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Do the fundamental constants change with time?

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Abstract. Comparisons between the redshifts of multiple spectral transitions from distant galaxies provide a sensitive probe of secular changes in fundamental constants like the fine structure constant and the proton-electron mass ratio. This article discusses the pros and cons of the various techniques that have been used to test for such changes, and summarizes the current status of the field and the directions for progress with upcoming radio and optical telescopes.

Keywords : line: profiles – techniques: spectroscopic – radio lines

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, tests of changes in various constants have attracted considerable attention in recent years. Uzan (2011) provides an excellent recent review of theoretical issues and experimental results in this field.

Most studies of changing fundamental constants, whether based on laboratory studies, geological methods or astronomical data, 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. Of course, these are not

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"fundamental constants" in the standard model, but arise as specific combinations of the constants therein (Uzan 2011). Most theoretical models predict simultaneous changes in different constants, but the relative amplitudes of the changes are model-dependent and may allow one to discriminate between models. It is hence important to test the possibility of changes in a range of dimensionless quantities in the standard model and relativity. In the case of α and μ, fractional changes in μ are expected to $10 - 500$ times larger than those in α (e.g. Calmet & Fritzsch 2002; Langacker, Segré & Strassler 2002), and there are even models that yield variation only in μ, but not in α (e.g. Barrow & Magueijo 2005).

Different techniques are sensitive to changes in the constants on very different timescales. Laboratory studies usually probe changes over timescales of a few years, geological methods over a few Gyr, and astronomical methods over $\sim 0.5 - 10$ Gyr. It is not straightforward to compare these results because the time variation is model-dependent and not even necessarily monotonic in nature. One must hence search for changes over a wide range of timescales. It is also important to use multiple independent techniques, with different systematic effects, because it is such (often unknown) systematic effects, rather than statistical errors, that typically limit most techniques.

In recent 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, as well as the development of new clocks with elements such as Hg^+, Al^+, Sr, etc (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). Repeated comparisons between optical ion clocks using trapped $^{199}Hg^+$ and $^{27}Al^+$ ions have yielded $\dot{\alpha}/\alpha < 4.6 \times 10^{-17}$ yr^{-1}, the best current constraint on changes in α over timescales of a few years (Rosenband et al. 2008)[1]. The best model-independent constraint on changes in μ from such laboratory studies is from a comparison between CS hyperfine and SF^6 ro-vibrational frequency standards, which yielded $\dot{\mu}/\mu < 1.1 \times 10^{-13}$ per year (Shelkovnikov et al. 2008). A major advance in such studies will come in the near future, when multiple such clocks will be placed in a satellite orbiting the Earth. This would significantly reduce systematic effects, and improve the sensitivity to fractional changes in α and μ by a few orders of magnitude (e.g. Reynaud, Salomon & Wolf 2009).

Laboratory studies typically have excellent control over systematic effects, but, unfortunately, are only sensitive to changes on relatively short timescales, of the order of a few years. Studies of fundamental constant variation on timescales of billions of years must hence take recourse to geological or astronomical methods. The most sensitive results in the former category are based on measurements of the abundances of different isotopes (especially those of samarium) in the Oklo natural fission reactor (Shlyakhter 1976). Unfortunately, the Oklo results tend to be model-dependent, requiring assumptions about the constancy of other parameters as well as modelling of the nuclear reactions and the physical structure of the reactor (e.g. Damour & Dyson 1996; Fujii & Iwamoto 2003; Gould, Sharapov & Lamoreaux 2006; Petrov et al. 2006). For example, the

[1]Limits quoted in this review are at 2σ significance, unless explicitly stated otherwise.

most recent result based on the ^{149}Sm abundance in the Oklo reactor, $-0.24 \times 10^{-7} < [\Delta\alpha/\alpha] < 0.11 \times 10^{-7}$ of Gould et al. (2006), makes the critical assumption that α alone changes with time.

Astrophysical methods to probe fundamental constant evolution on Gyr timescales fall in three broad categories: (1) spectroscopic techniques, comparing the redshifts of multiple spectral lines from cosmologically-distant galaxies (Savedoff 1956), (2) "CMB" methods, which use millimetre-wave imaging studies to measure anisotropies in the cosmic microwave background (Hannestad 1999; Kaplinghat, Scherrer & Turner 1999), and (3) "BBN" methods, based on the measurement of the abundances of elements like helium, deuterium and lithium, formed during primordial nucleosynthesis (Kolb, Perry & Walker 1986). The CMB and BBN approaches allow one to probe changes in the constants over the largest lookback times (in the case of BBN methods, upto a few seconds after the Big Bang!). However, both are hindered by the fact that one has to solve for the values of the cosmological parameters along with the changes in the constants (e.g. Rocha et al. 2004; Menegoni et al. 2009). The results of nucleosynthesis studies are additionally model-dependent because we do not know how the nuclear binding energies are related to the fundamental constants (Dent, Stern & Wetterich 2007). In addition, while the two methods probe large lookback times, they can, at best, only provide an estimate of the difference between the values of the constants today and at two specific epochs, $z \approx 1100$ (CMB) and $z \approx 10^{10}$ (BBN), with no information on the evolution at intermediate epochs. Assuming that one does find evidence for changing fundamental constants, it is this evolution that is likely to be critical in distinguishing between different theoretical models. While techniques based on redshifted spectral lines probe slightly smaller lookback times, these have the advantage of sensitivity to fundamental constant evolution over a wide range of timescales $\sim 0.5 - 10$ Gyrs, and from a variety of methods with very different systematics. In this review, I will discuss the various techniques, based on astronomical spectroscopy, that have been used to probe changes in three fundamental constants, the fine structure constant α, the proton-electron mass ratio $\mu \equiv m_p/m_e$, and the proton gyromagnetic ratio g_p.

2. Redshifted spectral lines

The idea that one can compare the velocities of spectral transitions from an external galaxy to test whether the fundamental constants depend on space and time is more than half a century old (Savedoff 1956). The frequencies of different spectral lines have different dependences on constants like α, μ and g_p, because the lines arise from different physical mechanisms (e.g. Lambda-doubling, hyperfine structure, molecular rotation, etc). Hence, if the values of the constants depend on space and time, the line rest frequencies too would depend on space and time and would not, in general, be the same in an external galaxy and in the laboratory. The use of the incorrect (laboratory) line rest frequency to determine the systemic velocity (or redshift) of the galaxy would then yield an incorrect velocity for the galaxy. Further, different estimates of the systemic velocity would be obtained from different lines, if the line frequencies have different dependences on the constants. Since the dependence of the line rest frequencies on the constants is known, the measured difference between the velocities (or redshifts) obtained from different lines immediately yields the fractional difference ($\Delta X/X$) in the value of a constant (or a combi-

nation of multiple constants) X in the laboratory and at the location of the galaxy. A well-known comparison is between redshifts measured using hyperfine and rotational line frequencies, which are respectively proportional to $g_p\alpha^2/\mu$ and $1/\mu$; the comparison is hence sensitive to changes in the quantity $g_p\alpha^2$ (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 to background active galactic nucleii. This is because such absorption arises along a narrow pencil beam towards the background quasar, while emission lines tend to arise from spatially extended regions. As a result, absorption profiles are typically far narrower (in velocity space) than emission profiles, allowing the line redshifts to be measured more accurately. Further, absorption line strengths do not decrease with distance, making them equally easy to detect nearby and at high redshifts (as long as there are higher-redshift quasars available as background torches). The vast majority of spectroscopic results on fundamental constant evolution are hence based on either absorption lines or stimulated emission lines. However, it should be pointed out that the few studies that use emission lines do provide an interesting complement, especially because they have very different systematic effects (e.g. Bahcall, Steinhardt & Schlegel 2004; Grupe, Pradhan & Frank 2005; Levshakov et al. 2008)

An important source of systematic errors that affects most techniques based on redshifted spectral lines is that the *intrinsic* velocity of different spectral lines is often different. This is because different lines can originate in different locations in the galaxy, at slightly different velocities, depending on local conditions. While this issue is exacerbated in the case of lines arising in different atomic or molecular species, even multiple lines arising from a single species may arise in different parts of a gas cloud, due to different excitation requirements. Such intra-cloud velocity differences are typically of the order of a few km/s, yielding systematic errors of order $v/c \approx 10^{-5}$ on estimates of fractional changes in the constants. This issue can be addressed by using statistically-large samples of absorbers, to average over such local effects (e.g. the many-multiplet method; Dzuba, Flambaum & Webb 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, Chengalur & Ghosh 2004).

3. 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. Modern eight-metre class telescopes and high-resolution echelle spectrographs allow these lines to be detected at high signal-to-noise ratios in quasar absorption spectra. Such techniques have hence yielded amongst the most sensitive probes of fundamental constant evolution; indeed, the majority of the current results are from optical studies. The three main optical techniques: (1) the alkali doublet method, (2) the many-multiplet method and its variants, and (3) the molecular hydrogen method.

3.1 The alkali doublet method

Fine splitting of the p-state in a number of ionic species (e.g. CIV, SiIV, etc) gives rise to two resonance lines at nearby wavelengths, due to the transitions $s_{1/2} \rightarrow p_{1/2}$ and $s_{1/2} \rightarrow p_{3/2}$. The difference between the wavelengths of the two lines is proportional to α^2; as such, the detection of both lines immediately yields a probe of changes in α (Savedoff 1956). This "alkali doublet" (AD) method was the first astronomical technique used to study fundamental constant evolution, and provided the main tool for such studies for three decades (e.g. Bahcall, Sargent & Schmidt 1967; Varshalovich & Potekhin 1994; Ivanchik, Potekhin & Varshalovich 1999). The best present result from this method is $[\Delta\alpha/\alpha] < 2.6 \times 10^{-5}$, from 21 SiIV absorption doublets at $2 < z < 3$, using spectra from the High Resolution Echelle Spectrograph (HIRES) on the Keck telescope (Murphy et al. 2001b).

The AD method has the important advantage that the doublet lines arise from the same gas and hence must have the same shape, apart from an absolute scaling. This is extremely useful in testing against systematic effects. Further, the doublet line wavelengths lie close to each other, implying that the lines typically fall on the same echelle order thus obviating the need for relative wavelength calibration across orders. Unfortunately, both Keck-HIRES and the Ultraviolet Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) have been shown to have significant intra-order distortions of the wavelength scale, when wavelength calibration is done with the standard thorium-argon (ThAr) lamp method (Griest et al. 2010; Whitmore, Murphy & Griest 2010). Systematic effects from such intra-order distortions are a serious concern for the AD method. Further, the rest wavelengths of the strong CIV lines have so far not been measured with sufficient accuracy in the laboratory for their use in the AD method, restricting such studies to the weaker SiIV 1393/1402 doublet, whose laboratory wavelengths are accurately known (Griesmann & Kling 2000). Finally, the main reason that the AD method has fallen out of recent favour is that it is an order of magnitude less sensitive than the many-multiplet method.

3.2 The many-multiplet method

The relativistic first-order correction to the electron energy in a many-electron ion depends on both the atomic species and the energy level in question. The correction is proportional to $(Z\alpha)^2$, where Z is the nuclear charge; however, it also contains a term due to many-body effects, whose sign depends on the energy level (Dzuba et al. 1999). The correction is hence much larger for a large ion than for a small one; as a result, the wavelengths of resonance transitions in large and small atoms have different dependences on α. Further, even within a single ion, the wavelengths of different transitions (e.g. $s \rightarrow p$ and $d \rightarrow p$ lines) have different dependences on α, due to many-body effects. The many-multiplet (MM) method relies on both these effects and is based on comparisons between both different multiplets within a single ion and transitions from different ions. This yields a significant increase in sensitivity to fractional changes in α over the AD method.

As noted by Bahcall et al. (2004), the increased sensitivity of the MM method comes with a concomitant increase in systematic effects. The transitions used in the MM method are widely separated in wavelength and hence require accurate relative wavelength calibration across echelle orders. Transitions in different species also need not have the same velocity structure, unlike in the case of the AD method. The MM method also requires the use of large absorber samples to average out systematic effects because transitions from different species are likely to have different intrinsic redshifts. Some of these issues can be ameliorated by only using transitions from a single species (e.g. FeII; Levshakov et al. 2005; Molaro et al. 2008).

The first application of the MM method to Keck-HIRES spectra found weak evidence for redshift evolution in the fine structure constant (Webb et al. 1999). Increasing the size of the absorber sample led to statistically-significant evidence for a lower value in α at high redshifts, $[\Delta\alpha/\alpha] = [-5.4 \pm 1.2] \times 10^{-6}$ from 143 absorbers at an average redshift $\langle z \rangle = 1.75$, (Webb et al. 2001; Murphy et al. 2004). This result has not been confirmed by a slew of later studies, mostly based on application of the MM or similar methods [e.g. the single ion differential α measurement (SIDAM); Levshakov et al. 2005] to VLT-UVES spectra. For example, a combination of the SIDAM method with VLT-UVES data yielded $[\Delta\alpha/\alpha] = (+5.7 \pm 2.7) \times 10^{-6}$ at $z \sim 1.84$ and $[\Delta\alpha/\alpha] = (-0.12 \pm 1.79) \times 10^{-6}$ at $z \sim 1.15$ (Molaro et al. 2008). Similarly, Agafonova et al. (2011) obtained $[\Delta\alpha/\alpha] = (-1.5 \pm 2.6) \times 10^{-6}$ from an absorber at $z = 1.58$, comparing SiII and FeII lines from a VLT-UVES spectrum with improved wavelength calibration. Note that most of the VLT-UVES results probing changes in α in the literature are based on studies of individual absorbers (e.g. Quast, Reimers & Levshakov 2004; Levshakov et al. 2005, 2006; Molaro et al. 2008; Agafonova et al. 2011). While Srianand et al. (2007) present results from a re-analysis of their VLT-UVES sample of 23 absorbers (correcting for a critical error in their original minimization procedure, pointed out by Murphy, Webb & Flambaum 2008), they exclude, without justification, two systems that show statistically-significant values of $[\Delta\alpha/\alpha]$ from their final result. Finally, the MM method has very recently been applied to a VLT-UVES sample of comparable size (154 absorbers towards 60 quasars) to the Keck-HIRES sample (Webb et al. 2011; King et al. 2012). These authors obtain $[\Delta\alpha/\alpha] = (+2.1 \pm 1.2) \times 10^{-6}$, 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 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 well fit by a spatial dipole.

Murphy et al. (2001a) and Murphy, Webb & Flambaum (2003) provide excellent discussions of the systematic effects inherent in the MM and AD methods; they find no evidence that their Keck-HIRES result from the MM method might be affected by such systematics [although see Bahcall et al. (2004) and Molaro et al. (2008)]. The possibility that the relative abundances of the isotopes of various species might change with redshift is perhaps the most important among the various systematic effects. This is because the transitions from different isotopes are blended for most species (especially Mg), and most analyses assume terrestrial isotopic abundances in order to determine the central line wavelength (Ashenfelter, Mathews & Olive 2004). In the case of Mg, higher fractional abundances of ^{25,26}Mg relative to ^{24}Mg in the $z < 1.8$ sample of Murphy et al. (2004) could yield the negative $[\Delta\alpha/\alpha]$ obtained by these authors (Ashenfelter

et al. 2004). In fact, it has been argued that the absorber sample containing MgII lines dominates the results of Murphy et al. (2004): the sub-sample with MgII lines yields a β-trimmed mean of $[\Delta\alpha/\alpha] = (-4.8 \pm 1.2) \times 10^{-6}$, while the sub-sample that excludes these transitions gives $[\Delta\alpha/\alpha] = (-1.1 \pm 1.7) \times 10^{-6}$ (Molaro et al. 2008). Recently, Agafonova et al. (2011) used a high-resolution VLT-UVES spectrum of an absorber at $z \sim 1.58$ to show that the heavy isotopes of Mg are indeed over-abundant relative to ^{24}Mg, by a factor of ≈ 10 compared to the solar abundance. Note, further, that only a few of the transitions used in the MM analysis have accurate laboratory measurements of the wavelengths of the different isotopic transitions. The low spectral resolution ($\gtrsim 5$ km/s) of current optical spectra makes it difficult to resolve this issue by direct observation, while indirect arguments depend on the details of models of galactic chemical evolution and are not very reliable (e.g. Ashenfelter et al. 2004; Fenner, Murphy & Gibson 2005).

An important source of systematic error affecting data from echelle spectrographs like Keck-HIRES and VLT-UVES was recently discovered by Griest et al. (2010) (see also Whitmore et al. 2010). Griest et al. (2010) placed an iodine cell in the Keck-HIRES light path, targetting an extremely bright quasar PHL957 to compensate for the loss of sensitivity due to the extra iodine absorption. This allowed them to derive absolute wavelength calibration solutions over the wavelength range ~ 5000Å -6200Å, and to then compare these to solutions derived from the standard ThAr calibration. Systematic intra-order errors were found in the ThAr wavelength calibration solutions, with peak errors of ~ 1 km/s near the order centres, decreasing to ~ 0.5 km/s at the order edges. The ThAr solutions were also found to drift with time, with offsets of ~ 0.5 km/s within a single night and ~ 2 km/s across multiple nights (Griest et al. 2010). Similar offsets, albeit of slightly lower peak amplitude (~ 0.2 km/s) were found by Whitmore et al. (2010) for VLT-UVES, again using an iodine cell, and by Centurion, Molaro & Levshakov (2009), using multiple FeII lines from a single absorber. The origin of these intra-order distortions is still unknown but it is clear that they are a serious problem for all optical methods based on echelle spectra, as they would give rise to velocity offsets between different transitions. Perhaps it should be emphasized that the Keck-HIRES signal $[\Delta\alpha/\alpha] = (-5.4 \pm 1.2) \times 10^{-6}$ of Murphy et al. (2004) corresponds to a velocity difference $\Delta V = 134$ m/s, significantly smaller than the above errors. Note that Murphy, Webb & Flambaum (2009) argue that the distortions should average out for large absorber and line samples. They attempted to model the distortions of Griest et al. (2010) with a saw-tooth model, extrapolating to wavelengths not covered by the iodine cell calibration, and found no significant effect of the distortions on the $[\Delta\alpha/\alpha]$ values obtained from individual absorbers. However, it is not clear that a simple saw-tooth model is a valid representation of the distortions, especially given that we do not understand either their origin or their dependence on physical conditions during the observations.

In passing, I note that the results of Webb et al. (2011) are also affected by the above wavelength calibration issues. Seven systems of their sample were observed with both Keck-HIRES and VLT-UVES, allowing a direct comparison between the wavelength scales of the two spectrographs. The velocity differences between the two wavelength scales could be modelled as a linear function of wavelength for six of the seven systems; applying this function to either the Keck-HIRES or the VLT-UVES dataset reduced the statistical significance of the spatial dipole from 4.1σ to 3.1σ (Webb et al. 2011). To make matters worse, more complex wavelength calibration

problems were found in the seventh system; the use of a non-linear transformation to model these effects caused the statistical significance of the result to further reduce to 2.2σ. While Webb et al. (2011) argue that this is an over-estimate of the systematic errors, it is clear that at least some of their spectra are affected by wavelength calibration uncertainties that are not at all well understood. It thus appears reasonable at present to be sceptical of the claimed detection of a spatial dipole.

3.3 Molecular hydrogen lines

The most abundant molecule in the Universe, molecular hydrogen (H_2), has numerous UV rovibrational 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. Deep VLT-UVES surveys have yielded about a dozen redshifted H_2 absorbers, mostly in high-z damped Lyman-α systems (e.g. Ledoux, Petitjean & Srianand 2003; Noterdaeme et al. 2008). However, only four of these systems have so far yielded constraints on changes in μ, in some cases using a combination of H_2 and HD transitions (e.g. Varshalovich & Levshakov 1993; Cowie & Songaila 1995; Ubachs & Reinhold 2004; Reinhold et al. 2006; King et al. 2008; Thompson et al. 2009; Malec et al. 2010; Wendt & Molaro 2011; King et al. 2011; van Weerdenburg et al. 2011). For example, van Weerdenburg et al. (2011) obtained $[\Delta\mu/\mu] = (+8.5 \pm 4.2) \times 10^{-6}$ from a VLT-UVES spectrum of the $z = 2.059$ absorber towards J2123−0050, while Malec et al. (2010) used a Keck-HIRES spectrum of the same absorber to find $[\Delta\mu/\mu] = (+5.6 \pm 6.2) \times 10^{-6}$. 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 $[\Delta\mu/\mu] = (+3.6 \pm 1.9) \times 10^{-6}$. Note that all the results are based on a simultaneous fit to the H_2, HD and Lyman-α forest transitions, rather than excluding blends with interlopers from the Lyman-α forest (e.g. Reinhold et al. 2006; Thompson et al. 2009; Wendt & Molaro 2011). While this strategy allows the retention of a larger number of H_2 lines, the effect on the results is unclear. Attempts have also been made to model the intra-order distortions in the Keck-HIRES and VLT-UVES wavelength scales, albeit usually by simplistic schemes (e.g. Malec et al. 2010; van Weerdenburg et al. 2011; King et al. 2011). The distortions remain an important source of systematic error for the H_2 method (e.g. Wendt & Molaro 2011), especially because the H_2 lines are typically at the blue end of the spectrum, where there are fewer Th/Ar lines available for calibration.

4. Radio techniques

Radio spectral lines provide a wide range of methods to probe changes in α, μ, g_p, and combinations thereof. The variety of techniques in this band stems from the fact that radio lines arise

from a host of physical mechanisms (e.g. combinations of inversion, hyperfine structure, rotation, Lambda-doubling, etc) especially due to the large number of degrees of freedom present in complex molecules. Comparisons between the redshifts of different radio lines (or between radio and optical lines) are thus sensitive to changes in various combinations of α, μ and g_p. These methods are also affected by very different systematic effects from those that plague the optical regime. For example, the radio frequency scale can be calibrated to accuracies of $\lesssim 10$ m/s, due to the use of accurate masers and local oscillators. This section first discusses a "hybrid" method, based on comparing the redshifts of radio and optical lines, before describing techniques based entirely on radio spectroscopy.

4.1 Radio-optical comparisons

The rest frequencies of radio lines are, in general, proportional to $F(\alpha, \mu, g_p) \times R$, where F is some function of α, μ and g_p and R is the Rydberg constant. The functional form of F depends on the physics of the transition; for example, $F \equiv g_p\alpha^2/\mu$ for the HI 21cm transition. Conversely, UV dipole transitions have rest frequencies that are independent of α, μ and g_p to zeroth order, except for the dependence on α through the Rydberg constant. This implies that one can compare the redshifts of radio lines and UV resonance lines from a single absorber to probe changes in $F(\alpha, \mu, g_p)$. This was first done by Wolfe et al. (1976), who compared the HI 21cm and MgII absorption redshifts in a $z \sim 0.524$ absorber to constrain changes in the quantity $X \equiv g_p\alpha^2/\mu$. More recently, Tzanavaris et al. (2007) compared the redshifts of the HI 21cm line and low-ionization metal lines in a sample of nine redshifted HI 21cm absorbers at $0.23 < z < 2.35$ to obtain $[\Delta X/X] < 2 \times 10^{-5}$ [see also Srianand et al. (2010) for results from a system at $z \sim 3.174$]. The problem with such comparisons is that the optical and radio absorption can arise on slightly different sightlines, and the velocity structures of the different profiles are often very different. It is hence typically difficult to identify which spectral components should be compared in the optical and radio profiles. For example, Tzanavaris et al. (2007) chose to assume that the deepest HI 21cm and metal-line absorption components arise in the same gas, which is by no means necessary in the case of complex profiles (e.g. Kanekar et al. 2006).

Absorbers with a single dominant spectral component in both HI 21cm and UV resonance lines are best-suited for the comparison between optical resonance and radio hyperfine lines. Further, the best UV lines for this purpose are those arising from neutral atomic species like CI, MgI, etc, which are likely to be physically associated with the neutral hydrogen. The CI multiplets are the lines of choice, as the ionization potentials of CI and HI are similar, 11.3 eV and 13.6 eV, respectively, and CI absorption typically arises in the cold gas that also gives rise to HI 21cm absorption (e.g. Jenkins & Tripp 2001; Srianand et al. 2005). In contrast, MgI is much more common than CI in high-redshift absorbers, but has a lower ionization potential (7.6 eV), as well as a high dielectronic recombination rate that can yield strong MgI absorption in warm, ionized gas (Pettini et al. 1977). Unfortunately, CI and HI 21cm lines have both been detected in only three redshifted absorbers, and one of these systems, at $z \sim 1.776$ towards 1331+170, has a multi-component CI profile (Dessauges-Zavadsky et al. 2004). The remaining two absorbers have narrow single-component profiles in both the CI and HI 21cm lines and yield $[\Delta X/X] = [+6.8 \pm 1.0(stat.) \pm 6.7(syst.)] \times 10^{-6}$ at $\langle z \rangle = 1.46$, where $X \equiv g_p\alpha^2/\mu$ (Kanekar et al. 2010b).

This result is formally inconsistent with the Keck-HIRES MM result $[\Delta\alpha/\alpha] = (-5.4 \pm 1.2) \times 10^{-6}$ (Murphy et al. 2004), unless fractional changes in g_p are larger than those in α and μ (Kanekar et al. 2010b).

The CI-HI comparison requires accurate *absolute* wavelength calibration of the optical spectra, unlike the MM and AD methods, which only require accurate *relative* wavelength calibration. As such, the CI-HI method is far worse affected by optical wavelength calibration issues than the MM and AD methods. Conversely, the MM method is based on a first-order relativistic effect, as the multiplet line wavelengths have the same zeroth-order dependence on α; in contrast, the CI-HI comparison is based on the zeroth-order dependence of the resonance and hyperfine line frequencies on α, μ and g_p. Systematic effects are hence less important by an order of magnitude in the CI-HI comparison than in the MM analysis (Kanekar et al. 2010b).

4.2 Radio comparisons

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 for techniques that rely entirely on radio lines. Most such techniques 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, Rupen & Yanny 1993; Wiklind & Combes 1995, 1996a,b, 1997; Carilli et al. 1997; Chengalur, de Bruyn & Narasimha 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 $Y \equiv g_p \alpha^2$ (see also Drinkwater et al. 1998). On the other hand, 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 $few \times 10^{-3}$. Very recently, Kanekar et al. (2012) compared the redshifts of HI 21cm and OH 18cm lines from a gravitational lens at $z \sim 0.765$ to obtain $[\Delta Z/Z] = (-5.2 \pm 4.3) \times 10^{-6}$, where $Z \equiv g_p [\mu\alpha^2]^{1.57}$ and the errors are dominated by the assumed velocity dispersion of ~ 1.2 km/s between the OH and HI components. Using the fact that changes in μ have been strongly constrained at these redshifts ($[\Delta\mu/\mu] < 4 \times 10^{-7}$ from two methods; see below), and assuming changes in g_p to be much smaller than those in α, these authors then obtained $[\Delta\alpha/\alpha] = (-1.7 \pm 1.4) \times 10^{-6}$ between $z = 0$ and $z = 0.765$.

Similar radio methods, not all of which have been applied to astronomical data, include comparisons between CII-158μm and CO lines (Levshakov et al. 2008), between and among CH and OH lines (Chengalur & Kanekar 2003; Darling 2003; Kanekar & Chengalur 2004; Kozlov 2009), between inversion and rotational lines (discussed in detail below; Flambaum & Kozlov 2007), etc. 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. For example, a large velocity offset, $\sim$ 15 km/s, has been found between the HI 21cm and HCO^+ redshifts in the $z \sim 0.674$ absorber towards B1504+377, perhaps due to small-scale structure in the absorbing gas (Wiklind & Combes 1996a; Carilli et al. 1997; Kanekar & Chengalur 2008). Such local velocity offsets are especially important for comparisons based on small samples, where the offsets are unlikely to average out.

4.3 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. The line frequencies have a strong dependence on the tunneling probability, and thence, on the reduced mass of the molecule (van Veldhoven et al. 2004). Flambaum & Kozlov (2007) used this to demonstrate that a comparison between inversion and rotational line redshifts is extremely sensitive to changes in the proton-electron mass ratio 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 $z = 0.886$ system has a complicated line profile and current results are strongly limited by the quality of the NH_3 spectra. Menten et al. (2008) obtain $[\Delta\mu/\mu] < 3.8{\times}10^{-6}$ from this system by comparing the redshifts of NH_3 inversion and rotation lines (albeit at very different frequencies, $\sim$ 12 GHz and $\sim$ 303 GHz, respectively) while Henkel et al. (2009) find $[\Delta\mu/\mu] < 1.4 \times 10^{-6}$ (3σ confidence), comparing NH_3 inversion and HC_3N rotational lines at similar frequencies. Note that some of the NH_3 lines detected at $z = 0.886$ towards B1830−210 (notably the strongest 1-1, 2-2, and 3-3 transitions) are affected by satellite radio frequency interference, rendering their redshift estimates unreliable.

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. An estimate of the velocity dispersion in the absorbing clouds was obtained by comparing the CS and H_2CO line redshifts; these were found to agree within $\sim$ 68 m/s, far lower than the statistical errors in the comparison between NH_3 and CS lines. Unknown systematic effects include (1) changes in the morphology of the background source as a result of lensing, due to which the sightlines through the absorbing clouds might be different at different epochs, and (2) velocity offsets between nitrogen-bearing and carbon-bearing molecular species. Note that this is the most stringent constraint on fractional changes in any constant from any astronomical method.

4.4 Conjugate satellite OH lines

The OH rotational ground state is broken up into four sub-levels by Lambda-doubling and hyperfine splitting. The satellite OH 18cm lines arise due to transitions within the OH ground state that connect sub-levels with different total angular momenta ($\Delta F = \pm 1$). 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 conjugate satellite OH system is currently known, at $z \sim 0.247$ towards PKS 1413+135 (Kanekar et al. 2004; Darling 2004); a second system, at $z \sim 0.765$ towards PMN J0134−0931 (Kanekar et al. 2005), was recently shown to not be perfectly conjugate (Kanekar et al. 2012). The satellite OH 18cm lines of the $z \sim 0.247$ system have recently yielded tentative evidence of a change in one or more of α, μ and g_p: Kanekar, Chengalur & Ghosh (2010a) used deep Arecibo Telescope and Westerbork Synthesis Radio Telescope (WSRT) observations to obtain $[\Delta G/G] = (-1.18 \pm 0.46) \times 10^{-5}$ (weighted mean), where $G \equiv g_p \left[\mu\alpha^2\right]^{1.85}$, suggesting (at 99.1% confidence) smaller values of α, μ, and/or g_p at $z \sim 0.247$. Kanekar et al. (2010a) also applied the same technique to a nearby conjugate system, Cen.A (van Langevelde et al. 1995), and obtained the expected null result, $[\Delta G/G] < 1.16 \times 10^{-5}$ from $z \sim 0.0018$.

Conjugate satellite systems are ideal to probe changes in α, μ and g_p because the conjugate behaviour guarantees that the satellite OH 18cm lines arise from the same gas. This effectively rules out local velocity offsets as a source of systematic effects. Any measured difference between the line redshifts can only arise due to changes in one (or more) of α, μ and g_p (Kanekar et al. 2004). The technique also contains a stringent test of itself, in that the two line profiles must match within the noise if they arise in the same gas and if they are to be used to probe fundamental constant evolution. Further, the velocity offset between the lines can be simply determined from a cross-correlation analysis, as the line shapes are the same. It is not necessary to model the profiles with multiple Gaussian components, which can, especially for complex profiles, itself affect the result. Line interlopers are also unlikely to be a source of problems for this method, unlike the situation in the optical regime; the nearest isotopic OH transitions are more than 50 MHz away and this part of the radio spectrum has very few other known astronomical transitions. Overall, the conjugate-satellites method appears to be more free of systematic effects than other astronomical techniques. However, it should be noted that, unlike the MM, AD, and H_2 methods, the conjugate-satellites method cannot be used to directly measure changes in an individual constant, but is sensitive to changes in a combination of α, μ and g_p.

4.5 Methanol transitions

In methanol (CH_3OH), the internal rotation of OH relative to the methyl group is hindered by repulsion due to the torsional potential, with three potential wells. Tunneling through the different potential barriers gives rise to a multitude of microwave transitions, many of which have been detected in the interstellar medium (e.g. Batrla et al. 1987; Menten 1991). Jansen et al. (2011) found that the splitting between the different CH_3OH energy levels is highly sensitive to the reduced moment of inertia of the molecule; this implies that the different line frequencies have very different dependences on the proton-electron mass ratio μ (see also Levshakov, Kozlov & Reimers 2011). In principle, the CH_3OH lines could well prove to be the best tracers of changes in μ, because (1) their sensitivity to such changes is larger than that of NH_3 inversion lines and

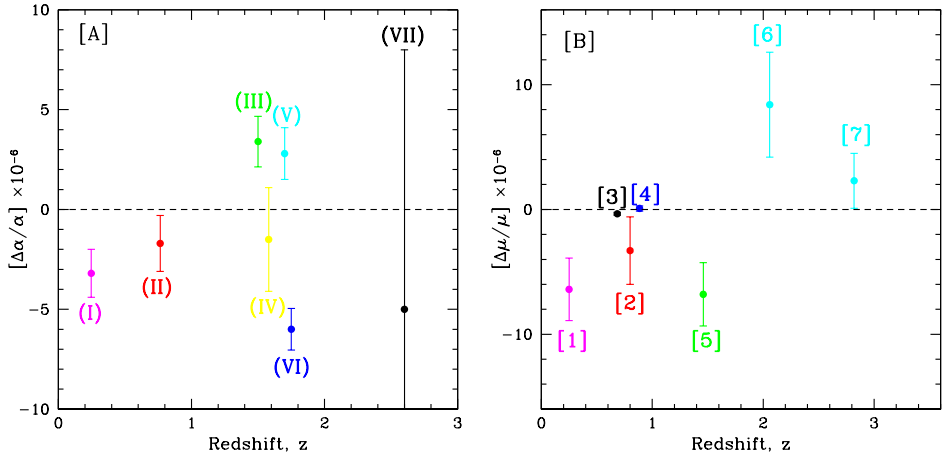

Figure 1. The state of the art in studies probing fundamental constant evolution with redshifted spectral lines. [A] Left panel: Estimates of $[\Delta\alpha/\alpha]$ plotted versus redshift, from [1] the conjugate satellite OH 18cm method (Kanekar et al. 2010a), [2] an HI 21cm-OH 18cm comparison (Kanekar et al. 2012), [3] resonance-hyperfine (CI-HI 21cm) comparisons (Kanekar et al. 2010b), [4] a single VLT-UVES MM absorber (Agafonova et al. 2011), [5] a large VLT-UVES MM sample (Webb et al. 2011), [6] a large Keck-HIRES MM sample (Murphy et al. 2004), and [7] an SiIV alkali-doublet sample (Murphy et al. 2001b). [B] Right panel: Estimates of $[\Delta\mu/\mu]$ plotted versus redshift, using comparisons between [1] conjugate satellite OH 18cm lines (Kanekar et al. 2010a), [2] HI 21cm and OH 18cm lines (Kanekar et al. 2012), [3] NH_3 and CS/H_2CO rotational lines (Kanekar 2011), [4] CH_3OH lines (Ellingsen et al. 2012), [5] HI 21cm and CI lines (Kanekar et al. 2010b), and H_2 lines ([6] van Weerdenburg et al. 2011 and [7] King et al. 2011). 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 results [1], [2] and [3] for $[\Delta\alpha/\alpha]$ and results [1], [2], and [5] for $[\Delta\mu/\mu]$.

(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 [although see Ellingsen, Voronkov & Breen (2011) for a contrary view]. So far, methanol has only been detected from a single cosmologically-distant system, the $z = 0.886$ lens towards B1830−210 (Muller et al. 2011; Ellingsen et al. 2012). Even these low-sensitivity CH_3OH detection spectra have already yielded the stringent constraint $[\Delta\mu/\mu] < 4.2 \times 10^{-7}$ on fractional changes in μ (Ellingsen et al. 2012).

5. The state of the art

Figure 1 summarizes the best present results on fundamental constant evolution from various radio and optical methods based on astronomical spectroscopy. It should be emphasized that the radio methods typically probe combinations of α, μ and g_p, which makes it difficult to compare results from different techniques without further assumptions. Following Kanekar (2008), the

figure uses two limiting cases, $[\Delta\alpha/\alpha] >> [\Delta\mu/\mu]$ and $[\Delta\alpha/\alpha] << [\Delta\mu/\mu]$, assuming that fractional changes in g_p are much smaller than those in α and μ (e.g. Langacker et al. 2002). The results shown are from the alkali-doublet, many-multiplet, CI-HI 21cm, HI 21cm-OH, inversion-rotation, conjugate-satellites, methanol and H_2 methods. It is clear from the figure that the best results from the conjugate-satellites, VLT-UVES MM, Keck-HIRES MM and HI 21cm-OH methods have similar sensitivities to changes in α, although at very different lookback times, and with different systematic effects, while the inversion-rotation and methanol techniques are the most sensitive to changes in μ. The Keck-HIRES MM result of Murphy et al. (2004) remains the only one showing statistically-significant evidence for changes in one of the constants.

The figure also emphasizes the fact that radio and optical techniques currently probe very different redshift ranges. The optical methods use UV transitions that only move into the optical waveband (say, $\gtrsim$ 3200Å) for absorbers beyond a certain redshift. For example, the H_2 technique can only be used on absorbers at $z \gtrsim 2$, the SiIV AD technique at $z \gtrsim 1.3$ and the SIDAM method (with the FeIIλ1608 line; Quast et al. 2004) at $z \gtrsim 1$. Similarly, only a handful of lines from singly-ionized species are redshifted above 3200Å from $z \lesssim 0.6$, implying that the MM method also works best at higher redshifts ($z \gtrsim 0.8$). On the other hand, the five known radio molecular absorbers are all at $z < 0.9$, which limits present application of the radio methods to low redshifts. Today's radio and optical studies thus provide complementary views on fundamental constant evolution, with the best high-z measurements based on optical techniques and the best low-z ones from the radio regime.

6. Future studies

The current limitations of optical and radio methods are very different in nature. The optical approaches are affected by line blending, relative wavelength calibration, unknown relative isotopic abundances at high redshifts, etc. All the optical methods use redshifted UV transitions, implying that one cannot obtain a measure of local systematic effects by applying the techniques to Galactic sightlines. Conversely, radio-based techniques are critically limited by the paucity of known HI 21cm and radio molecular absorbers at cosmological distances. Local velocity offsets are hence an important source of systematic effects in radio studies (except for the conjugate-satellites method and, possibly, the methods using CH_3OH lines).

Next generation optical and radio facilities will address many of the above issues in the coming decade. The new optical spectrographs mounted on 30-m class optical telescopes will yield higher sensitivity, improved spectral resolution (alleviating problems with line blends), and, critically, significantly better wavelength calibration schemes (e.g. via laser frequency combs, which are now being implemented in spectrographs on 2-m class telescopes; e.g. Steinmetz et al. 2008). The improved sensitivity and resolution should yield far more redshifted H_2 absorbers and alkali-doublet pairs suitable for studies of changes in μ and α. However, unresolved isotopic structure will continue to remain an issue even for advanced spectrographs like CODEX, with a resolution $R \sim 150000$ (e.g. Molaro, Murphy & Levshakov 2006). For example, the Mg isotopic transitions are separated by only ~ 0.85 km/s in MgIIλ2803 and ~ 0.4 km/s in MgIλ2853

(Murphy et al. 2001b), which would not be resolved even with CODEX. Laboratory or theoretical determinations of the isotopic structure of different species will be critical, to allow independent applications of the MM method or its variants to multiple species with different isotopic structures (e.g. Drullinger, Wineland & Bergquist 1980; Berengut, Flambaum & Kozlov 2006). Unknown relative isotopic abundances in high-z absorbers are likely to be remain an important source of systematic effects. If this issue can be overcome, it should be possible to achieve sensitivities of $[\Delta\alpha/\alpha] \sim 10^{-7}$ with the MM method. Extensions of the MM method akin to the SIDAM method are also likely to be of much interest, especially if these use species with widely separated isotopic transitions. For the H_2 method, higher-order corrections to the Born-Oppenheimer approximation will be necessary to reach sensitivities of $[\Delta\mu/\mu] \sim 10^{-7}$ (e.g. Reinhold et al. 2006). Accurate laboratory measurements of the wavelengths of both the H_2 lines and the UV transitions used in the MM and AD methods (some of which are only known to a fractional accuracy of $\sim 10^{-6}$; e.g. Aldenius 2009) will also be critical in achieving sensitivities of $[\Delta\alpha/\alpha]$, $[\Delta\mu/\mu] \sim 10^{-7}$. Unfortunately, it is unlikely to be possible to quantify systematic effects affecting these methods through Galactic studies, as this would require space-based ultraviolet spectroscopy.

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 that are now coming online. For example, the wide-band receivers and correlators of the Expanded Very Large Array (EVLA) and the Atacama Large Millimeter Array 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, which have not been possible so far, should yield large samples of high-z CO/HCO^+ absorbers, which can then be followed up in the OH, NH_3, and HI 21cm lines. The new EVLA 1.4 GHz receivers will allow similar "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 EVLA L-band continuum observation automatically yielding such an absorption survey towards all background sources in the field of view. Similar studies will be possible at higher redshifts with the new $500 - 900$ MHz receivers on the Giant Metrewave Radio Telescope. The new focal plane array receivers on the Australian SKA Pathfinder array (Johnston et al. 2007) and the WSRT (Verheijen et al. 2008) will allow blind surveys for redshifted HI 21cm absorption over large fields of view, yielding hundreds of new HI 21cm absorbers at $0 < z < 1$ over the next five years, in addition to new OH 18cm absorbers and conjugate-satellite OH systems. Deep (>> 100-hour) integrations with existing telescopes on the conjugate-satellite OH system at $z \sim 0.247$ towards PKS 1413+135 should achieve sensitivities of $[\Delta\alpha/\alpha], [\Delta\mu/\mu] \sim few \times 10^{-7}$, while sensitivities of $[\Delta\mu/\mu] \sim few \times 10^{-8}$ should be possible using the inversion-rotation and methanol methods on the lenses towards B0218+357 and B1830−210. Finally, while significant progress has been made over the last few years in finding new radio transitions and molecular species for use as probes of fundamental constant evolution (e.g. Flambaum & Kozlov 2007; Kozlov 2009; Jansen et al. 2011; Ilyushin et al. 2012), increasing the number of such species through detailed theoretical analysis of their molecular structure remains important, to both derive new techniques with independent systematic effects, and find spectral lines whose rest frequencies have strong dependences on different constants.

7. Summary

Optical and radio spectroscopic techniques have played complementary roles in searching for changes in the fundamental constants of physics on cosmological timescales. High redshifts, $z \sim 1-3$, have been the domain of optical methods, while the late-time behaviour, at $z \lesssim 0.9$, has been best studied with radio schemes. 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, with an improvement of nearly two orders of magnitude over the last decade. In the case of the fine structure constant α, the best techniques today have 1σ sensitivities of $\sim 10^{-6}$, at redshifts $0.25 \lesssim z \lesssim 2$, while, in the case of the proton-electron mass ratio, two methods have achieved 1σ sensitivities of $\sim 1-2\times10^{-7}$, at $z \sim 0.8$. At present, it appears fair to say that the Keck-HIRES MM result, $[\Delta\alpha/\alpha] = [-5.4 \pm 1.2] \times 10^{-6}$ at $\langle z \rangle = 1.75$, which suggests a smaller value of α at high redshifts (Murphy et al. 2004) has been neither contradicted nor confirmed by any other study. Recently, the conjugate-satellite OH method also found tentative evidence (with $\sim 2.6\sigma$ significance) for smaller values of α, μ and/or g_p at $z \sim 0.247$ (Kanekar et al. 2010a). It remains critically important to confirm or deny these results, with either observations at independent telescopes or independent techniques.

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 (in $[\Delta\alpha/\alpha]$) from the Oklo nuclear reactor, but via multiple techniques, probing a range of lookback times, and with fewer assumptions. The conjugate-satellite OH and methanol methods are likely to be the most reliable probes of fundamental constant evolution, unless the issue of unknown relative isotopic abundances in the MM method can be resolved. 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.

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