Probing fundamental constant evolution with the Arecibo telescope

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1 Introduction

The possibility of changes in the low-energy fundamental "constants" has long been of interest to physicists (e.g. Dirac 1937). While the original hypothesis of fundamental constant evolution was made by Dirac to account for what appeared to be improbable numerical coincidences in the values of the constants, modern higher-dimensional theories contain the fairly generic prediction that low-energy constants like the fine structure constant α, the electron-proton mass ratio $\mu \equiv m_e/m_p$, the proton gyromagnetic ratio g_p, etc, are dynamical quantities, showing spatio-temporal evolution (e.g. Uzan 2003). The detection of such changes provides an avenue to probe new physics and is especially important because most other predictions of these models lie at very high energies ($\gtrsim 10^{19}$ GeV), well beyond our reach in the foreseeable future. It has also been suggested that measurements of changing constants could allow us to determine the equation of state of the dark energy that dominates the present cosmological energy density, as any dynamical scalar field that gives rise to dark energy is also expected to result in changes in the low-energy constants (e.g. Avelino et al. 2006).

Unfortunately, the amplitudes and time-scales of the putative changes are entirely unknown; it is thus crucial to carry out experiments or observations that probe as wide a range of time-scales as possible. It is also important to test for changes in different constants: for example, changes in μ are expected to be significantly larger than those in α, by a factor of ~ 50 in some models (e.g. Calmet & Fritzsch 2002). Atomic clocks and isotopic abundances in the Oklo natural fission reactor provide the tightest terrestrial constraints on fractional changes in the fine structure constant, $(1/\alpha)\,[\Delta\alpha/\Delta t] < 4 \times 10^{-15}$ per year, over three years (Peik et al. 2004) and $[\Delta\alpha/\alpha] < 1.2 \times 10^{-7}$, over $\sim 1.8 \times 10^{9}$ years (Damour & Dyson 1996), respectively. However, these and similar studies (including planned high-sensitivity experiments like ACES) only probe fairly small fractions of the age of the Universe. In addition, while the Oklo reactor constraints are presently the most sensitive (in absolute magnitude) to changes in α, the arguments used to derive these constraints contain critical assumptions about the constancy of other quantities (e.g. Uzan 2003).

2 Astrophysical constraints : optical spectroscopy

Astrophysical techniques, based on comparisons between the redshifts of spectral lines from distant galaxies, provide a test of changes in the fundamental constants over large lookback times (Savedoff 1956). The sensitivity of these measurements has dramatically improved in the last decade with the advent of 10-metre class optical telescopes. Allied with the development of a new technique, the many-multiplet method (Dzuba et al. 1999), these have provided the first high-significance claim of a detection of evolution in the fine structure constant: Murphy, Webb,

& Flambaum (2003) used the HIRES spectrograph on the Keck telescope to find $[\Delta\alpha/\alpha] = [-0.54 \pm 0.12] \times 10^{-5}$ from 128 absorbers in the redshift range $0.2 < z < 3.7$, implying that α was smaller at earlier times. While strongly conflicting results were later obtained by Srianand et al. (2004), based on the application of a similar technique to VLT-UVES data, it has recently been pointed out that errors in the latter analysis were under-estimated by a factor of ~ 3, implying that the two datasets are only in marginal disagreement (Murphy et al. 2006). More recently, Reinhold et al. (2006) used ro-vibrational lines of molecular hydrogen (Thompson 1975) to obtain $[\Delta\mu/\mu] = [-2.0 \pm 0.6] \times 10^{-5}$ for $0 < z \lesssim 3$, suggesting that μ was also smaller at earlier epochs.

It should be emphasized that both techniques that have found evidence for changes in the constants are based on optical spectroscopy, where wavelength calibration, line blending, local velocity offsets, isotopic abundances, interloping absorbers, etc, are all possible sources of systematic error (e.g. Murphy et al. 2003). Given the possibility that under-estimated or unknown systematics might dominate the errors from a given technique, it is crucial that independent techniques, with entirely different systematic effects, be used. In addition, optical techniques are all based on ultraviolet transitions, making it very difficult to confirm that the expected null result is obtained on comparisons between these lines in the Galaxy and implying that systematic effects cannot easily be ruled out. The obvious corollary is that these lines only move into optical wavebands (say, > 3200Å) from absorbers beyond a certain redshift; this means that, for example, the H_2 technique can only be used at $z \gtrsim 2$ and the SiIV alkali doublet technique at $z \gtrsim 1.3$. Similarly, only a handful of lines from singly-ionized species are redshifted above 3200Å at $z \lesssim 0.6$, implying that the many-multiplet method too is primarily useful at higher redshifts ($z \gtrsim 0.8$). We discuss here the use of radio spectroscopy in redshifted microwave OH lines as a tool to probe fundamental constant evolution, and consider possible avenues through which the Arecibo telescope could make a significant impact on this field.

3 Microwave hydroxyl (OH) transitions

The microwave OH transitions arise from two very different physical mechanisms, Λ-doubling and hyperfine splitting, and the transition frequencies hence have different dependences on the fundamental constants α, μ and g_p. Comparisons between the redshifts of different ground-state lines from a single cosmologically-distant system can hence be used to probe changes in these constants (Chengalur & Kanekar 2003; Darling 2003). In addition, comparisons between the redshifts of excited state OH lines provide entirely independent estimates of changes in α, μ and g_p (Kanekar & Chengalur 2004), allowing one to break the degeneracy between α, μ and g_p and measure changes in each constant separately. Finally, one can also compare the redshifts of OH 1667 MHz and H I 21cm absorption in a statistically large absorber sample to obtain an independent probe of any evolution (Chengalur & Kanekar 2003; Kanekar et al. 2005). The advantage here is that the radio structure of the background source is very similar at the nearby H I 21cm and OH 1667 MHz frequencies, implying that the lines of sight are likely to be similar in the two transitions ($\lesssim 1.2$ km/s; Kanekar et al. 2005)

The primary advantages of OH-based schemes over optical techniques are the high spectral resolution ($\lesssim 1$ km/s) at radio frequencies, alleviating problems with line blending, and the fact that the frequency scale is set by accurate masers and local oscillators, usually allowing frequency calibration to better than ~ 10 m/s. In addition, all the OH transitions arise from a single species, reducing the possibility that any observed redshift differences might arise from local velocity offsets between different species in the absorbing molecular cloud. OH lines are also observable with the same (or better) sensitivity in the Galaxy, allowing tests for local systematics. Finally, all the known redshifted OH absorbers lie at $z < 0.9$, implying that these techniques allow one to study any late-time evolution in the constants. Clearly, OH lines, either alone or in conjunction with the H I 21cm line, provide an important approach to probing fundamental constant evolution. The best present constraint from a comparison between the H I and "main-line" OH redshifts has a 2σ sensitivity of $[\Delta\alpha/\alpha] < 6.7 \times 10^{-6}$ or $[\Delta\mu/\mu] < 1.4 \times 10^{-5}$ over a lookback time of ~ 6.5 Gyr, nearly half the age of the Universe (Kanekar et al. 2005).

4 "Conjugate" satellite OH lines

In rare cases, the 18cm satellite OH lines have the special property of being "conjugate" to each other, with the same shapes but with one line in absorption and the other in emission (van Langevelde et al. 1995; Kanekar et al. 2004; Darling 2004). Crucially, such conjugate behavior *guarantees that the satellite lines arise from the same gas.* These lines are thus perfectly suited for the purpose of measuring any evolution in α, μ and g_p between the source redshift and today, via a comparison between the sum and difference of satellite redshifts, as systematic velocity offsets between the lines are ruled out by the pumping mechanism. Any measured difference between the redshifts must then arise due to a change in one or more of the above fundamental constants (Kanekar et al. 2004). Equally important, unlike most other techniques, the conjugate satellite lines allow a 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). Further, the process of fitting multiple Gaussians (or Voigt profiles) to a spectral line of arbitrary shape to determine the redshifts of individual spectral components within the profile can itself affect the results, especially in the case of complex profiles. Another advantage in the case of conjugate satellite lines 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 fit each profile with multiple components. The technique also contains a stringent test of its own applicability, in that the shapes of the two lines must agree if they arise in the same gas.

Only two conjugate satellite OH systems are known at cosmological distances, at $z \sim 0.247$ towards PKS 1413+135 (Kanekar et al. 2004; Darling 2004) and $z \sim 0.765$ towards PMN J0134−0931 (Kanekar et al. 2005). Recent Arecibo observations of the former system have yielded the best present OH-based constraints on changes in α and μ; when combined with WSRT data on the source, we obtain 2σ sensitivities of $[\Delta\alpha/\alpha] < 3.8 \times 10^{-6}$ and $[\Delta\mu/\mu] < 7.6 \times 10^{-6}$ over ~ 2.7 Gyrs. Assuming linear evolution in α and μ, this yields 2σ sensitivities of $[1/t]\,[\Delta\alpha/\alpha] < 1.4 \times 10^{-15}$ and $[1/t]\,[\Delta\mu/\mu] < 2.8 \times 10^{-15}$ yr^{-1}; for comparison, the best constraints on $[1/t]\,[\Delta\alpha/\alpha]$ from atomic clocks are a factor of three poorer than this; the above OH results are among the best constraints on changes in α and μ from any technique and with no obvious systematic effects.

5 Probing fundamental constant evolution with the Arecibo telescope

The main drawback to OH-based techniques is that OH lines are difficult to detect as they are both very weak and occur in regions teeming with terrestrial radio frequency interference (RFI). At present, only five redshifted absorbers have been found in the ground state 1665 and 1667 MHz transitions towards background quasars (Chengalur et al. 1999; Kanekar & Chengalur 2002, 2003; Kanekar et al. 2005), all of which have also been detected in the HI 21cm line. No excited-state OH lines have so far been detected at cosmological distances, and there are only two known conjugate satellite systems. Despite the dramatic improvement in the sensitivity of the radio measurements in the last few years, these are based on a tiny sample, suggesting that we are still only scratching the surface of the field.

There are two clear avenues by which the Arecibo telescope can make a significant impact on studies of fundamental constant evolution. Most obvious of these is through deeper integrations on known conjugate OH systems. The best present constraint on changes in α and μ from OH spectroscopy comes from a 40-hour Arecibo integration on the $z \sim 0.247$ conjugate system towards PKS 1413+135, for which the 1612 and 1720 MHz OH lines lie within the sensitive Arecibo L-band, at frequencies that are relatively free of RFI. It should be possible to achieve 2σ sensitivities of $[\Delta\alpha/\alpha] \sim \times 5 \times 10^{-7}$ and $[\Delta\mu/\mu] \sim 10^{-6}$ on this system with deep (*few* hundred hour) integrations with Arecibo in the next few years. This would be comparable to the sensitivity of the Oklo measurement but with fewer assumptions and out to a larger lookback time.

5.1 Blind surveys in the 6cm H2CO line

The other strategy, which also has repercussions for our understanding for the evolution of molecular gas with redshift, involves using the excellent Arecibo frequency coverage and sensitivity to carry out a blind survey for redshifted molecular absorption towards a radio-selected sample of background sources. Such a survey would be best carried out in the H2CO 6cm line, whose opacity has been found to be $> 1\%$ for HCO^+ column densities larger than $\sim 10^{12}$ cm^{-2} (Liszt & Lucas 1995). The HCO^+ column densities of all known redshifted molecular absorbers are more than an order of magnitude larger than this, implying that all such high-column-density systems would be detected in the survey. Searches towards a radio-selected flux-limited sample of background sources would also not contain any bias against dusty lines of sight (unlike the situation for optically-selected samples). Further, unlike the case for redshifted H I 21cm and OH lines, this frequency range is relatively free of RFI, rendering a blind survey a more tractable proposition. Any detected systems (either H2CO absorbers or H2CO megamasers) would be followed up in the OH, H I 21cm, and HCO^+ lines, and comparisons between the line redshifts then used to probe changes in the fundamental constants [see sections (3) and (4) and Chengalur & Kanekar (2003)].

At present, the frequency range between 2.5 GHz and 4.8 GHz (i.e. $z \sim 0 - 0.9$) is covered at Arecibo by three separate receivers, the S-band-low, S-band-high and C-band, requiring multiple frequency settings to cover the entire range. Further, the current WAPP correlator can only handle a bandwidth of upto 800 MHz, again requiring multiple settings. We have used the Kühr et al. 1981 1-Jy sample to estimate the required integration time to search for 1%

H2CO absorption in the redshift range $0.2 < z < 0.9$ towards all sources in the Arecibo sky, and find that this would require a total time of ~ 60 double-position-switched hours (Ghosh & Salter 2000). The total redshift path of such a survey is then $\Delta z = \Sigma(z_{max} - z_{min}) \sim 52$, where $z_{min} = 0.2$, z_{max} is the source redshift and the sum is over all sources in the sample (e.g. Prochaska et al. 2005). This is comparable to the redshift path of the best present radio-selected damped Lyman-α surveys: for example, the CORALS survey of Ellison et al. 2001 and the UCSD survey of Jorgenson et al. 2006 had redshift paths of $\Delta z \sim 55$ and $\Delta z \sim 42$, respectively. We expect such a survey of even the relatively-small Kühr et al. (1981) sample to yield $\sim 5 - 10$ molecular absorbers, based on the number density of DLAs at these redshifts. This could be easily extended to far larger source samples based, for example, on the NVSS or FIRST surveys.

In passing, we feel it worthwhile to note that no other telescope in the world has the frequency coverage to carry out such a blind survey in the H2CO 6cm line. While there are other transitions in which similar surveys might be carried out (e.g. HCO^+ 1-0, CO 1-0, etc), these typically have far higher redshifted frequencies, implying a significantly wider frequency coverage (and thus, larger bandwidths) to cover a similar redshift range. Conversely, the low frequency of the H2CO 6cm transition implies that a large redshift range can be covered with even a single 800 MHz setting of the WAPP backend. Of course, low-frequency absorption surveys also have the advantage that the number of bright sources against which absorption might be detected is far higher at centimetre wavelengths than at millimetre ones. Finally, in addition to any intervening absorbers, such a survey would also automatically result in the detection of any absorbing material in the host galaxy of the background source.

While the above $0.2 < z < 0.9$ survey of the Kühr et al. (1981) sample can be done in reasonable integration times with the present Arecibo receivers and backends, extending it to a significantly larger number of sources and a wider redshift range would require large investments of observing time. An obvious way to increase the redshift coverage would be to increase the survey upper frequency from ~ 4 GHz to ~ 7.7 GHz, thus covering the frequency range $2.5 - 7.7$ GHz. This would result in uniform coverage of any H2CO absorbers in the redshift range $0 < z < 4.9$, with absorbers in the range $0 < z < 0.9$ detected in the 6cm line and those in the range $0.9 < z < 4.9$, in the corresponding line at ~ 2cm (which is usually stronger than the 6cm line; e.g. Jethava et al. 2007). Besides providing new molecular absorbers to probe fundamental constant evolution, such a survey would allow us to obtain a census of molecular absorbers as a function of redshift and to thus study the evolution of quantities such as the cosmological mass density in molecular gas, etc, as has been possible for HI through optical surveys for damped Lyman-α systems (e.g. Prochaska et al. 2005). The efficiency of such a blind Arecibo survey could be significantly increased by (1) a wide-band receiever that covers the frequency range $\sim 2-8$ GHz and (2) a new backend that can handle bandwidths of $\gtrsim 5$ GHz with a spectral resolution of ~ 5 km/s, enabling the entire frequency range to be covered in a single setting. In addition, a present limitation of the Arecibo telescope is the requirement of double-position-switching to avoid standing waves when carrying out observations that require a high spectral dynamic range. A study of feed designs specifically for the purpose of minimising these standing waves would be of immense interest. Alternatively, sub-reflector control could also help in correcting for bandpass ripples without costing extra telescope time.

6 Summary

In summary, radio spectroscopic techniques have a crucial role to play in probing changes in the fundamental constants, due to their precise frequency calibration, high spectral resolution, entirely independent systematics and sensitivity to evolution at $z \lesssim 1$. The excellent sensitivity and frequency coverage of the Arecibo telescope imply that it is likely to be at the forefront of this field until the advent of next-generation facilities like the Square Kilometer Array. Deep Arecibo integrations on known conjugate OH systems like the $z \sim 0.247$ absorber/emitter towards PKS 1413+135 will allow us to reach $[\Delta\alpha/\alpha]$ sensitivities comparable to those obtained from the Oklo nuclear reactor and with far fewer systematics, while sensitivities to $[\Delta\mu/\mu]$ will be by far the best from any technique. Blind Arecibo H2CO 6cm surveys should allow the detection of a significant population of new molecular absorbers at $z \lesssim 4.9$, which could be followed up in other atomic and molecular transitions to probe changes in the fundamental constants. Increasing the backend bandwidth (to $\gtrsim 5$ GHz), building a single wide-band $2-8$ GHz receiver and research into feed designs and sub-reflector control to improve the spectral dynamic range with normal position-switching, will all have important repercussions on the ability of the Arecibo telescope to make a significant impact in this field.

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