Improved constraints on possible variation of physical constants from QSO absorption lines

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Improved constraints on possible variation of physical constants from $\text{H}\,\,21\text{cm}$ and molecular QSO absorption lines

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Abstract

QSO absorption spectra provide an extremely useful probe of possible cosmological variation in various physical constants. Comparison of $\text{H}\,21\text{cm}$ absorption with corresponding molecular (rotational) absorption spectra allows us to constrain variation in $y \equiv \alpha^2 g_p$ where $\alpha$ is the fine structure constant and $g_p$ is the proton $g$-factor. We analyse spectra of two QSOs, PKS1413+135 and TXS0218+357, and derive values of $\Delta y/y$ at absorption redshifts of $z = 0.2467$ and $0.6847$ by simultaneous fitting of the $\text{H}\,21\text{cm}$ and molecular lines. We find $\Delta y/y = (-0.20 \pm 0.44) \times 10^{-5}$ and $\Delta y/y = (-0.16 \pm 0.54) \times 10^{-5}$ respectively, indicating an insignificantly smaller $y$ in the past. We compare our results with other recent constraints from the same two QSOs (Drinkwater et al. 1998; Carilli et al. 2000) and with our recent optical constraints which indicated a smaller $\alpha$ at higher redshifts.

Key words: line: profiles – techniques: spectroscopic – quasars: individual: TXS0218+357 – quasars: individual: PKS1413+135 – quasars: absorption lines

1 INTRODUCTION

Currently, many modern unified theories provide strong motivation for experimental searches for variation in physical constants. Kaluza-Klein, Superstring and M-theory require the existence of extra spatial dimensions which are compactified on small scales. The coupling constants in our 3-dimensional subspace of these theories are related to the scale sizes of the extra dimensions. Therefore, if the extra dimensions evolve with cosmology, we expect our 3-dimensional constants to vary (e.g. Forgács & Horváth 1979; Marciano 1984; Barrow 1987; Damour & Polyakov 1994). Currently, there seems to be no mechanism for keeping the sizes of the extra dimensions constant (Li & Gott 1998) and so these modern theories naturally predict variations in the fundamental constants.

Experimentally, quasar (QSO) absorption lines provide an ideal probe of cosmological variation of physical constants. Savedoff (1956) first analysed doublet separations seen in galaxy emission spectra to obtain constraints on variation in the fine structure constant, $\alpha \equiv e^2/\hbar c$. Absorption lines in intervening clouds along the line of sight to QSOs are substantially narrower than intrinsic emission lines and so provide a much more precise probe of $\alpha$ at high redshift. Bahcall, Sargent & Schmidt (1967) first used the doublet spacings of gas seen in absorption against background QSOs to derive firm upper limits on possible variation of $\alpha$. We summarize results from optical absorption line studies in Section 4, suffice it to say here that the tightest constraint on $\Delta\alpha/\alpha$ found to date is a tentative detection of variation at $\Delta\alpha/\alpha = (-0.72 \pm 0.18) \times 10^{-5}$ in 49 absorption clouds over the redshift range $0.5 < z < 3.5$ (Murphy et al. 2001a; Webb et al. 2001).†

Even tighter constraints can be placed on variability of combinations of physical constants using radio QSO absorption spectra. A comparison of $\text{H}\,21\text{cm}$ and molecular rotational absorption spectra is particularly convenient. The $\text{H}\,21\text{cm}$ hyperfine transition frequency is proportional to $\mu_p\mu_B/(\hbar a^2)$ where $\mu_p = g_pe\hbar/(4m_pc)$ and $\mu_B = e\hbar/(2m_ec)$ is the Bohr magneton. Here, $g_p$ is the proton $g$-factor, $m_p$ and $m_e$ are the masses of the proton and electron respectively and $a = \hbar^2/(m_ec^2)$ is the Bohr radius. The rota-

† See Murphy et al. (2001a) for a summary of all relevant constraints on $\Delta\alpha/\alpha$. 
tional transition frequencies of diatomic molecules, such as CO, are proportional to $\hbar/(Ma^2)$ where $M$ is the reduced mass. Therefore, the ratio of the hyperfine and molecular rotational frequencies is proportional to $\alpha^2 g_p M/m_p$. Variations in this quantity will be dominated by variations in $y \equiv \alpha^2 g_p$ since variations in $M/m_p$ are suppressed by a factor $m_p/U \sim 100$ where $U$ is the binding energy of nucleons in nuclei. If any variation in $y$ occurs, it will be observed as a difference in redshift between the $\mathrm{H}\alpha$ cm ($z_H$), and molecular ($z_{mol}$) absorption lines:

$$\Delta y/y = \frac{y_H - y_m}{y_m} \approx \frac{\Delta z}{1+z} \equiv \frac{z_{mol} - z_H}{1+z_{mol}} \ (1)$$

where $y_H$ and $y_m$ are the values of $y$ at the absorption redshift $z$ and in the laboratory respectively.

The first comparison of $\mathrm{H}\alpha$ cm and molecular absorption was made by Varshalovich & Potekhin (1996). They compared the published redshifts of the CO absorption (reported in Wiklind & Combes 1994) and $\mathrm{H}\alpha$ cm absorption (reported in Carilli, Perlman & Stocke 1992) towards PKS 1413+135. They interpreted any shift as a change in the molecular mass. Therefore, the ratio of the hyperfine and molecular $\Delta y/y$ is proportional to $\Delta M/M$ since variations in $y$ occur, it will be observed as a difference in redshift between the $\mathrm{H}\alpha$ cm ($z_H$), and molecular ($z_{mol}$) absorption lines:

$$\Delta y/y = \frac{y_H - y_m}{y_m} \approx \frac{\Delta z}{1+z} \equiv \frac{z_{mol} - z_H}{1+z_{mol}} \ (1)$$

where $y_H$ and $y_m$ are the values of $y$ at the absorption redshift $z$ and in the laboratory respectively.

The present work aims at turning our upper limit on $\Delta y/y$ into a measurement of $\Delta y/y$ by fitting Voigt profiles to the $\mathrm{H}\alpha$ cm data rather than using the published redshifts. The errors on the redshift of each velocity component in the $\mathrm{H}\alpha$ data were reduced by an order of magnitude compared to the estimates of Varshalovich & Potekhin (1996). We also applied this analysis to another absorber towards TXS 0218+357 at $z_{abs} = 0.685$. In D98 we derived an upper limit on any variation in $y$ for both absorbers: $|\Delta y/y| < 0.5 \times 10^{-5}$.

The present work aims at turning our upper limit on $\Delta y/y$ in D98 into a measurement of $\Delta y/y$ by fitting simultaneously the $\mathrm{H}\alpha$ cm data and the rotational lines of several molecular species. We describe the available data in Section 2 and describe our analysis and results in Section 3. We discuss our new results in Section 4, comparing them with other constraints on $\alpha$ variability.

2 AVAILABLE DATA

Only 4 QSOs have had mm-band rotational molecular absorption detected along their lines of site: TXS 0218+357, PKS 1413+135, B3 1504+377 and PKS 1830–211. Below we describe the molecular and $\mathrm{H}\alpha$ data available for the first two of these QSOs. We do not have sufficient data to consider PKS 1830–211. The molecular absorption profile is very broad (FWHM ~ 40 kms$^{-1}$, Wiklind & Combes 1998)

2.1 TXS 0218+357

TXS 0218+357 is a gravitationally lensed QSO (Patnaik et al. 1993), probably at a redshift $z_{em} \approx 0.94$ (Wiklind & Combes 1995), showing absorption in the lensing galaxy at $z_{abs} = 0.6847$ (Carilli, Rupen & Yanny 1993). VLBI observations (Patnaik et al. 1993; Biggs, Brown & Wilkinson 2001) show two, compact, flat-spectrum components (A to the SW and B to the NE) and a steep-spectrum Einstein ring. The background QSO shows intensity variability on intraday (Biggs et al. 2001) and longer (~monthly) time-scales (O’Dea et al. 1992; Patnaik et al. 1993). We use the spectrum of this QSO despite the fact that it is lensed since the A component provides the dominant absorption in both the molecular (Menten & Reid 1996) and $\mathrm{H}\alpha$ cm (Carilli et al. 2000, hereafter C00) bands. Thus, the profile of the $z = 0.6847$ absorber should not vary significantly over the time between molecular and $\mathrm{H}\alpha$ cm observations.

In this paper we use the $\mathrm{H}\alpha$ cm spectrum of the $z = 0.6847$ absorption system published by Carilli et al. (1993) (FWHM = 6.9 kms$^{-1}$). Spectra of CO(1–2), $^{13}\mathrm{CO}(1–2)$, $^{18}\mathrm{O}(1–2)$ and CO(2–3) are taken from Combes & Wiklind (1995) (FWHM ~ 30 ms$^{-1}$) and those of HCO$^+$(1–2) and HCN(1–2) are from Wiklind & Combes (1995) (FWHM ~ 2 kms$^{-1}$). These data are presented in Fig. 1.

2.2 PKS 1413+135

PKS 1413+135 is at the centre of an edge on spiral galaxy at $z_{em} = 0.24671$ and the absorption occurs in the disk of this galaxy (Wiklind & Combes 1997). VLBI observations (C00) show that the $\mathrm{H}\alpha$ cm continuum flux is dominated by a jet extending from an inverted-spectrum nucleus. The nucleus dominates the mm continuum emission (Perlman et al. 1996). Thus, the $\mathrm{H}\alpha$ cm and molecular absorption lie along different sight lines separated by $\sim 003$ (C00). We address this problem and its effect on our results in Section 4.

Here we use the $\mathrm{H}\alpha$ cm spectrum of the $z = 0.2467$ absorption system observed by Carilli et al. (1992) (FWHM $\approx 1.3$ kms$^{-1}$). The molecular absorption lines of CO(0–1), HCO$^+$(1–2) and HCO$^+$(2–3) (FWHM $\sim 40$ ms$^{-1}$) were observed with the narrow band autocorrelator at the IRAM 30 m telescope on Pico Veleta. The details of these observations are reported in Wiklind & Combes (1997). These data are presented in Fig. 2.
3 ANALYSIS, RESULTS AND ERRORS

We used vpfit$^5$ to fit multi-velocity component Voigt profiles to both the H\textsc{i} 21 cm and molecular absorption lines. The laboratory values for the transition frequencies were taken from Pickett et al. (1998)$^6$ and Essen et al. (1971) and are given in Table 1. By simultaneously fitting several molecular transitions of differing strengths in the same absorber, we get the best possible estimate of the velocity structure. We determine the number of velocity components to be fitted to each system by requiring that the reduced $\chi^2$ for the fit be $\sim 1$.

We use an iterative technique to find the best fit value of $\Delta y/y$. We vary $\Delta y/y$ outside vpfit (i.e. we vary the ratio of the hyperfine and molecular frequencies) and fit all lines simultaneously. During the fit we force the redshift parameters for corresponding velocity components to be the same for all transitions, thereby reducing the number of free parameters. We change $\Delta y/y$ at each iteration of the routine, i.e. to find $\chi^2$ as a function of $\Delta y/y$. The best fit value of $\Delta y/y$ is that which gives the minimum $\chi^2$, $\chi^2_{\text{min}}$, and the 1σ error in $\Delta y/y$ is found using $\chi^2_{\text{min}} + 1$.

For the $z = 0.6847$ absorption system towards TXS0218+357 we find the best fit value of $\Delta y/y = (-0.16 \pm 0.36) \times 10^{-5}$ and for the $z = 0.2467$ absorption system towards PKS1413+135 we find $\Delta y/y = (-0.20 \pm 0.20) \times 10^{-5}$. To check internal consistency, we have investigated the effect of removing individual transitions from the analysis of each absorption system. Our values of $\Delta y/y$ showed no significant change upon removal of any molecular transition. In particular, we found no change when we removed either or both the CS(2–3) and $^{13}$CO(0–1) transitions from our analysis of TXS0218+357. The low velocity component does not seem to be present in these transitions and was not fitted (see Fig. 1). The fact that the results are insensitive to removal of these lines indicates the robustness of our line

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Spectra of the $z = 0.6847$ absorption system towards TXS0218+357. The data are plotted as a histogram and the solid line represents our Voigt profile fit. The tick-marks above the data show the position of the fitted velocity components. The residuals (i.e. [data]-[fit]), normalized to a constant 1σ-error (defined by the signal-to-noise ratio in the continuum), are shown above each spectrum. Note that two independent spectra of CO(1–2) have been included.}
\end{figure}
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Figure 2. Spectra of the $z = 0.2467$ absorption system towards PKS 1413+135. The data are plotted as a histogram and the solid line represents our Voigt profile fit. The tick-marks above the data show the position of the fitted velocity components. The residuals (i.e. [data]-[fit]), normalized to a constant 1σ-error (defined by the signal-to-noise ratio in the continuum), are shown above each spectrum.

Table 1. Laboratory frequencies of transitions used in our analysis. Molecular frequencies are taken from Pickett et al. (1998) and the H\textsubscript{1} 21 cm frequency is from Essen et al. (1971).

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>Frequency/GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0–1</td>
<td>115.2712018(5)</td>
</tr>
<tr>
<td></td>
<td>1–2</td>
<td>230.5380000(5)</td>
</tr>
<tr>
<td></td>
<td>2–3</td>
<td>345.7959899(5)</td>
</tr>
<tr>
<td>$^{13}$CO</td>
<td>1–2</td>
<td>220.3986765(53)</td>
</tr>
<tr>
<td>C\textsubscript{18}O</td>
<td>1–2</td>
<td>219.5603568(81)</td>
</tr>
<tr>
<td>CS</td>
<td>2–3</td>
<td>146.969033(50)</td>
</tr>
<tr>
<td>HCO\textsuperscript{+}</td>
<td>1–2</td>
<td>178.375065(50)</td>
</tr>
<tr>
<td></td>
<td>2–3</td>
<td>267.557619(10)</td>
</tr>
<tr>
<td>HCN</td>
<td>1–2</td>
<td>177.261110(2)</td>
</tr>
<tr>
<td>H\textsubscript{1}</td>
<td>21 cm</td>
<td>1.420405751766(1)</td>
</tr>
</tbody>
</table>

fitting method and highlights the advantage of using many different molecular transitions.

The 1σ errors we quote above are statistical only. However, as noted in Section 2.2, the fact that we probe slightly different sight lines with the molecular and H\textsubscript{1} 21 cm observations may result in an additional random error. D98 have investigated this problem empirically by fitting several QSO spectra with Galactic absorption and comparing the fitted redshifts of the HCO\textsuperscript{+} and H\textsubscript{1} velocity components. D98 find a close correspondence between the velocity components of HCO\textsuperscript{+} and H\textsubscript{1} with a Gaussian dispersion of only 1.2 km s\textsuperscript{-1}. This corresponds to an error $\Delta y/y = 0.4 \times 10^{-5}$. Our two results, being of similar value and so close to zero, suggest that this error estimate may be too large. However, it is clear that such a conclusion can only be reached with a larger sample of absorption systems and so we have added this error in quadrature to obtain our final results:

$$\Delta y/y = (-0.20 \pm 0.44) \times 10^{-5} \text{ at } z = 0.2467 \text{ and } \Delta y/y = (-0.16 \pm 0.54) \times 10^{-5} \text{ at } z = 0.6847$$ (2)

or

$$\Delta y/y = (-0.17 \pm 0.54) \times 10^{-5} \text{ at } z = 0.6847$$ (3)
\[ \Delta \alpha / \alpha = (-0.10 \pm 0.22) \times 10^{-5} \text{ at } z = 0.2467 \] and
\[ \Delta \alpha / \alpha = (-0.08 \pm 0.27) \times 10^{-5} \text{ at } z = 0.6847 \] (3)
assuming (perhaps incorrectly) a constant \( g_p \).

4 DISCUSSION

Very recently, C00 has reported upper limits on \( \Delta y / y \) using the same two absorption systems we analyse above. They obtained new H I 21 cm spectra of each absorber and compared the measured redshift with the published molecular redshifts. C00 find \( \Delta y / y = (+1.0 \pm 0.3) \times 10^{-5} \) for TXS0218+357 and \( \Delta y / y = (+1.29 \pm 0.08) \times 10^{-5} \) for PKS1413+135 where the errors are statistical only. They add to this an additional error of \( \pm 1 \times 10^{-5} \), which is derived from other measurement uncertainties in the H I data (e.g., frequency calibration uncertainties). However, C00 argue that the line of sight problem above could lead to errors as large as 10 km s\(^{-1}\) on the basis of typical sub-kiloparsec ISM motions. They therefore conclude with an upper limit of \( |\Delta y / y| < 3.5 \times 10^{-15} \text{ yr}^{-1} \) (assuming constant \( g_p \)) for a look-back time (within their assumed cosmology) of 4.8 Gyr to \( z = 0.6847 \). This corresponds to \( |\Delta y / y| < 1.7 \times 10^{-5} \).

This final dominant error term of 10 km s\(^{-1}\) is much greater than the 1.2 km s\(^{-1}\) error we apply in equations 2 and 3, but we stress that our value has been obtained empirically and so should be reliable.

As mentioned in Section 1, tight constraints on \( \Delta \alpha / \alpha \) come from optical absorption line studies. One method is to compare the spacing of single alkali doublets (ADs) in QSO and laboratory spectra (Cowie & Songaila 1995; Varshalovich, Panchuk & Ivanchik 1996). The most precise constraint to date using this method was obtained by Murphy et al. (2000a), \( \Delta \alpha / \alpha = (-0.5 \pm 1.3) \times 10^{-5} \), where we analysed 21 Si iv doublets (2 < \( z \) < 3) in 13 QSO spectra (see Fig. 3). However, this method does not take advantage of the large relativistic shifts in the ground state energy since it compares transitions from the same ground state.

Recently, a new many-multiplet (MM) method was suggested (Dzuba et al. 1999a,b; Webb et al. 1999) which allows an order of magnitude gain in precision over the AD method. The magnitude of the relativistic shifts is sensitive to the nuclear charge and so comparison of transitions in light and heavy ions yields tight constraints on \( \Delta \alpha / \alpha \). Also, since any transition can be used, comparison of transitions with different ground states is possible. A further increase in precision comes from increased statistics since one is not restricted to using just a single AD.

The first application of the MM method (Webb et al. 1999) used 30 Mg ii/Mg ii Fe ii absorption systems (0.5 < \( z \) < 1.6) towards 17 QSOs and suggested that \( \alpha \) may have been smaller in the past: \( \Delta \alpha / \alpha = (-1.09 \pm 0.36) \times 10^{-5} \). More recently, we have re-analysed and confirmed the Webb et al. results with improved techniques and extended our analysis to a higher redshift sample of damped Lyman-\( \alpha \) systems (Murphy et al. 2001a; Webb et al. 2001). We compare our new mm/H I results with these optical results in Fig. 3 and we see that they are consistent. The weighted mean for the optical results, \( \Delta \alpha / \alpha = (-0.72 \pm 0.18) \times 10^{-5} \), is significant at the 4.1\( \sigma \) level and so a thorough search for systematic errors has been carried out (Murphy et al. 2001b). However, no effect was found that could explain the results. Fig. 3 clearly shows that, assuming a constant \( g_p \), a large sample of mm/H I absorption systems, over a somewhat larger redshift range, will allow us to confirm or rule out the change in \( \alpha \) implied by the optical data.

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Figure 3. Comparison of our new mm/H I constraints (crosses, from equation 3) and our recent optical constraints. The star represents the weighted mean of \( \Delta \alpha / \alpha \) using 21 Si iv alkali doublets from Murphy et al. (2000c) while the dots represent a 7 \( \times \) 7 binning of the 49 absorption systems analysed with the many-multiplet method in Murphy et al. (2000a).
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