Search for Time Variation of the Fine Structure Constant

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An order of magnitude sensitivity gain is described for using quasar spectra to investigate possible time or space variation in the fine structure constant α. Applied to a sample of 30 absorption systems, spanning redshifts $0.5 < z < 1.6$, we derive limits on variations in α over a wide range of epochs. For the whole sample, $\Delta\alpha/\alpha = (-1.1 \pm 0.4) \times 10^{-5}$. This deviation is dominated by measurements at $z > 1$, where $\Delta\alpha/\alpha = (-1.9 \pm 0.5) \times 10^{-5}$. For $z < 1$, $\Delta\alpha/\alpha = (-0.2 \pm 0.4) \times 10^{-5}$. While this is consistent with a time-varying α, further work is required to explore possible systematic errors in the data, although careful searches have so far revealed none. [S0031-9007(98)08267-2]

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There are several theoretical motivations to search for space-time variations in the fine structure "constant," α. Theories which attempt to unify gravity and other fundamental forces may require the existence of additional compact space dimensions. Any cosmological evolution in the mean scale factor of these additional dimensions will manifest itself as a time variation of our bare three-dimensional coupling constants [1]. Alternatively, theories have been considered which introduce new scalar fields whose couplings with the Maxwell scalar $F_{ab}F^{ab}$ allow a time-varying α [2]. The measurement of any variation in α would clearly have profound implications for our understanding of fundamental physics.

Spectroscopic observations of gas clouds seen in absorption against background quasars can be used to search for time variation of α. Analyses involving optical spectroscopy of quasar absorbers have concentrated on the relativistic fine-structure splitting of alkali-type doublets; the separation between lines in one multiplet is proportional to α^2, so small variations in the separation are directly proportional to α, to a good approximation.

While the simplicity of that method is appealing, the relativistic effect causing the fine splitting is small, restricting the potential accuracy. We demonstrate below how a substantial sensitivity gain is achieved by comparing the wavelengths of lines from *different* species, and develop a new procedure, simultaneously analyzing the Mg II 2796/2803 doublet and up to five Fe II transitions (Fe II 2344, 2374, 2383, 2587, 2600 Å) from three different multiplets. These particular transitions are chosen for the following reasons: (i) They are commonly seen in quasar absorption systems; (ii) they fall into and span a suitable rest-wavelength range; (iii) an excellent database was available [3]; (iv) extremely precise laboratory wavelengths have been measured; and (v) the large Fe and Mg nuclear charge difference yields a considerable sensitivity gain.

We describe the details of the theoretical developments in a separate paper [4], here summarizing the main points. The energy equation for a transition from the ground state within a particular multiplet, observed at some redshift z, is given by

$$E_z = E_c + Q_1 Z^2[(\tfrac{\alpha_z}{\alpha_0})^2 - 1] + K_1(\mathbf{LS})Z^2(\tfrac{\alpha_z}{\alpha_0})^2 + K_2(\mathbf{LS})^2 Z^4(\tfrac{\alpha_z}{\alpha_0})^4, \quad (1)$$

where Z is the nuclear charge, $\mathbf{L}$ and $\mathbf{S}$ are the electron total orbital angular momentum and total spin, respectively, and E_c is the energy of the configuration center. The term in the coefficient Q_1 describes a relativistic correction to E_c for a given change in α, α_0 is the zero redshift value, and α_z is the value at some redshift z. Rearranged, this gives

$$E_z = E_{z=0} + [Q_1 + K_1(\mathbf{LS})]Z^2[(\tfrac{\alpha_z}{\alpha_0})^2 - 1] + K_2(\mathbf{LS})^2 Z^4[(\tfrac{\alpha_z}{\alpha_0})^4 - 1]. \quad (2)$$

Equation (2) is an extremely convenient formulation, the second and third terms contributing only if α deviates from the laboratory value. Accurate values for the relativistic coefficients, Q_1, K_1, and K_2, have been computed using relativistic many-body calculations and experimental data. The coefficients and laboratory rest wavelengths are given in Eq. (3). For Fe II, the relativistic coefficients (Q_1) are at least 1 order of magnitude larger than the spin-orbit coefficients (K_1). The variation of the Fe II transition frequencies with α is thus completely dominated by the Q_1 term. In Mg II, the relativistic corrections are small due to the smaller nuclear charge Z [see Eq. (2)], so while a change in α induces a relatively large change in the observed wavelengths of the Fe II transitions, the change is small for Mg II. The relative shifts are substantially greater than those for a single alkali doublet alone (such as Mg II), so Mg II acts as an "anchor" against which the larger Fe II shifts are measured. A comparison of the observed wavelengths of light and heavy atoms thus provides a dramatic increase in sensitivity compared to analyses of alkali doublets alone.

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Since it is already clear from previous observational constraints that any change in α will be very small [5–7], it is vital that $E_{z=0}$ is known accurately enough. Indeed, the *change* in the frequency interval between Mg II 2796 and Fe II 2383 induced by a fractional change $\Delta\alpha/\alpha = 10^{-5}$ is, using Eq. (3), 0.03 cm^{-1}. Thus, independent of the quality of the observations, the limiting accuracy in a determination of $\Delta\alpha/\alpha$ is $\sim 10^{-5}$ for an uncertainty in the laboratory frequency of ~ 0.03 cm^{-1}. This highlights the advantage of comparing light and heavy atoms. Previous analyses of alkali doublets [5,6] have used frequencies of about the accuracy above, but have been restricted to placing limits of $\Delta\alpha/\alpha \approx 10^{-4}$.

Very precise laboratory spectra of the Mg II 2796 and Mg II 2803 lines have recently been obtained [8], in excellent agreement with previous accurate measurements of Mg II 2796 alone [9,10]. Similarly, precise Fe II hollow-cathode spectra exist [11]. Inserting these laboratory wavelengths and our Q and K coefficients into Eq. (2), we obtain the dependence of frequency on α for Mg II [top two equations in Eq. (3) below] and Fe II,

$$\begin{aligned}
^2P\ J = 1/2: &\quad \omega = 35\,669.286(2) + 119.6x\,,\\
J = 3/2: &\quad \omega = 35\,760.835(2) + 211.2x\,,\\
^6D\ J = 9/2: &\quad \omega = 38\,458.9871(20) + 1394x + 38y\,,\\
J = 7/2: &\quad \omega = 38\,660.0494(20) + 1632x + 0y\,,\\
^6F\ J = 11/2: &\quad \omega = 41\,968.0642(20) + 1622x + 3y\,,\\
J = 9/2: &\quad \omega = 42\,114.8329(20) + 1772x + 0y\,,\\
^6P\ J = 7/2: &\quad \omega = 42\,658.2404(20) + 1398x - 13y\,,
\end{aligned} \tag{3}$$

where $x = [(\frac{\alpha_z}{\alpha_0})^2 - 1]$ and $y = [(\frac{\alpha_z}{\alpha_0})^4 - 1]$.

The astronomical data used for this analysis was obtained using the HIRES echelle spectrograph [12] on the Keck I 10-m telescope during three observing runs in 1994–1996. High-quality spectra of 25 quasars were obtained, in which intervening absorption systems at low/intermediate redshift have been identified exhibiting Fe II, Mg II, and other species. Full observational details are given in Ref. [3].

We now determine the relative positions of the Fe II and Mg II lines and estimate $\Delta\alpha/\alpha$ for each absorption system in the sample. Measuring each line (i.e., Mg II 2796, Mg II 2803, and 5 Fe II lines) independently is not optimal, because the number of fitting parameters is not minimized, as discussed below. The procedure used is iterative, where all available lines are fitted simultaneously with Voigt profiles, using VPFIT, a non-linear least-squares program designed specifically for analyzing quasar absorption spectra [13]. We minimize the total number of free parameters by linking physically related parameters: (i) The redshifts of the corresponding Fe II and Mg II components are tied; (ii) the column densities N(Fe II), N(Mg II) for individual components can vary independently of each other, but the velocity dispersion parameters b(Fe II), b(Mg II), ($b = \sqrt{2}\,\sigma$), in corresponding components, are constrained by $\sqrt{(24/56)}\,b(\text{Mg II}) \le b(\text{Fe II}) \le b(\text{Mg II})$. We carry out 150 separate fits to each absorption system, varying α slightly each time, using Eq. (3) to compute the input rest-frame wavelengths. That procedure is performed 3 times, twice where the b parameters are related according to the two extremes above (i.e., thermal or turbulent line-broadening) and a third time where all b parameters vary independently. The fitting procedure returns a value of χ^2_{min} which was computed as a function of $\Delta\alpha/\alpha$. We used the standard statistical procedure of estimating 1σ errors on $\Delta\alpha/\alpha$ from $\chi^2_{\text{min}} \pm 1$.

Several consistency checks are imposed before accepting a result. First, the χ^2_{min} for each individual spectral region being fitted must be statistically acceptable (i.e., its reduced χ^2 is ≈ 1). It follows that χ^2_{min} for the fit as a whole is statistically consistent with the number of degrees of freedom for that fit. Second, we require statistical consistency between the three separate analyses (for the three different b constraints). If any of the three $\Delta\alpha/\alpha$ differ by more than 1σ from either of the other two, the system is rejected. These criteria lead to the rejection of only about 1/10 of the sample, reflecting the good general statistical robustness of the procedure. The final $\Delta\alpha/\alpha$ accepted corresponded to the lowest of the three values of χ^2_{min}.

The best-fit values of $\Delta\alpha/\alpha$, and the 1σ error bars, are plotted against redshift in Fig. 1. For $z < 1$ there is no departure from the present-day value. The scatter in the data is consistent with the individual error bars; i.e., there is no evidence for any space or time variations in α. However, at $z > 1$ the situation is less clear, with 14 points giving $\chi^2 = 34.9$, 3 falling above zero and the rest below. Figure 1 shows there is a dip in a relatively narrow redshift interval $0.9 < z < 1.2$, where 9 out of the 10 points lie below zero, and it is this dip which causes the overall $z > 1$ χ^2 to be high. Assuming that this is a statistical fluctuation and that we have somehow underestimated the errors, we can increase the error bars on each point by a constant amount, S, where $S \ge 0$ such that the reduced $\chi^2 = 1$, i.e., the error on the ith point becomes $\sigma_i' = \sigma_i + S$ (where σ_i is the value illustrated in Fig. 1). The results of this procedure, for the sample as a whole, and in two redshift ranges are

$$\begin{aligned}
\tfrac{\Delta\alpha}{\alpha} &= (-1.09 \pm 0.36) \times 10^{-5} \qquad (0.6 < z < 1.6)\,,\\
\tfrac{\Delta\alpha}{\alpha} &= (-0.17 \pm 0.39) \times 10^{-5} \qquad (0.6 < z < 1.0)\,,\\
\tfrac{\Delta\alpha}{\alpha} &= (-1.88 \pm 0.53) \times 10^{-5} \qquad (1.0 < z < 1.6)\,.
\end{aligned} \tag{4}$$

The values of S are, in order, $S = 0.46$, 0.06, and 0.53. The whole sample departs from zero at the 3.0σ level towards smaller values of α. However, the $z < 1$ points alone show no significant trend, suggesting that there are no significant errors in the adopted laboratory Fe II and Mg II wavelengths, or in the general procedure.

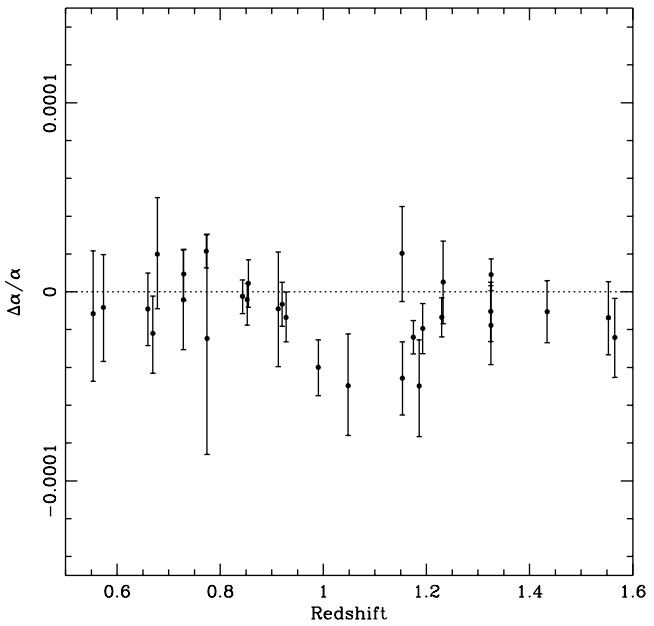

FIG. 1. Plot of $\Delta\alpha/\alpha$ vs z for 30 Fe II/Mg II absorption systems. All the transitions given in Eq. (3) were used, where available. Plotted error bars were determined from $\chi^2_{\rm min} \pm 1$ (but statistical results estimated using larger errors, as discussed in the text).

However, at $z > 1$, there is a 3.5σ deviation. We have also experimented with other statistical methods which also give more conservative error estimates than a simple weighted mean (e.g., a Bayesian method), and obtain results consistent with those given above (to be reported elsewhere).

What systematic (nonphysical) effects could mimic such an effect (either a general trend towards negative $\Delta\alpha/\alpha$ for $z > 1$ or the curious "cusp" in the range $0.9 < z < 1.2$)? The quality of the spectroscopic data does not deteriorate with redshift (this would be revealed by larger error bars at higher redshift) but, in fact, improves [3]. The unmodified error bars reflect uncertainties due to signal to noise, spectral resolution, velocity structure, and the number of absorption lines fitted, and assume we have properly deconvolved the absorption features into their correct number of individual components. However, this assumption may be wrong. There may be weak blended unresolved lines, even with data of the high quality we have here. For a specific absorption system, an interloper could indeed mimic a shift, e.g., if it were blended with one of the Mg II 2796 or 2803 anchors. Nevertheless, it is unlikely that this occurs preferentially for $z > 1$ and not for $z < 1$. Nor should *random* blending create a negative $\Delta\alpha/\alpha$ trend; it should merely increase the scatter about a mean of zero. An extensive search for a *systematic* blend (i.e., a weak transition from some other species at the same redshift as the absorbing cloud), falling close to one of the Mg or Fe absorption lines, proved negative (details to be reported elsewhere).

Uncertainties in the Fe or Mg laboratory wavelengths cannot be responsible, since any errors would be an order of magnitude below the observed effect, and in any case, the $z < 1$ points reveal no offset. We also checked to see whether uncertainty in the instrumental resolution could introduce errors, and found the results insensitive to this. It is conceivable that certain absorption redshifts could be less reliable, due to the positioning of the Fe II and Mg II lines with respect to the echelle order edges, where wavelength calibration may be worse. At higher wavelengths, the HIRES optical format is such that there are gaps in the wavelength coverage. Also, the ThAr calibration spectrum has fewer lines per unit wavelength at higher wavelengths. These effects could mean that wavelength calibration is less reliable for higher redshift points than the lower redshift ones. Alternatively, perhaps there is a subtle bug in the wavelength calibration software. The $z > 1$ effect we have found is very small: a gradual drift of $\sim$2.5 times the wavelength calibration residuals, over the range corresponding to the observed Fe II and Mg II lines, could produce an effect of the significance we have found. Previous analyses of similar quality data have not demanded such high precision, so such errors could have gone unnoticed in other spectroscopic analyses.

Can any of these effects produce the apparent trend we find? We have carried out extensive numerical experiments aimed specifically at testing for these potential systematic problems. These involved carrying out an identical analysis on the wavelength calibration spectra (ThAr) as for the quasar spectra, measuring the emission line wavelengths and inferring a "change" in α from shifts between the measured and laboratory wavelengths (details to be reported elsewhere). The results were unambiguous, in that any errors in the wavelength calibration across all spectral orders are so small that they could not contribute significantly to the apparent offset at $z > 1$, unless the literature values for the calibration spectral lines (ThAr) are substantially in error, with a gradual nonlinear shift in the ThAr wavelengths.

We consider all of the above potential errors to be rather unlikely. Since the effect is dominated by the $0.9 < z < 1.2$ points, and because a genuine physical effect confined to one specific epoch in the history of the Universe does not seem at present to be well motivated by theoretical expectations, we presume the explanation is that there are additional undiscovered velocity components in the absorbing gas for those particular absorption systems, even though all points have been subjected to the same analysis. Further observations of different species in these clouds could answer this. Our results should thus be regarded as stringent upper limits on any possible time variation rather than a positive detection of a change.

We may compare our results with other recent values. Observations at $z \sim 3$ [6] have yielded an upper limit $|\Delta\alpha/\alpha| < 3.5 \times 10^{-4}$. Our analysis is at lower redshift, so a comparison requires choosing some (arbitrary) functional form of the evolution. At lower redshifts, a recent analysis of radio wavelength spectra of atomic

hydrogen and molecular gas [7] gives limits $|\Delta\alpha/\alpha| < 3 \times 10^{-6}$ at two redshifts, $z = 0.25, 0.68$. An additional recent constraint of $(3.5 \pm 5.5) \times 10^{-6}$ [6] comes from a comparison of hyperfine and optical redshifts. These limits are consistent with the results given in Eq. (4). The strongest terrestrial constraint on the time evolution of α comes from the Oklo natural nuclear reactor [14]. The Oklo event is estimated to have taken place around 1.8×10^9 years ago (corresponding to $z \approx 0.1$). We adopt a cosmological model with $q_0 = 1/2$, $\Lambda = 0$, and take the age of the Universe to be 13×10^9 years. The Oklo data have recently been reexamined [15], and upper limits on a change in α are $-0.9 \times 10^{-7} < (\alpha^{\mathrm{Oklo}} - \alpha_0)/\alpha_0 < 1.2 \times 10^{-7}$, assuming the weak and strong couplings are unchanged. These bounds are clearly consistent with our results for $z < 1$. For the cosmological parameters quoted, if we adopt $\bar{z} = 0.8$, the midpoint of our lower redshift range, Eq. (4) implies

$$\frac{\langle\dot{\alpha}\rangle}{\alpha} = (-2.2 \pm 5.1) \times 10^{-16}\ \mathrm{yr}^{-1} \qquad (0.6 < z < 1.0)\,. \tag{5}$$

What other physical phenomena, other than time variability of α, could give rise to the observational effect we report? The spacing of the Mg II and Fe II isotopes is such that a significant change in the isotopic ratios could explain the observations. However, the change would need to be substantial; for example, this would require *most* of the Mg in the Universe at $z > 1$ to be in ^{26}Mg (the present epoch abundance is $\sim$10%), and a physical mechanism found to convert almost all the ^{26}Mg into ^{24}Mg by the present epoch. If large scale magnetic fields exist, and the quasar light is polarized, these could potentially give rise to correlated apparent shifts in absorbers in neighboring regions of the Universe. However, for magnetic fields to be responsible for the global effect in α for $z > 1$ (but not for $z < 1$), a sharp variation at $z \sim 1$ or some form of oscillatory variation would be required, both of which are hard to motivate.

Some authors have suggested more exotic forms of evolution of the constants, including oscillations [1]. These could arise from new light bosons with mass m, producing periodic variations in the frequency of the radiation emitted at high z, with a modulation frequency $\sim m^{-1}$ [16]. The creation of time-varying α by approximate global symmetry [2] allows oscillatory variations introduced by the decaying mean oscillations of a scalar field coupling to $F_{ab}F^{ab}$. We note that as we move above $z = 1.25$, for a critical-density noninflationary universe, we can encounter causally disconnected regions of the Universe. The observational sensitivity achieved by these observations exceeds that of current microwave background observations, and a larger data set than ours may contain important new cosmological information.

The work we have presented here demonstrates the possibilities for extending this type of study to incorporate different species, other than Mg and Fe, spanning a wider redshift baseline, so equally impressive constraints should be obtainable at higher redshifts. Future analyses of other species will be hampered by the lack of accurate laboratory wavelengths. We hope that this paper will provide an impetus for new high-precision laboratory measurements.

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