Conjugate 18cm OH Satellite Lines at a Cosmological Distance

Nissim Kanekar
Kapteyn Astronomical Institute, University of Groningen, The Netherlands,

Jayaram N. Chengalur
National Centre for Radio Astrophysics, Pune 411 007, India

Tapasi Ghosh
Arecibo Observatory, Arecibo, PR 00612, USA

(Dated: March 20, 2022)

We have detected the two 18cm OH satellite lines from the $z \sim 0.247$ source PKS1413+135, the 1720 MHz line in emission and the 1612 MHz line in absorption. The 1720 MHz luminosity is $L_{\text{OH}} \sim 354 L_\odot$, more than an order of magnitude larger than that of any other known 1720 MHz maser. The profiles of the two satellite lines are conjugate, implying that they arise in the same gas. This allows us to test for any changes in the values of fundamental constants, without being affected by systematic uncertainties arising from relative motions between the gas clouds in which the different lines arise. Our data constrain changes in $G \equiv g_p/\alpha [\bar{\alpha}/\bar{\alpha}]^{1.849}$, where $y \equiv m_e/m_p$; we find $\Delta G/G = 2.2 \pm 3.8 \times 10^{-5}$, consistent with no changes in $\alpha$, $g_p$ and $y$.

PACS numbers: 98.80.Ex,06.20.Jr,33.20.Bx,98.58.-w

INTRODUCTION

In recent times, much interest has centred on the possibility that fundamental “constants” such as the fine structure constant $\alpha$ might vary with cosmic time (e.g. [1, 2, 3]). Many theoretical models, including Kaluza-Klein theories and superstring theories, predict spatio-temporal variation of these constants. However, terrestrial experiments have so far shown no evidence for such changes. For example, the strongest presently available constraints on changes in $\alpha$ arise from isotopic abundances measured in the Oklo natural fission reactor, which give the constraint $\Delta \alpha/\alpha < 1.2 \times 10^{-7}$ on fractional changes in the fine structure constant $\alpha$. Uzan [4] provides an excellent review of current experimental and observational constraints on changes in $\alpha$ and other fundamental constants.

While terrestrial studies such as the Oklo experiment have a high sensitivity, these measurements only probe a small fraction of the age of the Universe. For example, the Oklo reactor operated about 1.8 Gyr ago, less than a sixth of the age of the Universe [5]. Thus, current terrestrial experiments cannot rule out earlier changes in the fundamental constants, quite possible if these changes are non-monotonic in nature.

Astrophysical studies of redshifted spectral lines provide a powerful probe of putative changes in fundamental constants over large fractions of the age of the Universe (e.g. [6, 7, 8, 9]). Perhaps the most interesting of these estimates arise from the new “many-multiplet” method [1, 4], which has been used in conjunction with Keck telescope spectra to obtain $\Delta \alpha/\alpha = (-0.54 \pm 0.12) \times 10^{-5}$ over the redshift range $0.2 < z < 3.7$ [9] (see, however, [10]). On the other hand, the many-multiplet method was recently applied to Very Large Telescope (VLT) data to obtain $\Delta \alpha/\alpha = (-0.6 \pm 0.5) \times 10^{-6}$ over the redshift range $0.4 < z < 2.3$ [3], in direct conflict with the Keck results. Further, many theoretical analyses predict that changes in $\alpha$ should be accompanied by much larger changes in other constants, such as the ratio of electron mass to proton mass $m_e/m_p$ (e.g. [11, 12]). However, fractional changes in $m_e/m_p$ have been found to be less than $(-0.5 \pm 3.6) \times 10^{-5}$ over a similar redshift range ($0 < z < 2.75$) [13].

Given the importance of changes in fundamental constants for theoretical physics, it is important that this be tested by independent techniques. This is especially true since the same technique (i.e. the many-multiplet method) has yielded strongly divergent results when applied to data from different telescopes, suggesting that systematic errors play a significant role (e.g. [14]). We have recently [7] developed a new technique to simultaneously constrain changes in $\alpha$, the ratio of electron mass to proton mass $y \equiv m_e/m_p$, and the proton gyromagnetic ratio $g_p$, using the multiple 18cm OH lines. This makes use of the fact that these lines arise from two very different physical mechanisms, Lambda-doubling and hyperfine splitting [15], and thus have very different dependences on $\alpha$, $y$, and $g_p$. If $g_p$ is assumed to remain unchanged (e.g. [2, 3]), observations of all four OH 18cm transitions in a single cosmologically distant galaxy can be used to simultaneously estimate any changes in $y$ and $\alpha$. Further, since these lines arise from the same species, a comparison of the OH column density obtained from each line can be used to test whether the lines arise from the same gas. This is often an issue in other techniques, since lines from different species are used in the comparison, giving rise to systematic uncertainties arising from the possibility of relative motions between the gas clouds in which the different lines arise.

Only the “main” 18cm OH lines (at frequencies of ~ 1667 and 1665 MHz) have hitherto been detected at cosmological distances [12, 13, 14]; the satellite lines (at ~ 1612 and 1720 MHz), which are critical to the above test, have not been found until now. We report here the first detection of the satellite OH lines at cosmologically significant distances, from the
z \approx 0.247 \text{ source PKS1413+135.}

**SPECTRA AND RESULTS**

Spectra of the redshifted OH 1612 and 1720 MHz lines from PKS1413+135 were obtained with the Westerbork Synthesis Radio Telescope (WSRT) in June 2003, while the 1665 and 1677 MHz transitions were observed with the Giant Metrewave Radio Telescope (GMRT) in October 2001. The top three panels of Fig. 1 show the 1720, 1612 and 1667 MHz spectra, respectively, while the bottom panel shows the sum of the 1612 and 1720 MHz optical depth profiles; the velocity resolution is \sim 1.1 \text{ km/s} for the satellite lines and \sim 3.5 \text{ km/s} for the 1677 MHz line. Note that PKS1413+135 is unresolved by the GMRT and WSRT beams; the optical depths plotted here are the ratio of line depth to the total flux density for the different transitions. The RMS noise in each of the satellite spectra is \sim 0.002 (per 1.1 km/s channel) while that in the 1667 MHz spectrum is \sim 0.0008 (per 3.5 km/s channel), in units of optical depth.

The most striking feature of Fig. 1 is that the 1612 and 1720 MHz lines are conjugate to each other; this can be clearly seen in Fig. 1[D], where the sum of the 1612 and 1720 MHz optical depth profiles is consistent with noise. We note that the weak feature seen at \sim -20 \text{ km/s} in Fig. 1[D] is not statistically significant (< \text{3\sigma}), even after smoothing the profile to increase the signal-to-noise ratio. The peaks of the two profiles also arise at the same redshift, within the error bars.

Such conjugate behavior of the satellite lines has been seen earlier in extra-galactic sources \cite{24,21} and essentially arises due to competition between two decay routes to the \Pi_3/2 (J = 3/2) ground state, after the molecules have been pumped from the ground to the higher excited rotational states \cite{22}. The pumping can take place either due to collisions or far-infrared (FIR) radiation. If the last step of the cascade is the 119\mu transition 2\Pi_3/2 (J = 5/2) \rightarrow 2\Pi_3/2 (J = 3/2), the 1720 MHz line is inverted and the 1612 MHz line anti-inverted; conversely, if the final step is the 79\mu decay 2\Pi_1/2 (J = 1/2) \rightarrow 2\Pi_3/2 (J = 3/2), it results in 1612 MHz inversion and 1720 MHz anti-inversion \cite{22}. The fact that the 1720 MHz line is seen in emission and the 1612 MHz line in absorption in PKS1413+135 implies that the former route dominates and gives the constraint \( N_{\text{OH}}/\Delta V \lesssim 10^{15} \text{ cm}^{-2} \text{ (km/s)}^{-1} \) \cite{20}, where \( N_{\text{OH}} \) is the OH column density and \( \Delta V \), the velocity width; in our case, \( \Delta V \sim 20 \text{ km/s} \), implying that \( N_{\text{OH}} \lesssim 2 \times 10^{16} \text{ cm}^{-2} \). Further, all pumping mechanisms require that the 119\mu transition be optically thick for the 1720 MHz line to be inverted; this corresponds to the lower limit \( N_{\text{OH}}/\Delta V \gtrsim 1 \times 10^{14} \text{ cm}^{-2} \text{ (km/s)}^{-1} \) \cite{21}, i.e. \( N_{\text{OH}} \gtrsim 2 \times 10^{15} \text{ cm}^{-2} \) in the present case. We thus obtain the range \( 2 \times 10^{15} \lesssim N_{\text{OH}} \lesssim 2 \times 10^{16} \text{ cm}^{-2} \) for the OH column density. At lower optical depth, the 119\mu line is optically thin and the 1720 MHz line is not inverted; at higher \( N_{\text{OH}} \), the inversion switches to the 1612 MHz line. Implications for other physical conditions in the absorbing/emitting cloud will be discussed elsewhere.

The 1720 MHz profile implies an OH luminosity \( L_{\text{OH}} \sim 354L_{\odot} \text{, well into the OH megamaser range} \) \cite{23}. This is by far the brightest known 1720 MHz maser line, more than an order of magnitude more luminous than Arp 220 (\( L_{\text{OH}} \sim 12L_{\odot} \)), the only other known 1720 MHz megamer \cite{22}. Interestingly enough, PKS1413+135 is an excellent candidate for main line OH megamer emission, on the basis of its high FIR flux \cite{23,25}; in fact, the empirical relation, \( \log L_{\text{OH}} = (1.2 \pm 0.1)\log L_{\text{FIR}} - (11.7 \pm 1.2) \) (in solar units) \cite{25} predicts a main line megamer luminosity of \( L_{\text{OH}} \sim 300L_{\odot} \), similar to that obtained in the 1720 MHz line. It is unclear whether this is merely a coincidence, especially given the spread in the relation between \( L_{\text{OH}} \) and \( L_{\text{FIR}} \) \cite{25}.

**CONSTRAINING THE VARIATION OF FUNDAMENTAL CONSTANTS**

Crucially, the conjugate behavior of the satellite lines guarantees that they arise from the same gas. However, the main line profiles are quite different, suggesting that this absorption occurs at a different spatial location. The main lines (the 1665 MHz line is not shown here) peak at \( z = 0.24671 \), coincident in velocity with other molecular species (such as CO and HCO\(^{+}\)) that have been detected in PKS1413+135 \cite{26}. They also show a “tail” at positive velocities, with a total velocity spread of \sim 15 km/s. On the other hand, while the two satellite lines have a similar velocity width (\sim 20 km/s), they show blueshifted, edge-brightened profiles, with the absorption/emission peaking \sim -15 km/s away from \( z = 0.24671 \). Further, while the satellite features are seen to extend to \( v = 0 \), the main lines are not detected at the velocity corresponding to the peak of the satellite lines.

Most of the astrophysical techniques used to estimate changes in fundamental constants (e.g. \cite{6,2,9}) involve a comparison between the redshifts of spectral lines of different species, i.e. the assumption that these different species have no velocity offsets between them. In fact, even a comparison between lines of the same species (e.g. \cite{13,27}) does not rule out the above systematic uncertainty, as the different lines might well be excited in different regions of the gas cloud. In the present case, the very different shapes of the profiles of the “main” and “satellite” line profiles implies that one cannot compare the peak redshifts of all four lines to simultaneously constrain changes in \( y \equiv m_e/m_p \) and \( \alpha \). However, the conjugate behavior of the OH satellite lines implies that they arise from precisely the same gas; we hence have a unique situation where systematic velocity offsets between two spectral lines are not an issue. Again, the satellite line frequencies have very different dependences on the “constants” \( y, \alpha \equiv m_e/m_p \) and the proton g-factor \( g_p \); this can be clearly seen from equations (9) and (11) in Paper 1 (note that the sum of satellite line frequencies is equal to the sum of main line frequencies in the OH radical). A comparison between the measured 1612 and 1720 MHz redshifts thus allows one to measure changes...
in the quantity \( G \equiv g_0\left[\alpha^2/y\right]^{1.849} \). In particular, if \( z_s \) and \( z_d \) are the redshifts derived from the sum and difference of the measured 1612 and 1720 MHz line frequencies, respectively, it can be shown that
\[
\frac{\Delta G}{G} = \frac{z_s - z_d}{1 + \bar{z}},
\]
where \( \bar{z} \) is the average of \( z_s \) and \( z_d \).

As mentioned earlier, the peaks of the two satellite profiles arise at the same redshift, within our observing resolution of \( \sim 4.8 \) kHz. However, since the two profiles are conjugate, we can improve the accuracy of the comparison between the peak redshifts by fitting a template profile to each spectrum. Note that the same template is fit to both spectra and this procedure is carried out solely for the purpose of comparing the peak redshifts. We use a double-Gaussian template for this purpose, to account for both the narrow peak as well as the extended shoulder. Several of these two-component fits were found to be statistically indistinguishable; in essence, the profile cannot be uniquely decomposed into two Gaussians as the signal-to-noise ratio of the shoulder is quite low. Using different templates allowed us to estimate the systematic error in the measured redshifts, arising due to the choice of template. In all cases, the redshifts of the peak were found to agree to within \( 2.8 \) kHz, for both the 1720 MHz and 1612 MHz lines. We hence use this figure as our estimate of the error in the redshifts (including both systematic and random errors). We note that attempts were also made to fit a single Gaussian component to the narrow peak in both satellite line profiles; again, the peak redshifts were found to be in agreement within an error of \( 2.8 \) kHz.

The sum of the frequencies of the peaks of the satellite profiles is then measured to be \( 2673.356 \pm 0.004 \) MHz, while their difference is \( 86.8733 \pm 0.004 \) MHz. In both cases, the errors have been added in quadrature – it should be emphasized that this is a conservative estimate in the case of the difference of the frequencies, since the systematic error in the choice of the
template cancels out here, to first order. The above frequencies correspond to redshifts \( z_e = 0.246658 \pm 0.0000015 \) and \( z_d = 0.24663 \pm 0.0000046 \), respectively, in agreement within the error bars. This gives the limit \( \Delta G/G = 2.2 \pm 3.8 \times 10^{-5} \) on changes in the quantity \( G \) from \( z \sim 0.247 \) to the present epoch. Again, we emphasize that the errors on \( \Delta G/G \) are dominated by the error on the difference in frequencies and the latter is certainly lower than 2.8 kHz, since the systematic errors from the fitting procedure cancels to first order; we choose, however, to remain conservative in our error estimates.

We note that the strong dependence of the quantity \( G \) on the fine structure constant \( \alpha \) (\( G \sim \alpha^{3.698} \)) implies that the observations are extremely sensitive to changes in \( \alpha \). If we assume, as is often done, (e.g. \([12]\)) that neither \( g_p \) nor \( y \) varies with cosmological epoch, the above constraint on \( \Delta G/G \) translates to \( \Delta \alpha/\alpha = 0.6 \pm 1.0 \times 10^{-5} \). Similarly, \( G \) also has a strong dependence on the electron-proton mass ratio \( y \equiv m_e/m_p \) (although weaker than that on \( \alpha \)), with \( G \sim y^{-1.849} \); we obtain the constraint \( \Delta y/y = (-1.2 \pm 2.0) \times 10^{-5} \), assuming that \( \alpha \) and \( g_p \) remain unchanged. This is similar to the best current limits on changes in \( y \) from observations of the Lyman and Werner band lines of molecular hydrogen \([13]\), although the latter constraints, of course, probe a larger redshift range. We also note that the changes in \( \alpha \) and \( y \) are of opposite sign and it would require something of a conspiracy for both these quantities to vary, while leaving \( G \) unchanged. The data towards PKS1413+135 are thus consistent with the different constants remaining constant from \( z \sim 0.247 \) to today.

The relative sensitivity of the present technique adds to its importance. While results from the many-multiplet method (e.g. \([3,23]\)) on fractional changes in \( \alpha \) have lower errors at the present time, this method requires the use of many absorption systems, both to cancel systematic effects and to increase sensitivity. Further, as mentioned earlier, the conflicting results from analyses based on Keck and VLT spectra suggest that unknown systematics dominate the errors here. On the other hand, our present limits are derived from a single system and provide an entirely independent constraint on changes in \( \alpha \), \( y \) and \( g_p \). It should also be noted that the present satellite spectra have a resolution of only \( \sim 1.1 \) km/s; higher resolution spectroscopy in both lines will allow far tighter constraints on changes in \( G \equiv g_p[\alpha^2/y]^{1.849} \). For example, observations of PKS1413+135 with the Square Kilometer Array \([28]\), a next generation radio telescope, will be able to detect fractional changes \( \Delta G/G \sim \text{few} \times 10^{-7} \). This implies a sensitivity of \( \sim 10^{-7} \) to changes in \( \Delta \alpha/\alpha \), comparable to those obtained with the Oklo reactor experiment.

Finally, the 1720 MHz inversion arises due to an over-population of the \( F = 2 \) level of the ground state relative to the \( F = 1 \) level, as transitions from the \( F = 3 \) level of the \( J = 5/2 \) state to the latter level are forbidden. This should also give rise to an over-population of the above \( F = 3 \) level, relative to the \( J = 5/2, F = 2 \) level (by \( \sim 50 \% \); \([29]\)) and could result in the inversion (and anti-inversion) of the corresponding \( J = 5/2 \) satellite lines (at rest frequencies of \( \sim 6049 \) MHz and 6016 MHz). A detection of these lines would allow one to independently constrain changes in all three constants \( \alpha, y \) and \( g_p \); these observations are presently being carried out.

In summary, we report the first detection of the 18cm OH satellite lines at cosmological distances. The 1720 MHz line is found in emission, with a luminosity larger by more than an order of magnitude than any other known 1720 MHz maser; the 1612 MHz line is in absorption, as are the other ground state OH lines. The satellite line profiles are found to be conjugate, in that the sum of their optical depths is consistent with noise; this implies that the two lines arise in precisely the same gas. A comparison between the satellite line redshifts then yields constraints on \( G \equiv g_p[\alpha^2/y]^{1.849} \), a combination of the fine structure constant \( \alpha \), the electron-proton mass ratio \( y \equiv m_e/m_p \) and the proton gyromagnetic ratio \( g_p \). We find \( \Delta G/G = 2.2 \pm 3.8 \times 10^{-5} \), consistent with the different constants remaining unchanged from \( z \sim 0.247 \) (a lookback time of \( \sim 2.9 \) Gyr) to the present epoch. If \( y \) and \( g_p \) are assumed to remain constant, we obtain \( \Delta \alpha/\alpha = 0.6 \pm 1.0 \times 10^{-7} \), over the redshift range \( 0 < z < 0.247 \).

We thank Rene Vermeulen for much help with the planning and scheduling of the WSRT observations. The WSRT is operated by the ASTRON (Netherlands Foundation for Research in Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO). We also thank the staff of the GMRT that made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research.

* Electronic address: nissim@astro.rug.nl
† Electronic address: chengalur@ncra.tifr.res.in
‡ Electronic address: tgosh@naic.edu

[1] J. K. Webb, V. V. Flambaum, C. W. Churchill, M. J. Drinkwater, and J. D. Barrow, Phys. Rev. Lett. 82, 884 (1999).
[2] J. K. Webb, M. T. Murphy, V. V. Flambaum, V. A. Dzuba, J. D. Barrow, C. W. Churchill, J. X. Prochaska, and A. M. Wolfe, Phys. Rev. Lett. 87, 091301 (2001).
[3] R. Srianand, H. Chand, P. Petitjean, and B. Aracil, Phys. Rev. Lett. 92, 121302 (2004).
[4] T. Damour and F. J. Dyson, Nucl. Phys. B 480, 37 (1996).
[5] J.-P. Uzan, Rev. Mod. Phys 75, 403 (2003).
[6] C. L. Carilli, K. M. Menten, J. T. Stocke, E. Perlman, R. Vermeulen, F. Briggs, A. G. de Bruyn, A. Conway, and C. P. Moore, Phys. Rev. Lett. 85, 5511 (2000).
[7] J. N. Chengalur and N. Kanekar, Phys. Rev. Lett. 91, 241302 (2003).
[8] V. A. Dzuba, V. V. Flambaum, and J. H. Webb, Phys. Rev. Lett. 82, 888 (1999).
[9] M. T. Murphy, J. K. Webb, and V. V. Flambaum, MNRAS 345, 609 (2003).
[10] J. D. Bekenstein, astro-ph/0301566 (2003).
[11] X. Calmet and H. Fritzsch, Phys. Lett. B 540, 173 (2002).
[12] P. G. Langacker, G. Segré, and M. J. Strassler, Phys. Lett. B 528, 121 (2002).
[13] W. Ubachs and E. Reinhold, Phys. Rev. Lett. 92, 101302 (2004).
Throughout this paper, we use an LCDM cosmology, with \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \) and \( H_0 = 70 \text{ km/s Mpc}^{-1} \).