CONSTRaining Fundamental Constant Evolution With H_1 And OH lines

N. Kanekar\textsuperscript{1,6}, G. I. Langston\textsuperscript{2}, J. T. Stocke\textsuperscript{3}, C. L. Carilli\textsuperscript{4}, and K. M. Merten\textsuperscript{5}

\textsuperscript{1} National Centre for Radio Astrophysics, TIFR, Ganeshkhind, Pune-411007, India; nkanekar@ncra.tifr.res.in
\textsuperscript{2} National Radio Astronomy Observatory, Green Bank, WV 24944, USA
\textsuperscript{3} CASA, Department of Astrophysical and Planetary Sciences, University of Colorado, 389-UCB, Boulder, CO 80309, USA
\textsuperscript{4} National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM 87801, USA
\textsuperscript{5} Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Received 2011 December 22; accepted 2012 January 12; published 2012 January 30

ABSTRACT

We report deep Green Bank Telescope spectroscopy in the redshifted H\textsubscript{1} 21 cm and OH 18 cm lines from the \(z = 0.765\) absorption system toward PMN J0134−0931. A comparison between the “satellite” OH 18 cm line redshifts, or between the redshifts of the H\textsubscript{1} 21 cm and “main” OH 18 cm lines, is sensitive to changes in different combinations of three fundamental constants, the fine structure constant \(\alpha\), the proton–electron mass ratio \(\mu \equiv m_p/m_e\), and the proton g-factor \(g_p\). We find that the satellite OH 18 cm lines are not perfectly conjugate, with both different line shapes and stronger 1612 MHz absorption than 1720 MHz emission. This implies that the satellite lines of this absorber are not suitable to probe fundamental constant evolution. A comparison between the redshifts of the H\textsubscript{1} 21 cm and OH 18 cm lines, via a multi-Gaussian fit, yields the strong constraint [\(\Delta F/F = (-5.2 \pm 4.3) \times 10^{-9}\), where \(F \equiv g_p(\mu \alpha)^4\)]\textsuperscript{1} and the error budget includes contributions from both statistical and systematic errors. We thus find no evidence for a change in the constants between \(z = 0.765\) and the present epoch. Incorporating the constraint \([\Delta \mu/\mu] < 3.6 \times 10^{-7}\) from another absorber at a similar redshift and assuming that fractional changes in \(g_p\) are much smaller than those in \(\alpha\), we obtain \([\Delta \alpha/\alpha] = (-1.7 \pm 1.4) \times 10^{-6}\) over a look-back time of 6.7 Gyr.

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

Online-only material: color figures

1. INTRODUCTION

The standard model of particle physics implicitly assumes that the values of coupling constants and particle masses do not depend on space or time. Conversely, variation in such “fundamental constants” appears to be a generic feature of higher-dimensional theories aiming to unify the standard model and general relativity (e.g., Marciano 1984). Studies of fundamental constant evolution are hence of much interest as they both probe the foundations of the standard model and allow the possibility of distinguishing between different unification models at low energy scales (Uzan 2011).

While laboratory atomic clock studies have yielded strong constraints on short-term changes in the fine structure constant \(\alpha\) (e.g., Rosenband et al. 2008), such studies are not sensitive to changes on Gyr timescales. A wide range of methods, based on various spectral transitions, has been used to probe changes in \(\alpha\), the proton–electron mass ratio \(\mu \equiv m_p/m_e\), and the proton g-factor \(g_p\) on cosmological timescales (e.g., Bahcall 2005; Wolfe et al. 1976; Varshalovich & Levshakov 1993; Dzuba et al. 1999; Darling 2003; Chengalur & Kanekar 2003; Kanekar & Chengalur 2004; Flambaum & Kozlov 2007). Significant progress has recently been made in both the development of new techniques and the sensitivity of measurements. A combination of the many-multiplet method (Dzuba et al. 1999) with spectra from the High Resolution Echelle Spectrograph (HIRES) on the Keck telescope has found evidence for changes in \(\alpha\) with redshift, \([\Delta \alpha/\alpha] = (-5.7 \pm 1.1) \times 10^{-9}\) for 143 absorbers at an average redshift \(\bar{z} = 1.75\) (Murphy et al. 2004). Later studies applying this method to spectra from the Ultraviolet Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) have not confirmed this result (e.g., Srianand et al. 2007; Molaro et al. 2008). Recently, Webb et al. (2011) applied the many-multiplet method to a large VLT-UVES sample and also did not find evidence supporting the Keck-HIRES result. While Webb et al. (2011) attempted to reconcile the Keck-HIRES and VLT-UVES results by proposing spatio-temporal changes in \(\alpha\), a simpler explanation is that the errors in both studies have been underestimated, especially given that systematic and unexplained errors have been shown to be present in the wavelength calibration of both spectrographs (Griest et al. 2010; Whitmore et al. 2010; Agafonova et al. 2011). Keck-HIRES and VLT-UVES spectra in redshifted H\textsubscript{2} lines have also yielded constraints on changes in \(\mu\): the best current result is \([\Delta \mu/\mu] < 4.4 \times 10^{-6}\) (\(\bar{z} \sim 2.8\); King et al. 2011), although the errors here too may have been underestimated due to wavelength calibration issues.

Radio spectroscopic techniques provide independent probes of fundamental constant evolution, with different systematic effects from those in optical schemes (e.g., Kanekar 2008). Such methods include comparisons between rotational and H\textsubscript{1} 21 cm hyperfine lines (Drinkwater et al. 1998), between different hydroxyl (OH) lines or H\textsubscript{1} 21 cm and OH 18 cm lines (Darling 2003; Chengalur & Kanekar 2003; Kanekar & Chengalur 2004; Flambaum & Kozlov 2007), and between far-infrared fine structure lines and rotational lines (Levshakov et al. 2008), etc., each sensitive to different combinations of \(\alpha\), \(\mu\), and \(g_p\). For example, the inversion-rotation comparison has yielded the best current constraint on changes in \(\mu\) from any astronomical method, \([\Delta \mu/\mu] < 3.5 \times 10^{-7}\) over \(0 < z < 0.685\) (Kanekar 2011).

---

8 Ramanujan Fellow.
In general, techniques using multiple spectral lines from a single atomic or molecular species (e.g., OH, methanol, Fe II, etc.) are preferable to those using different species, as lines in the former case are likely to arise in the same gas, making the technique less susceptible to local velocity offsets.

The satellite OH 18 cm lines have the special property of having exactly the same shape and opposite sign in certain astrophysical circumstances, due to a population inversion mechanism and quantum mechanical selection rules (Elitzur 1992; van Langevelde et al. 1995). This “conjugate” behavior makes them ideal probes of fundamental constant evolution (Kanekar et al. 2004; Kanekar 2008). Only two such conjugate OH 18 cm systems have so far been discovered at cosmological distances, at \( z \approx 0.247 \) toward PKS 1413+135 (Kanekar et al. 2004; Darling 2004) and \( z \approx 0.765 \) toward PMN J0134−0931 (Kanekar et al. 2005). A high-sensitivity study of PKS 1413+135 with the Westerbork Synthesis Radio Telescope and the Arecibo Telescope found tentative evidence (at 99.1% confidence level) for changes in \( \alpha, \mu, \) and/or \( g_\nu \) (Kanekar et al. 2010a).

In this Letter, we report deep Green Bank Telescope (GBT) observations of the redshifted \( \text{H}^\text{i} \) 21 cm and OH 18 cm lines in the \( z \approx 0.765 \) system toward PMN J0134−0931 that yield strong constraints on changes in the fundamental constants.

2. OBSERVATIONS, DATA ANALYSIS, AND SPECTRA

The GBT observations of the \( \text{H}^\text{i} \) 21 cm and OH 18 cm lines from the \( z \approx 0.765 \) gravitational lens toward PMN J0134−0931 (Winn et al. 2002; Kanekar & Briggs 2003) were carried out between 2005 September and 2006 October (proposal AGBT05C-037), using the PFI-800 and PF2 receivers, respectively. The observations used the AutoCorrelation Spectrometer (ACS) with 9-level sampling, two polarizations and 10 s integrations. A single ACS 12.5 MHz band, sub-divided into 32768 channels, was used for the \( \text{H}^\text{i} \) 21 cm line, while four ACS 12.5 MHz sub-bands, each sub-divided into 8192 channels, were used for the ground-state OH 18 cm lines. The system pass-band was calibrated by position-switching every five minutes, with system temperatures measured using a noise diode. The on-source times were \( \sim 15 \) hr for the \( \text{H}^\text{i} \) 21 cm line and \( \sim 30 \) hr for the OH 18 cm lines.

All data were analyzed in the package DISH, using standard procedures. The OH 18 cm data were especially affected by intermittent radio-frequency interference (RFI); a visual inspection of every calibrated 10 s integration was used to excise data affected by RFI. Most of the data were found to have narrowband RFI at \( \sim 945 \) MHz, close to the center of the OH 1667 MHz absorption profile. The channels affected by RFI were entirely edited out in the final spectrum, along with 25 channels on either side (i.e., the frequency range 944.867–945.150 MHz). Similarly, weak RFI was also found adjacent to the satellite OH 18 cm profiles, due to which a few channels in the final spectra were blanked out.

The final \( \text{H}^\text{i} \) 21 cm and “main” OH 18 cm optical depth spectra are shown in the upper panels of Figure 1, while the “satellite” OH 18 cm spectra are shown in Figure 2. The \( \text{H}^\text{i} \) 21 cm and OH 18 cm spectra have velocity resolutions of \( \sim 0.3 \) km s\(^{-1}\) and \( \sim 1.0 \) km s\(^{-1}\), respectively (after Hanning-smoothing and resampling), and root-mean-square optical depth noise values of 0.0019 per 0.3 km s\(^{-1}\) channel (\( \text{H}^\text{i} \) 21 cm) and \( \sim 0.0011–0.0012 \) per 1.0 km s\(^{-1}\) channel (OH 18 cm lines). Note that these are “apparent” optical depths, derived using the total flux density of PMN J0134−0931 at the line frequencies. PMN J0134−0931 is a five-component gravitational lens system with an angular extent of \( \approx 0.7 \) (Winn et al. 2002), i.e., \( \approx 5 \) kpc at \( z = 0.765 \) and unresolved by the GBT beam. The \( \text{H}^\text{i} \) 21 cm and OH 18 cm features are likely to arise against only one or two of the source components, implying that the “true” optical depths are probably significantly larger than the measured optical depths.

Figure 2 shows that, while the 1720 MHz line is in emission and the 1612 MHz line is in absorption, the two lines have different strengths with the peak optical depths in the 1720 MHz and 1612 MHz lines being \( \approx 0.007 \) and \( \approx 0.01 \), respectively. Thus, although the satellite OH lines have similar shapes, they are not exactly conjugate, with the 1612 MHz line about 1.5 times stronger than the 1720 MHz line. We tried a number of analysis procedures and RFI excision schemes to test whether
the difference between the satellite line profiles might arise due to RFI; the difference was found to be present in all cases. Further, the flux densities of PMN J0134−0931 measured in the 1612 MHz and 1720 MHz spectra were very similar (≈0.7 Jy in each), and the rms noise values on the two spectra are comparable, indicating that there is no scaling error in the flux density calibration. It is thus unlikely that the difference between the satellite line profiles arises due to either RFI or problems with the flux density scale.

3. PROBING FUNDAMENTAL CONSTANT EVOLUTION

3.1. The Satellite OH Lines

The $2\Pi_{3/2}(J = 3/2)$ OH rotational ground state is split into four sub-levels by $\Delta F$-doubling and hyperfine splitting; two sub-levels have total angular momentum quantum number $F = 2$, while the other two have $F = 1$. The satellite OH 18 cm lines correspond to transitions with $\Delta F = \pm 1$ between these sub-levels. Similarly, two sub-levels of every excited rotational state have $F = J + 1/2$, while the other two have $F = J − 1/2$.

The satellite OH 18 cm lines are said to be “conjugate” when they have the same shape, but with one line in emission and the other in absorption (Elitzur 1992). This arises because, when the OH molecules are pumped to excited states (by collisions or far-infrared radiation), the downward cascade to the ground state yields population inversion in the ground-state sub-levels as certain transitions are forbidden by the selection rules $\Delta F = 0, \pm 1$. If the last stage of the cascade is the intraladder $119 \mu m$ transition $2\Pi_{3/2}(J = 5/2) \rightarrow 2\Pi_{3/2}(J = 3/2)$, transitions between the $F = 3$ and $F = 1$ sub-levels are forbidden; this would overpopulate sub-levels with $F = 2$ relative to those with $F = 1$. As a result, the 1720 MHz transition would not be anti-inverted; this is the situation in Figure 2, with the 1720 MHz and 1612 MHz transitions in emission and absorption, respectively.

If the $119 \mu m$ lines connecting the excited and ground states are optically thick (which depends on the local particle number density and velocity gradient; Elitzur 1976; Guibert et al. 1978), the rate coefficients for the different branches of the cascade are independent of line strength. This implies that the same number of particles are present in the two $F = 2$ ground-state sub-levels, and, similarly, in the two $F = 1$ sub-levels. The 1720 MHz and 1612 MHz lines then have identical strengths and shapes, albeit opposite sign (Elitzur 1992). This is the ideal situation for the use of the satellite OH 18 cm lines to probe changes in the fundamental constants as the identical line shapes guarantee that the lines arise from the same gas (Kanekar & Chengalur 2004; Kanekar 2008).

Exactly conjugate satellite OH 18 cm lines have been observed in several extragalactic sources including Cen A (van Langevelde et al. 1995), M82 (Seaquist et al. 1997), NGC 253 (Frayer et al. 1998), and PKS 1413+135 (Kanekar et al. 2010a). In Cen A and NGC 253, the satellite lines are conjugate over a wide range of conditions and even show the crossover from absorption to emission (and vice versa) in each transition. As such, the fact that the satellite lines toward PMN J0134−0931 are not perfectly conjugate is both unusual and unexpected. If the $119 \mu m$ transitions that dominate the downward cascade are not optically thick, the rate coefficients of the decay routes to the different sub-levels are different and one would not obtain conjugate behavior (Elitzur 1976). Alternatively, there may be absorption at the satellite line velocities from the molecular cloud that gives rise to part of the main OH 18 cm absorption. For example, there is a main OH 18 cm component at $z = 0.76385$ (see Table 1), with peak 1667 MHz opacity $\approx 0.0129$. If the OH ground-state levels in this cloud are thermalized, the satellite lines would have peak optical depths of $\approx 0.0014$ (nine times weaker than the 1667 MHz line). The 1612 MHz absorption would hence be increased, and the 1720 MHz emission reduced, by this amount, yielding a difference of $\approx 0.0028$ between the satellite optical depths, consistent with the observed difference.

Since the satellite OH 18 cm lines are not perfectly conjugate, it cannot be assumed that the lines arise from the same gas. The lines also have slightly different shapes, in addition to the different strengths. This implies unknown systematic effects if these lines are used in studies of fundamental constant evolution. We hence conclude that the satellite OH 18 cm lines in the $z \approx 0.765$ absorber toward PMN J0134−0931 are not suitable to probe changes in $\alpha$, $\mu$, and $g_p$.

3.2. The “Main” OH 18 cm and H I 21 cm Lines

A comparison between the redshifts of the “main” OH 18 cm lines and the H I 21 cm line is sensitive to changes in $F \equiv g_p(\alpha^2 \mu)^{1/5}7$ (Chengalur & Kanekar 2003). We used a multi-Gaussian fit to the H I 21 cm and main OH 18 cm lines to test for changes in $F$, assuming the same velocity structure in the different lines. Independent fits to the H I and OH lines found a four-component model to give a good fit to each line, with good agreement between the line widths of the corresponding H I and OH components. Turbulent broadening was hence assumed to dominate the line widths, with the H I and OH widths of each component tied together in the fit. No assumption was made about the relative strengths of the main OH lines. However, since the main OH 18 cm line frequencies have the same dependence on $\alpha$, $\mu$, and $g_p$ to first order (Chengalur & Kanekar 2003; Kozlov 2009), the OH line redshifts of each component were tied together. The fit included a single velocity offset between
The parameters of the fit are summarized in Table 1; the error on each parameter has been increased by a factor of $\sqrt{\chi^2}$ to account for the fact that the best-fit value of $\chi^2$ is slightly larger than unity ($\chi^2/v = 1.09$), probably because the rms optical depth noise on the spectra has been marginally underestimated. The best-fit velocity offset is $\Delta V = (1.57 \pm 0.44) \text{ km s}^{-1}$, with the H1 21 cm line bluew over of the OH 18 cm lines.

The above error on $\Delta V$ is the statistical error from the fit. Other contributions to the error budget include errors in the line rest frequencies and the frequency scale calibration, and local velocity offsets between the clouds giving rise to the H1 21 cm and OH 18 cm lines; the latter dominate the systematic errors. Kanekar et al. (2005) estimated the Galactic dispersion between H1 21 cm and OH 18 cm velocities to be <1.2 km s$^{-1}$, using the measured dispersion between Galactic H1 21 cm and HCO$^+$ velocities (Drinkwater et al. 1998) and the good match between HCO$^+$ and OH velocities (Liszt & Lucas 2000). We will assume that this dispersion also applies to the $z \sim 0.765$ absorber. For comparison, the main OH 18 cm frequencies have been measured with an accuracy of 12 Hz ($\sim 2$ m s$^{-1}$; Hudson et al. 2006), while the error in the GBT frequency scale (mainly due to Doppler tracking) is $\lesssim 15$ m s$^{-1}$.

Our final result for the velocity offset between H1 21 cm and OH 18 cm lines, including both statistical and systematic errors, is thus $\Delta V = [-1.57 \pm 0.44 \text{(stat.)} \pm 1.2 \text{(syst.)}] \text{ km s}^{-1}$. This yields $[\Delta F/F] = [-5.2 \pm 1.5 \text{(stat.)} \pm 4.0 \text{(syst.)}] \times 10^{-6}$. Adding the statistical and systematic errors in quadrature gives $[\Delta F/F] = [-5.2 \pm 4.3] \times 10^{-6}$. We thus find no evidence for a change in $\alpha$, $\mu$, or $g_p$ between $z = 0.765$ and today, i.e., over a period of 6.7 Gyr.$^7$

4. DISCUSSION

The previous section constrains changes in $F \equiv g_p [\alpha^2 \mu]^1.57$ and does not yield independent constraints on changes in $\alpha$, $\mu$, and $g_p$. However, this result can be used to obtain the sensitivity to changes in each parameter by assuming that the other two do not vary with time. The $1\sigma$ sensitivities are $[\Delta \alpha/\alpha] = 1.4 \times 10^{-6}$, $[\Delta \mu/\mu] = 2.7 \times 10^{-6}$, and $[\Delta g_p/g_p] = 4.3 \times 10^{-6}$. A stringent constraint on changes in $\mu$ was recently obtained by Kanekar (2011) from a comparison between NH$_3$ inversion and CS/H$_2$CO rotational lines at $z = 0.685$ toward B0218+357: $[\Delta \mu/\mu] < 3.6 \times 10^{-7}$ between $z = 0.685$ and the present epoch. Assuming that there are no spatial variations in the constants, we can replace $[\Delta \mu/\mu]$ in the expression for $[\Delta F/F]$ to get $[\Delta g_p/g_p] + 3.14 \times [\Delta \alpha/\alpha] = [-5.2 \pm 4.3] \times 10^{-6}$. If we further assume that $[\Delta g_p/g_p] \ll [\Delta \alpha/\alpha]$, we obtain $[\Delta \alpha/\alpha] = [-1.7 \pm 1.4] \times 10^{-6}$ between $z = 0.765$ and today.

7 We use a standard LCDM cosmology, with $H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{b}} = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Komatsu et al. 2011).
Figure 3 shows a comparison between the best estimates of $[\Delta \alpha / \alpha]$ from a variety of techniques today (Murphy et al. 2001, 2004; Kanekar et al. 2010a, 2010b; Webb et al. 2011; Agafonova et al. 2011). The Keck-HIRES many-multiplet data set is the only one that finds statistically significant evidence for changes in $\alpha$. However, systematic wavelength calibration errors may have been underestimated here (Griest et al. 2010). At present, there appears to be no strong evidence from astronomical spectroscopy for changes in the fundamental constants on cosmological timescales.

In summary, we have carried out deep GBT spectroscopy in the redshifted H$\alpha$ 21 cm and OH 18 cm transitions from the $z = 0.765$ absorber toward PMN J0134$-$0931. We find that the satellite OH 18 cm lines are not perfectly conjugate, with the 1612 MHz absorption $\sim 1.5$ times stronger than the 1720 MHz emission. The fact that the satellite lines have different shapes implies that these should not be used to probe fundamental constant evolution, due to the possibility of unknown systematic effects. We obtain tight constraints on changes in the quantity $F \equiv g_\mu [\mu z^2]^{1/5}$ via a simultaneous fit to the H$\alpha$ 21 cm and OH 18 cm line profiles. A four-component Gaussian model assuming turbulent line broadening yields a good fit to both profiles, yielding $[\Delta F / F] = [-5.2 \pm 4.3] \times 10^{-6}$, including both statistical and systematic errors. We find no evidence for a change in $\alpha$, $\mu$, or $g_\mu$ between $z = 0.765$ and today.

We thank Bob Carswell, Carl Bignell, and Bob Garwood for much help with VPFIT, and the GBT observations and data analysis. N.K. acknowledges support from the Department of Science and Technology, India, via a Ramanujan Fellowship. C.C. acknowledges support from the Max-Planck Society and the Alexander von Humboldt Foundation. J.T.S. acknowledges support from NSF grant AST-0707480 and an NRAO travel grant. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the NSF.

REFERENCES

Agafonova, I. I., Molaro, P., Levshakov, S. A., & Hou, J. L. 2011, A&A, 529, 28
Bahcall, J. N., Sargent, W. L. W., & Schmidt, M. 1967, ApJ, 149, L11
Chengalur, J. N., & Kanekar, N. 2003, Phys. Rev. Lett., 91, 241302
Darling, J. 2003, Phys. Rev. Lett., 91, 011301
Darling, J. 2004, ApJ, 612, 58
Drinkwater, M. J., Webb, J. K., Barrow, J. D., & Flambaum, V. V. 1998, MNRAS, 295, 457
Dzuba, V. A., Flambaum, V. V., & Webb, J. K. 1999, Phys. Rev. Lett., 82, 888
Elitzur, M. 1976, ApJ, 203, 124
Elitzur, M. 1992, Astronomical Masers (Dordrect, NL: Kluwer)
Flambaum, V. V., & Kozlov, M. G. 2007, Phys. Rev. Lett., 98, 240801
Frayer, D. T., Seaquist, E. R., & Frail, D. A. 1998, AJ, 115, 559
Griest, K., Whitmore, J. B., Wolfe, A. M., et al. 2010, ApJ, 706, 158
Guilbert, J., Elitzur, M., & Rees, N.-Q. 1978, A&A, 66, 395
Hudson, E. R., Lewandowski, H. J., Sawyer, B. C., & Ye, J. 2006, Phys. Rev. Lett., 96, 143004
Jansen, P. Xu, L.-H., Kleiner, I., Ubachs, W., &Bethlem, H. L. 2011, Phys. Rev. Lett., 106, 100801
Kanekar, N. 2011, ApJ, 728, L12
Kanekar, N., Carilli, C. L., Langston, G. I., et al. 2005, Phys. Rev. Lett., 95, 261301
Kanekar, N., & Chengalur, J. N. 2004, MNRAS, 350, L17
Kanekar, N., Chengalur, J. N., & Ghosh, T. 2004, Phys. Rev. Lett., 93, 051302
Kanekar, N., Chengalur, J. N., & Ghosh, T. 2010a, ApJ, 716, L23
Kanekar, N., Chengalur, J. N., & Lane, W. M. 2007, MNRAS, 375, 1528
Kanekar, N., Prochaska, J. X., Ellison, S. L., &Chengalur, J. N. 2010b, ApJ, 712, L148
Kanekar, N., Subrahmanyan, R., Ellison, S. L., Lane, W. M., &Chengalur, J. N. 2006, MNRAS, 370, L46
King, J. A., Murphy, M. T., Ubachs, W., & Webb, J. K. 2011, MNRAS, 417, 301
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Kozlov, M. G. 2009, Phys. Rev. A, 80, 022118
Kozlov, M. G., & Levshakov, S. A. 2011, ApJ, 726, 65
Levshakov, S. A., Kozlov, M. G., & Reimers, D. 2011, ApJ, 738, 26
Levshakov, S. A., Reimers, D., Kozlov, M. G., Porsev, S. G., & Molaro, P. 2008, A&A, 479, 719
Liszt, H., & Lucas, R. 2000, A&A, 355, 333
Marciano, W. J. 1984, Phys. Rev. Lett., 52, 489
Molaro, P., Reimers, D., Agafonova, I. I., & Levshakov, S. A. 2008, Eur. Phys. J. Spec. Top., 163, 173
Murphy, M. T., Flambaum, V. V., Webb, J. K., et al. 2004, in Astrophysics, Clocks and Fundamental Constants, ed. S. G. Karshenboim & E. Peik (Lecture Notes in Physics, Vol. 648; Berlin: Springer), 131
Murphy, M. T., Webb, J. K., Flambaum, V. V., et al. 2001, MNRAS, 327, 1208
Rosenband, T., Hume, D. B., Schmidt, P. O., et al. 2008, Science, 319, 1808
Seaquist, E. R., Frayer, D. T., & Frail, D. A. 1997, ApJ, 487, L131
Srianand, R., Chand, H., Petitjean, P., & Aracil, B. 2007, Phys. Rev. Lett., 99, 239002
Srianand, R., Gupta, N., Petriejan, P., Noterdaeme, P., & Ledoux, C. 2010, MNRAS, 405, 1888
Thompson, R. I. 1975, Astrophys. Lett., 16, 3
Tzanavaris, P., Webb, J. K., Murphy, M. T., Flambaum, V. V., & Curran, S. J. 2005, Phys. Rev. Lett., 95, 1301
Uzan, J.-P. 2011, Living Rev. Relativ., 14, 2
van Langevelde, H. J., van Dishoeck, E. F., Sevenster, M. N., & Israel, F. P. 1995, ApJ, 448, L123
Varshalovich, D. A., & Levshakov, S. A. 1993, JETP Lett.,58, 237
Webb, J. K., King, J. A., Murphy, M. T., et al. 2011, Phys. Rev. Lett., 107, 191101
Whitmore, J. B., Murphy, M. T., & Griest, K. 2010, ApJ, 723, 89
Winn, J. N., Lovell, J. E. J., Chen, H., et al. 2002, ApJ, 564, 143
Wolfe, A. M., Brown, R. L., & Roberts, M. S. 1976, Phys. Rev. Lett., 37, 179