

## A LABORATORY FOR CONSTRAINING COSMIC EVOLUTION OF THE FINE-STRUCTURE CONSTANT: CONJUGATE 18 CENTIMETER OH LINES TOWARD PKS 1413+135 AT $z = 0.24671$

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### ABSTRACT

We report the detection of the satellite 18 cm OH lines at 1612 and 1720 MHz in the  $z = 0.24671$  molecular absorption system toward the radio source PKS 1413+135. The two OH lines are conjugate; the 1612 MHz line is seen in absorption while the 1720 MHz line is seen in weak maser emission of equal but negative optical depth. We do not detect the main 18 cm OH lines at 1667 and 1665 MHz down to 1.1 mJy rms in 4.0 km s<sup>-1</sup> channels. The detected and undetected 18 cm OH lines support a scenario of radiatively pumped stimulated absorption and emission with pumping dominated by the intraladder 119  $\mu\text{m}$  line of OH, suggesting a column density  $N(\text{OH}) \simeq 10^{15} - 10^{16} \text{ cm}^{-2}$ . Combined with simultaneous H I 21 cm observations and published CO data, we apply the OH redshifts to measurements of cosmic evolution of the fine-structure constant ( $\alpha \equiv e^2/\hbar c$ ). We obtain highly significant ( $\sim 25 \sigma$ ) velocity offsets between the OH and H I lines and the OH and CO lines, but measurements of  $\alpha$ -independent systematics demonstrate that the observed velocity differences are entirely attributable to physical velocity offsets between species rather than a change in  $\alpha$ . The OH alone, for which conjugate line profiles guarantee that both lines originate in the same molecular gas, provides a weak constraint of  $\Delta\alpha/\alpha_0 = (+0.51 \pm 1.26) \times 10^{-5}$  at  $z = 0.24671$ . Higher frequency OH line detections can provide a larger lever arm on  $\Delta\alpha$  and can increase precision by an order of magnitude. The OH molecule can thus provide precise measurements of the cosmic evolution of  $\alpha$  that include quantitative constraints on systematic errors. Application of this technique is limited only by the detectability of  $|\tau| \sim 0.01$  OH lines toward radio continuum sources and may be possible to  $z \sim 5$ .

*Subject headings:* cosmology: observations — galaxies: individual (PKS 1413+135) — galaxies: ISM — masers — quasars: absorption lines — radiation mechanisms: nonthermal

### 1. INTRODUCTION

Recent work to investigate the cosmic evolution of the fine-structure constant ( $\alpha \equiv e^2/\hbar c$ ) suggests a decrement in the past:  $\Delta\alpha/\alpha_0 = (-0.574 \pm 0.102) \times 10^{-5}$  for  $0.2 \leq z \leq 3.7$ , where  $\Delta\alpha \equiv \alpha(t) - \alpha_0$  (Murphy et al. 2003). This result applies the “many-multiplet” method to optical absorption lines in the spectra of high-redshift quasars;  $\alpha$  parameterizes the strength of electromagnetic interactions, and a changing  $\alpha$  will cause spectral line shifts from present-day values. Srianand et al. (2004) apply the same method to a new sample of Mg II absorption systems and find no change in  $\alpha$  over  $0.4 \leq z \leq 2.3$ :  $\Delta\alpha/\alpha_0 = (-0.06 \pm 0.06) \times 10^{-5}$ . Other methods, including terrestrial measurements from the Oklo natural fission reactor and meteorites provide mixed results: from Oklo, Fujii et al. (2000) obtain  $\Delta\alpha/\alpha_0 = (0.4 \pm 1.6) \times 10^{-8}$ , while Lamoreaux & Torgerson (2004) obtain  $\Delta\alpha/\alpha_0 \geq 4.5 \times 10^{-8}$  with 6  $\sigma$  confidence, both at  $z \simeq 0.16$  (2 Gyr), and Olive et al. (2004) obtain  $\Delta\alpha/\alpha_0 = (0.08 \pm 0.08) \times 10^{-5}$  at  $z \simeq 0.45$  from meteorites. Other astrophysical constraints obtain results consistent with no change in the fine-structure constant: O III emission-line shifts in quasars with  $0.16 < z < 0.80$  from the Sloan Digital Sky Survey obtain  $\Delta\alpha/\alpha_0 = (7 \pm 14) \times 10^{-5}$  (Bahcall et al. 2004); and comparisons of H I 21 cm (1420 MHz) line redshifts ( $\nu \propto \alpha^4$ ) to molecular rotation transitions ( $\nu \propto \alpha^2$ ) in molecular absorption systems obtain  $\Delta\alpha/\alpha_0 = (-0.10 \pm 0.22) \times 10^{-5}$  at  $z = 0.24671$  and  $\Delta\alpha/\alpha_0 = (-0.08 \pm 0.27) \times 10^{-5}$  at  $z = 0.6847$  (Murphy et al. 2001).

Radio observations of molecular and H I absorption lines show much promise for exceptionally precise measurements of the value of  $\alpha$  across a large span of cosmic time. These lines

are generally narrow and simple. Complex molecules and molecules with unbalanced electron angular momentum, like OH and CH, offer multiple transitions with differing dependence on  $\alpha$ , providing measurements of  $\Delta\alpha$  from a *single species* including quantitative estimates of systematic velocity offsets between species (Darling 2003). These same molecules can also provide simultaneous constraints on the cosmic variation of  $\alpha$ , the proton  $g$  factor  $g_p$ , and  $m_e/m_p$  (Chengalur & Kanekar 2003; Kanekar & Chengalur 2004).

Further, OH can form a natural maser across a wide range of physical settings, and observed ratios of the four ground-state 18 cm OH lines, at 1612, 1665, 1667, and 1720 MHz, provide clues to the physical conditions associated with the masing. A special case occurs when both emission and absorption are stimulated in pairs of “conjugate” OH lines, lines that are identical except for the sign of the optical depth. Conjugate lines are a direct result of quantum selection rules and an optically thick far-infrared transition from a single dominant excited rotation state (Elitzur 1992; van Langevelde et al. 1995). Conjugate lines can be added to obtain a perfect null, indicating that the lines are produced in the same molecular gas complex. Hence, conjugate lines provide a valuable laboratory for precision measurements of fundamental constants: lines are guaranteed to reside in the same physical location at the same physical velocity, so any relative line shift in a conjugate pair indicates a change in physical constants rather than systematic effects.

The primary difficulty with the molecular absorption line approach to changing constants is the dearth of molecular absorption systems. To our knowledge, only six centimeter- and millimeter-detected molecular absorbers at  $z \gtrsim 0.1$  are known; only four of these have  $z > 0.2$ , and the highest

redshift system is PKS 1830–211 at  $z = 0.8858$  (Wiklind & Combes 1996; Chengalur et al. 1999). Numerous groups are currently searching for additional high-redshift millimeter molecular absorption systems (e.g., Murphy et al. 2003).

This paper presents new observations of the OH 18 cm and H I 21 cm lines toward PKS 1413+135 at  $z = 0.24671$  that reveal conjugate OH satellite lines (§§ 2 and 3). The conjugate lines are guaranteed to originate in the same gas complex (§ 4) and provide a new laboratory for a measurement of the fine-structure constant at  $z = 0.24671$  (§ 5). The OH lines also provide quantitative estimates of the systematic velocity offsets between species (such as OH, H I, and CO), demonstrating that seemingly significant nonzero  $\Delta\alpha/\alpha_0$  measurements are in fact consistent with zero once systematic effects have been removed.

## 2. OBSERVATIONS

We observed the molecular absorption system at  $z = 0.24671$  toward the radio source PKS 1413+135 at the NRAO Green Bank Telescope<sup>1</sup> on 2003 December 14, 17, and 19, simultaneously observing the four  ${}^2\Pi_{3/2} J = 3/2$  OH lines, at 1612.23101, 1665.40184, 1667.35903, and 1720.52998 MHz, and the H I line at 1420.405751786 MHz, each appropriately redshifted and tracked in a barycentric reference frame. We observed four 12.5 MHz bandpasses centered on the 1420, 1612, 1667, and 1720 MHz lines in two linear polarizations in a 5 minute position-switched mode with a winking calibration diode and data recorded every 0.5 s. Bandpasses were divided into 8192 channels, but the nature of the autocorrelation spectrometer reduced the effective spectral resolution to 3.05 kHz or  $0.80 \text{ km s}^{-1}$  for H I at  $z = 0.24671$ . Fast sampling was intended to facilitate radio frequency interference (RFI) excision, but the observed bands were generally clean in the vicinity of the observed lines. The OH 1720 MHz line did show some nearby RFI, but careful inspection and flagging eliminated any possible disruption or contamination of the line profile.

Records were individually calibrated and bandpasses flattened using the winking calibration diode and the corresponding off-source records. Records and polarizations were subsequently averaged to obtain a final spectrum. Spectra were Hanning smoothed, and a linear or quadratic baseline was fit and subtracted from a narrow spectral window centered on each line (including the 1665 MHz line). The total on-source integration time was 90 minutes for the OH lines and 120 minutes for the H I line. We reached a typical rms noise of 1.8 mJy in 3.05 kHz channels. All data reduction was performed in AIPS++.<sup>2</sup>

Our single-dish flux density measurements of PKS 1413+135 are consistent with previous observations. At 1140 MHz, the observed flux density is 1.367 Jy, consistent with the Carilli et al. (1992) measurement of  $1.25 \pm 0.15$  Jy. At 1380 MHz, we obtain 1.085 Jy and Condon et al. (1998) measured  $1.092 \pm 0.033$  Jy. At 1293 and 1337 MHz, we obtain 1.162 and 1.192 Jy, respectively. Flux calibration of these data seems to be reliable but can be systematically affected by in- and out-of-band RFI, especially in the 1140 MHz band, which contains abundant strong RFI. Systematic flux calibration errors in these data appear to be well below 10%.

<sup>1</sup> The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

<sup>2</sup> The AIPS++ (Astronomical Information Processing System) is freely available for use under the GNU Public License. Further information may be obtained from <http://aips2.nrao.edu>.

## 3. RESULTS

Of the five lines observed toward PKS 1413+135, only three were detected: the 1612 and 1720 MHz lines of OH and the 21 cm line of H I (Fig. 1). The H I and 1612 MHz lines were detected in absorption. The 1720 MHz line has a profile similar to the 1612 MHz line profile modulo the spectral noise but with a negative optical depth. The 1667 MHz line is not detected, contrary to the detection by Kanekar & Chengalur (2002). We obtain an rms noise value of 1.1 mJy in boxcar-smoothed spectra with  $4.0 \text{ km s}^{-1}$  resolution similar to the resolution obtained by Kanekar & Chengalur (2002), who detect the 1667 MHz line in absorption at 7.9 mJy. The 1665 MHz line is not detected at a limit similar to that of the 1667 MHz line (Table 1). Gaussian fits to the detected lines are listed in Table 1; the OH lines are well fitted by single Gaussian profiles, but the H I profile requires four components. The broad component H I 4 may be an artifact associated with the RFI above  $\sim 80 \text{ km s}^{-1}$ . To within the quoted uncertainties in the Gaussian fits, the two OH line profiles are indistinguishable in redshift, width, and  $|\tau|$ .

Although there is evidence for a nonzero spectral index across the observed bands, optical depths are computed assuming a constant flux density of 1.2 Jy at 1100–1400 MHz for PKS 1413+135. This assumption is broadly consistent with the observations at the 10% uncertainty level and simplifies comparisons with previous observations. The core-jet radio continuum of PKS 1413+135 is extended on scales of 60 mas (215 pc), and the H I absorption is certainly associated with the jet, although it may extend across the core as well (Carilli et al. 2000; Perlman et al. 2002). Optical depths are thus likely to be lower bounds, because the continuum covering factor is unknown.

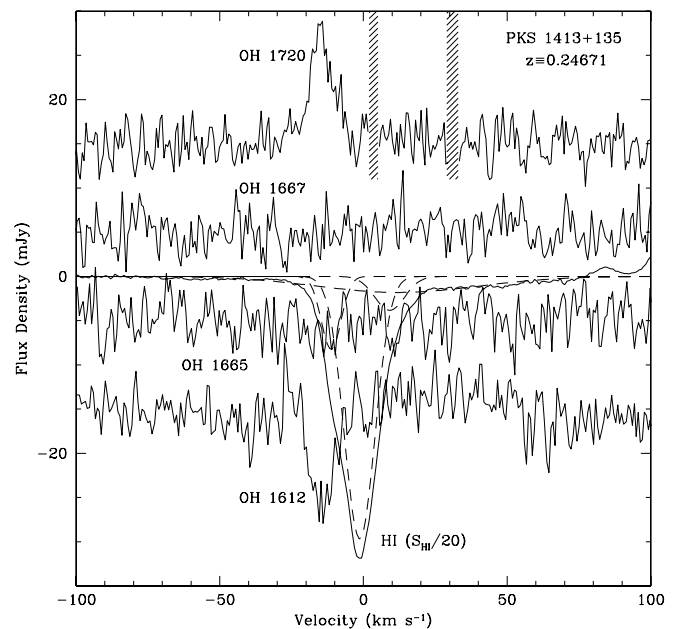


Fig. 1.—OH and H I lines at  $z = 0.24671$  toward PKS 1413+135. All lines were observed in a barycentric frame, zero velocity refers to a redshift of  $z = 0.24671$ , and the velocity scale is in the rest frame of the absorption system. A linear or quadratic fit to the spectral baseline has been subtracted from each spectrum. The H I spectrum has been scaled down by a factor of 20 and the OH spectra have been offset from zero by  $-15$ ,  $-5$ ,  $5$ , and  $15$  mJy for the 1612, 1665, 1667, and 1720 MHz lines, respectively. The dashed lines show the four Gaussian components fit to the H I profile. The positive features in the H I spectrum are RFI, and the broad H I component (H I 4) may be an artifact of this interference. Shaded regions in the 1720 MHz spectrum at 31 and  $4 \text{ km s}^{-1}$  are regions where RFI was excised and no on-sky data exists.

TABLE 1  
OBSERVED AND FIT PROPERTIES OF OH AND H I LINES TOWARD PKS 1413+135

LINE	GAUSSIAN FITS					
	$\nu_c$ (MHz)	$z_c$	$S_c$ (mJy)	$\tau_c$	$\Delta V$ (km s <sup>-1</sup> )	$\int \tau dV$ (km s <sup>-1</sup> )
OH 1612 .....	1293.2502 ± 0.0015	0.2466505 ± 0.0000014	-11.67 ± 0.93	0.0098 ± 0.0008	8.7 ± 0.8	0.091
OH 1665 <sup>a</sup> .....	...	...	(1.3)	(0.0011)	...	...
OH 1667 <sup>a</sup> .....	...	...	(1.1)	(0.0009)	...	...
OH 1720 .....	1380.1238 ± 0.0037	0.2466490 ± 0.0000034	+11.7 ± 2.0	-0.0097 ± 0.0017	10.1 ± 1.9	-0.108
H I 1 <sup>b</sup> .....	1139.3282 ± 0.0014	0.2467046 ± 0.0000015	-594 ± 20	0.68 ± 0.03	12.6 ± 1.8	13.4 <sup>c</sup>
H I 2 .....	1139.3660 ± 0.0026	0.2466633 ± 0.0000028	-165 ± 52	0.15 ± 0.05	8.1 ± 1.2	...
H I 3 .....	1139.2886 ± 0.0193	0.246748 ± 0.000021	-76 ± 55	0.07 ± 0.05	12.3 ± 5.4	...
H I 4 .....	1139.2775 ± 0.0112	0.246760 ± 0.000012	-36 ± 5	0.030 ± 0.004	65.8 ± 6.8	...

<sup>a</sup> The 1665 and 1667 MHz lines were not detected. The listed flux densities and optical depths are rms noise values in boxcar-smoothed spectra with 4.0 km s<sup>-1</sup> resolution similar to the resolution of the OH 1667 MHz observations of PKS 1413+135 by Kanekar & Chengalur (2002).

<sup>b</sup> This is the dominant H I line, and it is used to determine the H I redshift. Note that the blending with other lines makes the peak frequency of the main H I line more uncertain than would typically be expected for such a high signal-to-noise spectrum.

<sup>c</sup> This integrated optical depth includes all observed H I absorption.

Despite the uniform assumptions about the source continuum level, we observe a significantly deeper H I absorption ( $\tau_c = 0.757 \pm 0.002$ , statistical error only) than Carilli et al. (1992), who obtained a peak optical depth of  $0.34 \pm 0.04$ . Given the incomplete covering of the continuum source, our result is compatible with  $\tau = 0.89$  obtained from VLBI observations by Carilli et al. (2000). Note that the quoted errors in the H I profile fits are very conservative and take into account the blended line profile; fitting with fewer components would give a lower uncertainty in the line position but a larger residual to the fit. Note also that a single-component Gaussian fit to the H I asymmetric profile produces an offset from the peak optical depth.

#### 4. CONJUGATE OH LINES

The optical depths in the 18 cm OH satellite lines are of the order of  $\pm 0.01$ , while the main lines are suppressed by an order of magnitude, below  $\tau \sim 0.001$ . The observed conjugate satellite lines and the suppressed main lines are consistent with a scenario of radiatively pumped stimulated absorption and emission with pumping dominated by optically thick radiative decay from the  $^2\Pi_{3/2}$ ,  $J = 5/2$  rotation state 119  $\mu\text{m}$  above the OH ground state  $^2\Pi_{3/2}$ ,  $J = 3/2$ . As explained by Elitzur (1992) and van Langevelde et al. (1995), the 18 cm transitions compete for the same infrared pumping photons. Since the population of the ground states is governed by the selection rule  $\Delta F = \pm 1$ , 0 (and a change in parity), and if the radiative decay to the ground state is optically thick, then the  $F = 2$ , 3 states of the  $J = 5/2$  level overpopulate the  $F = 2$  states compared to the  $F = 1$  states of the  $J = 3/2$  ground level ( $\Delta F = \pm 2$  is forbidden). The main OH lines follow the rule  $\Delta F = 0$ , while the satellite lines have  $\Delta F = \pm 1$ . Since 1720 MHz emission follows  $F = 2^+ \rightarrow 1^-$ , it is seen in emission. The 1612 MHz line appears as stimulated absorption via  $F = 2^- \rightarrow 1^+$ . The conjugate behavior of the satellite lines maintains equal populations in the two  $F = 1$  states and equal populations in the two  $F = 2$  states, suppressing nonthermal  $\Delta F = 0$  main line (1665 and 1667 MHz) emission or absorption.

Extragalactic conjugate OH satellite lines have been observed toward NGC 4945 (Whiteoak & Gardner 1975), Cen A (van Langevelde et al. 1995), M82 (Seaquist et al. 1997), and NGC 253 (Frayer et al. 1998). In some cases, like NGC 253, the OH satellite lines are conjugate over a wide range of

conditions and show crossover from absorption to emission (and vice versa). The 1612 MHz line changes to emission when the radiative pumping becomes dominated by the cross-ladder 79  $\mu\text{m}$  transition from the  $^2\Pi_{1/2}$ ,  $J = 1/2$  state (van Langevelde et al. 1995).

The scenario proposed for PKS 1413+135 is valid for an optically thick 119  $\mu\text{m}$  intraladder transition but requires an optically thin 79  $\mu\text{m}$  cross-ladder transition. Since the intraladder and cross-ladder Einstein coefficients differ by nearly an order of magnitude, there is an order of magnitude range in the OH column density  $10^{14} \text{ cm}^{-2} \text{ km}^{-1} \text{ s} \lesssim N_{\text{OH}}/\Delta V \lesssim 10^{15} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}$  for conjugate behavior with 1720 MHz in emission (van Langevelde et al. 1995). For  $\Delta V \approx 10 \text{ km s}^{-1}$ ,  $N_{\text{OH}} \approx 10^{15} - 10^{16} \text{ cm}^{-2}$ . Assuming an OH abundance of  $N_{\text{OH}} \approx 10^{-7} N_{\text{H}_2}$ , we obtain an order-of-magnitude estimate of the molecular hydrogen column of  $N_{\text{H}_2} \approx 10^{22} - 10^{23} \text{ cm}^{-2}$ . This is significantly different from CO estimates by Wiklind & Combes (1997) of  $N_{\text{H}_2} \geq 4 \times 10^{20} \text{ cm}^{-2}$ , which they stress may be a severe underestimate for a dense, clumpy medium. The CO may also be in a different physical region than the OH (§ 5). Note that the usual direct determination of the OH column from the integrated optical depth (Liszt & Lucas 1996) is inappropriate for this case of stimulated transitions.

#### 5. MEASURING THE FINE-STRUCTURE CONSTANT

OH lines can provide precise constraints on cosmic evolution of the physical constants  $\alpha$ , the proton  $g$  factor ( $g_p$ ), and the ratio of electron to proton mass (Darling 2003; Chengalur & Kanekar 2003; Kanekar & Chengalur 2004). The following treatment assumes that  $\alpha$  evolution provides the dominant contribution to any changes in line rest frequencies. Since only the satellite 18 cm OH lines have been detected in PKS 1413+135, we provide supplemental equations to Darling (2003), which focused on the main OH lines.

The 18 cm OH lines can be decomposed into a  $\Lambda$ -doubled term, which depends weakly on  $\alpha$ , and a hyperfine term, which has the usual strong  $\alpha^4$  dependence (Darling 2003). From these, sums and differences of lines can form pure  $\Lambda$ -doubled and pure hyperfine quantities:

$$\Sigma\nu \equiv \nu_{1720} + \nu_{1612} = 2\Lambda\alpha^{0.4} \quad (1)$$

$$\Delta\nu \equiv \nu_{1720} - \nu_{1612} = 2(\Delta^+ + \Delta^-)\alpha^4, \quad (2)$$

TABLE 2  
FINE-STRUCTURE CONSTANT EVOLUTION FROM OH, H I, AND CO LINES

LINE 1	LINE 2	$z_1$	$z_2$	$\Delta\alpha/\alpha_0$	
				Apparent ( $\times 10^{-5}$ )	Corrected ( $\times 10^{-5}$ )
OH 1720 .....	OH 1612	$0.2466490 \pm 0.0000034$	$0.2466505 \pm 0.0000014$	$+0.51 \pm 1.26$	...
OH 1720 .....	H I 1	$0.2466490 \pm 0.0000034$	$0.2467046 \pm 0.0000015$	$-1.278 \pm 0.085$	$+0.51 \pm 1.33$
OH 1612 .....	H I 1	$0.2466505 \pm 0.0000014$	$0.2467046 \pm 0.0000015$	$-1.167 \pm 0.045$	$+0.51 \pm 1.25$
OH $\Sigma\nu$ .....	H I 1	$0.2466498 \pm 0.0000019$	$0.2467046 \pm 0.0000015$	$-1.223 \pm 0.054$	$+0.51 \pm 1.29$
OH $\Delta\nu$ .....	H I 1	$0.246627 \pm 0.000058$	$0.2467046 \pm 0.0000015$	$+1.73 \pm 1.29^a$	...
OH 1720 .....	CO (0 $\rightarrow$ 1)	$0.2466490 \pm 0.0000034$	$0.2467091 \pm 0.0000003$	$-3.23 \pm 0.18$	$+0.51 \pm 1.39$
OH 1612 .....	CO (0 $\rightarrow$ 1)	$0.2466505 \pm 0.0000014$	$0.2467091 \pm 0.0000003$	$-2.73 \pm 0.07$	$+0.51 \pm 1.20$
OH $\Sigma\nu$ .....	CO (0 $\rightarrow$ 1)	$0.2466498 \pm 0.0000019$	$0.2467091 \pm 0.0000003$	$-2.98 \pm 0.10$	$+0.51 \pm 1.29$
OH $\Delta\nu$ .....	CO (0 $\rightarrow$ 1)	$0.246627 \pm 0.000058$	$0.2467091 \pm 0.0000003$	$+3.30 \pm 2.32$	$+0.51 \pm 2.53$
H I 1 .....	CO (0 $\rightarrow$ 1)	$0.2467046 \pm 0.0000015$	$0.2467091 \pm 0.0000003$	$+0.179 \pm 0.063$	...

NOTE.—OH and H I redshifts from this work; CO (0  $\rightarrow$  1) redshift from Wiklind & Combes (1997).

<sup>a</sup> This is not a true measure of  $\Delta\alpha/\alpha_0$ ; it is a measure of the systematic offset between the OH and H I lines translated into a  $\Delta\alpha/\alpha_0$  offset.

where  $\Delta^+ = 9.720353(25) \times 10^9$  MHz and  $\Delta^- = 9.375256(25) \times 10^9$  MHz set the strength of hyperfine splitting,  $\Lambda = 11926.36309(51)$  MHz sets the strength of the  $\Lambda$ -doubling, and the exponents on  $\alpha$  are accurate to  $\leq 5\%$  (Darling 2003). Redshift differences between pairs of OH lines can be tied directly to changes in  $\alpha$ , mitigating systematic effects by comparing highly correlated lines from a single species:

$$\frac{z_{1612} - z_{1720}}{1 + z_{1720}} \simeq 1.8 \left( \frac{\Delta\alpha}{\alpha_0} \right) \left( \frac{\Sigma\nu\Delta\nu}{\nu_{1720}\nu_{1612}} \right)_0. \quad (3)$$

The conjugate OH lines in PKS 1413+135 provide an ideal laboratory for  $\alpha$  measurements because the lines are guaranteed to arise from the same molecular gas. From the OH lines alone, we obtain  $\Delta\alpha/\alpha_0 = (0.5 \pm 1.3) \times 10^{-5}$ , consistent with no change in  $\alpha$  (Table 2). The precision of this OH-only measurement could be significantly improved by comparing the 18 cm OH transitions to higher frequency OH transitions at 4 and 6 GHz.

The OH redshifts can be compared to molecular-line or H I redshifts for additional independent measurements of  $\alpha$ , and one can employ the pure  $\Lambda$ -doubled and pure hyperfine OH quantities to constrain systematic velocity offsets and measurement errors between species. In particular,  $z_{H I} - z_{\Delta\nu} = 0$  in the absence of systematic offsets between species. Any nonzero value obtained from this expression thus quantifies the systematic errors in other H I-OH determinations of  $\alpha$ . Table 2 lists and Figure 2 plots apparent  $\Delta\alpha/\alpha_0$  values from pairs of OH, H I, and CO lines (note that from four lines, there are only three independent values). These values are computed from OH satellite line analogs to the main line expressions presented in Darling (2003):

$$\frac{z_{H I} - z_{1612}}{1 + z_{1612}} \simeq -1.8 \frac{\Delta\alpha}{\alpha_0} \left( \frac{\Sigma\nu}{\nu_{1612}} \right)_0; \quad (4)$$

$$\frac{z_{H I} - z_{1720}}{1 + z_{1720}} \simeq -1.8 \frac{\Delta\alpha}{\alpha_0} \left( \frac{\Sigma\nu}{\nu_{1720}} \right)_0; \quad (5)$$

$$\frac{z_{CO} - z_{1612}}{1 + z_{1612}} \simeq -\frac{\Delta\alpha}{\alpha_0} \left( \frac{0.8 \Sigma\nu + \Delta\nu}{\nu_{1612}} \right)_0; \quad (6)$$

$$\frac{z_{CO} - z_{1720}}{1 + z_{1720}} \simeq -\frac{\Delta\alpha}{\alpha_0} \left( \frac{0.8 \Sigma\nu - \Delta\nu}{\nu_{1720}} \right)_0. \quad (7)$$

The expressions for comparisons of CO and H I to  $\Sigma\nu$  and  $\Delta\nu$  are identical to those presented in Darling (2003).

OH-H I and OH-CO line pairs show highly significant offsets in the *apparent* value of  $\alpha$  at  $z = 0.24671$  [ $\Delta\alpha/\alpha_0 = (-1.223 \pm 0.054) \times 10^{-5}$  and  $\Delta\alpha/\alpha_0 = (-2.98 \pm 0.10) \times 10^{-5}$ , respectively], but are these offsets due to a changing  $\alpha$  or are they due to systematic errors and/or velocity offsets

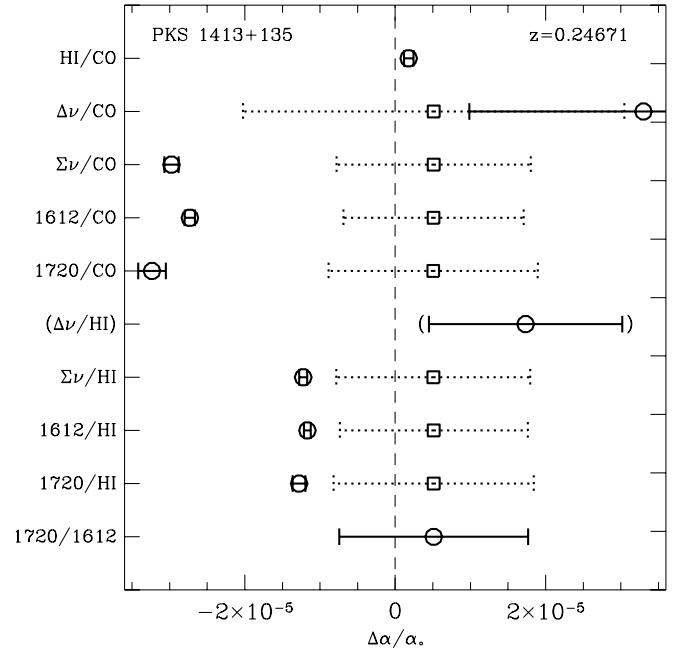


FIG. 2.—Changes in the fine-structure constant measured from pairs of OH, H I, and CO lines at  $z = 0.24671$  toward PKS 1413+135. Circles with solid error bars are apparent changes measured from redshift pairs, and the squares with dotted error bars are  $\Delta\alpha/\alpha_0$  values corrected for systematic offsets between species. Note that from four lines, there are only three independent apparent  $\Delta\alpha/\alpha_0$  values and only two independent systematic-corrected values. The  $\Delta\nu/H I$  quantity is not a true measure of  $\Delta\alpha/\alpha_0$ ; it is a measure of the  $\alpha$ -independent systematic offset between the OH and H I redshifts, translated into a  $\Delta\alpha/\alpha_0$  measure to indicate the magnitude of the correction applied to the apparent OH-H I values. The OH and H I lines were observed in a barycentric frame, but the CO reference frame is heliocentric; the difference between frames is of the order of  $10 \text{ m s}^{-1}$ , which is an order of magnitude less than the uncertainty in the H I and CO line centroids. The CO redshift refers to the strongest CO  $J = 0 \rightarrow 1$  line observed by Wiklind & Combes (1997).

between species? We are confident that the simultaneous observations of OH and H I conducted at the Green Bank Telescope produce reliable relative offsets between lines, and we can thus exclude many systematic effects related to the atmosphere, telescope, Doppler tracking, back end, and data-reduction pathways. To assess the possibility that the offset is a physical velocity difference between the H I and OH gas, we employ the pure hyperfine  $z_{\text{H I}} - z_{\Delta\nu}$  estimate of the systematics:  $\Delta z_{\text{sys}}(\text{OH-H I}) = (7.78 \pm 5.77) \times 10^{-5}$ , which is  $18.7 \pm 13.9 \text{ km s}^{-1}$  in the rest frame of PKS 1413+135. This quantity, translated into a  $\Delta\alpha/\alpha_0$  offset of  $(+1.73 \pm 1.29) \times 10^{-5}$ , shows that the systematic offsets, while uncertain in magnitude, can account for *all* of the apparent change in  $\alpha$  in OH-H I line pairs. A similar argument applies to the OH-CO line pairs, but since OH lines cannot form a quantity that depends on  $\alpha^2$ , the  $\Sigma\nu$ -CO and  $\Delta\nu$ -CO quantities bracket the true value of  $\Delta\alpha/\alpha_0$  and should produce consistent values in the absence of systematic effects. Since they are not consistent in PKS 1413+135, we can solve for the systematic velocity offsets between OH and CO (see Appendix). We obtain  $\Delta z_{\text{sys}}(\text{OH-CO}) = (6.95 \pm 2.57) \times 10^{-5}$ , which is  $16.7 \pm 6.2 \text{ km s}^{-1}$  in the rest frame. Hence, the OH-CO systematic offsets can account for the apparent change in  $\alpha$  in OH-CO line pairs as well. The interspecies systematic corrections have been applied to the appropriate line pairs and are listed in Table 2 and plotted in Figure 2. Finally, the H I-CO pair indicates a  $2.9 \sigma$  deviation from  $\Delta\alpha = 0$  that the OH observations suggest could be completely attributed to systematic effects, as suggested by Carilli et al. (2000).

It is no coincidence that all corrected points in Figure 2 have the same value and nearly the same uncertainties. The correction for systematic offsets between species relies on the measurement of  $\Delta\nu$  to quantify the systematics, but this difference in frequencies is precisely the quantity used to derive  $\Delta\alpha/\alpha_0$  from the 1720-1612 MHz line pair of OH. In removing the systematic effects, we have used the OH redshift as a fiducial, so the corrected points are only as precise as the OH zero point. Correction for  $\alpha$ -independent effects is equivalent to requiring all measurements to produce the same value of  $\Delta\alpha/\alpha_0$ , which is exactly what the correction procedure has produced. The systematic corrections thus reduce the number of independent  $\Delta\alpha/\alpha_0$  values to just two. The correction for systematic effects between species reveals that, contrary to the small statistical error bars on apparent measurements between species, the most precise measurement involving OH lines is the OH-only measurement obtained from the OH satellite lines.

## 6. CONCLUSIONS

Our observations of the 18 cm OH lines support a scenario of radiatively pumped stimulated absorption and emission with pumping dominated by the intraladder 119  $\mu\text{m}$  line of OH, suggesting a column density  $N(\text{OH}) \simeq 10^{15} - 10^{16} \text{ cm}^{-2}$ . The OH alone, for which conjugate line profiles guarantee that both lines originate in the same molecular gas, provides a weak constraint on the evolution of the fine-structure constant of  $\Delta\alpha/\alpha_0 = (+0.51 \pm 1.26) \times 10^{-5}$ . This result illustrates the need for higher frequency OH line detections to provide a larger lever arm on  $\Delta\alpha$ , but it also illustrates the power of the OH molecule to provide precise measurements of the cosmic evolution of  $\alpha$  that include quantitative constraints on systematic errors. We obtain a highly significant ( $\sim 25 \sigma$ ) velocity offset between the OH and H I and the OH and CO lines, which is entirely attributable to systematic velocity offsets between species. The OH-H I offset is likely to be a physical velocity offset (perhaps due to different physical locations in the extended absorber), and the OH-CO offset may be a combination of physical and measurement-based systematics. We obtain a marginally significant ( $2.9 \sigma$ ) H I-CO offset, which the OH observations indicate is likely due to systematic effects, as anticipated by Carilli et al. (2000).

Detection of conjugate OH lines at higher redshifts will provide new constraints on the cosmic evolution of physical constants. While the detection of new centimeter and millimeter molecular absorption systems has proved to be a difficult and thus far fruitless task, recent and future improvements in frequency coverage, instantaneous bandwidth, sensitivity, and radio frequency interference (RFI) mitigation should facilitate new discoveries in the near future. There is room for optimism for detecting conjugate OH lines at high redshift because, like absorption lines and weak maser lines, the strength of conjugate OH lines depends only on the flux density of the background radio continuum source and not on the redshift. Also, as Frayer et al. (1998) point out, the density, temperature, and molecular column density conditions required to form conjugate OH lines are common in the centers of active galaxies, so conjugate OH lines may be most efficiently identified in searches for intrinsic absorption in radio-loud active galaxies rather than in blind searches for intervening absorption-line systems.

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## APPENDIX

### QUANTIFYING SYSTEMATIC OFFSETS BETWEEN SPECIES

Redshift offsets between species with the same  $\alpha$  dependence will, to first order, quantify the net systematic effects, be they instrumental, propagation effects, or physical velocity differences between species. Hence, in the case of H I and (to first order) the pure hyperfine quantity  $\Delta\nu$  derived from the frequency differences between pairs of main or satellite OH lines, we expect redshift differences to be a measure of systematics rather than changes in fundamental constants:  $z_{\text{H I}} - z_{\Delta\nu} = \Delta z_{\text{sys}}$ . The derived  $\Delta z_{\text{sys}}$  should then be applied as a correction to the  $\Delta\alpha/\alpha_0$  values obtained from H I-OH line pairs.

Systematic corrections can also be measured and applied in cases where there is no convenient cancellation of  $\alpha$  terms; only different  $\alpha$  dependencies are required. For example, comparison of the sum and difference,  $\Sigma\nu$  and  $\Delta\nu$ , of an OH main or satellite line pair to a transition in species X with dependence  $\alpha^\gamma$  will give

$$z_X - z_{\Sigma\nu} = \beta_\Sigma (1 + z_{\Sigma\nu}) \frac{\Delta\alpha}{\alpha_0} + \Delta z_{\text{sys}} \quad (\text{A1})$$

$$z_X - z_{\Delta\nu} = \beta_{\Delta}(1 + z_{\Delta\nu}) \frac{\Delta\alpha}{\alpha_0} + \Delta z_{\text{sys}}, \quad (\text{A2})$$

where  $\beta_{\Delta} = 4 - \gamma$ ,  $\beta_{\Sigma} = \eta - \gamma$  with  $\eta = 0.4$  for  ${}^2\Pi_{3/2}$  and  $\eta = 5$  for  ${}^2\Pi_{1/2}$  states, and  $\Delta z_{\text{sys}}$  represents an average  $\alpha$ -independent offset between species. The requirement of a consistent measurement of  $\Delta\alpha/\alpha_0$  from both line comparisons provides a solution for  $\Delta z_{\text{sys}}$ :

$$\Delta z_{\text{sys}} = z_X + \frac{z_{\Sigma\nu}\beta_{\Delta} - z_{\Delta\nu}\beta_{\Sigma}}{\beta_{\Sigma} - \beta_{\Delta}}. \quad (\text{A3})$$

In the case where  $\beta_{\Sigma} = \beta_{\Delta}$ , there is no leverage on  $\Delta z_{\text{sys}}$ , and systematics cannot be quantified. In the case where  $\beta_{\Sigma} = 0$  or  $\beta_{\Delta} = 0$  (which is the case for H I),  $\Delta z_{\text{sys}}$  can be measured directly from the  $\alpha$ -canceled line pair.

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