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TIME EVOLUTION OF THE FINE STRUCTURE CONSTANT

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ABSTRACT

We present a short review of the current quasar (QSO) absorption line constraints on possible variation of the fine structure constant, $\alpha \equiv e^2/\hbar c$. Particular attention is paid to recent optical Keck/HIRES spectra of 49 absorption systems which indicate a smaller α in the past [1, 2]. Here we present new preliminary results from 128 absorption systems: $\Delta\alpha/\alpha = (-0.57 \pm 0.10) \times 10^{-5}$ over the redshift range $0.2 < z < 3.7$, in agreement with the previous results. Known potential systematic errors cannot explain these results. We compare them with strong 'local' constraints and discuss other (radio and millimeter-wave) QSO absorption line constraints on

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variations in $\alpha^2 g_p$ and $\alpha^2 g_p m_e/m_p$ (g_p is the proton g-factor and m_e/m_p is the electron/proton mass ratio). Finally, we discuss future efforts to rule out or confirm the current $5.7\,\sigma$ optical detection.

1 Introduction

The assumption that the constants of Nature remain constant in spacetime should be experimentally tested [3]. Strong motivation for *varying* constants comes from modern unified theories [4, 5, 6]. Here we review the QSO absorption line constraints on possible variation of the electromagnetic coupling constant, α. Our most recent published results are summarized in reference [2] and in Section 4 we present new preliminary results from a significantly extended optical sample.

2 QSO Absorption Systems and the Alkali Doublet Method

For small variations in α, the relative wavelength separation between the transitions of an alkali doublet (AD) is proportional to α. Savedoff [7] first utilized this to constrain possible variations in α from AD separations seen in galaxy emission spectra. The advantage of this technique is the large look-back times inherent in such cosmological observations ($\sim 10\,$Gyr). Absorption lines produced by intervening clouds along the line of sight to QSOs are substantially narrower than intrinsic emission lines and so yield tighter limits on α-variation [8].

Spectrographs on 8–10-m optical telescopes can record high resolution (FWHM $\sim 7\,\mathrm{kms}^{-1}$), high signal-to-noise (S/N ~ 30 per pixel) spectra of high redshift QSOs over most of the optical range (i.e. 3000–8000 Å) in several $\sim 1\,$hr exposures. Fig. 1 shows an example QSO spectrum with a C IV AD. Many velocity components of the absorption system are clearly resolved.

Varshalovich et al. [10] have recently used spectra of 16 Si IV ADs with a mean redshift $\langle z_{\mathrm{abs}}\rangle = 2.6$ to obtain a value for the fractional difference between α in the laboratory and in the QSO spectra, $\Delta\alpha/\alpha \equiv (\alpha_z - \alpha_0)/\alpha_0 = (-4.6 \pm 4.3_{\mathrm{stat}} \pm 1.4_{\mathrm{sys}}) \times 10^{-5}$. The systematic error term arose from uncertainties in the laboratory wavelengths of the Si IV transitions: the astronomical spectra were of comparable quality to UV laboratory spectra. Significant improvements in the laboratory wavelengths [11] reduce this systematic error to 0.2×10^{-5} $(1\,\sigma)$. We have analyzed 21 high quality Si IV doublets observed with the HIRES spectrograph on the Keck I 10-m telescope in Hawaii, finding [12]

$$\Delta\alpha/\alpha = (-0.5 \pm 1.3_{\mathrm{stat}}) \times 10^{-5} \tag{1}$$

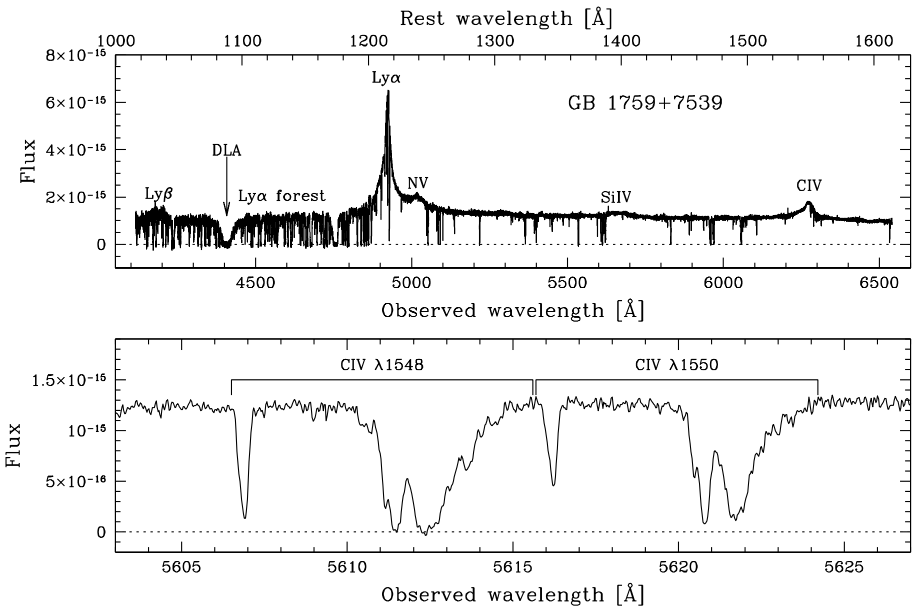

Figure 1: Keck/HIRES spectrum of QSO GB 1759+7539 [9]. The full spectrum (upper panel) shows several emission lines intrinsic to the QSO (Ly-α, Ly-β, N IV, Si IV, C IV). The damped Ly-α system (DLA) at $z_{\rm abs} = 2.6253$ gives rise to heavy element absorption lines in the red portion of the spectrum. The lower panel details a small region containing a C IV alkali doublet. The separation between corresponding velocity components in the two transitions is proportional to α for $\Delta\alpha/\alpha \ll 1$.

at $\langle z_{\rm abs} \rangle = 2.8$. The factor of 3 improvement in precision is due to the high spectral resolution of the HIRES data. This is currently the strongest constraint on $\Delta\alpha/\alpha$ from the AD method.

3 The Many-multiplet Method

The AD method is simple, but inefficient. The s ground state is most sensitive to changes in α (i.e. it has the largest relativistic corrections) but is common to both transitions (Fig. 2a). A more sensitive method is to compare transitions from different multiplets and/or atoms, allowing the ground states to constrain $\Delta\alpha/\alpha$ (Fig. 2b). This is the many multiplet (MM) introduced in [13, 14].

To illustrate the MM method, consider the following semi-empirical equation for the relativistic correction, Δ, for a transition from the ground state with total angular momentum, j:

$$\Delta \propto (Z\alpha)^2 \left[\frac{1}{j + 1/2} - C \right] , \qquad (2)$$

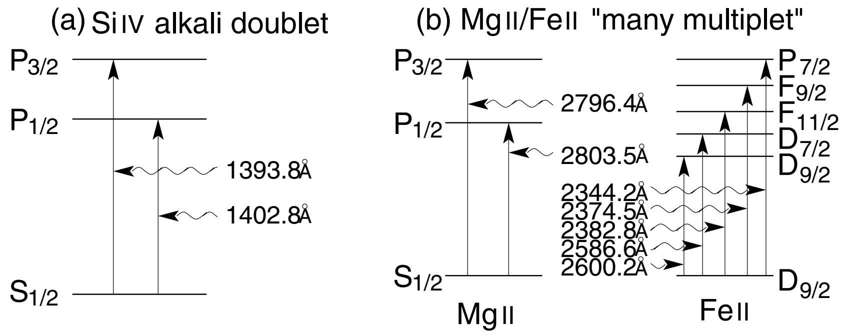

Figure 2: (a) The AD method is not sensitive to the maximal relativistic corrections in the common S ground state. (b) Comparison of different ions increases sensitivity to $\Delta\alpha/\alpha$, increases statistics and decreases systematic errors.

where Z is nuclear charge and many-body effects are described by $C \sim 0.6$. To obtain strong constraints on $\Delta\alpha/\alpha$ one can (a) compare transitions of light ($Z \sim 10$) atoms/ions with those of heavy ($Z \sim 30$) ones and/or (b) compare s–p and d–p transitions of heavy elements. For the latter, the relativistic corrections will be of opposite sign which further increases sensitivity to α-variation and strengthens the MM method against systematic errors in the QSO spectra (see Section 5).

More formally, we may write the following equation for the rest-frequency, ω_z, of *any* transition observed in the QSO spectra at a redshift z:

$$\omega_z = \omega_0 + q\left[\left(\frac{\alpha_z}{\alpha}\right)^2 - 1\right], \qquad (3)$$

where ω_0 is the frequency measured in the laboratory on Earth (we omit higher order terms here for simplicity). Laboratory measurements [15, 16, 11] of ω_0 for many transitions commonly observed in QSO spectra now allow a precision of $\Delta\alpha/\alpha \sim 10^{-7}$ to be achieved. The q coefficient contains all the relativistic corrections and measures the sensitivity of each transition frequency to changes in α. These have been calculated in [13, 17, 18, 19] to $< 10\%$ precision using the Dirac-Hartree-Fock approximation and many-body perturbation theory. Note that the form of Eq. 3 ensures one cannot infer a non-zero $\Delta\alpha/\alpha$ due to errors in the q coefficients.

Fig. 3 shows the distribution of q coefficients in (rest) wavelength space. Our sample conveniently divides into low- and high-z subsamples with very different properties. Note the simple arrangement for the low-z Mg/Fe II systems: the Mg transitions are used as anchors against which the large, positive shifts in the Fe II transitions can be measured. Compare this with the complex arrangement for the high-z systems: low-order distortions to the wavelength scale will have a varied and complex affect on $\Delta\alpha/\alpha$ depending on which transitions are fitted in a given

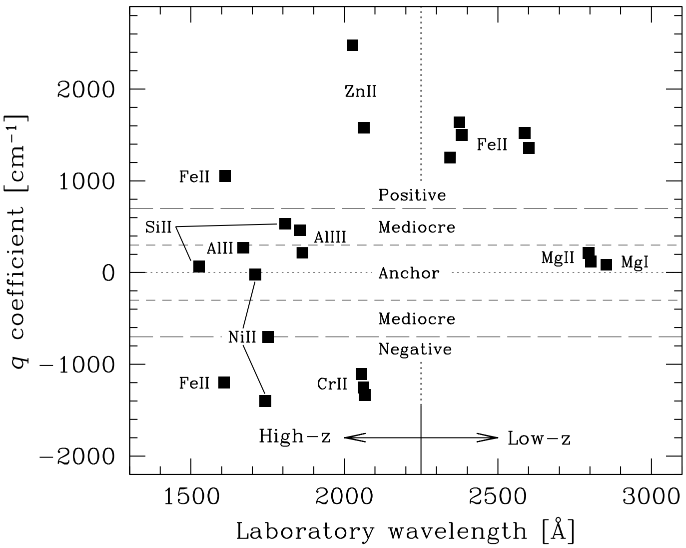

Figure 3: Distribution of q coefficients for the transitions used in the MM method. For the low-z Mg/Fe systems, a compression of the spectrum can mimic $\Delta\alpha/\alpha < 0$. However, the complex arrangement at high-z indicates resistance to such systematics.

absorption system. In general, the complexity at high-z will yield more robust values of $\Delta\alpha/\alpha$.

4 Recent Results

For each absorption system we fit multiple velocity component Voigt profiles to all available (typically ∼5) MM transitions. We minimize χ^2 for all velocity components *simultaneously* to obtain the best fitting value of $\Delta\alpha/\alpha$. The $1\,\sigma$ error is derived from the diagonal terms of the final parameter covariance matrix. Monte Carlo simulations demonstrate the reliability of both $\Delta\alpha/\alpha$ and the errors.

The MM method was first applied to 30 low-z Mg/Fe systems and provided a tentative non-zero $\Delta\alpha/\alpha$ [14]. In [1] we extended the sample of [14] to 49 absorption systems, finding $4.1\,\sigma$ evidence for a smaller α in the redshift range $0.5 < z_{\rm abs} < 3.5$. We have now increased our sample to 128 absorption systems, all observed with Keck/HIRES. Our new preliminary weighted mean is

$$\Delta\alpha/\alpha = (-0.57 \pm 0.10) \times 10^{-5} \tag{4}$$

for $0.2 < z_{\rm abs} < 3.7$, i.e. $5.7\,\sigma$ statistical evidence for a smaller α in high redshift absorption systems. We plot $\Delta\alpha/\alpha$ versus $z_{\rm abs}$ in Fig. 4. Note the overall internal consistency of the results. Fig. 5 suggests possible evolution of α with cosmological

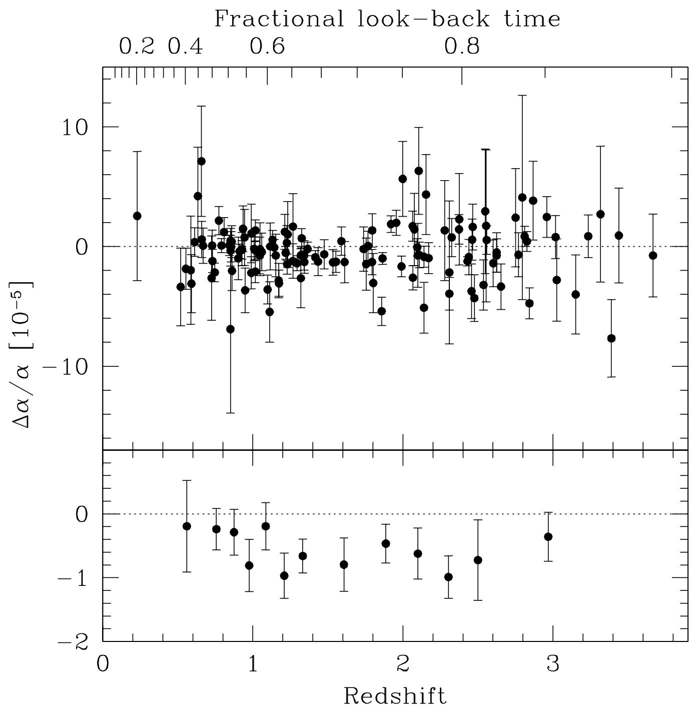

Figure 4: Distribution of $\Delta\alpha/\alpha$ over absorption redshift. The upper panel shows $\Delta\alpha/\alpha$ for 128 absorption systems with $1\,\sigma$ errors. We bin $\Delta\alpha/\alpha$ in the lower panel, presenting the weighted mean $\Delta\alpha/\alpha$ and $1\,\sigma$ error at the mean redshift for each bin.

time, although see Section 7 for further discussion and caveats of fixing $\Delta\alpha/\alpha = 0$ at $z = 0$.

5 Systematic Errors?

The statistical error in this result is now small: we do detect line shifts in the QSO spectra. But are the line shifts due to systematic errors or really due to varying α? We have thoroughly searched for possible systematic errors in our previous results [20], finding none which provide an alternative interpretation of the data. We have extended this search to the new data in Fig. 4 with similar results. Currently, our two largest sources of possible systematic error are:

1. Atmospheric dispersion effects: Before 1996 Keck/HIRES had no image rotator and so the effects of atmospheric dispersion on the wavelength scale could not be avoided. Effective compression of the spectra may result, possibly mimicking a negative $\Delta\alpha/\alpha$ at low-z. 77 of our 128 absorption systems could have been affected. However, we find *no evidence for these effects*: the "affected" and "unaffected" subsamples yield the same $\Delta\alpha/\alpha$. Nevertheless, we modelled

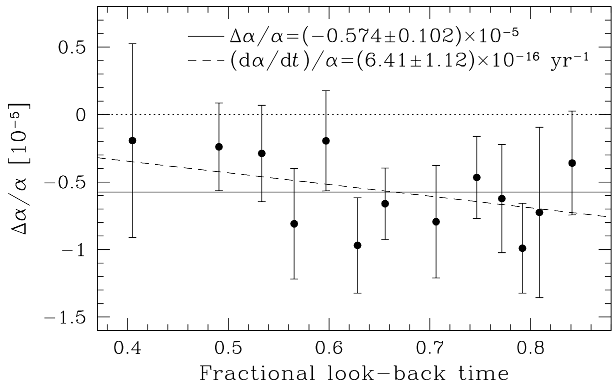

Figure 5: Temporal variation in α. The points are the binned values of $\Delta\alpha/\alpha$ from Fig. 4, the solid line is the weighted mean and the dashed line is a fit to the raw (i.e. unbinned) data fixed to $\Delta\alpha/\alpha = 0$ at $z = 0$. A χ^2 analysis indicates that an evolving $\Delta\alpha/\alpha$ is preferred.

the potential effect and correct the 77 affected systems in Fig. 6 (top panel). This correction reduces the significance of the low-z points but increases the significance of those at high-z, enhancing the apparent trend in $\Delta\alpha/\alpha$ with z.

2. Isotopic ratio evolution: We fit Mg and Si absorption lines with terrestrial values of the isotopic ratios. If the isotopic abundances in the absorption clouds are different to the terrestrial values then we may introduce artificial line shifts, potentially leading to $\Delta\alpha/\alpha \neq 0$. Galactic observations [21] and theoretical models [22] strongly suggest that only the ^{24}Mg and ^{28}Si isotopes will exist in the absorption clouds with significant abundances. The middle panel of Fig. 6 shows that the low-z points become *more* significant when we fit only these isotopes to our data.

The above two effects cannot explain our results. Indeed, applying both corrections (lower panel of Fig. 6), yields a more significant result.

6 Other QSO Absorption Line Methods

Comparing absorption lines of the hydrogen hyperfine (21-cm) transition and millimeter-wave molecular rotational transitions offers an order of magnitude gain in precision over the MM method (per absorption system). The 21-cm/mm frequency ratio is $\propto \alpha^2 g_p$ [23]: $\Delta\alpha/\alpha \neq 0$ manifests itself as a difference between the 21-cm and mm absorption redshifts. A similar difference may arise between 21-cm and optical absorption lines, in this case constraining $\alpha^2 g_p m_e/m_p$ [24]. Here, g_p is the proton g-factor and m_e/m_p is the electron-proton mass ratio.

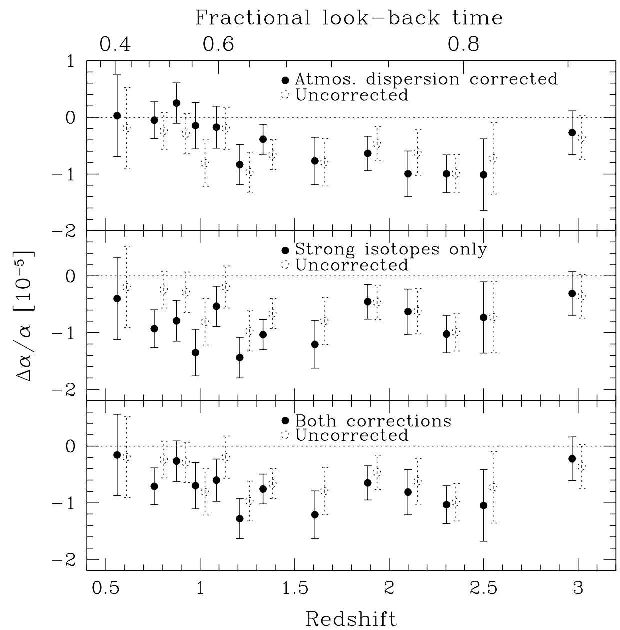

Figure 6: Summary of systematic effects. The top two panels compare the uncorrected results in Fig. 4 with those corrected for our two most important potential systematic effects: atmospheric dispersion and isotopic ratio evolution. The lower panel combines the two corrections.

However, systematic errors in these techniques are more difficult to quantify than for the optical MM method. Since the radio and mm continuum emission come from separate regions of the background QSO, the 21-cm and mm absorption may occur along slightly different sight-lines. Thus, a statistical sample of such measurements is required. Unfortunately, due to the paucity of known absorption systems, only two 21-cm/mm comparisons [25, 26] and one 21-cm/optical comparison [24] presently exist (Fig. 7).

7 Other Limits on Varying α

We summarize the strongest current constraints on α-variation in Fig. 7. For brevity, we do not discuss the reliability of the 'local' constraints, and refer the reader to [27] for a review.

Instead we focus on a comparison of the local and cosmological constraints. Despite the tight limits on $\Delta\alpha/\alpha$ from laboratory atomic clocks, the Oklo phenomenon and meteoritic β-decay, a simple non-linear evolution of α with time can explain all results simultaneously. Moreover, we emphasize that it is dangerous to compare local and cosmological limits without a better understanding of possible

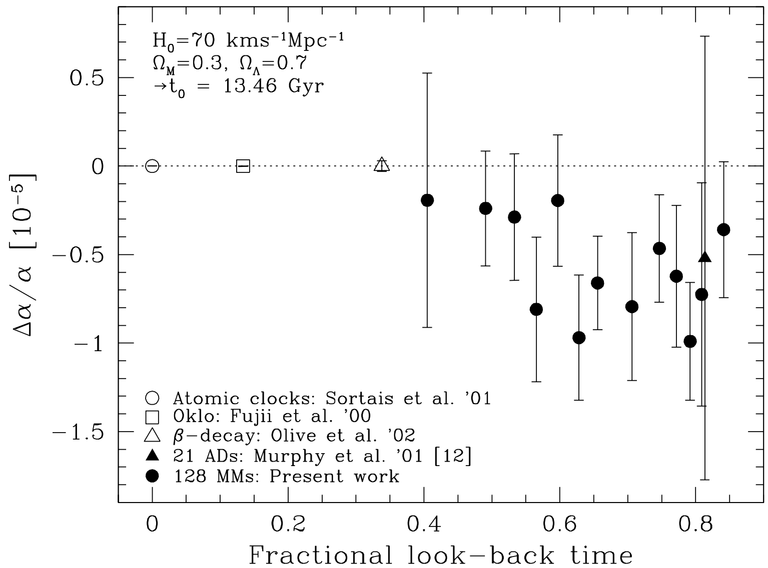

Figure 7: Comparison of the strongest current constraints on $\Delta\alpha/\alpha$ from 'local' tests (open symbols) and QSO absorption lines (solid symbols).

spatial variations in α [3, 28]. For example, absorption spectroscopy of $z_{\rm abs} \approx 0$ absorption clouds in our Galaxy may not yield $\Delta\alpha/\alpha = 0$ (cf. Fig. 5). Even comparing the different QSO absorption constraints is difficult since the MM and AD methods constrain α whereas the 21-cm/mm and 21-cm/optical methods constrain $\alpha^2 g_p$ and $\alpha^2 g_p m_e/m_p$ respectively.

8 The Future

Although the results in Fig. 4 would have tremendous theoretical implications, confirming or refuting them is an observational issue. We are taking two main steps to check our recent results:

1. Independent optical data. The greatest present concern is that only one instrument has been used for all our observations. QSO spectra of similar quality to the Keck/HIRES data are now becoming available. Data from other telescopes/instruments (e.g. VLT/UVES) will provide an important check on our results.

2. Further 21-cm/mm/optical comparisons. We are carrying out observations aimed at identifying new H I 21-cm and mm-band molecular rotational absorption systems (e.g. [29]). Obtaining a statistical sample of 21-cm/mm and

21-cm/optical comparison is vital for negating the line-of-sight velocity differences discussed above.

If step (1) confirms our Keck/HIRES results then step (2) will be a crucial check with entirely different systematic errors.

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