CONSTRAINING CHANGES IN THE PROTON–ELECTRON MASS RATIO WITH INVERSION AND ROTATIONAL LINES

Nissim Kanekar
National Centre for Radio Astrophysics, TIFR, Ganeshkhind, Pune-411007, India

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ABSTRACT

We report deep Green Bank Telescope spectroscopy in the redshifted NH₃ (1,1), CS 1–0, and H₂CO 0_{00}–1_{01} lines from the z ∼ 0.685 absorber toward B0218+357. The inversion (NH₃) and rotational (CS, H₂CO) line frequencies have different dependences on the proton–electron mass ratio μ, implying that a comparison between the line redshifts is sensitive to changes in μ. A joint three-component fit to the NH₃, CS, and H₂CO lines yields [Δμ/μ] = (−3.5 ± 1.2) × 10⁻⁷, from z ∼ 0.685 to today, where the error includes systematic effects from comparing lines from different species and possible frequency-dependent source morphology. Two additional sources of systematic error remain, due to time variability in the source morphology and velocity offsets between nitrogen-bearing and carbon-bearing species. We find no statistically significant (≥3σ) evidence for changes in μ and obtain the stringent 3σ constraint, [Δμ/μ] < 3.6 × 10⁻⁷, over 6.2 Gyr; this is the best present limit on temporal changes in μ from any technique, and for any look-back time, by a factor ≳5.

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

Online-only material: color figure

1. INTRODUCTION

A generic prediction of theories that attempt to unify the standard model of particle physics with general relativity is that particle masses and low-energy coupling constants vary with space and time. A detection of such changes would imply new physics beyond the standard model. Tests of changes in fundamental “constants” such as the fine-structure constant α, the proton–electron mass ratio μ, or the proton g-factor gp are of much interest (e.g., Uzan 2003).

Redshifted atomic and molecular spectral lines provide an interesting avenue to probe the possibility of fundamental constant evolution over cosmological timescales (Savedoff 1956). Comparisons between the redshifts of lines whose rest frequencies have different dependences on a constant like α are sensitive to changes in the constant (see Kanekar 2008 for a recent review). There are a number of such techniques, using comparisons between different transitions (e.g., Thompson 1975; Wolfe et al. 1976; Dzuba et al. 1999; Darling 2003; Chengalur & Kanekar 2003; Kanekar & Chengalur 2004; Flambaum & Kozlov 2007). Indeed, one of these techniques, the many-multiplet method, has yielded evidence for changes in α: Murphy et al. (2004) obtained [Δα/α] = (−5.4 ± 1.2) × 10⁻⁶ from 143 absorbers with z = 1.75 (see also Murphy et al. 2003). This result has as yet been neither confirmed nor ruled out (e.g., Srianand et al. 2007; Molaro et al. 2008; Murphy et al. 2008b; Kanekar et al. 2010b), but evidence has now been found for additional systematic effects in the data, due to errors in the wavelength calibration (Griest et al. 2010). Recently, an independent technique, using radio “conjugate” satellite OH lines (Kanekar et al. 2004; Kanekar et al. 2005), found weak evidence (at ~99.1% confidence level) for changes in a combination of α, μ, and gp; Kanekar et al. (2010a) obtained [ΔG/G] = (−1.18 ± 0.46) × 10⁻⁵, for between z ∼ 0.247 and the present epoch, where G = gp(μα²)¹.₈⁵. If changes in α are assumed to dominate over those in μ and gp, one obtains [Δα/α] = (−3.1 ± 1.2) × 10⁻⁶, consistent with the result of Murphy et al. (2004), albeit at a lower redshift.

For three decades, rovibrational molecular hydrogen (H₂) lines provided the sole method to directly probe changes in the proton–electron mass ratio (Thompson 1975). Unfortunately, few redshifted H₂ absorbers have been detected so far (e.g., Ledoux et al. 2003), and, of these, only four have been found suitable to study changes in μ (e.g., Ivanchik et al. 2005; Reinhold et al. 2006; King et al. 2008; Thompson et al. 2009; Malec et al. 2010; Wendt & Molaro 2011). These results have also been controversial: Reinhold et al. (2006) obtained [Δμ/μ] = (+2.0 ± 0.6) × 10⁻⁵ from two absorbers at z ∼ 2.6–3.0, i.e., evidence for a larger value of μ at high redshift (see also Ivanchik et al. 2005). However, independent re-analyses of these data by King et al. (2008) and Thompson et al. (2009), using improved wavelength calibration techniques, have not found evidence for changes in μ. King et al. (2008) obtain [Δμ/μ] = (+2.6 ± 3.0) × 10⁻⁶ from three absorbers at z ∼ 2.6–3.0 (including the two systems of Reinhold et al. 2006); note, however, that Wendt & Molaro (2011) argue that systematic errors have been underestimated in the latter analysis.

A new laboratory technique to probe changes in μ was proposed by van Velthoven et al. (2004), using inversion transitions of deuterated ammonia (ND₃). Flambaum & Kozlov (2007) adapted this technique to astrophysical circumstances, using ammonia (NH₃) inversion lines and rotational lines. Rotational and inversion line frequencies have different dependences on μ, and a comparison between the redshifts of NH₃ inversion lines and rotational lines (e.g., CO, HCO⁺, CS, etc.) lines from a single cosmologically distant absorber is thus sensitive to changes in μ. Only two redshifted NH₃ absorbers are currently known, at z ∼ 0.685 toward B0218+357 (Henkel et al. 2005) and z ∼ 0.886 toward B1830−210 (Henkel et al. 2008). In both cases, the NH₃ detection spectra have been used to obtain initial constraints on changes in μ (Murphy et al. 2008a; Henkel et al. 2009). Finally, the ammonia technique has also been used...
to search for spatial changes in $\mu$: Levshakov et al. (2010) obtained the (conservative) constraint $[\Delta \mu/\mu] < 3 \times 10^{-8}$ from studies of multiple molecular clouds in the Galaxy.

The $z \sim 0.685$ absorber toward B0218+357 has a far smaller velocity spread than the $z \sim 0.886$ system toward B1830–210 (Wiklind & Combes 1995, 1996b), making it a better candidate for accurate redshift measurements. The carbon monosulfide (CS) 1–0 line (rest frequency: 48.9909572 GHz; Kim & Yamamoto 2003) is a good rotational transition for the comparison with the NH$_3$ inversion lines because it is known to be unsaturated in the $z \sim 0.685$ absorber (Combes et al. 1997) and it lies at a frequency relatively close to that of the NH$_3$ (1,1) lines. The formaldehyde (H$_2$CO) 0$_{00}$–1$_{01}$ line (rest frequency: 72.83794810 GHz; Cornet & Winnewisser 1980) was chosen as a second rotational transition, to obtain an estimate of systematic effects in the above comparison; this too is known to be unsaturated in the $z \sim 0.685$ absorber (Jethava et al. 2007). This Letter reports Green Bank Telescope (GBT) spectroscopy in the redshifted NH$_3$ (1,1), CS 1–0, and H$_2$CO 0$_{00}$–1$_{01}$ lines that yield the best present constraints on changes in the proton–electron mass ratio.

2. OBSERVATIONS, DATA ANALYSIS, AND RESULTS

The GBT observations of the NH$_3$ (1,1) and CS 1–0 lines at $z \sim 0.685$ toward B0218+357 were carried out in 2008 January and August (proposals AGBT07C-016 and AGBT07C-054), using the Ku- and Ka-band receivers, respectively. A spectrum in the redshifted H$_2$CO 0$_{00}$–1$_{01}$ line was obtained in 2008 July with the GBT Q-band receiver, as part of an absorption survey of the $z \sim 0.685$ galaxy (proposals AGBT07C-054). Bandpass calibration was carried out via beam switching for the NH$_3$ observations, and with sub-reflector nodding for the higher-frequency CS and H$_2$CO observations. Two polarizations were used for the observations of the NH$_3$ (Ku-band) and H$_2$CO (Q-band) lines, and a single Ku-band polarization for the CS line. The total observing times were 6 hr (NH$_3$), 1.5 hr (CS), and 3 hr (H$_2$CO), with the NH$_3$ observations split into two observing sessions, in 2008 January and August. Standard procedures in DISH (for the NH$_3$ lines) and GBTIDL (for the CS and H$_2$CO lines) were used to analyze the data. The final NH$_3$, CS, and H$_2$CO spectra are shown in Figures 1(a), (b), and (c); these have velocity resolutions of ~0.26, 0.12, and 2.8 km s$^{-1}$, respectively (after Hanning-smoothing and re-sampling), and root-mean-square noise values of ~0.00082, 0.0097, and 0.0026, in optical depth units, per independent velocity channel.

A GBT Ku-band search was also carried out for the CCS 1–0 transition at $z \sim 0.685$; no absorption was detected at the redshifted CCS line frequency, with a 3$\sigma$ optical depth limit of ~0.0016 per 4.2 km s$^{-1}$ channel. The K- and Ku-band receivers were further used to search for redshifted NH$_3$ (1,1) absorption from two other redshifted molecular absorbers, at $z \sim 0.247$ toward B1413+135 (Wiklind & Combes 1997) and $z \sim 0.674$ toward B1504+377 (Wiklind & Combes 1996a), with no detected absorption in either case. The 3$\sigma$ optical depth limits were 0.00068 per 4 km s$^{-1}$ channel (B1413+135) and 0.00061 per 4 km s$^{-1}$ channel (B1504+377).

The test for changes in the proton–electron mass ratio $\mu$ was carried out through a simultaneous fit to the NH$_3$ (1,1), CS 1–0, and H$_2$CO 0$_{00}$–1$_{01}$ spectra, using the package VPFIT.\footnote{http://www.ast.cam.ac.uk/~rfc/vpfit.html} The velocity structure in all optically thin lines was assumed to be the same, in both the number of absorbing “clouds” and their redshifts. Turbulence was assumed to be the dominant contributor to the line widths, which were hence tied together in the fit (Murphy et al. 2008a). The NH$_3$ hyperfine structure was included by assuming local thermodynamic equilibrium (LTE), with the hyperfine ratios taken from Table S1 of Murphy et al. (2008a). Finally, the fit also included a single velocity offset between the spectral components in the inversion and rotational transitions, to account for a possible change in the proton–electron mass ratio.

A simultaneous multi-component Voigt profile fit was carried out to the three spectra of Figure 1 with the above assumptions, aiming to minimize $\chi^2$ by varying the fit parameters. A three-component fit was found to yield $\chi^2 = 1.05$ and no evidence for structure in the residuals after subtracting out the fits to each spectrum (see the lower panels of Figure 1). Specifically, a Kolmogorov–Smirnov rank-1 test found the fit residuals for all lines to be consistent with a normal distribution within $\sim 3\sigma$ confidence. One- and two-component fits were found to yield both a larger $\chi^2$ and clear non-Gaussian structure in the residual spectra. While increasing the number of spectral components to four did yield a marginally lower $\chi^2$ ($\sim 1.02$), the additional spectral component was only weakly detected in the H$_2$CO spectrum (at $\lesssim 3\sigma$ significance) and was not visible in the NH$_3$ or CS transitions. A three-component model thus appears to provide a good fit to the data; however, for completeness, results from the four-component fit will also be mentioned below.

For the coupled three-component model, the number of fit parameters is 16, three redshifts, three line widths, nine optical depths in the NH$_3$, CS, and H$_2$CO lines, and the velocity offset between the inversion and rotational transitions. The parameters of the best three-component fit are listed in Table 1; the best-fit velocity offset is $\Delta V = (−0.36 \pm 0.10)$ km s$^{-1}$, with the NH$_3$ lines blueshifted relative to the rotational lines. A similar result is obtained from the best-fit four-component model, $\Delta V = (−0.39 \pm 0.11)$ km s$^{-1}$. Similar results are also obtained from carrying out three-component fits to the NH$_3$ and CS lines (i.e., without including the H$_2$CO line), and to the NH$_3$ and H$_2$CO lines (i.e., without the CS line).

To obtain an estimate of systematic effects, a similar three-component fit was also carried out to the CS and H$_2$CO rotational lines alone (i.e., without including the NH$_3$ inversion lines). This yielded a velocity offset of $\Delta V = (0.029 \pm 0.068)$ km s$^{-1}$, between the CS and H$_2$CO lines. The $3\sigma$ error obtained here, when comparing two rotational lines, will be used as an estimate of the systematic error due to local velocity offsets between different species in the absorber.

The fractional change in the proton–electron mass ratio $\mu$ is related to the measured velocity offset between inversion and rotational lines $\Delta V$ by the expression (Flambaum & Kozlov 2007) $[\Delta \mu/\mu] = 0.289 ([z_{\text{inv}} - z_{\text{rot}}]/(1 + z)) \approx 0.289 [\Delta V/c]$, where $z_{\text{inv}}$ and $z_{\text{rot}}$ are, respectively, the inversion and rotational redshifts, and $z$ is their average. Our final velocity offset is $\Delta V = [−0.36 \pm 0.10(\text{stat}.)] \pm 0.068(\text{syst}.)$ km s$^{-1}$; this yields $[\Delta \mu/\mu] = [−3.47 \pm 0.96(\text{stat}.)] \pm 0.66(\text{syst}.)] \times 10^{-7}$. Adding the statistical and systematic errors in quadrature, we obtain $[\Delta \mu/\mu] = (−3.5 \pm 1.2) \times 10^{-7}$, between $z \sim 0.685$ and the present epoch.

3. DISCUSSION

An excellent summary of the systematic effects inherent in the comparison between rotational and inversion lines in the $z \sim 0.685$ absorber is given by Murphy et al. (2008a).
Figure 1. GBT spectra in the redshifted (a) NH$_3$ (1,1), (b) CS 1–0, and (c) H$_2$CO 000–101 transitions from the $z \sim 0.685$ absorber toward B0218+357. The upper panels show normalized line depth in each transition plotted against velocity, in km s$^{-1}$, relative to a heliocentric redshift of $z = 0.684676$; the three-component fit is overlaid on each spectrum. The lower panels show the residuals from the spectra after subtracting out the joint three-component fit; these are consistent with noise.

(A color version of this figure is available in the online journal.)

Table 1

| No. | Velocity Offset (km s$^{-1}$) | Redshift | FWHM (km s$^{-1}$) | NH$_3$ Line Depth $\times 100$ | CS Line Depth $\times 100$ | H$_2$CO Line Depth $\times 100$ |
|-----|-------------------------------|----------|-------------------|--------------------------|------------------------|--------------------------|
| 1   | 0.6846935(2)                 | 0.684684935(2) | 3.99 ± 0.13      | 0.496 ± 0.060            | 13.83 ± 0.78           | 15.61 ± 0.84             |
| 2   | (-0.36 ± 0.10)               | 0.6846858(10)  | 10.60 ± 0.45     | 0.734 ± 0.026            | 4.39 ± 0.33            | 3.00 ± 0.39              |
| 3   | 0.6846214(7)                 | 0.6846214(7)   | 3.53 ± 0.33      | 0.128 ± 0.032            | 2.84 ± 0.28            | 5.17 ± 0.37              |

Notes. The second column contains the best-fit velocity offset between the rotational and inversion lines; note that a single velocity offset was assumed for all spectral components. The redshifts of Column 3 are in the heliocentric frame, while the line depths ($\times 100$), listed in the last three columns, have been normalized by the source continuum at each observing frequency.

These include the following: (1) the assumption that different transitions have the same number of spectral components, and at the same redshifts, (2) the background source morphology is frequency-dependent, implying that the NH$_3$ and rotational transitions might arise along slightly different sight lines, (3) the background source flux density (and hence morphology) varies with time, so observations at different epochs might probe different sight lines, (4) the assumption of LTE for the NH$_3$ hyperfine structure, (5) saturation effects if highly saturated lines (e.g., the HCO$^+$ and HCN lines used by Murphy et al. 2008a) are used, and (6) local velocity offsets between the species giving rise to the transitions. As noted by Murphy et al.
(2008a), all these effects could yield significant contributions to their systematic errors. For example, the inversion and rotational transitions used by Murphy et al. (2008a) were at very different frequencies, \(\sim 14\) GHz and \(\sim 106\) GHz; changes in the background source morphology could thus result in different sight lines in the different transitions. The NH\(_3\) and HCO\(^+\) / HCN observations were separated by a few years, implying that temporal variability in the source morphology could also be an issue, especially given that saturated transitions were used in the analysis. Finally, the NH\(_3\) spectra were of too low signal-to-noise ratio (S/N) to detect the NH\(_3\) hyperfine structure and to test for non-LTE effects.

Most of the above issues have been directly addressed in the present work. All three transitions used in the analysis are unsaturated and have been observed at high S/N, and with the same telescope. The two outlying NH\(_3\) hyperfine components (at \(\pm 19.5\) km s\(^{-1}\) relative to the strongest component) in the NH\(_3\) (1, 1) line have also been clearly detected (see Figure 1(a)). As noted by Murphy et al. (2008a), non-LTE effects resulting in hyperfine “anomalies” should cause the satellite hyperfine components (with \(\Delta F_i \neq 0\), where \(F_i\) is the quadrupole quantum number) to have different optical depths. No evidence for such non-LTE conditions is apparent in the \(\pm 19.5\) km s\(^{-1}\) satellite hyperfine components in Figure 1(a); the optical depths are found to agree within the noise.

We note, finally, that the systematic error of \(7.6 \times 10^{-7}\) in the result of Murphy et al. (2008a) contains two contributions: (1) \(7 \times 10^{-7}\) because spectral components detected in the HCO\(^+\) and HCN spectra may not be detected in the NH\(_3\) spectra, due either to the large frequency difference between the inversion and rotation lines or to the fact that the HCO\(^+\) and HCN lines are optically thick and (2) \(3 \times 10^{-7}\) due to the possibility of non-LTE effects in the NH\(_3\) spectra. Our choice of rotational lines and the higher sensitivity of our NH\(_3\) spectra implies that neither of these are significant sources of systematic error in the present analysis.

Liszt et al. (2006) find that NH\(_3\) column densities correlate best with CS and H\(_2\)CO column densities in Galactic diffuse clouds; CS and H\(_2\)CO are thus likely to be the best rotational transitions for the inversion/rotation comparison, as the correlation in column densities suggests that the three species are likely to arise in the same part of a gas cloud. Galactic absorption has also been detected in all three species toward two quasars, B0355+508 and B0415+379 (Liszt & Lucas 1995; Lucas & Liszt 1998; Liszt et al. 2006); both sight lines show two components in all species, with line velocities agreeing within 0.2 km s\(^{-1}\) (see Table 1 of Liszt & Lucas 1995, Table 6 of Lucas & Liszt 1998, and Table A1 of Liszt et al. 2006); local velocity offsets between the species thus appear to be small. Further, the rotational and inversion line frequencies are much closer here than in the comparison of Murphy et al. (2008a), with the redshifted NH\(_3\), CS, and H\(_2\)CO lines at \(\sim 14\) GHz, \(\sim 29\) GHz, and \(\sim 43\) GHz, respectively. Changes in source morphology with frequency are thus a less important issue here than in the analysis of Murphy et al. (2008a). A direct test comes from the comparison between the two rotational lines, whose frequencies differ by a factor of \(\sim 1.5\), comparable to the ratio of the CS and NH\(_3\) frequencies (\(\sim 2\)). The CS–H\(_2\)CO comparison also provides an estimate of the systematic error due to local velocity offsets between different species in the clouds. This test found the CS and H\(_2\)CO line redshifts to agree within the noise; the 1\(\sigma\) error in this comparison has been used to quantify the systematic error due to both local velocity offsets and differing background source morphology at the different line frequencies. Finally, similar velocity offsets (consistent within the errors) were obtained in the independent comparisons between the NH\(_3\) and CS lines, and the NH\(_3\) and H\(_2\)CO lines.

A source of systematic effects that could not be directly addressed here is time variability in the background source morphology, which might yield different sight lines through the absorbing clouds at different epochs (Murphy et al. 2008a; see Muller & Guélin 2008 for the \(z \sim 0.886\) lens toward B1830–210). Unfortunately, the redshifted NH\(_3\), CS, and H\(_2\)CO transitions toward B0218+357 require different GBT receivers and cannot be observed simultaneously. The present NH\(_3\), CS, and H\(_2\)CO observations were carried out between 2008 January and August; the possibility that the weak offset between the inversion and rotational lines arises due to small changes in the sight line thus cannot be ruled out. Further, the agreement between CS and H\(_2\)CO velocities does not rule out the possibility that nitrogen-bearing species like NH\(_3\) arise at different velocities than carbon-bearing species like CS and H\(_2\)CO. This can only be tested by using rotational transitions of other nitrogen-bearing species (e.g., HC\(_3\)N, CH\(_3\)CN, etc.).

While there are two possible sources of systematic error that we are as yet unable to quantify, the present data show no statistically significant (\(\geq 3\sigma\)) evidence for changes in the proton–electron mass ratio. Our 3\(\sigma\) upper limit on changes in \(\mu\) is \([\Delta \mu/\mu] < 3.6 \times 10^{-7}\), between \(z \sim 0.685\) and \(z = 0\) (a look-back time of 6.2 Gyr). For comparison, Murphy et al. (2008a) obtained \([\Delta \mu/\mu] < 1.8 \times 10^{-6}\) (2\(\sigma\)) in the \(z \sim 0.685\) absorber toward B0218+357, while Henkel et al. (2009) obtained \([\Delta \mu/\mu] < 1.4 \times 10^{-6}\) (3\(\sigma\)) in the \(z \sim 0.886\) absorber toward B1830–210, with both results based on inversion/rotation comparisons. Note, however, that Henkel et al. (2009) used single-Gaussian fits for the NH\(_3\) and HC\(_3\)N lines toward B1830–210, although it is clear from the profiles of other unsaturated lines (e.g., CS) that at least three absorbing “clouds” are present along the sight line. Further, the GBT spectra in the strongest [(1, 1), (2, 2), and (3, 3)] NH\(_3\) lines toward B1830–210 were severely affected by radio frequency interference (see Figure 1 of Henkel et al. 2008). The effect of these issues on the results of Henkel et al. (2009) is unclear, but the error budget is likely to increase. At higher redshifts, the best published constraint on changes in \(\mu\) is that of King et al. (2008): \([\Delta \mu/\mu] < 6.0 \times 10^{-6}\), using H\(_2\) lines (but see Wendt & Molaro 2011). The present result, \([\Delta \mu/\mu] < 3.6 \times 10^{-7}\) (3\(\sigma\)) at \(z \sim 0.685\), is thus the most sensitive constraint on temporal changes in \(\mu\) at any redshift, by a factor \(\gtrsim 5\).

To compare this result with those from laboratory studies, it is necessary to assume a model for the variation of \(\mu\) with time. For linear variation, the present result yields \(\dot{\mu}/\mu < 5.6 \times 10^{-17}\) per year, more than an order of magnitude better than the best (model-dependent) laboratory constraint on changes in \(\mu\) (Rosenband et al. 2008).

In conclusion, we have used the GBT to obtain high S/N spectra in the NH\(_3\) (1, 1), CS 1–0, and H\(_2\)CO \(0_00–1_11\) transitions from the \(z \sim 0.685\) absorber toward B0218+357. A comparison between the redshifts of the inversion and rotational lines yields a velocity offset of \(\Delta V = -[0.36 \pm 0.10\) (stat.) \(\pm 0.068\) (syst.\)] km s\(^{-1}\), with the NH\(_3\) lines blueshifted relative to the rotational ones. Two sources of systematic error remain to be quantified, arising from (1) velocity offsets between nitrogen-bearing and carbon-bearing species and (2) time variability in the background source morphology, which might yield different sight lines at different epochs. We find no statistically significant
(\geq 3 \sigma) evidence for changes in \( \mu \), with the 3 \( \sigma \) constraint \( \Delta \mu / \mu < 3.6 \times 10^{-7} \) over a look-back time of 6.2 Gyr. This is the strongest present constraint on temporal changes in the proton–electron mass ratio.

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