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Possible Cosmological Spatial Variation in the Fine-structure Constant

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Abstract: Quasar absorption lines can be used to search for variations in the fine-structure constant, $\alpha \equiv e^2/(4\pi\epsilon_0\hbar c)$, over cosmological times and distances. Previous results from the Keck telescope, in Hawaii, have yielded evidence that α was smaller in the past at the 5σ level. We have analysed 154 quasar absorbers using publicly availble spectra from the VLT (Very Large Telescope), in Chile. The VLT results individually suggest that α may have been larger in the past. A joint analysis of the VLT and Keck data sets finds $> 4\sigma$ evidence for spatial variation in α that is well-represented by a dipole across the sky. The VLT and Keck data sets demonstrate a number of consistencies which supports the idea that the detected dipole effect is real. We are unaware of any systematic effect which can explain the observed dipole effect.

Keywords: fine-structure constant, quasar absorption lines, variation of fundamental constants, cosmology

INTRODUCTION

Quasar absorption lines (QALs), generated by the absorption of light by gas clouds located along the line of sight to quasars, can be observed at extremely high redshifts (z) corresponding to light-travel times approaching the age of the the universe. QALs can be used to constrain evolution in certain fundamental constants throughout time and space (Bahcall et al. 1967). The relative wavelengths of certain transitions observed in QALs can be used to constrain the fine-structure constant, $\alpha \equiv e^2/(4\pi\epsilon_0\hbar c)$. In particular, by comparing the relative spacings of the transitions with precise laboratory measurements one can constrain the relative deviation in α from laboratory values, $\Delta\alpha/\alpha \equiv (\alpha_z - \alpha_0)/\alpha_0$ (where α_z is the value of α at redshift z).

The many-multiplet method

For a particular atomic or ionic transition, the observed rest-frame wavenumber at redshift z, ω_z, depends on α as

$$\omega_z = \omega_0 + qx \tag{1}$$

where

$$x = (\alpha_z/\alpha_0)^2 - 1 \tag{2}$$

provided that $|\Delta\alpha/\alpha| \ll 1$. q is the "sensitivity coefficient" which determines how sensitive a particular transition is to a change in α (Dzuba et al. 1999, Murphy et al. 2003). The sign and magnitude of q is different for different transitions; $|q|$ increases with the square of the nuclear charge (Z^2), and the sign of q is opposite for *s*-*p* and for *d*-*p* transitions. In the many-multiplet method, one compares the relative spacing of transitions from different atomic and ionic species to measure $\Delta\alpha/\alpha$. The use of transitions from different species yields an order-of-magnitude sensitivity improvement from just examining transitions from one species. The use of a number of transitions that have q values of differing sign and magnitude helps control systematic effects (which do not "know" about the signs and magnitudes of the values of q).

Previous results and objective

Significant evidence has emerged from HIRES (High Resolution Echelle Spectrometer) on the Keck Telescope, in Hawaii, that α may have been smaller in the past. In particular, Murphy et al. (2004) analysed 143 absorption systems with spectra from the Keck telescope (see also Webb et al. 1999, 2001, Murphy et al. 2001, 2003), giving a weighted mean over all the systems of $\Delta\alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}$ — evidence that α may have been smaller at high redshift at the 5σ level. Due to the location of the Keck telescope (latitude $\sim 20°$N) the observations are obtained preferentially in one celestial hemisphere. Additionally, the use of only a single telescope to observe the quasar absorbers is undesirable.

Chand et al. (2004) analysed 23 absorption systems using spectra from UVES (the Ultraviolet and Visual Echelle Spectrograph) on the VLT (Very Large Telescope), in Chile (at $\sim 25°$S), however their analysis was shown to be unreliable (Murphy et al. 2007, 2008).

We have attempted to verify or dispute the results of Murphy et al. (2004) by analysing a large number of quasar absorbers from spectra in the publicly available VLT/UVES archive.

ANALYSIS METHODS & METHODOLOGY

To measure $\Delta\alpha/\alpha$ in each quasar absorber, we use the non-linear least squares program VPFIT to fit Voigt profile models to the observed absorption profiles. If the absorption occurred in a single cloud of gas, with no internal velocity structure, the absorption lines would comprise just a single, symmetric component, making the measurement of $\Delta\alpha/\alpha$ straightforward. However, in practice the vast majority of absorption systems display complicated "velocity structure". In order to measure $\Delta\alpha/\alpha$ reliably from such complicated profiles, a model of the velocity structure, with a minimum number of parameters, is constructed and fitted to all available transitions simultaneously. To determine the minimum number of parameters required for the model, we compare models with different numbers of parameters using the Akaike Information Criterion (AIC) (Akaike 1974). We attempt to find the model which minimises the AIC (and therefore best explains the data). VPFIT includes $\Delta\alpha/\alpha$ as a free parameter in the least-squares fit. By simultaneously minimising χ^2 with all other free parameters, we estimate $\Delta\alpha/\alpha$ and its associated error in each quasar absorber.

When we combine the $\Delta\alpha/\alpha$ values obtained from different absorbers under particular models, χ^2_ν ($\equiv \chi^2/\nu$, the χ^2 per degree of freedom) is somewhat greater than the expected value of unity, reflecting unmodelled uncertainties. The most likely sources of these uncertainties are such that the error introduced will be random from absorber to absorber, and therefore will average out over large numbers of absorbers (King et al. 2011). To account for the excess dispersion in the data, we grow our statistical errors ($\sigma_{\rm stat}$) in quadrature with an additional term $\sigma_{\rm rand}$ (i.e. $\sigma_i^2 = \sigma_{i,\rm stat}^2 + \sigma_{\rm rand}^2$) until χ^2_ν about the particular model is ~ 1.

Our methods and methodology are described in detail in Webb et al. (2010) and King et al. (2011).

VLT RESULTS

We have analysed 154 absorbers from 60 quasar sightlines, yielding 154 values of $\Delta\alpha/\alpha$. We consider different models for $\Delta\alpha/\alpha$ below, and compare our values of $\Delta\alpha/\alpha$ to those from Keck. One of the values of $\Delta\alpha/\alpha$ is clearly distinguished as an outlier using the Least Trimmed Squares method (Rousseeuw 1984), and therefore we exclude this $\Delta\alpha/\alpha$ value from all of our statistical analyses. For each absorber, the quasar name, redshift and $\Delta\alpha/\alpha$ value are available in King et al. (2011).

Weighted mean model

After adding $\sigma_{\rm rand} = 0.91 \times 10^{-5}$ in quadrature with our statistical errors, the weighted mean of the 153 VLT $\Delta\alpha/\alpha$ values is $\Delta\alpha/\alpha = (0.21 \pm 0.12) \times 10^{-5}$, with $\chi^2_\nu = 0.99$. This result differs from that of Murphy et al. (2004) at the $\sim 4.7\sigma$ level.

DIPOLE FIT

The Keck sample is dominated by quasars located in the northern celestial hemisphere, whilst the VLT sample is dominated by quasars located in the southern celestial hemisphere. The average Keck results of Murphy et al. (2004) suggest that $\Delta\alpha/\alpha < 0$, whilst the average VLT results suggest that $\Delta\alpha/\alpha > 0$. This north/south difference motivates us to consider potential spatial variation in α. We model the potential spatial variation by a simple dipole+monopole model as a first approximation, namely

$$\Delta\alpha/\alpha = A\cos(\Theta) + m, \tag{3}$$

where A is the dipole amplitude, Θ is the angle between the direction of maximal increase in $\Delta\alpha/\alpha$ (the dipole direction) and the quasar sightline under consideration and m is a constant which allows for a potential universal offset (a monopole) from the laboratory value of $\Delta\alpha/\alpha \equiv 0$. The dipole direction is given in J2000 equatorial coordinates (right ascension, RA, and declination, dec.) and is found when the dipole+monopole model is fitted to the $\Delta\alpha/\alpha$ values.

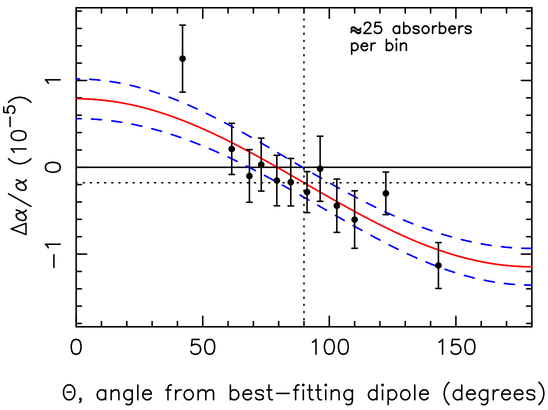

Figure 1. Plot showing binned values of $\Delta\alpha/\alpha$ (and associated 1σ uncertainties) for the combined Keck+VLT sample against the angle from the dipole direction. The red (solid) line shows the model, $\Delta\alpha/\alpha = A\cos(\Theta) + m$. The blue, dashed lines show the 1σ uncertainty on the model fit. The horizontal dotted line shows the value of the monopole, m. The $\Delta\alpha/\alpha$ values are well-represented by the dipole+monopole model, which is preferred over the monopole-only model at the 4.06σ level.

For a dipole+monopole fit to the combined Keck+VLT data, we find that $m = (-0.178 \pm 0.084) \times 10^{-5}$, $A = 0.97 \times 10^{-5}$ (1σ confidence limits $[0.77, 1.19] \times 10^{-5}$), RA $= (17.3 \pm 1.0)$ hr, dec. $= (-61 \pm 10)^\circ$. The dipole+monopole model is preferred over the monopole-only model at the 4.06σ confidence level, yielding signficant evidence for angular and therefore spatial variations in α. We show the dipole fit to the combined Keck+VLT sample in Figure 1.

The combined Keck and VLT $\Delta\alpha/\alpha$ sample displays several consistencies which suggest that the observed spatial variation in α is real:

i) Good alignment between Keck and VLT dipoles. The dipole directions in dipole+monopole models fitted independently to the Keck and VLT samples point in a similar direction, with the dipole vectors being separated by only 24 degrees. A bootstrap analysis shows that the chance of obtaining alignment this good or better by chance is $\approx$ 6 percent. For a dipole-only model, the dipole vectors are separated by 16 degrees, with a chance probability of 14 percent. The good alignment for a dipole-only model is illustrated in Figure 2.

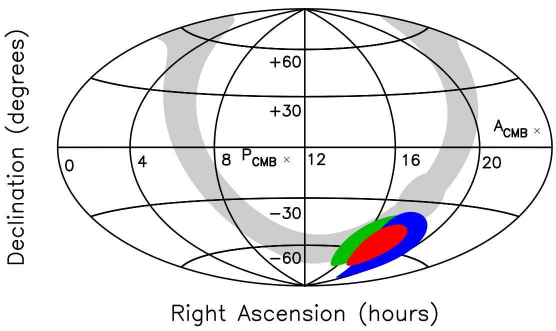

Figure 2. Plot in J2000 equatorial coodinates showing the 68.3 percent confidence limits on the location of the dipole direction in a dipole model fitted to $\Delta\alpha/\alpha$ values from Keck (green region), VLT (blue region) and the combined VLT+Keck sample (red region). The location of pole and antipole of the CMB dipole are marked for comparison (Lineweaver 1997). The grey band schematically indicates the galactic plane.

ii) Good alignment between dipole directions in dipole+monopole models fitted to $z < 1.6$ and $z > 1.6$ sample cuts. The dipole vectors in dipole+monopole models fitted to $z < 1.6$ and $z > 1.6$ cuts of the combined Keck + VLT sample are separated by 13 degrees. A bootstrap analysis shows that the chance of obtaining alignment this good or better by chance is ≈ 2 percent. This close alignment is particularly interesting because the transitions fitted in low- and high-redshift absorbers are quite different, and the expected pattern of line shifts for the high-redshift transitions is qualitatively very different to the low-redshift transitions. The fact that good agreement is found between the dipole directions in low- and high-redshift samples implies that it is unlikely that the observed dipole effect is due to unknown systematics.

iii) Good consistency in the overlap region. In the region of the sky which contains absorbers from both the Keck and VLT samples there is no significant evidence for inconsistency of the $\Delta\alpha/\alpha$ values between the two telescopes.

iv) No outliers. No values of $\Delta\alpha/\alpha$ deviate by more than 3σ from the dipole+monopole model after the inclusion of σ_{rand}, which suggests that the result is not being caused by statistical outliers. Further investigations (see Webb et al. 2010, King et al. 2011) show that the observed dipole effect is not being caused by a deviant subsample of the $\Delta\alpha/\alpha$ values.

SYSTEMATIC ERRORS

We have considered a range of potential systematic effects which could spuriously give rise to the observed dipole effect, including: the effect of differences in the isotopic abundances of Mg in the absorption clouds relative to terrestrial values; the dual-armed nature of the UVES spectrograph; systematic differences in the wavelength calibration scale of the Keck/HIRES and VLT/UVES spectral data, and; wavelength scale distortions that occur within each echelle order in the spectrograph, observed in both Keck/HIRES and VLT/UVES spectral data. None of these effects are of sufficient magnitude or character to be able to explain the observed dipole effect (King et al. 2011).

DISCUSSION

The confirmed detection of cosmological variation in α would demonstrate new physics at the most fundamental level. It would show the existence of a preferred cosmological frame, which would demonstrate the incompleteness of the Einstein Equivalence Principle.

Berengut & Flambaum (2010) explicitly demonstrate that the results presented here are consistent with measurements of β-decay in meteorites, atomic clock measurements and the natural nuclear reactor at Oklo. We are unaware of any experimental result which is in conflict with the results described here.

CONCLUSION

We have outlined here statistically significant evidence that the fine-structure constant may be different in different places in the universe. From an analysis of 293 absorbers from spectra from Keck/HIRES and VLT/UVES, we find $> 4\sigma$ evidence that the cosmological variation is well-described by a dipole+monopole model, implying the existence of a preferred axis in the universe. Our results demonstrate significant internal consistencies which suggests that the observed effect may be real. We are unable to find a systematic effect which explains the observed variation in α.

Clearly, the observed effect must be verified independently. Many of the absorbers in our sample lie near the equatorial region of the dipole, yielding reduced sensitivity to detect variation in α. This means that future, targeted observations along the dipole axis will have signficantly increased sensitivity to confirm or refute the effect described here.

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