Astrophysical Limits on the Evolution of Dimensionless Physical Constants over Cosmological Time

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ABSTRACT

We report new upper limits on any possible long-term time variation of the ratio of the electron to proton masses, \( \frac{m_e}{m_p} \), the fine-structure constant, \( \alpha \), and the quantity \( \alpha^2 g_p \left( \frac{m_e}{m_p} \right) \), where \( g_p \) is the proton gyromagnetic ratio. These limits are based on extremely high precision observations of \( \text{H}_2 \), \( \text{Si}^{3+} \), \( \text{C}^0 \) and \( \text{H}^0 \) in high-redshift quasar absorption lines. They amount to 95% confidence ranges of \((-7.6 \rightarrow 9.7) \times 10^{-14} \text{ yr}^{-1}\) for \( \frac{m_e}{m_p} \), \((-4.6 \rightarrow 4.2) \times 10^{-14} \text{ yr}^{-1}\) for \( \alpha \) and \((-2.2 \rightarrow 4.2) \times 10^{-15} \text{ yr}^{-1}\) for \( \alpha^2 g_p \left( \frac{m_e}{m_p} \right) \), where the elapsed time has been computed for a cosmology with \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0.5 \).

Subject headings: atomic data — cosmology:observations — cosmology:theory — quasars:absorption lines
1. Introduction

Current laboratory, geophysical and astrophysical constraints exclude any significant evolution of most of the dimensionless physical constants over cosmological time (Sisterna & Vucetich 1990). However, refining these limits remains important as they provide constraints on theories such as Kaluza-Klein and superstrings which allow solutions in which there can be time variation of these constants. We report improved astrophysical constraints on the fine-structure constant, $\alpha$ and the ratio of the electron to proton masses, $(m_e/m_p)$.

Savedoff (1956) first pointed out the possibility of using differential measurements of redshifted lines in cosmologically distant objects to test the evolution of certain of the dimensionless physical constants; since then various measurements have been outlined and the observational constraints greatly improved. Recent summaries of these astrophysical measurements may be found in Potekhin & Varshalovich (1994) and Levshakov (1994). In this paper we describe the use of extremely high signal-to-noise and high resolution ($R = 36,000$ to $47,000$) spectra of quasar absorption lines obtained with the Keck 10 m telescope to tighten the evolutionary constraints on $\alpha$, $(m_e/m_p)$ and $(\alpha^2 g_p m_e/m_p)$ by roughly an order of magnitude over previous measurements. Note that, in translating limits to time variation rates we have assumed a flat cosmology ($q_0 = 0.5, \Lambda = 0$) with a Hubble constant of $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Constraints on $(m_e/m_p)$

The presence of cosmological evolution in $(m_e/m_p)$ can be tested by using observations of molecular hydrogen in quasar absorption line systems, assuming that all other dimensional constants, particularly the fine-structure constant, do not vary in such a way as to compensate for the variation in $(m_e/m_p)$. This was first pointed out by Thompson (1975), who noted the different dependence of the electronic, vibrational and rotational energy levels on $(m_e/m_p)$. There is, however, a general unavailability of data at high redshift: to date, only one quasar, PKS 0528 – 250, is believed to have molecular hydrogen in its spectrum, at a redshift of 2.811 (Chaffee, Foltz & Black 1988). Varshalovich and Levshakov (1993) have analyzed this data to obtain a $1 \sigma$ limit of $d(m_e/m_p)/dt \leq 3 \times 10^{-13} \text{ yr}^{-1}$, assuming a time difference of $1.3 \times 10^{10} \text{ yr}$ between $z = 2.811$ and $z = 0$.

We have re-observed PKS 0528 – 250 at much higher spectral resolution ($R = 36,000$) and signal-to-noise, obtaining a 5.4 hour spectrum with the Keck Telescope which unambiguously confirms Chaffee et al.’s identification of molecular hydrogen, as demonstrated in
Fig. 1 which shows the 0–0 and 4–0 bands of the Lyman series. An analysis of the physical properties of the molecular hydrogen itself is given elsewhere (Songaila & Cowie 1995).

Table 1 summarises the properties of those lines that are isolated molecular hydrogen lines, based on their measured column densities and FWHM. In the Born-Oppenheimer approximation, the molecular hydrogen energy levels can be written,

$$E = E_{el} + \left(\frac{m_e}{m_p}\right)^{1/2} E_{vib} + \left(\frac{m_e}{m_p}\right) E_{rot}. \quad (1)$$

So, the energy shift in any vibration-rotation transition $j$ in the Lyman series has the form,

$$\Delta E_j = a + b_j \left(\frac{m_e}{m_p}\right)^{1/2} + c_j \left(\frac{m_e}{m_p}\right) \quad (2)$$

and the difference in energy between two transitions is,

$$(\Delta E_j - \Delta E_i) \sim b_{ji} \left(\frac{m_e}{m_p}\right)^{1/2} + c_{ji} \left(\frac{m_e}{m_p}\right). \quad (3)$$

To lowest order, a change in $(m_e/m_p) \equiv \mu$ induces a change in $\Delta E_i - \Delta E_j$ such that

$$\frac{\delta \mu}{\mu} \approx \frac{\delta v}{c} \left(\frac{2\Delta E_i}{\Delta E_i - \Delta E_j}\right) \quad (4)$$

where $\delta v$ is the mean offset compared to the laboratory value, of the energy difference between the two sets of lines, when that offset is represented as a velocity difference. While the above description is in fact adequate for the analysis and gives a clear insight into the method, we have in practice used the exact relationship,

$$\frac{\delta v}{c} = (k_i - k_j) \left(\frac{\delta \mu}{\mu}\right) = K_{ij} \left(\frac{\delta \mu}{\mu}\right) \quad (5)$$

where the $k$ coefficients have been tabulated by Varshalovich & Levshakov (1993).

A regression analysis based on the data of Table 1 then gives a best fit value $\delta \mu/\mu = 8 \times 10^{-5}$ and a 95% confidence range of $-5.5$ to $7 \times 10^{-4}$. The r.m.s. velocity spread is $2.5$ km s$^{-1}$. For our ‘standard’ cosmology, the time to $z = 2.811$ is $7.2 \times 10^9$ yr and our 95% confidence limit for $\dot{\mu}/\mu$ is $-7.6$ to $9.7 \times 10^{-14}$ yr$^{-1}$. This is approximately an order of magnitude improvement over the previous result.
3. Constraints on $\alpha$

The separation between the wavelength ($\lambda_1$) corresponding to the transition $^2S_{1/2} \rightarrow ^2P_{3/2}$ and that ($\lambda_2$) corresponding to the transition $^2S_{1/2} \rightarrow ^2P_{1/2}$ in an alkaline ion is proportional to $\alpha^2$ to lowest order in $\alpha$ (Bethe & Salpeter 1977). Writing $\bar{\lambda} = (2/3)\lambda_1 + \lambda_2$,

$$\frac{(\lambda_1 - \lambda_2)}{\lambda} = \frac{\Delta \lambda}{\bar{\lambda}} \sim \alpha^2.$$  \hspace{1cm} (6)

So any change in $\alpha$ will result in a corresponding change in $\Delta \lambda$ in the separation of the doublets in a high-z quasar (as was first used by Bahcall & Salpeter [1965] and Wolfe, Brown & Roberts [1976])

$$\frac{\delta \alpha}{\alpha} = \frac{\delta(\Delta \lambda)}{2\Delta \lambda}.$$ \hspace{1cm} (7)

$$\left(\frac{\delta \alpha}{\alpha}\right) \approx \left(\frac{\lambda}{2\Delta \lambda}\right) \left(\frac{\delta v}{c}\right).$$ \hspace{1cm} (8)

The most recent analyses using this method (Potekhin & Varshalovich 1994) have used very large inhomogeneous samples of C IV, N V, O VI, Mg II, Al III and Si IV doublets and obtained a 95% confidence limit of $|\alpha^{-1}(d\alpha/ dz)| < 5.6 \times 10^{-4}$.

We have improved this analysis using a homogeneous sample of doublets observed at high spectral resolution. However, before proceeding further, it is important to note that, for a given accuracy in determining $\Delta v/c$, the sensitivity of determining $\Delta \alpha$ is inversely proportional to the relative splitting of the doublet ($\Delta \lambda / \bar{\lambda}$). For this reason, Si IV, the most widely spaced of the doublets ($\lambda \lambda 1393.755$, $1402.770$ Å; Toresson 1960) is by far the most sensitive probe of $\alpha$, followed by Al III and Mg II. We have therefore restricted our analysis to the Si IV doublet. Choosing a doublet with large ($\Delta \lambda / \bar{\lambda}$) also alleviates a second problem, namely that, for many of these doublets, the laboratory wavelength separation is not known to very high precision. This enters directly in the ($\delta v/c$) term as a systematic uncertainty which is minimised for large ($\Delta \lambda / \bar{\lambda}$). For Si IV, Martin and Zalubas (1983) estimate the uncertainty in Toresson’s (1960) wavelengths at a maximum of $5 \, m\text{Å}$, which, if adopted as an extreme upper bound to the uncertainty in the doublet spacing, translates into an uncertainty of $1.0 \, \text{km s}^{-1}$ in $\Delta v$, and currently imposes a fundamental limit of $2.7 \times 10^{-4}$ on the accuracy to which $\delta \alpha / \alpha$ can be determined.

We have identified a number of Si IV doublets in high-z quasar absorption-line systems observed with the Keck HIRES spectrograph at $R = 36,000$. The redshift systems used in the analysis were seen not only in Si IV but also in lines of other species, such as C IV and Ly $\alpha$; therefore, the identifications do not depend solely on the spacing of the Si IV lines. Table 2 lists the relative velocity shifts for Si IV. As is illustrated in Fig. 2, the offsets have
been measured by cross-correlating the two members of the doublet. The r.m.s. uncertainty in this procedure is 1.1 km s$^{-1}$, determined from measurements of the more common C IV doublet. The 95% confidence limits inferred from Table 2 are ($\delta \alpha / \alpha$) = ($-2.2, 1.6 \times 10^{-4}$), comparable to the systematic error from the uncertainty in the laboratory wavelengths. Combining the two errors in quadrature, we have $|\delta \alpha / \alpha| < 3.5 \times 10^{-4}$ and our results imply $|\alpha^{-1} d\alpha / dz| < 1.1 \times 10^{-4}$, a factor of 5 lower than Potekhin and Varshalovich’s (1994) result. Further improvements will require either new laboratory determinations of the Si IV doublet separation, or local observations of the Si IV doublet spacing in the nearby interstellar and intergalactic gas. The later can be carried out by the spectrographs on the Hubble Space Telescope. To be useful for this purpose, high resolution measurements with the Goddard High Resolution Spectrograph would be required. Current published values are not adequate.

4. **Constraints on $\alpha^2 g_p(m_e/m_p)$**

The ratio of the frequencies of the hyperfine 21 cm absorption transition of neutral hydrogen ($\nu_a$) to an optical resonance transition ($\nu_b$) has the dependence

$$\frac{\nu_a}{\nu_b} \sim \alpha^2 g_p \left( \frac{m_e}{m_p} \right) \equiv X$$

so that evolution of this quantity will result in a difference in the measured redshifts of 21 cm and optical absorption

$$\delta z = z_{\text{opt}} - z_{21} = (1 + z) \left( \frac{\delta x}{x} \right).$$

The current best limits on this quantity are given by Tubbs and Wolfe (1980), who found $(1/x)(dx/dz) \leq 1.1 \times 10^{-4}$ for absorption in the quasar Q1331+170. The redshift of the hyperfine absorption in Q1331+170 is known to very high precision ($z_{21} = 1.77642 \pm 2 \times 10^{-5}$; Wolfe & Davis 1979) and the uncertainty in the Tubbs and Wolfe (1980) estimate arises primarily in the imprecision of the optical redshift. Recently, Songaila et al. (1994) have presented high S/N observations of C$^0$ absorption and fine-structure C$^0$, finding $z_{\text{opt}} = 1.77644 \pm 2 \times 10^{-5}$. Because the C$^0$ arises in the same cloud components responsible for the 21 cm absorption, the comparison of $z_{21}$ and $z_{\text{opt}}$ should be relatively secure against different kinematic structures being present in the two measurements. Combining the two redshifts, we find

$$\frac{\delta X}{X} = 7 \times 10^{-6} \pm 1.1 \times 10^{-5}$$

(11)

corresponding to a 95% confidence range for $(1/x)(dx/dz)$ of $(-2.2, 4.2 \times 10^{-15}$ yr$^{-1}$ for our standard cosmology.
5. Conclusion

The three constraints presented here can be compared with existing laboratory and astrophysical constraints. The limits on $\alpha^2 g_p(m_e/m_p)$ currently constitute the tightest astrophysical constraint on the evolution of these dimensionless parameters, implying $|\dot{\alpha}/\alpha| \leq 2.1 \times 10^{-15}$ yr$^{-1}$ and $|(m_e/m_p)/(m_e/m_p)| \leq 4.2 \times 10^{-15}$ yr$^{-1}$ at the 95% confidence level, in the absence of relative cancellation. For $\dot{\alpha}/\alpha$, the astrophysical measurement is now comparable to the best local tests (Sisterna & Vucetich 1990), which give $|\dot{\alpha}/\alpha| \leq 1.3 \times 10^{-15}$ yr$^{-1}$ (95% confidence), but, because of the larger timeline, may provide more stringent constraints on models with non-linear evolution of $\alpha$.

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Table 1. Molecular Hydrogen Lines in PKS 0528 – 250

| Line   | $\lambda_{\text{vac}}^a$ | $k^b$ | $\langle \delta v/c \rangle \times 10^{-5}^c$ |
|--------|--------------------------|-------|-------------------------------------------|
| 0–0 R(0) | 1108.128                 | 7.79  | 0.1                                       |
| 0–0 R(1) | 1108.633                 | 8.25  | −0.9                                      |
| 1–0 R(0) | 1092.195                 | 0.72  | −0.6                                      |
| 1–0 R(1) | 1092.732                 | 1.22  | 0.2                                       |
| 1–0 P(1) | 1094.052                 | 2.38  | 0.7                                       |
| 1–0 R(2) | 1094.225                 | 2.62  | 1.2                                       |
| 1–0 P(2) | 1096.438                 | 4.54  | 1.3                                       |
| 2–0 R(1) | 1077.699                 | −5.24 | −1.1                                      |
| 2–0 P(1) | 1078.925                 | −4.18 | 0.3                                       |
| 2–0 R(2) | 1079.226                 | −3.81 | 0.2                                       |
| 2–0 P(2) | 1081.226                 | −2.05 | −0.9                                      |
| 3–0 P(1) | 1064.605                 | −10.21| 0.5                                       |
| 3–0 R(2) | 1064.995                 | −9.73 | −0.4                                      |
| 3–0 P(2) | 1066.900                 | −8.10 | −1.2                                      |
| 4–0 R(0) | 1049.367                 | −17.27| 0.8                                       |
| 4–0 R(1) | 1049.959                 | −16.67| −1.0                                      |
| 4–0 P(1) | 1051.032                 | −15.76| −0.5                                      |
| 4–0 R(2) | 1051.498                 | −15.18| 1.4                                       |
| 4–0 P(2) | 1053.284                 | −13.67| 0.0                                       |

$^a$Dabrowski 1984  
$^b$Potekhin & Varshalovich 1994  
$^c$Frame of reference is such that $\langle \delta v/c \rangle = 0$
Table 2. Si IV Doublet Separations

| Quasar      | z   | δv  |
|-------------|-----|-----|
| 0302−003    | 2.785 | 0.8 |
| 0528−250    | 2.813 | 0.5 |
| 0528−250    | 2.810 | 0.4 |
| 0528−250    | 2.672 | −2.1|
| 1206+119    | 3.021 | −0.5|
| 2000−330    | 3.551 | −1.5|
| 2000−330    | 3.548 | 1.1 |
Fig. 1.— Spectra of the 0–0 and 4–0 vibration transitions of the Lyman series of molecular hydrogen at $z = 2.811$ in the quasar PKS 0528 $-$ 250. The spectrum is shown in the rest frame with the dashed lines indicating the wavelengths of the $J \leq 2$ transitions in each band. The remaining (generally broader) lines in the spectra are primarily Lyman alpha forest lines of intergalactic neutral hydrogen.

Fig. 2.— Cross correlation of the two lines of the Si IV doublet for a cloud in the spectrum of the quasar Q0302 $-$ 003. The quantity $(1 - S(\lambda))$ is plotted versus $v$, where $S$ is the normalised spectrum for the stronger line, and the quantity $2(1 - S(\lambda))$ (dashed line) is overplotted versus $v - \Delta v$ for the weaker line. Here $\Delta v$ is the measured offset. The vertical dashed lines show the velocity range over which the cross correlation function was computed.
