Astro2020 Science White Paper

Radio Sepectral Line Probe of Evolution of Fundamental Constants

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name:Tapasi Ghosh
Institution: Green Bank Observatory
Email: tghosh@nrao.edu
Phone: 304 456 2381

Co-authors: Nissim Kanekar, NCRA, TIFR, India.

Abstract (optional):
Comparisons between the redshifts of multiple spectral transitions from distant galaxies provide a sensitive probe of secular evolution in fundamental constants such as the fine structure constant and the proton-electron mass ratio over cosmological epochs. This white paper summarizes the current status of the field and the directions for progress with large radio telescopes and their new and improved instrumentation.

1 Introduction

The possibility of space-time variation in the fundamental constants has been of interest ever since the original suggestion of Dirac (1937) that large dimensionless constants should not appear in the laws of physics. While the standard model of particle physics critically assumes that coupling constants and the ratios of particle masses do not depend on space and time, changes in these quantities arise naturally in higher-dimensional theories aiming to unify the standard model and general relativity (e.g. Marciano, 1984; Damour & Polyakov, 1994). Given the exciting possibility of testing such theories at low energy scales, investigations of changes in various constants have attracted considerable attention (Uzan, 2011). Most such efforts to date have focussed on the coupling constant of electromagnetism, the fine structure constant α, and the proton-electron mass ratio $\mu \equiv m_p/m_e$, which gives the relative strengths of the strong force and the electro-weak force. These are not "fundamental constants" in the standard model, but arise as specific combinations of the constants therein (Uzan, 2011) (e.g. $\alpha = 2\pi e^2/hc$). In addition, different techniques are sensitive to changes in the constants on very different timescales.

1. Laboratory studies (a few years): Significant progress has taken place in laboratory studies of fundamental constant evolution, mostly due to improvements in the stability of different kinds of atomic and molecular clocks (e.g. Fischer et al., 2004; Peik et al., 2004; Fortier et al., 2007; Rosenband et al., 2008; Blatt et al., 2008; Shelkovnikov et al., 2008). For example, singly ionized Ytterbium, with ultranarrow optical clock transitions at 467 and 436 nm, has produced the first direct measurement of the frequency ratio of these two clock transitions, without reference to a cesium primary standard, and using the same single ion of $^{171}Yb^+$ (Godun , 2014). This has helped making a threefold improvement in the constraint on the time variation of the proton-to-electron mass ratio, $\dot{\mu}/\mu = 0.2(1.1) \times 10^{-16} yr^{-1}$, along with an improved constraint on time variation of the fine structure constant, $\dot{\alpha}/\alpha = -0.7(2.1) \times 10^{-17} yr^{-1}$.

2. Geological methods (a few billion years): Results in this category are based on measurements of the abundances of different isotopes and their decay products in the Okolo natural fission reactor (Shlyakhter, 1976). The most accurate result so far, using improved nuclear parameters and based on the ^{149}Sm abundance is $|(\alpha_{Okolo} - \alpha_{now}| < 1.1 \times 10^{-8} \alpha_{now}$ (95% confidence level) of Davis & Hamdan (2015).

3. Astrophysical methods to probe the evolution of fundamental constants on $\sim 0.5 - 10$ Gyr timescales fall in three broad categories: (i) spectroscopic techniques, comparing the redshifts of multiple spectral lines from cosmologically-distant galaxies (Savedoff, 1956), (ii) "CMB" methods, which use millimetre-wave imaging studies to measure anisotropies in the cosmic microwave background (Hannestad, 1999; Kaplinghat et al., 1999), and (iii) "BBN" methods, based on the measurement of the abundances of elements like helium, deuterium and lithium, formed during primordial nucleosynthesis (Kolb et al., 1986). While the CMB and BBN approaches allow probes of change in the constants over the largest lookback times, and at two specific epochs, $z \approx 1100$ (CMB) and $z \approx 10^{10}$ (BBN), redshifted spectral lines probe constant evolution over a wide range of timescales.

2 Redshifted Spectral Lines

The frequencies of different spectral lines arising from different physical mechanisms (e.g. Lambda-doubling, hyperfine structure, molecular rotation, etc) have different dependences on constants such as α, μ and the proton gyromagnetic ratio, g_p. Hence, if the values of these constants depend on space and time, the line-rest frequencies will also do so. This will yield incorrect values of velocities and redshifts for the galaxy. The measured difference between the velocities (or redshifts) obtained from different lines in the same object can then be used to calculate the fractional difference ($\Delta X/X$) in the value of a constant (or a combination of those). (e.g. Drinkwater et al., 1998; Carilli et al., 2000). The best spectral lines for the above purpose are usually quasar absorption lines detected in galaxies lying along the sightline as they are typically narrow, and their line-strengths do not decrease with distance. The vast majority of spectroscopic results on fundamental constant evolution are hence based on either absorption lines or stimulated emission lines. Any systematic error due to intrinsic velocities can be minimized by averaging results derived from large samples of absorbers. (e.g. the many-multiplet method; Dzuba et al., 1999) or by using special transitions where the physics of the transition causes such local effects to be negligible (e.g. the conjugate satellite OH method; Kanekar et al., 2004).

2.1 Optical Techniques

Optical spectroscopic techniques to probe changes in the fundamental constants are based on the plethora of strong ultraviolet (UV) ionic and molecular lines that are redshifted into the optical waveband. The three main optical techniques are:

1. The alkali doublet (AD) method was the first one to be used in the study of fundamental constant evolution and has been the main tool for over three decades (e.g. Bahcall et al., 1967; Varshalovich & Potekhin, 1994; Ivanchik et al., 1999; Murphy et al., 2001b)

2. The many-multiplet (MM) method and its variants: has been applied to a VLT-UVES sample of 154 absorbers towards 60 quasars to the Keck-HIRES sample (Webb et al., 2011; King et al., 2012) providing $[\Delta\alpha/\alpha] = (+2.1 \pm 1.2) \times 10^{-6}$, which was inconsistent with the Keck-HIRES result of Murphy et al. (2004) at $\sim 4.7\sigma$ significance. However, Webb et al. (2011) and King et al. (2012) include the possibility of spatio-temporal evolution of α in a joint fit to the VLT-UVES and Keck-HIRES data and find evidence, at $\sim 4.1\sigma$ significance, that the data are fit well by a spatial dipole.

3. The molecular hydrogen method: the most abundant molecule in the Universe, molecular hydrogen (H_2), has numerous UV ro-vibrational transitions whose rest wavelengths have different dependences on the reduced molecular mass. Thompson (1975) originally pointed out that comparisons between the H_2 line redshifts can be used to probe changes in the proton-electron mass ratio μ, and the technique was later improved by Varshalovich & Levshakov (1993). The main problem with this method is the difficulty in detecting the H_2 lines, which are weak and, for redshifted absorbers, located in the Lyman-α forest. The highest sensitivity results have been obtained from the $z \sim 2.811$ absorber towards PKS 0528−250, $[\Delta\mu/\mu] = (-1.4 \pm 3.9) \times 10^{-6}$ (King et al., 2008) and $[\Delta\mu/\mu] = (+0.3 \pm 3.7) \times 10^{-6}$ (King et al., 2011), both from VLT-UVES spectra. A weighted mean of the above results,

along with those from the two additional absorbers of King et al. (2008), gives $[\Delta\mu/\mu] = (+3.6 \pm 1.9) \times 10^{-6}$.

These accuracy of the optical spectroscopic methods are all limited by their wavelength calibration scheme (Griest et al., 2010). Other sources of systematic error include line blending at the low velocity resolution ($\sim 6 - 8$ km/s of many quasar spectra), line interlopers, saturation effects, (e.g. Murphy et al., 2003). In addtion, redshifted H_2 lines often fall in the Lyman-α forest complicating their use in measuring $[\Delta\mu/\mu]$, while the MM method is affected by unknown isotopic abundances in high-z galaxies.

3 Radio spetral lines

The wide variety of radio transitions implies that comparisons between the redshifts of different radio lines are sensitive to changes in different combinations of constants. Frequency calibration is also not an important issue in radio-spectral line measurements. Most such measurements so far are based on comparisons between the HI 21cm hyperfine line and various molecular lines (e.g. CO, OH, etc). At present, the main problem with such methods is that there are only five redshifted absorbers with detections of both the HI 21cm line and molecular lines (e.g. Carilli et al., 1993; Wiklind & Combes, 1995, 1996a,b, 1997; Carilli et al., 1997; Chengalur et al., 1999; Kanekar & Chengalur, 2002; Kanekar & Briggs, 2004; Kanekar et al., 2005), of which only three have been found suitable to probe changes in the constants. For example, Carilli et al. (2000) compared the redshift of the HI 21cm line with that of molecular rotation lines in two absorbers at $z \sim 0.247$ and $z \sim 0.685$ to obtain $[\Delta Y/Y] < 3.4 \times 10^{-5}$, where $Y \equiv g_p\alpha^2$. Kanekar & Chengalur (2003) compared HI 21cm hyperfine, OH 18cm Lambda-doubled and HCO^+ rotational lines to obtain weak but independent constraints on changes in g_p, α and μ, at the level of $afew \times 10^{-3}$. All such techniques comparing transitions from different species are affected by the fact that sightlines in the different transitions may probe different velocity structures in the absorbing gas clouds.

3.1 Ammonia Inversion Transitions

The tunneling of three hydrogen atoms through a potential barrier gives rise to a set of millimetre-wave inversion transitions in the ammonia (NH_3) molecule. Flambaum & Kozlov (2007) used this to demonstrate that a comparison between inversion and rotational line redshifts is extremely sensitive to changes in μ. Unfortunately, the NH_3 lines have so far been detected in only two redshifted absorbers, at $z \sim 0.685$ towards B0218+357 and $z \sim 0.886$ towards B1830−210 (Henkel et al., 2005, 2008). The most stringent constraints on changes in μ from the NH_3 method have been obtained from the $z = 0.685$ absorber towards B0218+357, which has narrow lines and hence lends itself to accurate redshift measurements (Flambaum & Kozlov, 2007; Murphy et al., 2008; Kanekar, 2011). The best present limit from this absorber is $[\Delta\mu/\mu] < 3.6 \times 10^{-7}$ (3σ confidence) from a comparison between the redshift of the NH_3 (1,1) line with those of the H_2CO and CS rotational lines.

3.2 Methanol Transitions

Jansen et al. (2011) found that the splitting between the different methanol (CH_3OH) energy levels is highly sensitive to the reduced moment of inertia of the molecule and hence on the proton-electron mass ratio μ. The CH_3OH lines could well prove to be the best tracers of changes in μ, because of (1) their sensitivity to such changes is larger than that of NH_3 inversion lines and (2) the large range of available CH_3OH lines, with very different frequency dependences on μ, implies that one can obtain multiple independent estimates of $[\Delta\mu/\mu]$ from a single redshifted absorber. So far, methanol has only been detected from a single cosmologically-distant system, the $z = 0.886$ lens towards B1830−210 yielding the stringent constraint of $[\Delta\mu/\mu] < 4.2 \times 10^{-7}$ on fractional changes in μ (Muller et al., 2011; Ellingsen et al., 2012).

3.3 Conjugate Satellite OH lines

The OH rotational ground state is broken up into four sub-levels by Lambda-doubling and hyperfine splitting. In certain astrophysical circumstances, the satellite OH 18cm lines have the same shape, but with one line in emission and the other in absorption. This "conjugate" behaviour arises due to an inversion of the level populations within the OH ground state (Elitzur, 1992; van Langevelde et al., 1995). Only a single completely conjugate satellite OH system is currently known, at $z \sim 0.247$ towards PKS 1413+135 (Kanekar et al., 2004; Darling, 2004). Recently, Kanekar et al. (2018) have used the Arecibo Telescope to carry out one of the deepest-ever integrations in radio spectroscopy, targetting the redshifted conjugate satellite OH 18 cm lines at $z \approx 0.247$ towards PKS 1413+135. An analysis of their new Arecibo data yielded $[\Delta X/X] = (+0.97 \pm 1.52) \times 10^{-6}$, where $X \equiv \mu\alpha^2$. Combining this with the earlier results from the Arecibo Telescope and the Westerbork Synthesis Radio Telescope, they obtain $[\Delta X/X] = (-1.0 \pm 1.3) \times 10^{-6}$, consistent with no changes in the quantity $\mu\alpha^2$ over the last 2.9 Gyr. This is the most stringent present constraint on fractional changes in $\mu\alpha^2$ from astronomical spectroscopy, and with no evidence for systematic effects.

Fig.1 demonstrates that today's radio and optical studies provide complementary view on the evolution of fundamental constants.

4 Future directions

A substantial increase in the number of redshifted radio absorbers with detected atomic and molecular transitions is a critical requirement for radio studies of fundamental constant evolution. This should be feasible with telescopes and insrumentation that are on the horizon. For example, the wide-band and feed-array receivers on the GBT and the Arecibo Telescope will enhance searches for HI 21cm and OH absorbers both towards compact background radio sources and towards new and improved samples of SDSS Type-2 quasars. Much improved performance of the GBT at W and Q band with the help of active surface adjustment also holds better promise for CO and HCO^+ detection in distant absorbers. A few large projects are currently underway using the Karl Jansky Very Large Array (JVLA), ATCA, GMRT and ASKAP. Future projects at ALMA will allow "blind" surveys for redshifted absorption in the strong mm-wave CO and HCO^+ rotational transitions towards a large number of background sources. Such surveys, should yield large samples of

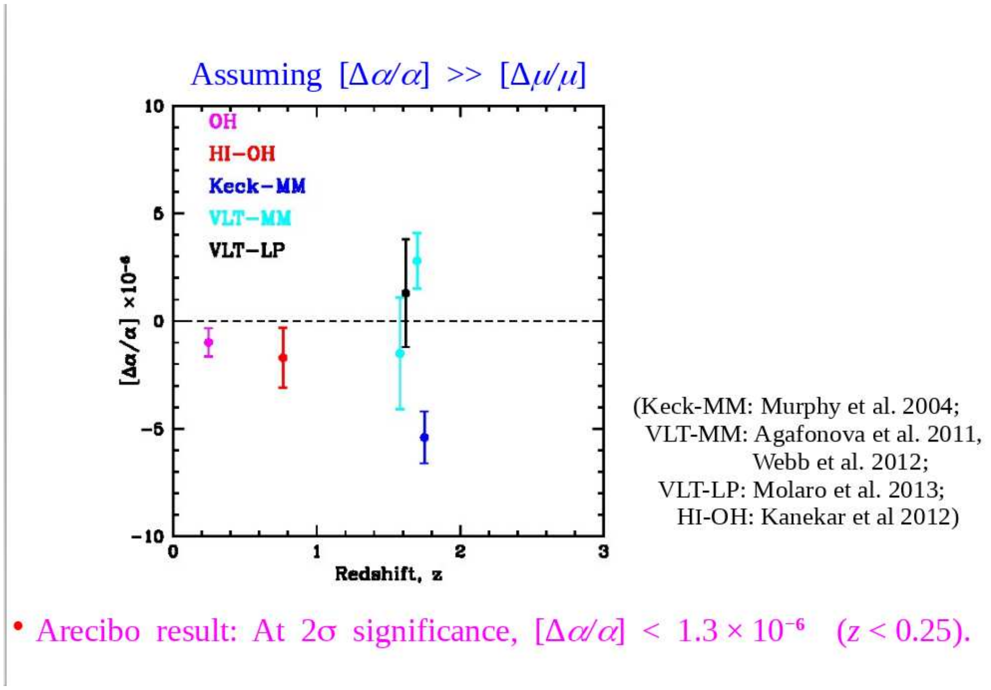

Figure 1: Estimates of $[\Delta\alpha/\alpha]$ plotted versus redshift, from various optical and radio spectroscopic methods

high-z CO/HCO^+ absorbers, which can then be followed up in the OH, NH_3, and HI 21cm lines using the Green Bank and Arecibo Telescope.

5 Summary

Optical and radio spectroscopic techniques have played complementary roles in searching for changes in the fundamental constants of physics on cosmological timescales. Significant improvements have been made in recent years, both in terms of increasing the number of techniques probing fundamental constant evolution and in raw sensitivity. The next decade is likely to continue to see significant progress in astronomical studies of fundamental constant evolution. It should be possible to achieve sensitivities to fractional changes in α and μ comparable to that from the Okolo nuclear reactor, but via multiple techniques, spanning a long range of lookback times. The conjugate-satellite OH and methanol methods are likely to be the most reliable probes of fundamental constant evolution. In any event, unknown systematic effects will continue to remain the bane of all techniques. It is critical that multiple independent techniques be used, both to guard against such effects and to continue to probe changes in multiple constants over a wide range of redshifts.

6 Reference

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