

PROBING FUNDAMENTAL CONSTANT EVOLUTION WITH REDSHIFTED CONJUGATE-SATELLITE OH LINES

NISSIM KANEKAR¹, JAYARAM N. CHENGALUR², TAPASI GHOSH³

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ABSTRACT

We report Westerbork Synthesis Radio Telescope and Arecibo Telescope observations of the redshifted satellite OH 18cm lines at $z \sim 0.247$ towards PKS 1413+135. The “conjugate” nature of these lines, with one line in emission and the other in absorption, but with the same shape, implies that the lines arise in the same gas. The satellite OH 18cm line frequencies also have different dependences on the fine structure constant α , the proton-electron mass ratio $\mu = m_p/m_e$, and the proton gyromagnetic ratio g_p . Comparisons between the satellite line redshifts in conjugate systems can hence be used to probe changes in α , μ , and g_p , with few systematic effects. The technique yields the expected null result when applied to Cen.A, a nearby conjugate satellite system. For the $z \sim 0.247$ system towards PKS 1413+135, we find, on combining results from the two telescopes, that $[\Delta G/G] = (-1.18 \pm 0.46) \times 10^{-5}$ (weighted mean), where $G = g_p [\mu \alpha^2]^{1.85}$; this is tentative evidence (with 2.6σ significance, or at 99.1% confidence) for a smaller value of α , μ , and/or g_p at $z \sim 0.247$, i.e. at a lookback time of ~ 2.9 Gyrs. If we assume that the dominant change is in α , this implies $[\Delta \alpha/\alpha] = (-3.1 \pm 1.2) \times 10^{-6}$. We find no evidence that the observed offset might be produced by systematic effects, either due to observational or analysis procedures, or local conditions in the molecular cloud.

Subject headings: atomic processes — galaxies: high-redshift — quasars: absorption lines

1. INTRODUCTION

Most modern higher-dimensional theories venturing beyond the standard model of particle physics contain the fairly generic feature that the low-energy fundamental constants should vary with time. The detection of such changes opens up an avenue to probe basic physics, especially important because other predictions of these models tend to lie at unattainably high energies ($\gtrsim 10^{19}$ GeV). Tests of such low-energy predictions of these models, such as changes in the constants, violation of the equivalence principles, etc, may provide the only means of distinguishing between different unified theories and are hence of much importance in physics.

Astrophysical techniques can be used to probe changes in fundamental constants like the fine structure constant α , the proton-electron mass ratio $\mu \equiv m_p/m_e$ and the proton gyromagnetic ratio g_p , over a large fraction of the age of the Universe (e.g. Savedoff 1956; Wolfe et al. 1976; Thompson 1975; Dzuba et al. 1999; Chengalur & Kanekar 2003). Indeed, Murphy et al. (2004) applied one such technique (the “many-multiplet method”; Dzuba et al. 1999) to High Resolution Echelle Spectrograph (HIRES) data from the Keck telescope to obtain $[\Delta \alpha/\alpha] = (-5.7 \pm 1.1) \times 10^{-6}$ from 143 absorbers at $0.2 < z < 4.2$, i.e. suggesting a smaller value of α at earlier times (see also Murphy et al. 2003). This result has not so far been confirmed with independent data on smaller samples from the Ultraviolet Echelle Spectrograph (UVES) on the Very Large Telescope (e.g. Molaro et al. 2008; Srianand et al. 2007; Murphy et al. 2008b). More recently, King et al. (2008) used redshifted molecular hydrogen (H_2) lines to place strong constraints on changes in μ , obtaining $[\Delta \mu/\mu] = (-2.6 \pm 3.0) \times 10^{-6}$ from three absorbers at $z \sim 2.8$. Note that these results are all based on optical spectra,

where wavelength calibration, line blending, intrinsic velocity offsets, isotopic abundances, interloping absorbers, etc, are all possible sources of systematic error, (e.g. Murphy et al. 2003; Griest et al. 2010). Further, the quoted errors in the result of Murphy et al. (2004) do not include effects from systematic distortions in the HIRES wavelength calibration (Griest et al. 2010); similar, but smaller, distortions have also been found in the wavelength scale of the VLT-UVES spectrograph (Centurion et al. 2009; Whitmore et al. 2010).

Given the possibility that underestimated or unknown systematics might dominate the errors from a given technique, it is important that independent techniques, with entirely different systematics, be used to test for changes in the constants. It is also crucial to probe evolution at all timescales, as the timescales of the putative changes are entirely unknown. Redshifted radio OH lines provide an independent approach to study changes in α , μ and g_p (Chengalur & Kanekar 2003; Darling 2003; Kanekar & Chengalur 2004). In rare cases, the satellite OH 18cm lines (at rest frequencies of 1612.230825 (15) MHz and 1720.529887 (10) MHz; Lev et al. 2006) are “conjugate” to each other; i.e. the lines have the same shapes, but one line is in absorption and the other in emission. This masing effect arises due to the quantum mechanical selection rules for decay routes to the $2\Pi_{3/2}$ ($J = 3/2$) OH ground state, after the molecules have been pumped to higher excited rotational states (Elitzur 1992). Crucially, the conjugate behavior ensures that the satellite lines arise from the same gas. These lines are thus well-suited for measuring changes in α , μ and g_p between the source redshift and today, as systematic velocity offsets between the lines are ruled out by the maser mechanism. Any observed difference between the line redshifts must then arise due to a change in one or more of the above constants (Kanekar 2008).

Only two conjugate OH systems are known at cosmological distances, at $z \sim 0.247$ towards PKS 1413+135 (Kanekar et al. 2004; Darling 2004) and at $z \sim 0.765$ towards PMN J0134–0931 (Kanekar et al. 2005). We report here on deep Westerbork Synthesis Radio Telescope (WSRT) and

¹ Ramanujan Fellow, National Centre for Radio Astrophysics, TIFR, Pune 411 007, India; National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM 87801, USA; nkanekar@ncra.tifr.res.in

² National Centre for Radio Astrophysics, TIFR, Pune 411 007, India

³ Arecibo Observatory, HC03 Box 53995, Arecibo, PR 00612, USA

Arecibo Telescope (AO) OH observations of PKS 1413+135, that yield tentative evidence for changes in α , μ and/or g_p over a lookback time of ~ 2.9 Gyr.

2. SPECTRA AND RESULTS

The WSRT and the AO were used to carry out deep integrations on the satellite OH lines of PKS 1413+135 between May and July 2005 (WSRT; ~ 58 hours) and June 2008 and May 2009 (AO; ~ 40 hours in double-position-switched mode; (Ghosh & Salter 2002)). The 1720 MHz and 1612 MHz lines were observed simultaneously in all runs, with velocity resolutions of ~ 0.35 km/s (AO) and ~ 0.57 km/s (WSRT), after Hanning smoothing. The WSRT data were analysed in “classic” AIPS, while the Arecibo data were analysed in IDL, both using standard procedures.

The top four panels of Fig. 1[A] and [B] show the satellite OH 18cm optical depth spectra from each telescope, with the 1720 MHz spectrum flipped in sign for the comparison. The WSRT spectra of Fig. 1[A] have root-mean-square (RMS) optical depth noise values of 8.7×10^{-4} (1612) and 8.3×10^{-4} (1720), per ~ 0.57 km/s channel, while the corresponding RMS noise values for the AO spectra of Fig. 1[B] are 4.6×10^{-4} (1612) and 4.4×10^{-4} (1720), per ~ 0.35 km/s channel. The bottom panels of the figure show the sum of the 1612 and 1720 MHz optical depth profiles from each telescope. The RMS noise values on the summed spectra are $\sim 1.2 \times 10^{-3}$ per ~ 0.57 km/s channel (WSRT) and $\sim 6.3 \times 10^{-4}$ per ~ 0.35 km/s channel (AO), consistent with the noise levels on the individual spectra. The summed spectra also show no evidence for non-Gaussian structure; indeed, a Kolmogorov-Smirnov (K-S) rank-1 test finds that the summed spectra are consistent (at $\leq 1.3\sigma$ significance) with being drawn from normal distributions. The satellite OH lines are thus conjugate at the signal-to-noise ratio of our observations.

Having confirmed that the satellite lines are conjugate within our measurement errors, the next step is to test whether they arise at the same redshift. For lines that are not conjugate, this is usually done by fitting Gaussians (or Voigt profiles) to each line, to measure the redshift of peak absorption (e.g. Murphy et al. 2003; Srianand et al. 2007; Kanekar et al. 2005). In the case of the WSRT and AO spectra, a three-component Gaussian model provides a good fit to each spectrum, yielding noise-like residuals. However, the process of fitting multiple spectral components to a spectral line of shape can itself affect the results, especially in the case of complex profiles. An important advantage of using conjugate satellite OH lines to probe fundamental constant evolution is that the shapes of the lines are known to be the same. One can thus directly determine the peak of the cross-correlation of the two lines, instead of having to decompose each profile into its components. The cross-correlation of the two WSRT satellite OH spectra was found to peak at $\Delta V = (-0.37 \pm 0.22)$ km/s, and that of the AO spectra at $\Delta V = (-0.20 \pm 0.10)$ km/s. The RMS noise values were estimated by cross-correlating 10^4 pairs of simulated spectra. Each simulated spectrum was obtained by adding independent representations of Gaussian random noise to the best 3-component fit, with the noise spectra characterized by the RMS values of the observed spectra. A weighted average of the WSRT and AO results gives a net velocity offset of (-0.23 ± 0.09) km/s between the two satellite lines, with the 1720 MHz line at a higher velocity.

Note that the sum of the optical depth spectra might be expected to approach zero more closely (i.e. to be more “noise-

like”) on applying the measured offset between the line profiles. At present, the fact that the measured offset is smaller than a pixel (\sim half a pixel for the Arecibo spectra) implies that this test is not very sensitive, especially because the offset is detected at relatively low statistical significance. Note, further, that a K-S test finds that the summed optical depth spectra, obtained without applying the velocity offset, are consistent with noise (at $\leq 1.3\sigma$ significance). However, we did carry out the above test on the higher-sensitivity Arecibo spectra, and found, as expected, that no statistically-significant difference is apparent in either the mean or the RMS noise of the summed spectrum, on applying the measured velocity offset before carrying out the sum. Finally, we emphasize that this would be a useful test to carry out on higher-sensitivity, higher-resolution data, to test for an offset of multiple pixels. This test would also verify that the two lines indeed have precisely the same shape, thus complementing the cross-correlation technique, which formally only measures the offset between the two profiles, assuming that they have the same shape.

The above agreement between the shapes (amplitudes and widths) of the satellite lines of Fig. 1 and the offset between the line redshifts is precisely the signature of an evolution in the fundamental constants that was being sought. Using the equations of Chengalur & Kanekar (2003), the velocity offsets measured in the cross-correlation analysis yield $[\Delta G/G] = (-1.9 \pm 1.1) \times 10^{-5}$ for the WSRT spectra, and $[\Delta G/G] = (-1.03 \pm 0.51) \times 10^{-5}$ for the AO spectra, where $G \equiv g_p [\mu\alpha^2]^{1.85}$. A weighted average of the WSRT and AO results gives $[\Delta G/G] = (-1.18 \pm 0.46) \times 10^{-5}$. This is weak ($\sim 2.6\sigma$) evidence for a change in α , μ and/or g_p , from the redshift of PKS 1413+135 to the present epoch, i.e. over 2.9 Gyrs.

We also carried out a similar cross-correlation analysis on the strong conjugate satellite OH lines from the nearby extra-galactic source Cen.A (van Langevelde et al. 1995), to test whether velocity offsets between the satellite lines are seen in local conjugate systems. The analysed OH spectra towards this source were kindly provided to us by Huib van Langevelde. The peak of the cross-correlation for the Cen.A spectra was found to be at $\Delta V = (+0.05 \pm 0.11)$ km/s, consistent with no velocity offset between the lines. This demonstrates that the conjugate satellite technique provides the expected null result for at least one local system, and at a sensitivity comparable to that of the datasets towards PKS 1413+135.

3. SYSTEMATIC EFFECTS

Systematic effects that might contribute to increased errors, above those determined from the cross-correlation analysis, stem from two possible sources. “Local” issues that could result in an observed offset include errors in the telescope frequency scale, doppler-tracking issues, terrestrial radio frequency interference (RFI), etc. However, both the WSRT and AO data were recorded in topocentric frequency, with no corrections made for Earth motion during the observations. These corrections were applied during the data analysis, using a model of Earth motion accurate to < 15 m/s, an order of magnitude lower than our measurement errors. Frequency calibration is also not usually an issue in radio spectroscopy, with the frequency scale set by the accuracy of masers and local oscillators (typically a few Hz, two orders of magnitude lower than our errors). The laboratory OH frequencies

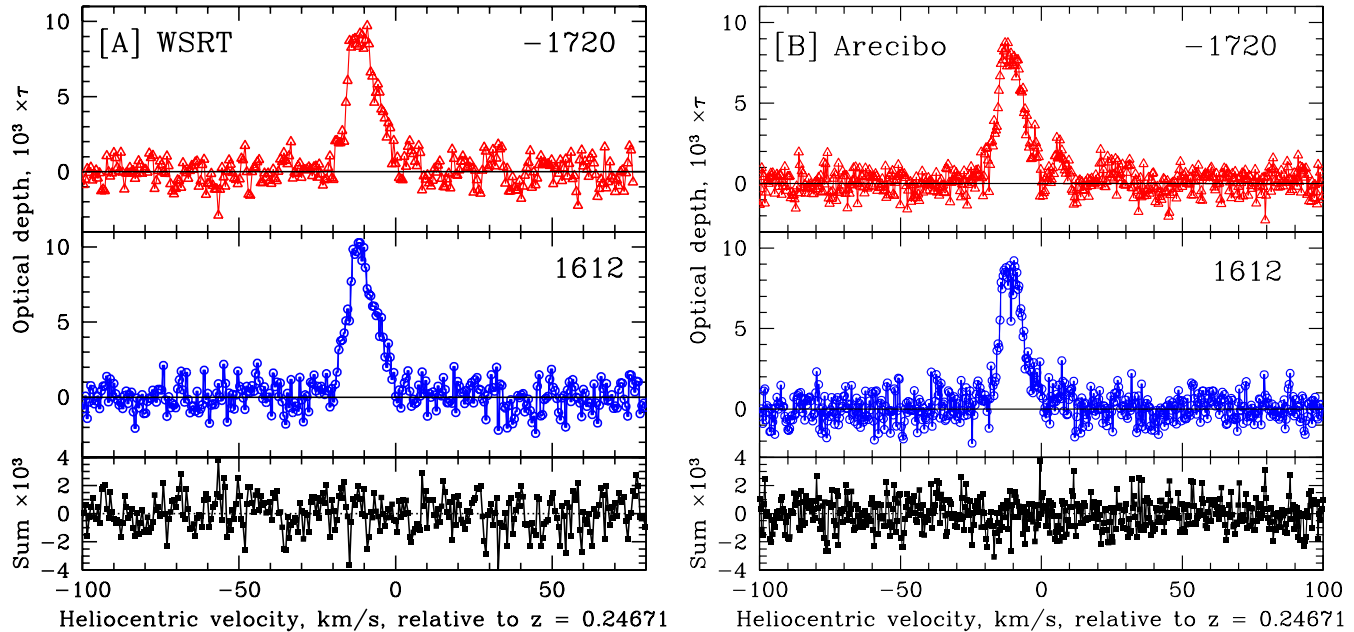


FIG. 1.— Top panels: WSRT and AO satellite OH spectra towards PKS 1413+135, with optical depth ($1000 \times \tau$) plotted against heliocentric velocity, in km/s, relative to $z = 0.24671$. The 1612 and 1720 MHz spectra are plotted using open circles and triangles, respectively, with the 1720 MHz spectrum flipped in sign. Bottom panels: The sum of the 1612 and 1720 MHz optical depth spectra from each telescope.

are known to an accuracy of ~ 15 Hz (Lev et al. 2006), again far smaller than our errors. Finally, there is no evidence for non-Gaussian structure in the baselines of the different spectra, that might limit their dynamic range. The only “local” source of systematic error in this technique thus appears to be RFI; the WSRT and AO data were carefully edited and there was no evidence of residual RFI in any of the spectra. Further, note that a consistent velocity offset between the satellite lines is found in both the WSRT and AO spectra, although the two datasets were acquired with telescopes on different continents and at different times; this makes it very unlikely that the offset might be caused by RFI.

Another category of systematics consists of “astronomical” effects that might cause intrinsic velocity offsets between the two lines (e.g. different “clouds” excited in each line, source inhomogeneities, an interloping line from a different transition, etc). However, unlike in the optical regime, there is no possibility of “confusing” lines from PKS 1413+135 or an interloper along the line of sight. All possible line interlopers at these frequencies are weak and only detectable in very high HI column density gas, requiring a sightline through a galaxy. The relatively-large AO beam intersects three known galaxies, the Milky Way, the host galaxy of PKS 1413+135 (at $z \sim 0.24671$) and SDSS J141557.20+131851.2, a galaxy at $z \sim 0.3687$; there are no transitions from any of these redshifts that might be blended with the OH satellite lines. For example, the nearest known Galactic lines are those of CH_2CHCN , at a frequency of ~ 1371.7 MHz, ~ 8.3 MHz away from the redshifted 1720 MHz frequency, while the closest known lines from $z \sim 0.24671$ are those of CH_3OCHO , ~ 1.0 MHz away from the redshifted 1612 MHz line frequency. Finally, we note that the separation between transitions from different OH isotopes at these frequencies is $\gtrsim 50$ MHz, much larger than our observing bandwidth.

The strongest argument against intrinsic velocity offsets, RFI, or additional spectral lines, playing a significant role is

the fact that the shapes of the satellite lines are in excellent agreement, in both WSRT and AO datasets. This is a crucial difference between the present technique, based on the conjugate satellite OH lines, and other approaches. Here, the observed lines themselves provide a stringent test of their use as a probe of fundamental constant evolution: the maser mechanism giving rise to the lines (Elitzur 1992) implies that *the line shapes must agree* if they arise in the same gas.

It should also be pointed out that the satellite line shapes only agree at our present sensitivity. An additional weak spectral component might be present in one of the two spectra, below our detection threshold; this could result in the cross-correlation peak being offset from zero velocity, while retaining the conjugate behaviour. While we cannot as yet formally rule out this possibility, it should be emphasized that this can easily be tested by deeper spectra in the satellite OH lines.

4. DISCUSSION

If the observed ($\sim 2.6\sigma$ significance) offset between the satellite lines is not caused by a “hidden” spectral component (or RFI) below our sensitivity threshold, it could be evidence for changes in one or more of α , μ , or g_p . Note that the conjugate satellite technique is directly sensitive to changes in $G \equiv g_p [\mu\alpha^2]^{1.85}$, and cannot provide additional information on which constant is changing. Our present result $\Delta G/G = (-1.18 \pm 0.46) \times 10^{-5}$ implies the relation $3.7 [\Delta\alpha/\alpha] + 1.85 [\Delta\mu/\mu] + [\Delta g_p/g_p] = (-1.18 \pm 0.46) \times 10^{-5}$, suggesting that one or more of α , μ and g_p had smaller values at $z = 0.247$ than at the present epoch. The limiting cases, assuming that only one of α , μ , and g_p changes, are $[\Delta\alpha/\alpha] = (-3.1 \pm 1.2) \times 10^{-6}$ (for $[\Delta\alpha/\alpha] \gg [\Delta\mu/\mu]$), $[\Delta g_p/g_p]$, $[\Delta\mu/\mu] = (-6.2 \pm 2.4) \times 10^{-6}$ (for $[\Delta\mu/\mu] \gg [\Delta\alpha/\alpha]$, $[\Delta g_p/g_p]$), and $[\Delta g_p/g_p] = (-1.18 \pm 0.46) \times 10^{-5}$ (for $[\Delta g_p/g_p] \gg [\Delta\alpha/\alpha]$, $[\Delta\mu/\mu]$).

Changes in g_p are expected to be far smaller than those in

μ and α (Langacker et al. 2002). Further, a stringent constraint on changes in μ from a higher redshift absorber has recently been obtained from comparisons between NH_3 inversion and HCN/HCO^+ rotational lines: Murphy et al. (2008a) find $[\Delta\mu/\mu] < 1.6 \times 10^{-6}$ (2σ) from a gravitational lens at $z \sim 0.685$. This suggests that changes in $G \equiv g_p[\mu\alpha^2]^{1.85}$ at $z \sim 0.25$ may be dominated by changes in α , i.e. the first limiting case above, yielding $[\Delta\alpha/\alpha] = (-3.1 \pm 1.2) \times 10^{-6}$. It is interesting that this result for $[\Delta\alpha/\alpha]$ is similar in both amplitude and sign to the value of $[\Delta\alpha/\alpha]$ obtained by Murphy et al. (2004) using the many-multiplet method at a higher redshift, $[\Delta\alpha/\alpha] = (-5.7 \pm 1.1) \times 10^{-6}$ at $\langle z \rangle = 1.75$.

Other sensitive astronomical techniques to probe fundamental constant evolution include those based on the many-multiplet method (Murphy et al. 2004), H_2 lines (King et al. 2008), H I 21cm and OH lines (Kanekar et al. 2005), inversion and rotational lines (Flambaum & Kozlov 2007), H I 21cm and ultraviolet carbon lines (Kanekar et al. 2010), etc. All of these are affected by systematic effects of different types (e.g. Kanekar 2008). For example, Griest et al. (2010) have recently shown that Keck-HIRES spectra are affected by wavelength calibration errors of unknown origin; the effect of these systematic errors on the many-multiplet result of Murphy et al. (2004) is not known, although it seems clear that the error budget will increase. Similar problems have been found with VLT-UVES spectra (e.g. Centurion et al. 2009; Whitmore et al. 2010), which would affect the H_2 results of King et al. (2008).

The importance of the conjugate satellite OH technique stems from the fact that it has fewer systematic effects than other approaches and allows a test of its own applicability, in the prediction that the shapes of the satellite OH lines must be the same. We have also demonstrated that the expected null result is obtained on applying the technique to a local conjugate satellite system, Cen.A. Equally important, and again unlike most other techniques, the conjugate satellite lines allow an estimate of changes in the fundamental constants from

a *single space-time location*, without any averaging over multiple absorbers (which, for example, is essential in the many-multiplet method to average out local systematics). The only apparent drawback to the technique is the possibility of RFI at the line frequencies; this can be ameliorated by using multiple telescopes, as done here, or multiple observing epochs, taking advantage of the shift in the line frequency in the terrestrial frame due to the motion of the Earth around the Sun.

In summary, we have obtained deep WSRT and Arecibo Telescope spectra in the redshifted satellite OH 18cm lines from PKS 1413+135, at $z \sim 0.247$. The lines are conjugate at our sensitivity, with the sum of the optical depths consistent with noise. We find that the peak of the cross-correlation of the satellite OH 18cm lines is offset from zero velocity (at $\sim 2.6\sigma$ significance), tentative evidence for a redshift offset between them. We have examined the data for systematic effects and find no evidence that such effects might give rise to the observed velocity offset. We have also verified that the cross-correlation of the satellite OH 18cm lines in the local conjugate satellite system in Cen.A peaks at zero velocity, within the errors. The observed offset in satellite line redshifts in PKS 1413+135 implies $\Delta G/G = (-1.18 \pm 0.46) \times 10^{-5}$, where $G \equiv g_p[\mu\alpha^2]^{1.85}$, suggesting that one or more of α , μ , and g_p had smaller values at $z \sim 0.247$ than at the present epoch.

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REFERENCES

- Centurion, M., Molaro, P., & Levshakov, S. 2009, MmSAI, proc. of IAU JD 9, P. Molaro & E. Vangoni eds., 80
- Chengalur, J. N. & Kanekar, N. 2003, Phys. Rev. Lett., 91, 241302
- Darling, J. 2003, Phys. Rev. Lett., 91, 011301
- 2004, ApJ, 612, 58
- Dzuba, V. A., Flambaum, V. V., & Webb, J. H. 1999, Phys. Rev. Lett., 82, 888
- Elitzur, M. 1992, Astronomical masers (Dordrecht, NL: Kluwer Academic)
- Flambaum, V. V. & Kozlov, M. G. 2007, Phys. Rev. Lett., 98, 240801
- Ghosh, T. & Salter, C. 2002, in ASP Conf. Ser., Vol. 278, Single-Dish Radio Astronomy: Techniques and Applications, ed. S. Stanimirovic et al., 521
- Griest, K., Whitmore, J. B., Wolfe, A. M., Prochaska, J. X., Howk, J. C., & Marcy, G. W. 2010, ApJ, 708, 158
- Kanekar, N. 2008, Mod. Phys. Lett. A, 23, 2711
- Kanekar, N., Carilli, C. L., Langston, G. I., Rocha, G., Combes, F., Subrahmanyan, R., Stocke, J. T., Menten, K. M., Briggs, F. H., & Wiklind, T. 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., Prochaska, J. X., Ellison, S. L., & Chengalur, J. N. 2010, ApJ, 712, L148
- King, J. A., Webb, J. K., Murphy, M. T., & Carswell, R. F. 2008, Phys. Rev. Lett., 101, 251304
- Langacker, P. G., Segré, G., & Strassler, M. J. 2002, Phys. Lett. B, 528, 121
- Lev, B. L., Meyer, E. R., Hudson, E. R., Sawyer, B. C., Bohn, J. L., & Ye, J. 2006, Phys. Rev. A, 74, 061402
- Molaro, P., Reimers, D., Agafonova, I. I., & Levshakov, S. A. 2008, European Physical Journal Special Topics, 163, 173
- Murphy, M. T., Flambaum, V. V., Muller, S., & Henkel, C. 2008a, Science, 320, 1611
- Murphy, M. T., Flambaum, V. V., Webb, J. K., Dzuba, V. V., Prochaska, J. X., & Wolfe, A. M. 2004, in Lecture Notes in Physics, Vol. 648, Astrophysics, Clocks and Fundamental Constants, ed. S. G. Karshenboim & E. Peik (Berlin: Springer-Verlag), 131
- Murphy, M. T., Webb, J. K., & Flambaum, V. V. 2003, MNRAS, 345, 609
- Murphy, M. T., Webb, J. K., & Flambaum, V. V. 2008b, MNRAS, 384, 1053
- Savedoff, M. P. 1956, Nature, 178, 688
- Srianand, R., Chand, H., Petitjean, P., & Aracil, B. 2007, Physical Review Letters, 99, 239002
- Thompson, R. I. 1975, ApJ, 16, 3
- van Langevelde, H. J., van Dishoek, E. F., Sevenster, M. N., & Israel, F. P. 1995, ApJ, 448, L123
- Whitmore, J. B., Murphy, M. T., & Griest, K. 2010, ApJ, submitted (arXiv:1003.3325)
- Wolfe, A. M., Broderick, J. J., Condon, J. J., & Johnston, K. J. 1976, ApJ, 208, L47