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Probing fundamental constant evolution with radio spectroscopy

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Abstract. Radio spectroscopy of cosmologically-distant galaxies in a variety of atomic and molecular transitions provides a powerful probe of changes in low-energy 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. In this article, I will discuss the advantages and disadvantages of these techniques vis-a-vis optical ones, and will then report on new results from two such radio techniques, based on comparisons between the redshifts of (1) "conjugate" satellite OH 18cm lines, and (2) inversion and rotational lines.

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

1. Introduction

In the standard model of particle physics, it is implicitly assumed that low-energy coupling constants and particle masses do not vary with space or time. This important assumption is often violated in modern higher-dimensional theories that aim to unify the standard model and general relativity; in most such models, fundamental "constants" like the fine structure constant α, the proton-electron mass ratio $\mu \equiv m_p/m_e$, etc, are expected to show spatio-temporal evolution (e.g. Marciano 1984). This is one of the few low-energy predictions of these models; testing the possibility of fundamental constant evolution is thus an important route to study new and basic physics.

Laboratory studies, usually based on comparisons between different optical frequency standards (e.g. atomic clocks using different materials), have yielded stringent constraints on changes in α and μ over time-scales of a few years. For example, Rosenband et al. (2008) obtained $[\dot{\alpha}/\alpha] < 4.6 \times 10^{-17}$ yr^{-1} over one year, while Shelkovnikov et al. (2008) found $[\dot{\mu}/\mu] < 1.2 \times 10^{-13}$ yr^{-1}, over two years, using comparisons between different atomic clocks[1]. While such studies have excellent control over systematic effects, they are limited to probing changes over timescales of only a few years. Conversely, although geological methods (e.g. measurements of relative isotopic abundances in the Oklo natural fission reactor, studies of the time variation of the β-decay rate, etc) can yield tight constraints on changes in α over lookback times of $\sim 2 - 4$ Gyrs, such techniques are typically model-dependent and usually involve critical assumptions about the constancy of other parameters (e.g. Gould et al. 2006).

Comparisons between the redshifts of different spectroscopic transitions arising in a single redshifted system can be used to study

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[1] All limits are quoted at 2σ significance.

changes in α, μ, etc. over a large fraction of the age of the Universe. So far, the only statistically-significant evidence for evolution has come from such techniques: Murphy et al. (2004) applied the "many-multiplet" method of Dzuba et al. (1999) to Keck-HIRES optical spectra of 143 absorbers to obtain $[\Delta\alpha/\alpha] = (-5.7 \pm 1.1) \times 10^{-6}$ over $0 < \langle z \rangle < 1.75$, suggesting that α was smaller at high redshifts. However, independent attempts to confirm this result have so far been unsuccessful (e.g. Molaro et al. 2008; Srianand et al. 2007), although Murphy et al. (2008 b) argue that the errors in some of these studies appear to have been under-estimated. Optical spectra have also been used to place constraints on changes in the proton-electron mass ratio: King et al. (2008) obtained $[\Delta\mu/\mu] < 6 \times 10^{-6}$ over $0 < \langle z \rangle < 2.8$, using ro-vibrational transitions of molecular hydrogen (H_2; Thompson 1975). Note that the above error estimates do not include the recently-detected distortions ($\sim 0.5 - 1$ km s^{-1}) in the wavelength scale of the Keck-HIRES spectrograph (Griest et al. 2009); slightly smaller, but similar, distortions have also been seen in the VLT-UVES spectrograph (Centurion et al. 2009). Further, both the H_2 and many-multiplet (MM) methods are also affected by a number of other systematic errors (e.g. the possibility of changes in the relative isotopic abundances with redshift, for the MM method; Ashenfelter et al. 2004).

2. Radio spectroscopic techniques

Radio transitions in molecules arise from very different physical mechanisms (e.g. rotation, inversion, Lambda-doubling, hyperfine-splitting), or combinations of these, because of which the line frequencies can have very different dependences on α, μ, and g_p. Comparisons between the redshifts of radio lines hence provide an independent probe of changes in the fundamental constants, with the immediate benefit that systematic effects are very different in the radio regime. Obvious advantages over optical techniques are the high spectral resolution (< 1 km s^{-1}) possible at radio frequencies, alleviating problems with line blending, and the fact that the radio frequency scale is set by accurate masers and local oscillators, allowing frequency calibration to better than ~ 10 m/s, far better than at optical wavelengths. The isotopic transitions are also typically not blended at radio frequencies (especially given the excellent spectral resolution), and the lines are observable both in the Galaxy and at all redshifts [see Kanekar (2008) for a recent review].

Radio techniques have already provided strong constraints on changes in different constants (e.g. Kanekar 2008). For example, Carilli et al. (2000) used HI 21cm and CO lines from two absorbers at $z \sim 0.25$ and $z \sim 0.68$ to obtain $[\Delta Y/Y] < 3.4 \times 10^{-5}$, where $Y \equiv g_p\alpha^2$. More recently, Kanekar et al. (2005) compared HI 21cm and OH 18cm redshifts in two absorbers at $z \sim 0.7$ to find $[\Delta Z/Z] < 2.1 \times 10^{-5}$, where $Z \equiv g_p[\mu\alpha^2]^{1.57}$.

Perhaps the two best current radio techniques are based on "conjugate" satellite OH 18cm lines, and comparisons between inversion and rotational transitions. The former has the fewest-known systematic effects of any technique, and is sensitive to changes in a combination of α, μ, and g_p, while the latter has a high sensitivity to changes in μ. The next two sections describe the two techniques and our recent results based on them, using data from the Westerbork Synthesis Radio Telescope (WSRT), the Arecibo Observatory (AO), and the Green Bank Telescope (GBT).

3. "Conjugate" satellite 18-cm OH lines

The four ground-state OH lines arise from a combination of Lambda-doubling and hyperfine-splitting, and the line frequencies have different dependences on α, μ and g_p (Chengalur & Kanekar 2003). Under certain astrophysical conditions (Elitzur 1992; van Langevelde et al. 1995), 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, with the same shapes, but with one line in absorption and the other in emission. This arises from the inversion of the ground-state Lambda-doubled OH energy levels, 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). The critical aspect, for the purpose of studies of fundamental constant evolution, is that the conjugate behaviour guarantees that the satellite OH 18cm lines arise in the same gas. As a result, these lines are ideal for measuring changes in α, μ and g_p between the source redshift and the present epoch, as local velocity offsets between the lines are ruled out by the inversion mechanism. Any observed difference between the line redshifts must then arise due to a change in one or more of the above constants (Kanekar et al. 2004).

At present, only two conjugate OH systems have been found at cosmological distances, at $z \sim 0.247$ towards B1413+135 (Kanekar et al. 2004; Darling 2004), and at $z \sim 0.765$ towards J0134−0931 (Kanekar et al. 2005). We used the WSRT and the AO to carry out deep observations of the former system, with 58 WSRT hours at a spectral resolution of $\sim$ 0.55 km s^{-1} and 40 AO double-position-switched (Ghosh & Salter 2002) hours at a spectral resolution of $\sim$ 0.35 km s^{-1}. The resulting spectra had root-mean-square (RMS) optical depths of $\sim$ 0.00085 per 0.55 km s^{-1} (WSRT), and $\sim$ 0.00045 per 0.35 km s^{-1} (AO). Each pair of spectra was found to be conjugate, with the sum of optical depths consistent with noise within the errors, and with no evidence for non-Gaussian structure in the spectral baselines.

A cross-correlation analysis was then used to determine the velocity offset between the two satellite lines. The error on the cross-correlation was determined by cross-correlating 10^4 pairs of simulated spectra, each obtained by adding independent representations of Gaussian random noise to the best-fit spectral profile, with the noise spectra characterized by the RMS noise values of the observed spectra. The cross-correlation of the two WSRT OH spectra was found to peak at $\Delta V = (-0.37 \pm 0.22)$ km s^{-1}, and that of the AO spectra at $\Delta V = (-0.20 \pm 0.10)$ km s^{-1}. A weighted average of the WSRT and AO results yields a net velocity offset of (-0.23 ± 0.09) km s^{-1} between the two satellite lines, with the 1720 MHz line at a higher velocity.

The equations of Chengalur & Kanekar (2003) can be used to translate the offset between the satellite redshifts into a result for changes in α, μ and g_p. The velocity offset of $\Delta V = (-0.23 \pm 0.09)$ km s^{-1} corresponds to $[\Delta G/G] = (-1.18 \pm 0.45) \times 10^{-5}$, where $G \equiv g_p \left[\mu\alpha^2\right]^{1.85}$. This is tantalizing ($\sim 2.6\sigma$) evidence for a change in α, μ and/or g_p, from the redshift of B1413+135 to the present epoch, i.e. over a lookback time of 2.9 Gyrs.

Possible systematic effects that might cause the offset between the satellite lines include terrestrial radio interference (RFI), and an additional spectral component in one of the lines. The strongest argument against such systematic effects is the agreement in the shapes of the satellite lines, in both WSRT and AO datasets. Note, however, that the satellite line shapes only agree at our present sensitivity, and we cannot rule out the possibility that a weak spectral component or RFI might be present in one of the spectra below our detection threshold, that might shift the cross-correlation peak away from zero velocity, while retaining the conjugate behaviour. Deeper spectra in the satellite OH lines will allow this possibility to be tested; these observations are now being carried out.

4. Inversion and rotational lines

Comparisons between the redshifts of ammonia (NH_3) inversion lines and rotational lines have a high sensitivity to changes in the proton-electron mass ratio $\mu \equiv m_p/m_e$, as the former frequencies have a far stronger dependence on μ than the latter ones (Flambaum & Kozlov 2007). The NH_3 inversion lines lie at $\sim$ 23 GHz, more than an order of magnitude lower than the NH_3 rotation line frequencies; rotational lines of other molecules have hence mainly be used for this comparison [although see Menten et al. (2008)]. The best current result from this method is that of Murphy et al. (2008a), who compared the redshifts of NH_3 and rotational (HCO^+ and HCN) lines in the $z \sim 0.685$ gravitational lens towards

B0218+357 to obtain $[\Delta\mu/\mu] < 1.8 \times 10^{-6}$ over $\sim$ 6.5 Gyr. While this is the most sensitive bound on changes in μ from any technique, the low errors of Murphy et al. rely critically on the assumption that the velocity structure of the optically-thin NH_3 lines is the same as that of the optically-thick HCO^+ and HCN lines. Further, the redshifted HCO^+ 2-1 and HCN 2-1 lines are at far higher frequencies than the NH_3 line ($\sim$ 105 GHz versus $\sim$ 14 GHz), implying that the HCO^+ and NH_3 sightlines could trace different paths through the cloud. Finally, the NH_3 spectra used by Murphy et al. (2008a) were detection spectra of low sensitivity (Henkel et al. 2005).

To address the above issues, we used the GBT to obtain high-sensitivity spectra in the NH_3 1-1 line and in *optically-thin* rotational lines at nearby frequencies. The primary rotational line used for this purpose was the CS 1-0 transition, because (1) it is a strong line, but not optically thick in the $z \sim 0.685$ lens, and (2) its frequency is within a factor of $\sim$ 2 of that of the NH_3 1-1 line. Besides this, a GBT spectrum was also obtained in the H_2CO ground-state rotational line from the $z \sim 0.685$ lens, while a spectrum in the ^{13}CO 2-1 rotational line was kindly provided by Francoise Combes. Comparisons between the redshifts of the CS 1-0, H_2CO ground-state, and ^{13}CO 2-1 rotational would test the possibility of local velocity offsets between different species in the molecular cloud. 5 hours of GBT time were obtained on the CS and NH_3 1-1 lines, with a spectral resolution better than 0.2 km s^{-1}, after Hanning-smoothing and re-sampling.

While a detailed analysis of the data is still being carried out, a preliminary joint fit to the NH_3 and CS profiles found no evidence for velocity offsets between these lines. 3 spectral components were sufficient to entirely model the velocity structure in each line (and in the H_2CO line), leaving residuals consistent with noise. The CS and H_2CO line redshifts were found to agree within $\sim$ 85 m/s, and the CS and ^{13}CO redshifts within $\sim$ 260 m/s; thus, the rotational lines showed no evidence for velocity offsets or differences in velocity structure. A joint fit was then carried out to the NH_3 and CS lines, assuming that each spectral component has the same velocity width in the two lines (i.e. turbulent broadening), and also assuming a single velocity offset in all components; this gave the offset $\Delta V = (-0.51 \pm 0.36)$ km s^{-1}, yielding $[\Delta\mu/\mu] = (-4.9 \pm 3.5) \times 10^{-7}$. The limit $[\Delta\mu/\mu] < 7 \times 10^{-7}$ is the best present constraint on fractional changes in μ, although it should be emphasized that this depends on the assumptions that the NH_3 hyperfine structure has thermal line ratios, and that the line broadening is dominated by turbulence.

5. Summary

Figure 1 shows a comparison between results from the best radio and optical techniques based on astronomical spectroscopy (some of which were presented at this Joint Discussion). Note that the radio methods typically probe combinations of α, μ and g_p, making it difficult to directly compare results from the different techniques without additional assumptions. Following Kanekar (2008), I will summarize the best present results for the two limiting cases, $[\Delta\alpha/\alpha] >> [\Delta\mu/\mu]$ and $[\Delta\alpha/\alpha] << [\Delta\mu/\mu]$, assuming that $\left[\Delta g_p/g_p\right] << [\Delta\alpha/\alpha], [\Delta\mu/\mu]$ (e.g. Langacker et al. 2002). The figure includes results from the alkali doublet, many-multiplet, single-ion-differential-α-measurement (SIDAM), HI 21cm vs. fine structure, HI 21cm vs. OH, NH_3 vs. rotational, conjugate-satellites, and H_2 methods (Murphy et al. 2001, 2004; King et al. 2008; Kanekar et al. 2005; Molaro et al. 2008; Kanekar et al. 2009; Thompson et al. 2009; Wendt et al. 2009; Malec et al. 2009). It is apparent that present results from the conjugate-satellites, many-multiplet and SIDAM methods have similar sensitivities to changes in α, although at very different lookback times, and with different systematic effects. Conversely, the NH_3 method is the most sensitive among probes of changes in μ, although it assumes turbulent broadening of all lines and thermal line ratios for the NH_3 hyperfine structure; the conjugate-satellites method has a lower sensitivity, but far fewer systematic effects.

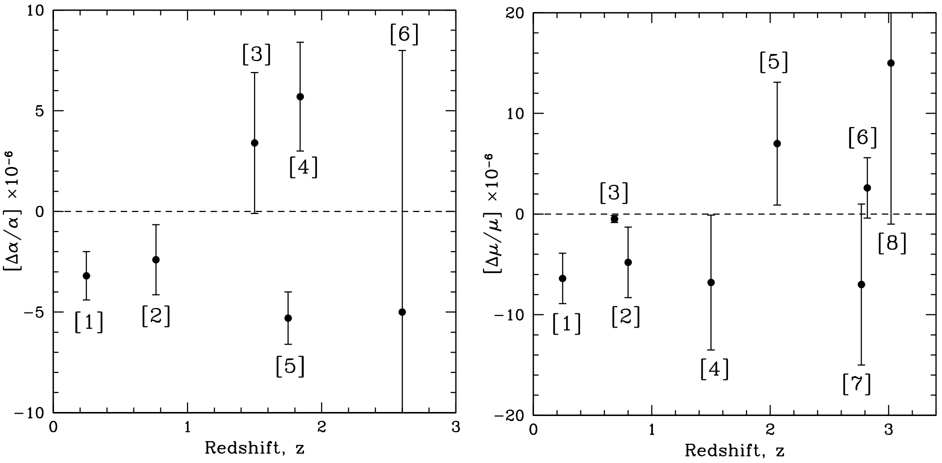

Fig. 1. The best current results from techniques probing fundamental constant evolution with redshifted spectral lines. The left panel [A] shows estimates for $[\Delta\alpha/\alpha]$ as a function of redshift, from comparisons between [1] conjugate-satellite OH lines (this work), [2] Hi 21cm and OH lines (Kanekar et al, in prep.), [3] Hi 21cm and resonance lines (Kanekar et al. 2009), [4] optical resonance lines, with the MM method (Murphy et al. 2004), [5] Feii lines using the SIDAM method (Molaro et al. 2008), and [6] Siiv alkali-doublet lines (Murphy et al. 2001). Panel [B] shows similar results for $[\Delta\mu/\mu]$, using comparisons between [1] conjugate-satellite OH lines (this work), [2] Hi 21cm and OH lines (Kanekar et al, in prep.), [3] NH_3 and rotational lines (this work), [4] Hi 21cm and resonance lines (Kanekar et al. 2009), and H_2 lines ([5] Malec et al, these proceedings; [6] (Thompson et al. 2009); [7] (King et al. 2008), and [8] Wendt & Reimers, these proceedings). The assumptions $[\Delta\alpha/\alpha] >> [\Delta\mu/\mu], \left[\Delta g_p/g_p\right]$ (in [A]) and $\left[\Delta g_p/g_p\right], [\Delta\alpha/\alpha] << [\Delta\mu/\mu]$ (in [B]) apply to the first three for $[\Delta\alpha/\alpha]$ and [1], [2], and [4] for $[\Delta\mu/\mu]$.

The main drawback of the radio methods is the paucity of radio absorbers at high redshifts, $z > 1$. This issue will be addressed by the upcoming Atacama Large Millimeter Array (ALMA) and Expanded Very Large Array (EVLA), whose wide-band correlators will, for the first time, allow “blind” surveys for redshifted absorption in the strong mm-wave rotational transitions towards a large number of background sources. This should yield large samples of high-z molecular absorbers, for follow-up studies in other molecular and atomic lines. It should then be possible to average over local velocity offsets or different kinematic structures to obtain reliable results when comparing line redshifts across species. A new population of redshifted conjugate satellite OH 18cm systems is also likely to be found, from both searches in absorbers detected in these mm-wave surveys, and direct low-frequency surveys with arrays like the Australian Square Kilometre Array Pathfinder (ASKAP) and the Giant Metrewave Radio Telescope (GMRT). In the long-term future, the Square Kilometer Array will be able to detect fractional changes of $[\Delta\alpha/\alpha]$, $[\Delta\mu/\mu] \sim 10^{-7}$, using conjugate satellite OH systems out to $z \sim 4$.

In summary, radio spectroscopic techniques provide an independent probe of changes in low-energy fundamental constants. Comparisons between NH_3 and rotational lines have yielded the highest sensitivity to changes in μ, over a lookback time of half the age of the Universe. Conversely, the sensitivity to changes in α and μ from a single conjugate satellite OH 18cm system at $z \sim 0.25$ is already similar to that from the many-multiplet and H_2

methods, and with far fewer systematic effects, albeit at a lower redshift. Indeed, the lack of apparent systematic effects in the conjugate-satellites method suggest that this is likely to be the most reliable probe of fundamental constant evolution, if new conjugate systems can be detected at high redshifts using telescopes like ASKAP, the GMRT and the EVLA.

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