Stringent Constraints on Fundamental Constant Evolution Using Conjugate 18 cm Satellite OH Lines

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Stringent constraints on fundamental constant evolution using conjugate 18 cm satellite OH lines

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We have used the Arecibo Telescope to carry out one of the deepest-ever integrations in radio astronomy, targetting the redshifted conjugate satellite OH 18 cm lines at $z \approx 0.247$ towards PKS 1413+135. The satellite OH 1720 MHz and 1612 MHz lines are respectively in emission and absorption, with exactly the same line shapes due to population inversion in the OH ground state levels. Since the 1720 and 1612 MHz line rest frequencies have different dependences on the fine structure constant α and the proton-electron mass ratio μ, a comparison between their measured redshifts allows one to probe changes in α and μ with cosmological time. In the case of conjugate satellite OH 18 cm lines, the predicted perfect cancellation of the sum of the line optical depths provides a strong test for the presence of systematic effects that might limit their use in probing fundamental constant evolution. A non-parametric analysis of our new Arecibo data yields $[\Delta X/X] = (+0.97 \pm 1.52) \times 10^{-6}$, where $X \equiv \mu\alpha^2$. Combining this with our earlier results from the Arecibo Telescope and the Westerbork Synthesis Radio Telescope, we 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.

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Introduction.— Over the last two decades, astronomical spectroscopy of high-redshift galaxies has provided the most sensitive probe of changes in fundamental "constants", such as the fine structure constant α and the proton-electron mass ratio $\mu \equiv m_p/m_e$, with cosmological time. Such temporal changes in low-energy constants like α and μ are a generic feature of higher-dimensional theories aiming to unify general relativity and the standard model of particle physics (e.g. [1, 2]), and are hence of much interest. The astronomical studies are of particular importance as they allow us to test for changes in the constants on Gyr timescales, which are typically inaccessible to laboratory studies (e.g. [3]).

The above astronomical techniques are based on comparisons between the measured redshifts of different spectral lines in high-redshift galaxies, using transitions whose rest frequencies have different (and known) dependences on a given constant. At radio frequencies, a variety of methods, based on various atomic and molecular lines [4–7], have been used to probe temporal changes in α and μ. For example, comparisons between inversion and rotational transitions in the $z = 0.685$ gravitational lens towards B0218+357 and between different methanol (CH_3OH) transitions in the $z = 0.886$ lens towards B1830−21 have yielded the most stringent constraints on changes in μ from any technique, $[\Delta\mu/\mu] < 4 \times 10^{-7}$ [8–10]. Comparisons between the hydroxyl (OH) and HI 21 cm lines in the $z = 0.765$ lens towards PMN J0134−0931 have yielded stringent constraints on changes in both α and μ [11, 12]. And a comparison between the the redshifts of "conjugate satellite" hydroxyl (OH) 18 cm lines from the $z = 0.247$ system towards PKS1413+135 has yielded tentative evidence (at $\approx 2.6\sigma$ significance) for changes in α and/or μ with cosmological time [13].

Amongst the various astronomical methods to probe fundamental constant evolution, techniques based on comparisons between multiple spectral lines of a single species (e.g. CH_3OH, OH, etc) are the least prone to systematic effects. An interesting situation arises in the case of the satellite OH 18 cm lines, which are "conjugate" under certain astrophysical conditions, i.e. have the same shape but opposite sign, with one line in emission and the other in absorption, such that the sum of the two optical depths exactly cancels out [14–16]. This arises due to population inversion in the ground state of the OH radical, due to quantum mechanical selection rules (when the infrared OH rotational lines that connect the OH ground state to the lower excited states are optically thick; [14]). Redshifted conjugate satellite OH lines provide an excellent probe of fundamental constant evolution, as the two satellite OH line frequencies have different dependences on α and μ [5, 16] and the conjugate behaviour guarantees that the lines arise from the same gas. If either α or μ were to change with cosmological time, the satellite line shapes should remain the same but the two lines would be offset from each other in velocity space. Conversely, any local systematic effects that might give rise to velocity offsets between the lines would also be expected to change the line shapes. This implies that the sum of the satellite optical depths would not cancel perfectly in the presence of such systematic effects (i.e. the lines would not remain "conjugate"). The cancellation of the sum of the satellite OH 18 cm optical depths, along with a velocity offset between the two lines, is thus a signature of changes in α and/or μ.

At present, the sole perfectly conjugate satellite OH 18 cm system known at cosmological distances is the $z = 0.247$ absorber-emitter towards PKS 1413+135 [16]. Our earlier deep Westerbork Synthesis Radio Telescope (WSRT) and Arecibo Telescope observations of this system [13] yielded tentative evidence, at 2.6σ significance, of a velocity offset between the two OH lines, but with the same line shapes, the signature expected from fundamental constant evolution. We report here further observations of this system, yielding one of the deepest-ever Arecibo Telescope integrations, that allow us to probe changes in $G \equiv \mu\alpha^2$ over a lookback time of 2.9 Gyr.

Spectra and results.— The Arecibo Telescope was used to carry out a 125-hour integration on the satellite OH 18 cm lines of PKS 1413+135 between April 2010 and June 2012. The observations were carried out in double-position-switched mode [17], with five-minute On and Off scans on PKS 1413+135 followed by two-minute On and Off scans on a nearby bandpass calibrator, PKS 1345+125. The 1720 MHz and 1612 MHz lines were observed simultaneously on all runs, using the WAPP backends, with bandwidths of 1.5625 MHz sub-divided into 4096 channels and centred on the redshifted satellite line frequencies. This yielded a velocity resolution of ≈ 0.18 km/s after Hanning smoothing and re-sampling. System temperatures were measured using a noise diode.

The initial data analysis was carried out in IDL, using standard procedures to produce calibrated spectra for the individual double-position-switched scans. Each 5-minute source spectrum was then visually inspected for the presence of any systematic effects (e.g. radio frequency interference, complex spectral baselines, etc); all spectra showing such effects were excluded from the analysis. Each 5-minute spectrum was then subjected to both the Kolmogorov-Smirnov and Anderson-Darling tests, to test for gaussianity; spectra failing these tests were also excluded. The above procedure was carried out for the two satellite spectra independently; any 5-minute spectrum excluded for one line was also excluded for the other, to ensure that the final spectra for the two lines are based on simultaneous data and hence, that line variability is not an issue. After all data editing (which excised $\lesssim 10\%$ of the data), each 5-minute spectrum was shifted to the heliocentric frame. The spectra were then converted to optical depth units, and finally averaged together for each line. For the 1720 MHz spectra, the weights for the averaging were determined from the measured root-mean-square (RMS) noise values; the same weights were used when averaging the 1612 MHz spectra, to ensure simultaneity of the final satellite OH 18 cm spectra.

The top and bottom panels of Fig. 1[A] show our final Arecibo Telescope satellite OH 18 cm optical depth spectra, with optical depth plotted versus velocity, in the heliocentric frame, in km s^{-1}, relative to $z = 0.24671$. The spectra have RMS optical depth noise values of 3.6×10^{-4} (1612 MHz) and 3.1×10^{-4} (1720 MHz), per ≈ 0.18 km s^{-1} channel. The Anderson-Darling test finds that the off-line regions of both spectra are consistent with arising from Gaussian noise; there is no evidence for systematic structure in either spectral baseline. Fig. 1[B] shows the sum of the 1612 and 1720 MHz optical depth profiles, again plotted against heliocentric velocity, in km s^{-1}, relative to $z = 0.24671$. The RMS noise on the summed spectrum is 5.1×10^{-4} per 0.18 km/s channel, consistent with the RMS noise values on the individual satellite spectra. The summed spectrum shows no evidence for non-Gaussian structure: both the Kolmogorov-Smirnov rank-1 test and Anderson-Darling test find that the summed spectrum is consistent with being drawn from a normal distribution. We thus find that the satellite OH 18 cm lines remain conjugate at the signal-to-noise ratio of our new Arecibo Telescope observations.

Most astronomical techniques probing fundamental constant evolution are based on the modelling of the line profiles as the sum of Gaussians or Voigt profiles. Multi-component fits are used to estimate the redshifts of the individual spectral components (e.g. [12, 18–20]). For complex profiles, this process of fitting multiple spectral components can itself affect the results (e.g. due to under-fitting or over-fitting the line profile). However, in the case of conjugate satellite OH 18 cm lines, the maser mechanism that gives rise to the conjugate behaviour guarantees that the lines have exactly the same shape. This implies that a non-parametric technique, based on cross-correlation of the two spectra, can be used to measure the redshift difference between the lines, and, hence, to probe changes in α and μ [13]. Specifically, the velocity offset from zero of the peak of the cross-correlation of the two OH lines directly yields the redshift difference between the lines. The fact that the cross-correlation technique is non-parametric and hence not susceptible to errors regarding the decomposition of a line into multiple spectral components is an important advantage of conjugate satellite OH lines over other approaches (e.g. the many-multiplet method; [21, 22]) in probing fundamental constant evolution.

We used the velocity range -20 km s^{-1} to $+2.6$ km s^{-1} (indicated by the dashed vertical lines in Fig. 1[B]), enclosing the strongest spectral line feature, for the cross-correlation; this was done in order to maximize the signal-to-noise ratio. The offset of the peak of the cross-correlation from zero velocity was measured via a Gaussian fit. Very similar results were obtained on using other functional forms (e.g. a parabolic form) for the cross-correlation as well as other non-parametric methods (e.g. the sliding distance method [23]). The RMS noise on the cross-correlation was obtained via a Monte Carlo approach, in which we cross-correlated 10^4 pairs of simulated satellite OH 18 cm spectra. The simulated spectra were obtained by adding Gaussian random noise (characterized by the RMS noise values on the observed spectra) to the best 4-component Gaussian fits to the 1720 MHz and 1612 MHz spectra. Note that the Gaussian fits were only used to obtain templates for the two spectra, and do not affect the results in any way. We find that the cross-correlation of the two satellite OH 18 cm lines peaks at a velocity offset of $\Delta V_{\rm new} = (+35.0 \pm 56.5)$ m/s (all quoted errors are at 1σ significance), with the 1720 MHz line at a lower velocity (i.e. at a lower redshift). Our present Arecibo observations thus find no evidence of a statistically significant velocity offset between the 1612 MHz and 1720 MHz spectra. Using equation (13) of Chengalur and Kanekar [5] then yields $[\Delta X/X] = (+0.97 \pm 1.52) \times 10^{-6}$, where $X \equiv \mu\alpha^2$.

Our earlier WSRT and Arecibo studies of the OH 18 cm lines from PKS 1413+135, carried out between 2006 and 2008, yielded a net velocity offset of $\Delta V_{\rm old} = (-230 \pm 90)$ m/s between the two satellite lines [13], yielding

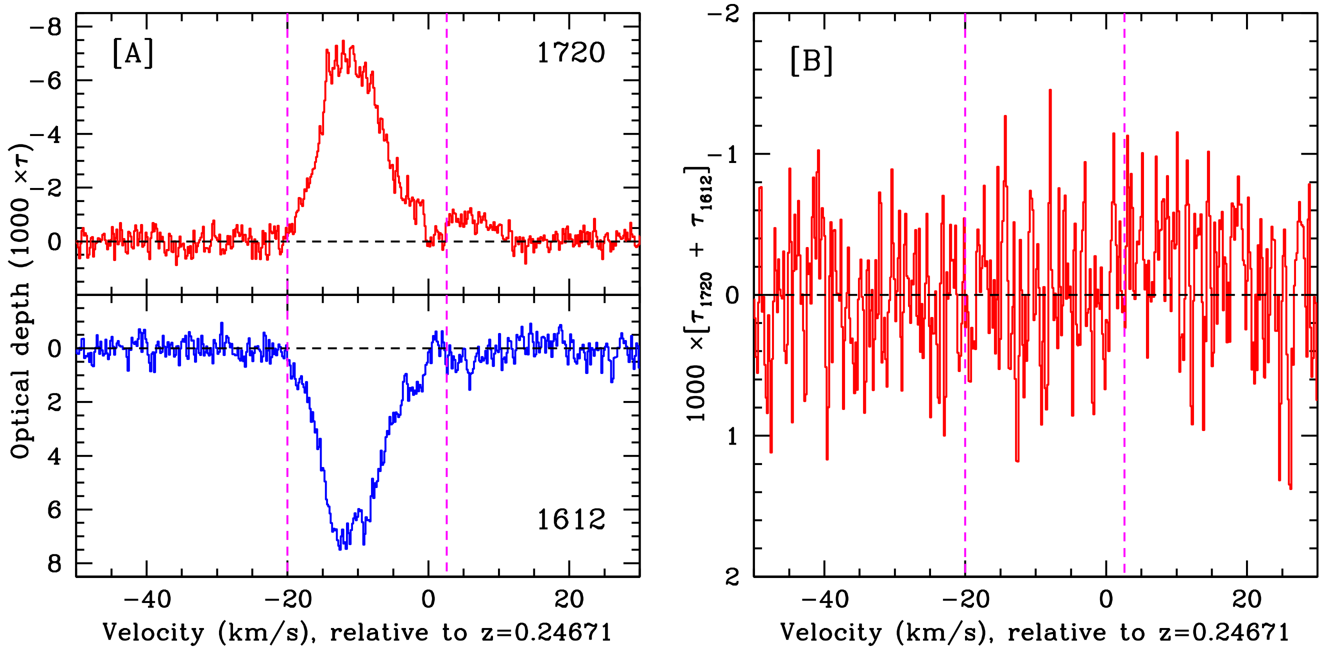

FIG. 1: [A] (left panel) Arecibo Telescope satellite OH 18 cm spectra towards PKS 1413+135, with optical depth ($1000 \times \tau$) plotted against heliocentric velocity, in km/s, relative to $z = 0.24671$. [B] (right panel) The sum of the 1612 and 1720 MHz optical depth spectra; this is seen to be consistent with noise. In both figures, the dashed vertical lines indicate the velocity range that was used for the cross-correlation analysis.

$[\Delta X/X] = (-6.3 \pm 2.5) \times 10^{-6}$. Combining the old and the new results for $[\Delta X/X]$, with appropriate weights based on the RMS noise values, our final result is $[\Delta X/X] = (-1.0 \pm 1.3) \times 10^{-6}$. We thus find no statistically significant evidence for changes in $X \equiv \mu\alpha^2$ over a lookback time of 2.9 Gyr.

Systematic effects.— Systematic effects in the conjugate satellite OH method that might contribute to increased errors, over and above those determined from the cross-correlation analysis, are discussed in detail in [13]. The systematics fall in two broad categories, those arising from observational issues [e.g. doppler tracking, frequency calibration, errors in the laboratory frequencies, radio frequency interference (RFI), etc] and astronomical issues (e.g. different intrinsic shapes of the two satellite OH lines, interloping lines from other transitions, etc). Errors arising from the above observational systematics are small compared to our measurement errors. Specifically, doppler corrections for Earth motion were carried out offline, using a model of Earth motion accurate to < 15 m/s, a factor of four smaller than our measurement error. The Arecibo Telescope frequency scale is set by the accuracy of masers and local oscillators (1 Hz), more than two orders of magnitude smaller than the measurement error. The satellite OH line frequencies have been measured in the laboratory with an accuracy of ≈ 15 Hz [24], more than an order of magnitude smaller than our measurement error. Finally, detailed statistical tests for non-Gaussian behaviour that might arise from RFI were carried out on both the individual 5-m spectra and the final averaged satellite OH spectra, and only spectra that passed these stringent tests were retained in the analysis. The fact that the satellite OH lines remain conjugate, with the sum of the two optical depth spectra consistent with random noise, indicates that RFI is not an important issue for these data.

Considering the second category, astronomical effects, Kanekar et al. [13] note that there is no possibility of line interlopers from other spectral transitions, either from the Milky Way or galaxies at different redshifts along the line of sight to PKS 1413+135, or from other molecular or atomic lines from PKS 1413+135 itself. And, as in the case of RFI, the strongest argument against the possibility of different intrinsic structure in the two satellite OH line profiles (or line interlopers) is the fact that the sum of the optical depth spectra is consistent with Gaussian noise, exactly as predicted by the maser mechanism for conjugate behaviour. This provides a stringent test for the use of the conjugate satellite OH lines to probe fundamental constant evolution: the satellite OH lines of PKS 1413+135 pass this test at our current sensitivity. Finally, an important test of the use of any technique to probe temporal evolution in the fundamental constants is that the same technique yield a null result in the local Universe. For the conjugate satellite OH technique, the expected null result was indeed obtained by Kanekar et al. [13] for the nearby conjugate satellite OH system in Cen.A (whose OH lines were observed with the Australia Telescope Compact Array; [15]), at a sensitivity similar to that of the present Arecibo Telescope spectra. Overall, we find no evidence that our result might be affected by systematic effects, related to either observational or astronomical issues.

Discussion— A wide variety of techniques, at optical and radio wavelengths, have been used to probe the possibility of temporal changes in α and μ, or combinations of these quantities. In the optical regime, using echelle spectrographs on 10m-class optical telescopes, the many-multiplet method [21], based on rest-frame ultraviolet spectral lines, has yielded the highest sensitivity to changes in α out to relatively high redshifts, $z \approx 3$ (e.g. [20, 22, 25–28]). The most sensitive results have *statistical errors* of $[\Delta\alpha/\alpha] \approx (1-2) \times 10^{-6}$, either based on individual systems (e.g. [28, 29]) or large absorption samples (e.g. [22, 25]). Conversely, redshifted ultraviolet ro-vibrational molecular hydrogen (H_2) lines have yielded the highest sensitivity to changes in μ, again out to $z \approx 3$ (e.g. [30–33]). The most sensitive of the results here have yielded statistical errors of $[\Delta\mu/\mu] \approx 2 \times 10^{-6}$ (e.g. [34]).

Unfortunately, while the above optical results have low *statistical* errors, it has recently become clear that most of these studies are afflicted by *systematic* errors (e.g. [35–37]). The problem here has to do with the wavelength calibration of the optical echelle spectrographs, mostly the Keck Telescope High Resolution Echelle Spectrograph (HiRES) and the Very Large Telescope (VLT) UltraViolet Echelle Spectrograph (UVES), that were used for the optical observations. As noted in [20, 37], *all* $[\Delta\alpha/\alpha]$ (and $[\Delta\mu/\mu]$) results derived from Keck-HIRES and VLT-UVES spectroscopy until 2014 are likely to be affected by systematic errors due to long-range distortions in the wavelength calibration. These distortions are still not understood and it is not possible in most cases to retrospectively correct the earlier spectra [20]. Recently, the many-multiplet method has been used with "super-calibration" techniques or comparisons between very nearby lines to reduce the effects of the above long-range distortions (e.g. [20, 27, 38]). For example, a comparison between ZnII and CrII lines in Keck-HIRES and VLT-UVES spectra of nine absorbers yielded $[\Delta\alpha/\alpha] = [+1.15 \pm 1.67(stat.) \pm 0.87(sys.)] \times 10^{-6}$ [20]. In another study, the long-range distortions in multiple VLT-UVES spectra of a single bright quasar (taken over a ten-year period) were corrected using high-accuracy spectra from the HARPS spectrograph. The many-multiplet method was then applied to these spectra, to obtain a high sensitivity to changes in α, $[\Delta\alpha/\alpha] = [-1.42 \pm 0.55(stat.) \pm 0.65(syst.)] \times 10^{-6}$ [28].

At radio wavelengths, the CH_3OH and NH_3 techniques have yielded stringent constraints on changes in μ, with $[\Delta\mu/\mu] \lesssim 4 \times 10^{-7}$ from individual absorbers at intermediate redshifts, $z \approx 0.685$ (NH_3; [8]) and $z \approx 0.886$ (CH_3OH; [10]). The CH_3OH technique is perhaps the most interesting of these radio methods as it yields both high sensitivity and a good control of systematic effects, as thermally-excited and optically-thin spectral transitions of a single molecule are used in the analysis, and one can test that the different lines have the expected ratios in thermal equilibrium [10].

In the case of the conjugate satellite OH lines, the technique is sensitive to changes in $X \equiv \mu\alpha^2$, and does not provide constraints on changes in the individual constants, without further assumptions. Our result implies $2.0\,[\Delta\alpha/\alpha] + [\Delta\mu/\mu] = (-1.0 \pm 1.3) \times 10^{-6}$ over $0 < z < 0.247$. This implies 1σ sensitivities of $[\Delta\alpha/\alpha] = 0.65 \times 10^{-6}$ (if we assume $[\Delta\mu/\mu] = 0$) and $[\Delta\mu/\mu] = 1.3 \times 10^{-6}$ (if we assume that $[\Delta\alpha/\alpha] = 0$). The crucial advantage of this method is that it allows one to directly test whether it can be applied at all, via the prediction that the two satellite OH lines must have the same shapes, with opposite signs. Like the CH_3OH method discussed above, this technique allows one to measure changes in the constants from a single space-time location, without the need to average over multiple absorbers (as would be required in most other techniques to overcome possible local velocity offsets between the gas clouds giving rise to the different lines). These two techniques are hence especially interesting to probe the possibility of space-time variation in α and μ.

Our results are based on one of the deepest-ever observations with the Arecibo Telescope, which has the largest collecting area and sensitivity of today's radio telescopes. However, new radio telescopes [e.g. the Five-Hundred-Metre Aperture Spherical Telescope (FAST) and the Square Kilometre Array (SKA)] are now being built or planned that will have even higher sensitivity than the Arecibo Telescope; these will allow both higher sensitivity on known conjugate satellite OH 18 cm systems like PKS 1413+135, and searches for new conjugate satellite systems at high redshifts. Modern high-frequency radio telescopes like the Very Large Array should allow an improvement in sensitivity to fractional changes in μ by more than an order of magnitude, using the NH_3 and CH_3OH lines. Finally, the combination of high sensitivity and new wavelength calibration schemes on next-generation large optical telescopes (e.g. the Thirty Meter Telescope, the Giant Magellan Telescope and the European Extremely Large Telescope) should also allow improvements in the sensitivity to fractional changes in α and μ by $1-2$ orders of magnitude via the many-multiplet method and ro-vibrational H_2 lines.

In summary, we have carried out an ultra-deep Arecibo Telescope observation of the OH 18 cm satellite lines from PKS 1413+135 at $z \approx 0.247$. We find that the satellite OH lines are conjugate within our measurement errors, with the 1720 MHz line in emission, the 1612 MHz line in absorption, and the sum of the two optical depth spectra consistent with Gaussian noise. We used a non-parametric technique, based on cross-correlation, to test for a velocity offset between the two OH lines, that might arise due to changes in α and/or μ. The cross-correlation analysis finds that the velocity offset between the lines is $\Delta V_{\rm new} = (+35.0 \pm 56.5)\,\mathrm{m\,s^{-1}}$, consistent with the null hypothesis of zero velocity offset between the OH 1612 MHz and 1720 MHz lines. This implies $[\Delta X/X] = (+0.97 \pm 1.52) \times 10^{-6}$, where $X \equiv \mu\alpha^2$. Combining this with the results from our earlier Arecibo/WSRT analysis yields our final result, $[\Delta X/X] = (-1.0 \pm 1.3) \times 10^{-6}$ over $0 < z < 0.247$, consistent with no change in $\mu\alpha^2$ over a lookback time of ≈ 2.9 Gyr.

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