Probing fundamental constant evolution with astronomical spectroscopy

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1. Do the Fundamental Constants Change With Time?

Most modern higher-dimensional theories that venture beyond the standard model of particle physics contain the prediction that low-energy fundamental constants such as the fine structure constant α, the proton-electron mass ratio $\mu \equiv m_p/m_e$, etc, are dynamical quantities, whose values vary with space and time (e.g. Marciano et al. 1984, PRL, 52, 489). The detection of such changes provides an avenue to explore new physics beyond the standard model; this is of much importance because most other predictions of these models lie at extremely high energies ($\gtrsim 10^{19}$ GeV). However, the timescales of these putative changes are model-dependent, implying that it is necessary to search for evolution over as wide a range of timescales as possible (especially as it is not even clear that any evolution will be monotonic). It is also important to probe changes in different constants, as the relative amplitudes of the changes could be very different. For example, fractional changes in μ are expected to be far larger than those in α, by factors of $\sim 50 - 500$ (e.g. Langacker et al. 2002, Phys. Lett. B, 528, 121).

On short timescales (a few years), laboratory experiments, usually based on frequency comparisons between atomic clocks and other optical frequency standards, have yielded strong constraints on changes in α and μ. The best constraints from such studies are $\dot{\alpha}/\alpha < 4.6 \times 10^{-17}$ yr^{-1}, over one year (Rosenband et al. 2008, Science, 319, 1808), and $\dot{\mu}/\mu < 1.2 \times 10^{-13}$ yr^{-1}, over two years (Shelkolnikov et al. 2008, PRL, 100, 150801). However, such studies are limited to probing changes in the constants over timescales of only a few years. Further, while 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; e.g. Uzan 2003, Rev. Mod. Phys, 75, 403) yield sensitive constraints on changes in α over lookback times of $\sim 1.8 - 4$ Gyr, such techniques are typically model-dependent and involve critical assumptions about the constancy of other parameters (e.g. Gould et al. 2006, Phys. Rev. C, 74, 024607).

Astrophysical techniques allow tests of changes in the fundamental constants over large lookback times, out to a large fraction of the age of the Universe. The methods can be broadly divided into the following three categories: (1) relative abundances of elements formed during Big Bang nucleosynthesis, (2) observations of CMB anisotropies, and (3) comparisons between the redshifts of spectral lines from distant galaxies. The first two of these probe the largest lookback times, but the results are not very sensitive due to degeneracies with the cosmological parameters, which are not *a priori* known. In this White Paper, I will focus on the third category, the use of astronomical spectroscopy to probe changes in three constants, α, $\mu \equiv m_p/m_e$ and the proton gyromagnetic ratio g_p, to answer the question:

- **Do the low-energy fundamental constants change with cosmological time ?**

2. Scientific Context: Astronomical Techniques to Probe Changes in α, μ, and g_p

The frequencies of different spectral transitions have different dependences on the fundamental constants α, μ and g_p, as they arise from different physical mechanisms. For example, the wavelength separation in an alkali-doublet is proportional to α^2, while hyperfine line frequencies are proportional to $g_p\mu\alpha^2$. If a given fundamental constant had a different value

at some redshift (or at a different spatial location), all rest frequencies that depend on this constant would be different at this redshift from values measured in terrestrial laboratories. In such a situation, *different spectral lines arising from a single cloud would yield different derived redshifts* as the incorrect laboratory rest frequency would be used for each line to estimate the cloud redshift. If the dependence of the different rest frequencies on the constant is known, a comparison between the derived line redshifts can be used to determine the fractional change in the constant between the space-time locations of the cloud and the Earth. Thus, for example, a comparison between redshifts measured from hyperfine and optical resonance transitions is sensitive to changes in $g_p[\alpha^2/\mu]$, while one between hyperfine and rotational lines is sensitive to changes in $g_p\alpha^2$.

Of course, a hurdle to such studies arises from the possibility of "local velocity offsets" between different lines, due to intra-cloud motions, as such offsets too could result in different redshifts for different lines. Typical intra-cloud velocities of ~ 10 km/s imply systematic errors of $\sim 10^{-5}$ on estimates of fractional changes in the constants (e.g. Carilli et al. 2000, PRL, 85, 5511). Such local velocity offsets can be addressed either by using statistically-large absorber samples, to average out local motions, or by using specific spectral transitions where the physics of the line mechanism itself causes such local offsets to be negligible.

It should be emphasized that all techniques that probe fundamental constant evolution (not merely astronomical ones) are affected to a greater or lesser degree by systematics peculiar to the technique. *Given the possibility that under-estimated or unknown systematics might dominate the errors from a given technique, it is important that independent techniques, with entirely different systematic effects, be used in such studies.* Of course, different redshift comparisons allow one to probe changes in different constants, or in different combinations of the constants. The best present astronomical techniques are discussed next, along with their known systematic effects (e.g. Kanekar 2008, Mod. Phys. Lett. A, 23, 2711).

2.1 The Alkali-doublet method: Changes in α

The fractional separation between alkali-doublet (AD) wavelengths is proportional to α^2, implying that the measured line redshifts immediately yield an estimate of fractional changes in the fine structure constant $[\Delta\alpha/\alpha]$ (Savedoff 1956, Nature, 178, 688). The best result from this technique[1] is $[\Delta\alpha/\alpha] < 2.6 \times 10^{-5}$, from Keck-HIRES absorption spectra of 21 SiIV doublets at $2 < z < 3$ (Murphy et al. 2001, MNRAS, 327, 1237). The fact that each line of a doublet pair must have the same shape provides a useful test against systematic effects (e.g. blended lines from an absorber at a different redshift). However, the small fractional wavelength separation between the lines also means that the technique is far less sensitive than, for example, the many-multiplet method.

2.2 The Many-multiplet Method: Changes in α

The many-multiplet (MM) method stems from the fact that the wavelengths of different optical resonance transitions, arising from either different species or different energy states in the same atom, have different dependences on α, due to relativistic effects (Dzuba et al. 1999, PRL, 82, 888). The relativistic corrections can be quite large for certain species, making this

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

method far more sensitive than the alkali-doublet method. However, large absorber samples are needed in the MM method to average out local velocity offsets.

The many-multiplet method is, so far, the only technique that has found statistically-significant evidence for changes in any of the fundamental constants. Murphy et al. (2004, LNP, 648, 131) obtained $[\Delta\alpha/\alpha] = [-0.57 \pm 0.11] \times 10^{-5}$ from Keck-HIRES data on 143 absorbers at $0.2 < z < 4.2$; if correct, this would imply that α was smaller at earlier times (see also Webb et al. 2001, PRL, 87, 091301; Murphy et al. 2003, MNRAS, 345, 609). While Srianand et al. (2004, PRL, 92, 121302) claimed to have ruled out the result of Murphy et al. (2004) using VLT-UVES data, it has now been demonstrated that the errors in the analysis of Srianand et al. (2004) were severely under-estimated (by a factor of ~ 3), due to problems in their χ^2-minimization procedure (Murphy et al. 2008, MNRAS, 384, 1053; see also Srianand et al. 2007, PRL, 99, 239002). Murphy et al. (2008) also argue that other VLT-UVES studies based on the MM method or its variants (e.g. Levshakov et al. 2005, A&A, 434, 827) are also unlikely to be reliable, due to the fitting of insufficient spectral components. Excellent discussions of the systematic effects inherent in the MM (and AD) methods are provided by Murphy et al. (2001, MNRAS, 327, 1223) and Murphy et al. (2003), who find no evidence that their Keck-HIRES result might be affected by such systematics (but see Molaro et al. 2007, arxiv/0712.4380). At present, it appears fair to say that the Keck-HIRES result $[\Delta\alpha/\alpha] == [-0.573 \pm 0.113] \times 10^{-5}$ at a mean redshift of $z \sim 1.75$ has not been ruled out by any subsequent study. Given the implications for theoretical physics, it is of much importance to test this result with other techniques.

An important source of systematic effects in the MM method is the possibility of isotopic abundance variation with redshift. For most species, different isotopic transitions are blended in even the highest-resolution optical quasar spectra; to make things worse, the isotopic structure is only known for a few of the transitions used in the MM analysis. Terrestrial isotopic abundances are hence assumed to determine the central line wavelength; as a result, isotopic abundance variations with redshift could mimic the observed effect (Ashenfelter et al. 2004, ApJ, 615, 82; Molaro et al. 2007). It is difficult to resolve this issue by direct observations, while indirect arguments depend on the details of galactic chemical evolution models (Ashenfelter et al. 2004; Fenner et al. 2005, MNRAS, 358, 468). Bahcall et al. (2004, ApJ, 600, 520) also point out that it is unclear whether the number of systems used in the MM method is sufficient to average out systematics from local velocity offsets, line blends and line mis-identifications to the claimed sensitivity of $(v/c) \sim 0.1$, i.e. $\Delta v \sim 0.3$ km/s. Unfortunately, the fact that the transitions used in the MM method lie at rest-frame UV wavelengths means that it is difficult to apply this method in the Galaxy, to test whether the expected null result is obtained at $z = 0$.

2.3 Molecular Hydrogen Lines: Changes in μ

Comparisons between the redshifts of ro-vibrational lines of molecular hydrogen (H_2) are sensitive to changes in the proton-electron mass ratio μ (Thompson 1975, ApL, 16, 3). A problem for this technique is that the H_2 lines are weak and often blended with Lyman-α forest absorption. The best result is from King et al. (2008, PRL, 101, 251304), who obtained $[\Delta\mu/\mu] < 6.0 \times 10^{-6}$ from three H_2 absorbers at $2.6 < z < 3.0$. However, King et al. (2008) carried out a simultaneous fit to the H_2 profiles as well as all Lyman-α forest transitions near

Technique	Quantity	Best present result	Redshift $< z >$	Ref.
AD method	$[\Delta\alpha/\alpha]$	$[\Delta\alpha/\alpha] < 2.6 \times 10^{-5}$	2.6	1
MM method	$[\Delta\alpha/\alpha]$	$[\Delta\alpha/\alpha] = [-0.57 \pm 0.11] \times 10^{-5}$	1.75	2
H_2 lines	$[\Delta\mu/\mu]$	$[\Delta\mu/\mu] < 6 \times 10^{-6}$	2.8	3
HI 21cm vs. optical	$X \equiv g_p[\alpha^2/\mu]$	$[\Delta X/X] < 2 \times 10^{-5}$	1.12	4
HI 21cm vs. rotational	$Y \equiv g_p\alpha^2$	$[\Delta Y/Y] < 3.4 \times 10^{-5}$	0.69	5
HI 21cm vs. OH 18cm	$Z \equiv g_p\,[\mu\alpha^2]^{1.57}$	$[\Delta Z/Z] < 2.1 \times 10^{-5}$	0.7	6
NH_3 vs. HCO^+	$[\Delta\mu/\mu]$	$[\Delta\mu/\mu] < 1.6 \times 10^{-6}$	0.69	7
Conjugate-satellite OH	$G \equiv g_p\,[\mu\alpha^2]^{1.85}$	$[\Delta G/G] < 1.1 \times 10^{-5}$	0.25	8

Table 1: The best current results from studies of fundamental constant evolution using redshifted spectral lines. References: (1) Murphy et al. (2001), (2) Murphy et al. (2004); (3) King et al. (2008, PRL, 101, 251304); (4) Tzanavaris et al. (2007, MNRAS, 374, 634); (5) Carilli et al. (2000, 85, 5511); (6) Kanekar et al. (2005, PRL, 95, 261301); (7) Murphy et al. (2008, Science, 320, 1611); (8) preliminary result, from Kanekar et al. (2009, in prep.)

the H_2 lines, rather than excluding possible blends with Lyman-α forest interlopers. While this allowed them to retain a far larger number of H_2 lines in the analysis and thus achieve a high sensitivity, it is unclear whether there was also a concomitant increase in systematic errors. Again, the H_2 lines lie at UV wavelengths, implying that it has not been possible to test whether this method yields the expected null result in the Galaxy. Applications of this technique are also limited by the paucity of known H_2 absorbers at high redshifts (e.g. Ledoux et al. 2006, A&A, 457, 71).

2.4 The HI 21cm line: Changes in α, μ, and g_p

HI 21cm absorption has been detected both in diffuse gas with optical resonance absorption against background luminous quasars, and in dark clouds that show radio molecular absorption against obscured quasars; it can hence provide multiple probes of changes in α, μ and g_p. Comparisons between HI 21cm and optical resonance redshifts are sensitive to changes in $X \equiv g_p[\alpha^2/\mu]$, between HI 21cm and molecular rotational redshifts to changes in $Y \equiv g_p\alpha^2$, and between HI 21cm and "main-line" OH 18cm redshifts to changes in $Z \equiv g_p[\mu\alpha^2]^{1.57}$ (Wolfe et al. 1976, PRL, 37, 179; Carilli et al. 2000; Chengalur & Kanekar 2003, PRL, 91, 241302). Note that the comparison between HI 21cm and OH 18cm lines is very sensitive to changes in α due to the strong dependence of Z on α ($Z \propto \alpha^{3.14}$). All of these techniques require large absorber samples to average out local velocity offsets, and are limited by the dearth of known redshifted HI 21cm and radio molecular absorbers. The best results from these methods are summarized in Table 1.

2.5 Ammonia lines: Changes in μ

The frequencies of inversion lines in the ammonia (NH_3) molecule have a far stronger dependence on μ than that of rotational line frequencies (Flambaum & Kozlov 2007, PRL, 98, 240801). Comparisons between the redshifts of inversion and rotational lines thus have a high sensitivity to changes in μ. While NH_3 absorption has only been detected in two absorbers at cosmological distances, one of these systems has already yielded the strong constraint $[\Delta\mu/\mu] < 1.8 \times 10^{-6}$ (Murphy et al. (2008, Science, 320, 1611). However, this result should be treated with caution as it is susceptible to many systematic effects, discussed in detail in Kanekar (2008).

2.6 Conjugate-Satellite Hydroxyl 18cm lines: Changes in α, μ, and g_p

A maser mechanism in the ground state of the OH molecule causes the satellite OH 18cm lines to become "conjugate" at high OH column densities (van Langevelde et al. 1995, ApJ, 448, L123). The two OH 18cm lines then have the same shape, but with one in emission, the other in absorption, and the two lines canceling each other on adding the optical depths. This is very interesting for studies of fundamental constant evolution because the two OH 18cm lines have different dependences on α, μ, and g_p; a comparison between the sum and difference of the satellite line redshifts is sensitive to changes in the quantity $G \equiv g_p \left[\mu\alpha^2\right]^{1.85}$, with high sensitivity to changes in both α and μ (Chengalur & Kanekar 2003). Further, the conjugate behaviour *guarantees that the satellite lines arise from the same gas.* Such systems are hence perfectly suited to probe changes in α, μ and g_p from the source redshift to today, as systematic velocity offsets between the lines are ruled out by the population inversion mechanism (Kanekar et al. 2004, PRL, 93, 051302; Darling 2004, ApJ, 612, 58). Any measured difference between the line redshifts must then arise due to a change in one or more of α, μ and g_p. This technique appears to be the least affected by systematic effects (Kanekar 2008), and also contains a stringent test of its own applicability, in that the shapes of the two OH 18cm lines must agree if they arise in the same gas. It has also been possible to demonstrate the expected "null" result in a local conjugate satellite system, at $z \sim 0.0018$ towards Cen A (Kanekar 2008).

Only two redshifted conjugate satellite systems are currently known, at $z \sim 0.247$ (Kanekar et al. 2004; Darling 2004) and $z \sim 0.765$ (Kanekar et al. 2005, PRL, 95, 261301). The best (preliminary) results have been obtained from the former system, for which Kanekar et al. (2009, in prep) obtain $[\Delta G/G] < 1.1 \times 10^{-5}$, where $G \equiv g_p \left[\mu\alpha^2\right]^{1.85}$ from Arecibo and Westerbork Synthesis Radio Telescope observations, consistent with no changes in α, μ and g_p from $z \sim 0.247$ to the present epoch. Note that averaging over multiple absorbers is not necessary in this technique, as local velocity offsets are ruled out by the conjugate behaviour. High sensitivity to changes in α, μ and g_p can thus be obtained by deep observations of the two known redshifted conjugate satellite systems. The only apparent drawback to this method is that its results are degenerate between changes in α, μ and g_p, and cannot be used to measure changes in a single constant without additional assumptions.

3. Studies Over the Next Decade

The optical and radio techniques of the previous section are currently limited by very different issues. Systematic effects in the optical techniques (the AD, MM and H_2 methods)

arise from issues like line blending, relative calibration of different echelle orders, unknown relative isotopic abundances at high redshifts and the fact that it is difficult to estimate systematic effects by Galactic studies. Conversely, the shortage of HI 21cm and radio molecular absorbers at high redshifts is the biggest drawback of the radio-based techniques, due to which one cannot average out local systematics (note that this does not affect the conjugate-satellites method).

Over the next decade, many of these issues will be addressed by new telescopes and associated instrumentation, at both radio and optical wavebands. The next generation of 30-metre-class optical telescopes and new optical spectrographs will yield far higher sensitivity, improved spectral resolution and better wavelength calibration. This should result in a significant increase in the number of both redshifted H_2 absorbers and alkali-doublet pairs suitable for studies of changes in μ and α. The H_2 and MM methods should allow 1σ sensitivities of $[\Delta\alpha/\alpha]\,, [\Delta\mu/\mu] \sim 10^{-7}$ from $z \sim 2$, more than an order of magnitude better than the best present results.

In the radio regime, increasing the number of redshifted absorbers (in both atomic and molecular lines) is a critical ingredient for future radio studies of fundamental constant evolution. This too should be feasible with upcoming telescopes and instrumentation. The wide-band receivers and correlators of the Green Bank Telescope (GBT), the Atacama Large Millimeter Array (ALMA) and the Expanded Very Large Array (EVLA) will, for the first time, allow "blind" surveys for redshifted CO/HCO^+ absorption against a large number of background sources. This should yield sizeable samples of high-z absorbers in these transitions, which can then be followed up in the OH 18cm, NH_3 and HI 21cm lines (note that two of the five known radio molecular absorbers show conjugate-satellite behaviour). The wideband coverage of the EVLA L-band receivers will allow "blind" surveys for redshifted HI 21cm and OH 18cm absorption out to $z_{\rm HI} \sim 0.5$ and $z_{\rm OH} \sim 0.7$, with every L-band continuum observation automatically yielding such an absorption survey towards all background sources in the field-of-view. Similarly, wide field-of-view surveys with the Australian SKA Pathfinder (ASKAP; Johnston et al. 2007, PASA, 24, 174) should yield ~ 250 new HI 21cm absorbers at $0.5 < z < 1$ in ~ 5000 ASKAP hours (besides OH 18cm absorbers and new conjugate-satellite OH systems). It should thus be possible to average over local velocity offsets or different kinematic structures to obtain reliable results when comparing redshifts between different radio lines or between radio and optical lines. In addition, deep ($few \times 100$ hours) integrations on the known conjugate systems with existing telescopes over the next few years should achieve 1σ sensitivities of $dG/G \lesssim 10^{-6}$, implying sensitivities of $[\Delta\alpha/\alpha] \lesssim 3 \times 10^{-7}$ and $[\Delta\mu/\mu] \lesssim 6 \times 10^{-7}$ to changes in α and μ.

4. Advancing the Science: Technical/Theoretical Developments

Vast progress is thus likely to be possible over the next decade in astronomical studies of fundamental constant evolution. It should be possible to achieve sensitivities to changes in α and μ comparable to the sensitivity to changes in α from the Oklo nuclear reactor, with far fewer systematics, over a larger lookback time, and via multiple techniques. However, a number of technical and theoretical developments would significantly contribute to progress in this field. These include: (1) implementation of new wavelength calibration schemes for optical telescopes, (2) focal-plane phased arrays for radio telescopes, (3) laboratory stud-

ies to accurately measure line frequencies, (4) a wideband spectrometer for ALMA, and (5) theoretical studies.

- **New wavelength calibration schemes:** A critical requirement for significantly increasing the sensitivity of optical techniques to changes in α and μ is accurate wavelength calibration across large wavelength ranges. Laser frequency combs offer the possibility of such precise absolute wavelength calibration (e.g. Steinmetz et al. 2008, Science, 321, 1335). However, even with the implementation of such combs, much research is needed into systematic effects associated with the spectrograph and detector systems.

- **Focal-plane phased arrays:** Blind surveys for HI 21cm absorption require a wide field-of-view, which is not presently available on high-sensitivity telescopes like the GBT and the EVLA. It should be possible to increase the GBT field-of-view (and perhaps that of the EVLA) by more than an order of magnitude through the use of focal-plane phased-array feeds. Development work is needed to obtain wide frequency coverage and low system temperatures for such focal-plane arrays, which are also critical for the next-generation Square Kilometer Array.

- **Laboratory studies:** The laboratory wavelengths of a number of optical and radio lines that might be used in studies of fundamental constant evolution are only known to a fractional precision of $\sim 10^{-6}$. This is insufficient to achieve the high sensitivities to changes in α or μ that will be possible over the next decade. Precision laboratory measurements of the rest wavelengths of various spectral lines will thus be of much importance (e.g. Hudson et al. 2006, PRL, 96, 143004).

- **ALMA development projects:** The first-generation ALMA correlator will have a bandwidth of 8 GHz. Blind surveys for redshifted molecular absorption will thus require multiple frequency settings to cover the entire 90 GHz (or 170 GHz) bands in the redshifted CO/HCO^+ lines. A 32 GHz spectrometer would allow wide redshift ranges in these lines to be surveyed with a single frequency setting, significantly improving the survey speed. The survey speed would also be vastly improved by the development of focal-plane arrays for ALMA.

- Theoretical studies: So far, few molecules have been examined for their use as probes of fundamental constant evolution; theoretical studies in this area are of much importance, both to obtain new techniques with independent systematic effects, and to find transitions with strong dependences on different constants (as was possible for the NH_3 inversion lines). Extensions of the many-multiplet method (e.g. the SIDAM method; Levshakov et al. 2005) would also be of much interest, especially if such extensions can be applied to species with widely separated isotopic transitions. Additional corrections to the Born-Oppenheimer approximation are also likely to be necessary to achieve sensitivities of $[\Delta\mu/\mu] \sim 10^{-7}$ in the H_2 method (e.g. Reinhold et al. 2006, PRL, 96, 151101).