PROBING FUNDAMENTAL CONSTANT EVOLUTION WITH NEUTRAL ATOMIC GAS LINES

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ABSTRACT

We have detected narrow H\textsc{i} 21 cm and C\textsc{i} absorption at \(z \sim 1.4–1.6\) toward Q0458–020 and Q2337–011, and use these lines to test for possible changes in the fine structure constant \(\alpha\), the proton–electron mass ratio \(\mu\), and the proton gyromagnetic ratio \(g_p\). A comparison between the H\textsc{i} 21 cm and C\textsc{i} line redshifts yields \(\Delta X/X = (+6.8 \pm 1.0) \times 10^{-6}\) over \(0 < \langle z \rangle < 1.46\), where \(X = g_p\alpha^2/\mu\), and the errors are purely statistical, from the Gaussian fits. The simple line profiles and the high sensitivity of the spectra imply that statistical errors in this comparison are an order of magnitude lower than in previous studies. Further, the C\textsc{i} lines arise in cold neutral gas that also gives rise to H\textsc{i} 21 cm absorption, and both background quasars are core-dominated, reducing the likelihood of systematic errors due to local velocity offsets between the hyperfine and resonance lines. The dominant source of systematic error lies in the absolute wavelength calibration of the optical spectra, which appears uncertain to \(\sim 2 \text{ km s}^{-1}\), yielding a maximum error in \(\Delta X/X\) of \(\sim 6.7 \times 10^{-6}\). Including this, we obtain \(\Delta X/X = (+6.8 \pm 1.0\text{ (statistical)} \pm 6.7\text{ (max. systematic)}) \times 10^{-6}\) over \(0 < \langle z \rangle < 1.46\). Using literature constraints on \(\Delta \mu/\mu\), this is inconsistent with claims of a smaller value of \(\alpha\) from the many-multiplet method, unless fractional changes in \(g_p\) are larger than those in \(\alpha\) and \(\mu\).

Key words: atomic processes – galaxies: high-redshift – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

A critical assumption in the standard model of particle physics is that low-energy coupling constants and particle masses do not vary with space or time. This assumption breaks down in most theories that attempt to unify the standard model and general relativity (e.g., Marciano 1984). The detection of such spatio-temporal variation in coupling constants like the fine structure constant \(\alpha\), or the ratios of particle masses (e.g., the proton–electron mass ratio \(\mu \equiv m_p/m_e\)) would imply new physics beyond the standard model and is hence of great interest (e.g., Uzan 2003).

Comparisons between the redshifts of spectral lines detected in distant galaxies provide an important tool for probing changes in \(\alpha, \mu, \) and the proton gyromagnetic ratio \(g_p\) over cosmological times (e.g., Wolfe et al. 1976; Dzuba et al. 1999; Chengalur & Kanekar 2003; Flambaum & Kozlov 2007). Most such studies have yielded constraints on changes in \(\alpha, \mu, \) and \(g_p\), with different systematic effects (see Kanekar 2008 for a recent review). At present, the only technique that has found statistically significant evidence for a change in one of the fundamental constants is the "many-multiplet" method (Dzuba et al. 1999). Murphy et al. (2004) obtained \(\Delta \alpha/\alpha = (-5.7 \pm 1.1) \times 10^{-6}\) from Keck High Resolution Ultraviolet Echelle Spectrometer (HIRES) optical spectra of 143 absorbers with a mean redshift \(\langle z \rangle = 1.75\), suggesting that \(\alpha\) was smaller at earlier times. Other studies, applying a similar technique to Very Large Telescope (VLT) data on smaller samples, have not confirmed this result (e.g., Levshakov et al. 2006; Srianand et al. 2007). However, Murphy et al. (2008b) argue that the errors in these studies have been underestimated, and that results from small samples are more prone to systematic effects related to the fitting of spectral components to complex absorption profiles.

In the case of \(\mu\), King et al. (2008) used VLT Ultraviolet Echelle Spectrograph (UVES) spectra of ro-vibrational H\textsc{ii} lines in three damped Ly\alpha systems at \(z \sim 2.6–3\) to find \(\Delta \mu/\mu = (-2.6 \pm 3.0) \times 10^{-6}\). Note that none of the above error estimates include recently detected systematic effects due to distortions in the wavelength scales of the HIRES and UVES spectographs (e.g., Griest et al. 2010). Finally, constraints on changes in \(\alpha, \mu, \) and \(g_p\) have also been obtained from radio techniques (e.g., Carilli et al. 2000; Kanekar et al. 2004, 2005; Murphy et al. 2008a), although at lower redshifts.

Comparisons between the redshifts of H\textsc{i} 21 cm (hyperfine) and ultraviolet resonance dipole transitions are sensitive to changes in \(X \equiv g_p\alpha^2/\mu\) (Wolfe et al. 1976). The best resonance lines for this method are those arising from neutral atomic species (e.g., C\textsc{i}, Fe\textsc{i}, etc.), as these species are most likely to be physically associated with the H\textsc{i}. The C\textsc{i} multiplets are likely to be the best among the neutral resonance transitions as they typically arise in cold gas which also gives rise to the H\textsc{i} 21 cm absorption (e.g., Jenkins & Tripp 2001; Srianand et al. 2005). The ionization potentials of C\textsc{i} and H\textsc{i} are also similar, 11.3 eV for C\textsc{i} and 13.6 eV for H\textsc{i} (cf. Mg\textsc{i}, which is more easily detectable than C\textsc{i} in high-z absorbers, has an ionization potential of 7.6 eV, as well as a high dielectronic recombination rate that can give significant Mg\textsc{i} absorption in warm, ionized gas; Pettini et al. 1977). Finally, absorbers with a single (or dominant) spectral component in both H\textsc{i} 21 cm and C\textsc{i} transitions are best-suited for such studies.

Both H\textsc{i} 21 cm and C\textsc{i} absorption have hitherto been detected in only one high-z absorber, the \(z \sim 1.776\) system toward 1331+170, yielding a weak constraint on changes in \(X \equiv g_p\alpha^2/\mu\) (Cowie & Songaila 1995). However, the C\textsc{i} line in this absorber has two clear spectral components (Dessauges-Zavadsky et al. 2004), implying ambiguities (and thus, large
systematic errors) in the comparison with the H I 21 cm line. In this Letter, we report the detection of narrow, single-component H I 21 cm and C I absorption in two absorbers at z ∼ 1.4–1.6, that allow a high-sensitivity study of changes in the fundamental constants.

2. SPECTRA AND RESULTS

The Giant Metrewave Radio Telescope (GMRT) and the Green Bank Telescope (GBT) were used to detect H I 21 cm absorption at z ∼ 1.3609 toward Q2337−011 and z ∼ 1.5605 toward Q0458−020, respectively, in a survey for H I 21 cm absorption in strong Mg II absorbers (GMRT proposals 7NKa02, 10NKa02, and GBT proposal 6A-026; see Kanekar et al. (2009) for details). The H I 21 cm spectra are shown in the lower panels of Figure 1. The root-mean-square (rms) noise values, measured from off-line regions in the spectra, are ∼0.03 per 1.9 km s⁻¹ channel (Q2337−011) and ∼0.0037 per 1.3 km s⁻¹ channel (Q0458−020), in optical depth units.

We then carried out a search for redshifted C I absorption from the two absorbers, using the high-sensitivity Keck-HIRES spectrum of Prochaska & Wolfe (1997) toward Q0458−020 (observed on 1995 October 31 and November 1), and a new HIRES spectrum of Q2337−011 (observed on 2006 September 18 and 19). This resulted in the detection of the C I λ1560 and C I λ1657 transitions at z ∼ 1.3609 toward Q2337−011, and the C I λ1560 and C I* λ1561 transitions at z ∼ 1.5605 toward Q0458−020. Of these, the C I λ1560 line toward Q2337−011 is blended with another line, while the C I* λ1561 line toward Q0458−020 is detected at low significance; these will, hence, not be used in the later analysis. The C I λ1657 line toward Q2337−011 and the C I λ1560 line toward Q0458−020 are shown in the upper panels of Figure 1. The signal-to-noise ratios (S/Ns) per pixel are ∼25 at a resolution of R ∼ 50,000 (Q2337−011) and ∼15 at R ∼ 37,000 (Q0458−020) in the vicinity of the above C I transitions.

For all spectra, the rms noise was measured from absorption-free spectral regions around the line in question. A single-Gaussian model was then used to independently fit each of the one-dimensional spectra in the H I 21 cm and C I lines. This model yielded an excellent fit to all spectra, with reduced chi-square values < 1.06 in all cases, and no evidence for statistically significant features in the residual spectra. A Kolmogorov–Smirnov rank-1 test found all residual one-dimensional spectra to be consistent (within 1.1σ significance) with being drawn from a normal distribution. The rms noise values used for the spectral fits were scaled (marginally) to obtain χ² = 1 in all cases; the resulting fits were then used to measure the peak absorption redshift for each transition. These redshifts are listed in Columns 2 and 3 of Table 1; note that the C I λ1560 and C I λ1567 lines have laboratory vacuum wavelengths of 1560.3092 Å and 1657.9283 Å, respectively (Morton 2003), while the H I 21 cm line frequency is 1420.405751766 (1) MHz (Essen et al. 1971).

A useful test of the limiting accuracy in such fits can be obtained by combining the minimum uncertainties contributed by all line pixels to determine the best velocity accuracy that might be obtained with a given spectral fit (Murphy et al. 2008b). In all cases, the redshift errors in Table 1 are larger than this limiting accuracy (by factors ≲ 2), as expected for real spectra. We also tested that adding additional components to the fits does not significantly alter the results.

Assuming that the H I 21 cm and C I lines arise in the same gas, the fractional change in $X = g_p\alpha^2/\mu$ is related to the observed
At the outset, it should be emphasized that, unlike the many-multiplet method which only requires accurate relative wavelength calibration between different lines in the same optical spectrum, the comparison between H\textsc{i} and C\textsc{i} lines requires accurate absolute wavelength calibration of the optical spectra. On the other hand, the many-multiplet method is based on a first-order effect (the wavelengths of transitions used in this analysis have the same zeroth-order dependence on $\alpha$), while the present method uses the zeroth-order dependences of the hyperfine and resonance line frequencies on $\alpha$, $\mu$, and $g_\text{R}$. This implies that systematic effects (e.g., due to wavelength miscalibration) are less important by an order of magnitude in the hyperfine/resonance comparison than in the many-multiplet analysis. For example, a velocity uncertainty of 0.3 km s$^{-1}$ implies an error of $|\Delta \alpha/\alpha| = 10^{-5}$ in the many-multiplet method (Murphy et al. 2001), but of $\Delta X/X = 10^{-6}$ in the hyperfine/resonance comparison.

The C\textsc{i} lines in both absorbers are at higher redshifts than the H\textsc{i} 21 cm lines, by $\sim 2$ km s$^{-1}$. Systematic effects that might cause such a velocity offset include (1) different relative isotopic abundances at $z \sim 1.5$ from the local universe, which might cause the rest C\textsc{i} wavelengths in the two absorbers to be higher than their laboratory values; (2) errors in the absolute wavelength calibration of the optical spectra; and (3) “local” velocity offsets between the C\textsc{i} and H\textsc{i} 21 cm lines in the two absorbers. Note that frequency miscalibration of the H\textsc{i} 21 cm spectra is unlikely to be the source of such errors, as the absolute frequency scale here is set by the accuracy of masers and local oscillators (typically $< 10$ Hz, 2 orders of magnitude lower than the observed velocity offset between the H\textsc{i} 21 cm and C\textsc{i} lines).

The velocity shifts of the $^{12}$C and $^{13}$C isotopic transitions relative to the main $^{12}$C isotopic lines are, respectively, $+0.46$ km s$^{-1}$ and $+0.84$ km s$^{-1}$ for the C\textsc{i} $\lambda 1657$ line, and $-3.29$ km s$^{-1}$ and $-6.10$ km s$^{-1}$ for the C\textsc{i} $\lambda 1560$ line (Berengut et al. 2006). The isotopic velocity shift is clearly too small to account for the observed velocity offset in the case of the C\textsc{i} $\lambda 1657$ line. Conversely, in the case of the C\textsc{i} $\lambda 1560$ line, the isotopic shift yields the opposite sign from the observed velocity offset between the C\textsc{i} and H\textsc{i} lines. We can thus rule out the hypothesis that differing carbon isotopic abundances (compared to Galactic values) might account for the observed velocity offset between the H\textsc{i} 21 cm and C\textsc{i} transitions.

Miscalibration of the absolute wavelength scale of the optical spectra could arise from a number of causes (e.g., Murphy et al. 2001). In particular, the spectrum toward Q0458--020 was obtained in 1995, before Keck-HIRES was fitted with an image rotator. It was thus not possible to hold the slit perpendicular to the horizon during these observations, implying that atmospheric dispersion across the slit could produce errors in the wavelength scale (Murphy et al. 2001). Further, while the data toward Q2337--011 were obtained in 2007, with the use of the image rotator, Griest et al. (2010) have found evidence for drifts in the Keck-HIRES wavelength scale with time, with amplitudes of $\sim 2$ km s$^{-1}$ over multiple observing epochs.

The source of these velocity drifts is still unclear, although temperature changes, changes in the position of the quasar on the slit, as well as physical shifts in the echelle grating or cross-disperser are all possible causes.

To test for systematic effects in the absolute wavelength calibration of the optical spectra, we analyzed archival Keck-HIRES data toward Q0458--020 from 2004 October 5 and 6 (obtained using the image rotator). While this spectrum has lower S/N than the 1995 spectrum (as the optically variable quasar was in a fainter state in 2004), the unsaturated Ni\textsc{ii} $\lambda 1317$ transition from a higher-redshift ($z = 2.03945$) damped Ly\textsc{a} system is clearly detected in both spectra; this line lies at $\sim 4003$ Å, within 10 Å of the C\textsc{i} $\lambda 1560$ line shown in Figure 1(B).

Cross-correlating the Ni\textsc{ii} lines detected in the two HIRES spectra yielded a cross-correlation peak at a velocity offset of $+1.60 \pm 0.84$ km s$^{-1}$; the error was determined by cross-correlating 10,000 pairs of simulated spectra with the shape and noise properties of the actual spectra. If this velocity offset between the Ni\textsc{ii} lines arises due to atmospheric dispersion across the slit during the 1995 observations, it would imply that the C\textsc{i} line redshift has been underestimated in the 1995 spectrum. Correcting for this effect would increase the redshift offset between the H\textsc{i} 21 cm and C\textsc{i} lines.

We also separately analyzed the Keck-HIRES data toward Q2337--011 from 2006 September 18 and 19, to test whether the same line redshift was obtained from the two runs. Figure 2 shows the C\textsc{i} $\lambda 1567$ line profiles obtained on September 18 and 19; these are clearly offset from each other. A single-component Gaussian fit was used to measure the C\textsc{i} $\lambda 1567$ redshift from each spectrum; the offset between the C\textsc{i} $\lambda 1567$ redshifts is $2.15 \pm 0.44$ km s$^{-1}$. Similar velocity offsets...
(≈2 km s⁻¹) were seen between other lines in the two spectra. Note that a single ThAr lamp exposure was used to calibrate the two science exposures on Q2337−011 on each day; the ThAr exposure was taken immediately before/after the science exposures. Interestingly, the C1 λ1657 redshift of September 18 [z_{C1} = 1.3608694(26)] is in reasonable agreement with the H1 21 cm redshift [z_{21cm} = 1.3608644(13)], indicated by the solid circle in Figure 2; the redshift offset between the H1 21 cm and C1 lines is dominated by the C1 data from September 19. The offsets of ≈2 km s⁻¹ between our two observing epochs are consistent with the velocity drifts in the HIRES wavelength scale found by Griest et al. (2010; see their Figure 5). Hence, we conclude that the absolute wavelength scale of HIRES could be in error by ≈2 km s⁻¹.

Finally, “local” velocity offsets between the H1 21 cm and C1 lines within the absorbing galaxies might also contribute to differences in the measured line redshifts. Both C1 and H1 21 cm absorption are expected to arise in cold gas, and, for both background quasars, a significant fraction of the radio flux density at the H1 21 cm line frequency arises from a compact core (Kanekar et al. 2009). In fact, Q2337−011 has a highly inverted spectrum, indicating that most of the flux density arises from a self-absorbed core (Kanekar et al. 2009). The cold cloud producing C1 absorption against the optical quasar is thus also likely to give rise to H1 21 cm absorption against the radio core. Assuming that gravity is important for cloud confinement on small scales, Murphy et al. (2003) obtain a velocity dispersion of ≈0.1 km s⁻¹ between different species in an individual cloud, which would yield a systematic error of ≈3.3 × 10⁻⁶ in ΔX/X, significantly lower than our statistical errors. We note, however, that larger velocity offsets due to small-scale structure in the absorbing gas cannot formally be ruled out.

4. DISCUSSION

Prior to this work, the most sensitive result constraining changes in X ≡ g_α α^2/μ using the hyperfine/resonance comparison was that of Tzanavaris et al. (2007). These authors compared redshifts of the deepest absorption in H1 21 cm and low-ionization metal lines to obtain ΔX/X = (6.3 ± 9.9) × 10⁻⁶ from a sample of nine absorbers at 0.23 < z < 2.35. Note that these error estimates do not include systematic effects. Considering only statistical errors, our result, ΔX/X = (+6.8 ± 1.0 (statistical)) × 10⁻⁶ over 0 < z < 1.46, is an order of magnitude more sensitive than that of Tzanavaris et al. (2007). Further, the low-ionization metal lines used by Tzanavaris et al. (2007) could also arise in warm H1 or ionized gas, and are not necessarily associated with the cold H1 that gives rise to the H1 21 cm absorption. Most of the absorbers used by Tzanavaris et al. (2007) also have complex H1 21 cm and metal line profiles, and it is not necessary that the deepest absorption in the two types of transitions arises in the same spectral component (Kanekar et al. 2006). This could give systematic errors of ≳ 10 km s⁻¹, far larger than the statistical errors of Tzanavaris et al. (2007), or the systematic errors in the present result.

The comparison between hyperfine and resonance transitions directly probes changes in X ≡ g_α α^2/μ, and one cannot obtain independent constraints on the individual constants without additional assumptions. Our result gives 2 × [Δμ/μ] + [Δg_α/μ] − [Δμ/μ] = (+6.8 ± 1.0 (statistical) ± 6.7 (systematic)) × 10⁻⁶. Note that 6.7 × 10⁻⁶ is the maximum estimated error due to systematics in the absolute wavelength calibration of the optical spectra, (and not a 1σ estimate, as in the case of the statistical error). This implies that 2 × [Δμ/μ] + [Δg_α/μ] − [Δμ/μ] ≥ (+0.1 ± 1.0) × 10⁻⁶. The Keck/HIRES result of Murphy et al. (2004) is [Δμ/μ] = (−5.7 ± 1.0) × 10⁻⁶, with z = 1.75. Consistency between the two results would require either (1) an additional wavelength calibration error of ≈1.7 km s⁻¹ in the H1 spectra, which appears unlikely; (2) a “local” velocity offset of ≈1.7 km s⁻¹ (and with the appropriate sign) between the H1 and C1 lines in both absorbers; (3) underestimated errors in the many-multiplet result (e.g., the distortions in the wavelength scale found by Griest et al. 2010); or (4) [Δg_α/μ] = ([Δμ/μ] ≥ (+6.14 ± 0.24) × 10⁻⁵ at z = 1.46. In other words, assuming that the errors in one (or both) of the results have not been underestimated, consistency between the results requires that fractional changes in μ and/or g_α are comparable to those in α. Strong constraints are available on fractional changes in μ at both higher and lower redshifts, Δμ/μ < 1.6 × 10⁻⁶ at z ≈ 0.685 (Murphy et al. 2008a) and Δμ/μ < 6.0 × 10⁻⁶ at z = 2.8 (King et al. 2008), making it unlikely that Δμ/μ ∼ 10⁻⁶ at z ∼ 1.46. We thus conclude that the present result appears inconsistent with the smaller value of α at z ≈ 1.75 found by Murphy et al. (2004), unless fractional changes in the proton gyromagnetic ratio g_p are larger than those in α and μ.

In summary, we have detected narrow H1 21 cm and C1 absorption in two absorbers at ≈1.4–1.6 toward Q0458−020 and Q2337−011, using the Keck telescope, the GMRT and the GBT. The C1 and H1 21 cm line frequencies have different dependences on the fundamental constants α, μ ≡ m_p/m_e, and g_p, allowing us to use the measured C1 and H1 21 cm line redshifts to test for putative changes in these constants. Comparing the H1 21 cm and C1 redshifts in the two absorbers yields the result ΔX/X = (+6.8 ± 1.0(statistical) ± 6.7(systematic)) × 10⁻⁶ over 0 < z < 1.46, where X ≡ g_α α^2/μ. This is inconsistent with evidence for a smaller value of α at similar redshifts from the many-multiplet method, unless fractional changes in g_p are larger than those in α and μ. Systematic errors in the hyperfine/resonance comparison are currently dominated by errors (≈2 km s⁻¹) in the absolute wavelength calibration of the optical spectra. However, the comparison between the H1 21 cm and C1 lines has a high sensitivity, and it should be possible to significantly reduce systematic effects by the use of new calibration techniques (e.g., laser frequency combs; Steinmetz et al. 2008). Increasing the number of detections of redshifted, narrow H1 21 cm and C1 absorption is thus of much importance.

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