spectra. Since spectrograph slit illuminations are different for quasar (point source) and ThAr calibration lamp (uniform illumination), the subsequent combination of individual exposures to form a one-dimensional spectrum may then contain relative velocity shifts between spectral segments coming from different exposures. This effect will exist in our data at some level and it is clearly important to know the impact on an ensemble of measurements of α .

Fortunately, six quasars in our sample have both Keck and VLT spectra, allowing a direct and empirical check on the effect above, and indeed any other systematics which produce relative velocity shifts along the spectrum. To do this we selected small spectral segments, each a few Å wide, flanked by unabsorbed continuum flux from the quasar, and fitted Voigt profiles using VPFIT, but adding an additional free parameter allowing a velocity shift

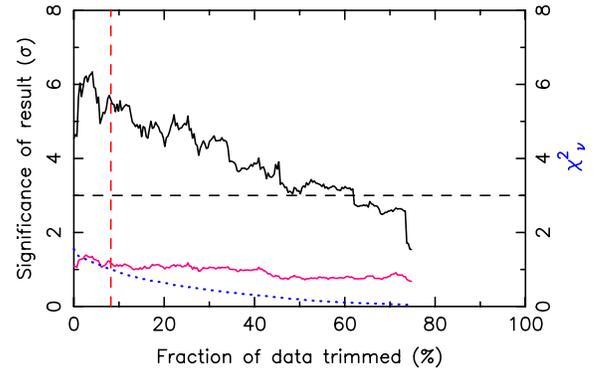


FIG. 4 (color online). As an alternative to increasing $\Delta\alpha/\alpha$ error bars, to account for the additional scatter in the data as described in the text, we instead use $\sigma_{\text{tot}}^2 = \sigma_{\text{stat}}^2$ and iteratively clip the most deviant $\Delta\alpha/\alpha$ value, fitting $\Delta\alpha/\alpha = Ar \cos\Theta$. Approximately 60% of the data must be discarded before the significance drops below 3σ showing the dipole signal is not due to a small subset of the data. The solid (pink) line at the bottom of the graph shows the dipole amplitude in units of 10^{-6} GLy $^{-1}$. The dotted (blue) line at the bottom of the graph shows χ^2_ν and the vertical dashed (red) line illustrates $\chi^2_\nu = 1$ when $\sim 8\%$ of the data has been trimmed, at which point the significance is $\sim 5.5\sigma$.

between the Keck and VLT segments, $\delta v(\lambda_{\text{obs}})_i$, where λ_{obs} is the observed wavelength and i refers to the i th quasar. All available absorption lines in the six spectra were used, including both Lyman- α forest lines and heavy element lines but excluding telluric features. In this way we can map any effective relative distortions in the calibrations between each pair of spectra. A total of 694 measurements were used from the six pairs of spectra over the observed wavelength range $3506 < \lambda < 8945 \text{ \AA}$.

We formed a composite function $\delta v(\lambda_{\text{obs}})$ after first normalizing $\langle \delta v(\lambda_{\text{obs}})_i \rangle = 0$ for each i to remove any potential small constant velocity offsets from each spectrum (expected from off centering of the quasar in the spectrograph slit), which cannot influence α .

Finally, we fit the composite $\delta v(\lambda_{\text{obs}})$ with a linear function $f(\delta v) = a\lambda_{\text{obs}} + b$ where $a = (-7 \pm 14) \times 10^{-5} \text{ km s}^{-1} \text{ \AA}^{-1}$, $b = 0.38 \pm 0.71 \text{ km s}^{-1}$. The final $f(\delta v)$ thus shows a weak (but statistically insignificant) velocity drift, and provides an empirical transformation between the Keck and VLT wavelength scales. For each VLT quasar absorption system, we modify the input laboratory wavelengths used in the Voigt profile fitting procedure λ_{lab} to $\lambda'_{\text{lab}} = \lambda_{\text{lab}} + \Delta\lambda_{\text{lab}}$ where $\Delta\lambda_{\text{lab}} = \lambda_{\text{lab}} \delta v(\lambda_{\text{obs}})/c$, and finally use the λ'_{lab} to recompute $\Delta\alpha/\alpha$ for the entire sample.

There was one complicating aspect of this effect excluded from the discussion above, arising from a seventh spectral pair. The $\delta v(\lambda_{\text{obs}})_7$ showed a more significant nonzero slope than the other six, suggesting a small but significant calibration problem with that particular spectrum. We therefore applied a slightly more complicated transformation to the data to allow for this, using a Monte Carlo simulation to estimate the potential impact on our full combined Keck and VLT sample of both the previous effect measured in six quasars *plus* the effect derived from the seventh quasar simultaneously, applied in appropriate proportions. The full details of this analysis will be discussed separately in [7].

A systematic of the same magnitude as that from the seventh pair cannot be present in any large fraction of our data, otherwise it would generate large numbers of noticeable outliers. If we apply $f(\delta v)$ from the six quasar pairs, the significance of the dipole + monopole model $\Delta\alpha/\alpha = A \cos\Theta + m$ is reduced to 3.1σ . Blindly including the effect of the seventh pair under a Monte Carlo method reduces the significance to a most likely value of 2.2σ . However, in this circumstance we introduce significant extra scatter into the data above that already observed, implying that it overestimates any systematic effect of this type. Additionally, the trend of $\delta v(\lambda_{\text{obs}})_i$ against wavelength is different in magnitude and sign for each quasar pair, implying that these effects are likely to average out for an ensemble of observations. Thus, the application of the effect as described above should be regarded as extreme in terms of impact on estimating $\Delta\alpha/\alpha$.

Conclusions.—Quasar spectra obtained using two separate observatories show a spatial variation in the relative spacings of absorption lines which could be due to an as yet undetected systematic effect, or a dipole variation of α . A fit to the dipole gives a significance of $\geq 4.2\sigma$, assuming the error bars described above. Assuming a dipole interpretation, the two data sets exhibit internal consistency and the directions of the independently derived spatial dipoles agree. The magnitudes of the apparent $\Delta\alpha/\alpha$ variation in both data sets also agree. A subset of the quasar spectra observed at both observatories permits a direct test for systematics. So far, none are found which are likely to emulate the apparent cosmological dipole in α we detect. Consistency with other astronomical data is discussed in [14]. Consistency with laboratory, meteorite, and Oklo natural reactor is discussed in [15]. Short-wavelength oscillatory variations in the wavelength scale such as those reported by [16,17], do not significantly impact on our results. To explain our results in terms of systematics would require at least two different, finely tuned, effects. Future similar measurements targeting the apparent pole and antipole directions will maximize detection sensitivity, and further observations duplicated on two independent telescopes will better constrain systematics. Most importantly, an independent technique is required to check these results. Qualitatively, our results could violate the equivalence principle and infer a very large or infinite Universe, within which our “local” Hubble volume represents a tiny fraction, with correspondingly small variations in the physical constants.

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