Discovery of OH Absorption from a Galaxy at \( z \approx 0.05 \): Implications for Large Surveys with SKA Pathfinders

N. Gupta\(^1\), E. Momjian\(^2\), R. Srianand\(^1\), P. Petitjean\(^3\), P. Noterdaeme\(^1\), D. Gyanchandani\(^4\), R. Sharma\(^4\), and S. Kulkarni\(^4\)

\(^1\)Inter-Univeristy Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India; ngupta@iucaa.in
\(^2\)National Radio Astronomy Observatory, P.O. Box O, 1003 Lopezville Road, Socorro, NM 87801, USA
\(^3\)UPMC-CNRS, UMR7095, Institut d’Astrophysique de Paris, F-75014 Paris, France
\(^4\)ThoughtWorks Technologies India Private Limited, Yerawada, Pune 411 006, India

Received 2018 March 16; revised 2018 May 22; accepted 2018 May 31; published 2018 June 18

Abstract

We present the first detection of OH absorption in diffuse gas at \( z > 0 \), along with another eight stringent limits on OH column densities for cold atomic gas in galaxies at \( 0 < z < 0.4 \). The absorbing gas detected toward Q0248+430 (\( z_a = 1.313 \)) originates from a tidal tail emanating from a highly star-forming galaxy G0248+430 (\( z_e = 0.0519 \)) at an impact parameter of 15 kpc. The measured column density is \( N(\text{OH}) = (6.3 \pm 0.8) \times 10^{13} \left( \frac{f_{\text{c}}}{0.5} \right) \left( \frac{T_{\text{ex}}}{2500 \text{ K}} \right) \text{ cm}^{-2} \), where \( f_{\text{c}} \) and \( T_{\text{ex}} \) are the covering factor and the excitation temperature of the absorbing gas, respectively. In our Galaxy, the column densities of OH in diffuse clouds are of the order of \( N(\text{OH}) \sim 10^{13-14} \text{ cm}^{-2} \). From the incidence (number per unit redshift, \( n_{21} \)) of H1 21 cm absorbers at 0.5 \( < z < 1 \) and assuming no redshift evolution, we estimate the incidence of OH absorbers (with \( \log N(\text{OH}) > 13.6 \)) to be \( n_{\text{OH}} = 0.008 \pm 0.008 \) at \( z \approx 0.1 \). Based on this we expect to detect 10\(^{20-20} \) such OH absorbers from the MeerKAT Absorption Line Survey (MALS). Using H1 21 cm and OH 1667 MHz absorption lines detected toward Q0248+430, we estimate \( (\Delta F/F) = (5.2 \pm 4.5) \times 10^{-6} \), where \( F \equiv g_{\text{p}}(\alpha^2/\mu)\alpha^{1.4} \). \( \alpha \) is the fine structure constant, \( \mu \) is the electron–proton mass ratio, and \( g_{\text{p}} \) is the proton gyromagnetic ratio. This corresponds to \( \Delta \alpha/\alpha(z = 0.0519) = (1.7 \pm 1.4) \times 10^{-6} \), which is among the stringent constraints on the fractional variation of \( \alpha \).

Key words: galaxies: ISM – quasars: absorption lines

1. Introduction

The hydroxyl radical (OH) was the first interstellar molecule to be detected at radio wavelengths (Weinreb et al. 1963). Since then there have been extensive surveys of OH emission and absorption from diffuse (\( N(\text{OH}) \sim 10^{13-14} \text{ cm}^{-2} \)) and dense (\( N(\text{OH}) \sim 10^{15-16} \text{ cm}^{-2} \)) interstellar clouds in the Galaxy (e.g., Dickey et al. 1981; Wannier et al. 1993; Li et al. 2018), and along with HCO\(^+\), it has emerged as one of the best indicators of H\(_2\) column densities (Liszt & Lucas 1999). It is most commonly observed in 18 cm ground-state transitions that occur at rest frequencies of 1665.402 and 1667.359 (main lines), and 1612.231 and 1720.530 MHz (satellite lines). The relative strengths of these lines are rarely found to be in the local thermodynamic equilibrium (LTE) ratios, i.e., \( 1612:1665:1667:1720 \text{ MHz} = 1.5:9:1 \). They often exhibit maser emission in regions associated with high-density and far-infrared (FIR) radiation (Cohen 1995).

OH megamasers (OHMs), being good tracers of extreme starburst activity and merger history, have also been extensively surveyed in luminous infrared galaxies, and already been detected up to \( z = 0.265 \) (e.g., Baan 1989; Darling & Giovanelli 2002; Fernandez et al. 2010). Furthermore, the detection of main lines and the so-called conjugate behavior of the satellite lines have been reported toward a handful of radio-bright active galactic nuclei (AGNs; e.g., van Langevelde et al. 1995; Darling 2004).

But OH has been very rarely searched in normal star-forming galaxies (e.g., Borthakur et al. 2011; Zwaan et al. 2015). Specifically, from the literature there is only one sight line, 4C +57.23 (Zwaan et al. 2015), which satisfies the selection criteria of the study presented here. To date, only three intervening OH absorbers at \( z > 0 \) are known: (i) J0134−0931 (\( z = 0.765; \) Kanekar et al. 2005); (ii) B0218+357 (\( z = 0.685; \) Chengalur & Kanekar 2003); and (iii) PKS 1830−211 (\( z = 0.886; \) Chengalur et al. 1999). These have led to some of the most stringent (\(< 10^{-5} \)) constraints on the fractional variations of fundamental constants of physics (Uzan 2011). In all three cases, the absorbing gas is from a lensing galaxy and the \( N(\text{OH}) \sim 10^{15-16} \text{ cm}^{-2} \), i.e., similar to dense molecular clouds in the Galaxy.

In this Letter, we report the first survey of OH main-line absorption from cold atomic gas, as revealed by H1 21 cm absorption (Heiles & Troland 2003), in a sample of \( z < 0.4 \) galaxies. Throughout this Letter we use the \( \Lambda \)CDM cosmology with \( \Omega_m = 0.27 \), \( \Omega_\Lambda = 0.73 \) and \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. Sample, Observations and Data Analysis

We used the Giant Metrewave Radio Telescope (GMRT), the Karl G. Jansky Very Large Array (VLA), and the Westerbork Synthesis Radio Telescope (WSRT) to search for OH 18 cm main lines in 9 H1 21 cm absorbers. In eight cases, the intervening 21 cm absorption originates from cold atomic gas associated with galaxies at \( z < 0.4 \). The names of background quasars and foreground galaxies that we refer to as quasar-galaxy pairs (QGPs), their redshifts, and H1 21 cm optical depths are provided in Table 1. This sample essentially represents all of the \( z < 0.4 \) H1 21 cm absorption in QGPs that were known in 2013 either from the literature or our own survey (see Dutta et al. 2017 for the latest), and considering the radio frequency interference (RFI) environment, could be observed for OH with the above-mentioned telescopes. In the case of J1443+0214, the absorption is associated with a low surface-brightness galaxy that, unlike other QGPs, is identified only via narrow optical emission lines detected on top of the
Table 1
Details of 21 cm Absorbers for OH Absorption Line Search

| Quasar          | Galaxy            | $z_e$ | $z_d$ | $\int dv(HI)$ | Referencea | Peak Flux Density (mJy beam$^{-1}$) | Spectral Resolution (km s$^{-1}$) | Spectral rms (mJy beam$^{-1}$) | $\int n_{OH} dv(OH)$b |
|-----------------|-------------------|-------|-------|---------------|------------|------------------------------------|----------------------------------|-------------------------------|------------------------|
| (1)             | (2)               | (3)   | (4)   | (5)           | (6)        | (7)                                | (8)                              | (9)                           | (10)                   |
| 3C232           | NGC3067           | 0.530 | 0.0049| 0.11          | 1          | 1563                               | 1.4                              | 1.7                           | <0.006                 |
| Q0248+430       | G0248+430         | 1.313 | 0.0519| 0.43          | 2          | 1207                               | 1.5                              | 2.1                           | 0.08 ± 0.01             |
| J084957.97      | J084958.10        | 0.584 | 0.3120| 0.95          | 3          | 200                                | 0.9                              | 3.9d, 4.4d              | <0.091                 |
| J104257.58      | J104257.74        | 2.665 | 0.0332| 0.19          | 5          | 295                                | 1.5                              | 1.5                           | <0.027                 |
| +074850.5       | +074751.3         |       |       |               |            |                                    |                                  |                               |                        |
| J124157.54      | J124157.26        | 2.625 | 0.1430| 2.90          | 6          | 67                                 | 1.6                              | 1.2                           | <0.099                 |
| +062341.6       | +063327.6         |       |       |               |            |                                    |                                  |                               |                        |
| J124355.78      | J124357.15        | 1.520 | 0.0169| 2.24          | 7          | 187                                | 1.4                              | 1.3                           | <0.035                 |
| +043438.5       | +043436.5         |       |       |               |            |                                    |                                  |                               |                        |
| J144304.53      | Emission lines    | 1.820 | 0.3714| 3.38          | 3          | 144                                | 2.0                              | 1.4                           | <0.059                 |
| +021419.3       |                   |       |       |               |            |                                    |                                  |                               |                        |
| J163956.35      | J163956.38        | 0.993 | 0.0790| 15.7          | 8          | 152                                | 1.6                              | 1.4d                          | ...                    |
| +112758.7       | +112802.1         |       |       |               |            |                                    |                                  |                               |                        |
| J094221.98      | ...               | 0.1230|       | 49.9          | 4          | 112                                | 3.3                              | 1.1d, 1.0d              | <0.070                 |
| +062335.2       |                   |       |       |               |            |                                    |                                  |                               |                        |

Notes.

a References for H I absorption data—1: Carilli & van Gorkom (1992); 2: this work; 3: Gupta et al. (2013); 4: Srianand et al. (2015); 5: Borthakur et al. (2010); 6: Gupta et al. (2010); 7: Gupta et al. (2017b); 8: Srianand et al. (2013).

b Integrated OH optical depth of 1667 MHz line or, in case of non-detections, 3σ upper limit for a spectral resolution of 2 km s$^{-1}$.

c The 3σ optical depth limit is 0.009 km s$^{-1}$.

d rms in the subband covering 1665 and 1667 MHz lines, respectively.

The QSO spectrum. We also included the associated 21 cm absorption from the merging pair J0942+0623. This is one of the strongest H I 21 cm absorbers (N(H I) $\sim 10^{22}$ cm$^{-2}$; Srianand et al. 2015), and hence, a promising candidate for molecular line search.

Five quasars, namely 3C232, Q0248+430, J1042+0748, J1241+6332, and J1243+4043, were observed with the WSRT in Maxi-short configuration in 2010 December. A baseband bandwidth of 10 MHz split into 2048 frequency channels was used. The on-source time was $\sim$10 hr per QGP. J1443+4043 was observed with the GMRT for $\sim$6 hr on 2012 June 2 using a bandwidth of $\sim$4 MHz split into 512 channels. The remaining three quasars were observed with the VLA in A or A $\rightarrow$ D configurations over 2012 October–2013 January. The WIDAR correlator was set up to split 16 subbands into 128 frequency channels. The subband widths of 0.5 MHz, 2 MHz, and 1 MHz were used for J0849+5108, J0942+0623, and J1639+1127, respectively. The total on-source time was 3–8 hr per QGP. For GMRT and WSRT observations, the same baseband covered both the main lines, whereas for VLA observations these were placed in two separate subbands.

The VLA and GMRT data were reduced using the Automated Radio Telescope Imaging Pipeline (ARTIP: Sharma et al. 2018). The WSRT data were calibrated using AIPS. The continuum and imaging line including self-calibration were performed using ARTIP. For Q0248+430, the continuum-subtracted spectral line cube was deconvolved using CLEAN down to twice the single channel noise using image masks. The OHM emission and OH 1667 MHz absorption detected from this QGP are spatially separated by 15′, and by $\sim$116 km s$^{-1}$ in velocity space. The CLEANing mask included pixels with OHM emission, and the region over which the radio continuum from the quasar is detected. We also examined the channel maps to ensure that no part of the detected signal is due to residual deconvolution errors or continuum subtraction.

The Stokes I peak flux densities of quasars are provided in Table 1. The spatial resolution of GMRT and VLA images is 2''–3''. For J1042+0748 and the remaining WSRT maps the spatial resolution is 190''×10'' and $\sim$15'', respectively. The spectral resolution and the corresponding rms values are in the range of 0.9–3.3 km s$^{-1}$ and 1.2–4.4 mJy beam$^{-1}$, respectively (see columns 8–9 of Table 1). For J1639+1127, the VLA subband covering 1667 MHz line was affected by RFI. The 3σ optical depth limit for the 1665 MHz line is 0.050 km s$^{-1}$.

3. OH Detection at $z = 0.05$: QGP 0248+430

The radio-optical overlay of this QGP is shown in Figure 1. The QSO Q0248+430 ($z_e = 1.313$) is at an angular separation of 15'' ($\sim$15 kpc at $z_e = 0.05$) from the foreground galaxy G0248+430. The latter is actually a pair of merging spiral galaxies separated by 3.5 kpc (Kollatschny et al. 1991). They are labeled as G1 and G2, respectively, in Figure 1 and constitute a rare system where optical emission lines from both the nuclei indicate non-thermal activity (Borgeest et al. 1991). The tidal tail emanating from G0248+430 has bluer colors compared to the galaxy and extends across the line of sight to Q0248+430 (see Figure 1; Borgeest et al. 1991). It also shows stellar absorption lines confirming the presence of star formation activity in the tail.
We detect OHM emission coincident with the central region of the galaxy. The OH absorption toward the background quasar is detected from the gas associated with the tidal tail.

3.1. OHM Emission in G0248+430

The optical imaging, spectroscopy, and strong FIR emission suggest that the system has undergone a very recent and strong starburst. We estimate the IR luminosity of the galaxy using the flux densities from the IRAS Far Source Catalog (Moshir et al. 1990), \( f(12 \mu m, 25 \mu m, 100 \mu m, 600 \mu m) = [<6.54 \times 10^{-2}, 0.19 \pm 0.01, 4.02 \pm 0.28, 6.92 \pm 0.42] Jy \) and the following equation from Sanders & Mirabel (1996),

\[
L_{\text{IR}}(L_{\odot}) = 5.67 \times 10^{5} D_{\odot}^{2} (13.48 f_{12} + 5.16 f_{25} + 2.58 f_{60} + f_{100}),
\]

where \( D_{\odot} \) is the luminosity distance in Mpc, to be \( L_{\text{IR}} < 5.81 \times 10^{11} L_{\odot} \).

Highly luminous IR galaxies such as G0248+430 are often associated with OHMs. Kazes et al. (1989) reported the detection of OHM from this galaxy but did not provide any detail. We present OHM emission from the galaxy in Figure 2. (see also “x” in Figure 1). Both of the main lines are detected. To separate the contributions of two hyperfine lines, we model these using multiple Gaussian components. We note that Gaussian component fitting provides a convenient measure of source/spectral structure even if they do not necessarily represent discrete physical structures. Under the assumption that both the lines originate from the same gas, the centers and widths of the components for 1665 MHz line are tied to those of the 1667 MHz line. The overall structure of the 1667 MHz line is reasonably modeled by a four-component fit. As discussed below, we believe that the remaining structure in the residuals is an artifact of the limited spatial resolution (~20 x 10 kpc^2) of the WSRT image. Therefore, we do not attempt to improve it further by adding more components. Noticeably, the components A2, C3, and D2 are barely detected and contribute only ~7% to the total integrated flux density of the 1665 MHz line (see Table 2). The integrated flux densities of the 1665 and 1667 MHz lines are 2.1 and 8.0 Jy km s\(^{-1}\) respectively. These correspond to a total OH luminosity of 860 \( L_{\odot} \). This is about a factor of 6 higher than the luminosity expected from the \( L_{\text{FIR}} - L_{\text{OH}} \) correlation (c.f. Equation 4 of Darling & Giovanelli 2002), but is not unusual or significant considering the statistical scatter in the relationship. Here, the FIR luminosity is estimated using the following equation from Sanders & Mirabel (1996)

\[
L_{\text{FIR}}(L_{\odot}) = 3.96 \times 10^{5} D_{\odot}^{2} (2.58 f_{60} + f_{100}).
\]

The hyperfine ratio of the observed 1667 to 1665 MHz line integrated flux densities is 3.8. The ratios of the flux densities of individual Gaussian components fitted to these lines are also far from the value of 1.8 expected for LTE. In general, Very Long Baseline Interferometry (VLBI) observations often resolve OHMs into multiple components (e.g., Momjian et al. 2006). The detailed modeling of these suggests that the observed differences between 1667 and 1665 MHz line ratios can be explained by the exponential amplification of the background radiation by unsaturated maser clouds overlapping in space and velocity (e.g., Parra et al. 2005; Lockett & Elitzur 2008; Willett et al. 2011).

3.2. OH Absorption from G0248+430

The presence of cold atomic gas and metals in the tidal tail emanating from G0248+430 have been inferred from H\( \text{I} \) 21 cm, Na\( \text{I} \), and Ca\( \text{II} \) absorption detections toward Q0248+430 (Womble et al. 1990; Hwang & Chioi 2004). The ratio \( N(\text{Ca}\text{II})/N(\text{Na}\text{I}) \) is similar to the values observed in the Galactic disk. Here we report the detection of OH absorption toward Q0248+430, implying the presence of molecular gas in the tidal tail. The stokes-I OH absorption spectra are shown in Figure 2. Only the 1667 MHz line is detected. The total optical depth obtained by integrating over the absorption profile is \( \tau_{1667} dv(\text{OH}) = 0.08 \pm 0.01 \text{ km s}^{-1} \). The absorption is also consistently reproduced in individual XX and YY spectra. We integrate the 1665 MHz spectrum over ~20 to +20 km s\(^{-1}\) and obtain \( \tau_{1666} dv(\text{OH}) = 0.04 \pm 0.01 \text{ km s}^{-1} \). We consider this to be a non-detection with an upper limit on the integrated optical depth, \( \tau_{\text{vd}} < 0.04 \text{ km s}^{-1} \). This will be consistent with it being subthermal or in LTE. For an optically thin cloud, the integrated OH optical depth of the 1667 MHz line is related to the OH column density \( N(\text{OH}) \) through

\[
N(\text{OH}) = 2.24 \times 10^{14} \frac{T_{\text{ex}}}{f_{\text{OH}}} \int \tau_{1667}(v) dv \text{ cm}^{-2},
\]

where \( T_{\text{ex}} \) is the excitation temperature in Kelvins, \( \tau_{1667}(v) \) is the optical depth of the 1667 MHz line at velocity \( v \), and \( f_{\text{OH}} \) is the covering factor (e.g., Liszt & Lucas 1996). For Q0248+430, adopting \( f_{\text{OH}} = 1 \), \( T_{\text{ex}} = 3.5 \text{ K} \), which is the peak of the log-normal function fitted to the \( T_{\text{ex}} \) distribution of OH absorbers observed in the Galaxy (Li et al. 2018) and \( \int \tau_{1667} dv(\text{OH}) = 0.08 \pm 0.01 \text{ km s}^{-1} \) from Table 1, we get

\[
N(\text{OH}) = (6.3 \pm 0.8) \times 10^{13} \left( \frac{T_{\text{ex}}}{3.5} \right) \left( \frac{1}{f_{\text{OH}}} \right) \text{ cm}^{-2}.
\]

This is similar to the \( N(\text{OH}) \) \( \sim 10^{13-14} \text{ cm}^{-2} \) observed in diffuse clouds in the Galaxy, but 15–500 times lower than the column densities of...
three previously known intervening OH absorbers from gravitational lenses (c.f. Section 4).

We reprocessed the archival VLA data used for H I 21 cm absorption analysis in Hwang & Chiu (2004). We measure the peak flux density to be 944 mJy beam$^{-1}$, and the total integrated 21 cm optical depth measured from the spectrum, $\int \tau_{21} dv = 0.43 \pm 0.02 \text{ km s}^{-1}$ (see Figure 2). For an optically thin cloud the $\int \tau_{21} dv$ is related to the neutral hydrogen column density $N$(H I), spin temperature $T_s$, and covering factor $f_c^{\text{HI}}$ through

$$N(\text{H} \text{ I}) = 1.823 \times 10^{18} \frac{T_s}{T_{\text{HI}}} \int \tau(v) dv \text{ cm}^{-2}. \quad (4)$$

For $f_c^{\text{HI}} = 1$, as discussed below and adopting $T_s = 70 \text{ K}$, which is the median column density weighted $T_s$ for the cold neutral medium (CNM) in our Galaxy (Heiles & Troland 2003), we get $N(\text{H} \text{ I}) = (5.5 \pm 0.3) \times 10^{11}(T_s/70)(1.0/f_c^{\text{HI}})$cm$^{-2}$. The [OH]/[H I] abundance ratio for Q0248+430 is $10^{-6}$, which, although not unusual, is about an order of magnitude higher than the typical ratio ($\sim 10^{-7}$) observed in the Galaxy (Li et al. 2018). A much larger $T_s$ ($\sim 1000 \text{ K}$), as is more commonly seen in $z > 2$ H I absorbers (Srianand et al. 2012; Kanekar et al. 2014), and/or $f_c^{\text{OH}} < 1$ would give $[\text{OH}]/[\text{H} \text{ I}]$ more in accord with Galactic observations.

In the VLBI image at 2.3 GHz, Q0248+430 is resolved into multiple components with an overall extent of 26 mas (27 pc at $z_q = 0.05$; Fey & Charloot 2000). VLBI spectroscopic observations of low-$z$ H I 21 cm absorbers show that for diffuse interstellar medium (ISM) the extent of CNM gas is $>20$ pc (Keeney et al. 2005; Gupta et al. 2017b). Therefore, it is quite likely that the H I absorber in front of Q0248+430 fully covers the radio emission i.e., $f_c^{\text{HI}} = 1$. However, the sizes of diffuse H$_2$ components associated with damped Ly$\alpha$ systems have been inferred to be $<15$ pc (Srianand et al. 2012; Noterdaeme et al. 2017), implying that probably $f_c^{\text{OH}} < 1$.

### 3.3. Variation of Fundamental Constants

As OH and H I absorption line frequencies depend differently on $\alpha$ (the fine structure constant), $\mu$ (the electron–proton mass ratio), and $g_p$ (the proton gyromagnetic ratio), relative shifts between the observed frequencies of these lines can be used to constrain the variations of these fundamental constants of physics. But this crucially requires that both the absorption lines originate from the same gas. For Q0248+430, the H I 21 cm absorption is broader compared to the OH absorption. Specifically, the 90% of the total OH and H I optical depths are contained within 30 $\pm$ 1 and 43 $\pm$ 5 km s$^{-1}$, respectively. The 1667 MHz line clearly shows two absorption components. We use two Gaussian components, X$_1$ and Y$_1$, to model it and determine the frequencies of the two peaks (Table 2). The 21 cm line has much higher signal-to-noise ratio (S/N), but the spectral resolution is coarser by a factor of four. Aside from absorption corresponding to X$_1$ and Y$_1$, the 21 cm line also has an additional absorption component at ~20 km s$^{-1}$. Therefore, we model it using three components, X$_2$, Y$_2$, and Z$_2$, with the widths of first two components fixed to X$_1$ and Y$_1$, respectively (Table 2). We note that the broad 21 cm absorption ($\sigma = 10 \pm 3$) corresponding to Z$_2$ is reported here for the first time (c.f. Figure 7 of Hwang & Chiu 2004).

We next compare redshifted frequencies of H I and OH absorption components, X$_i$ and Y$_i$, for $i$ = 1 and 2, to constrain $\Delta F/F = (z_{\text{OH}} - z_{\text{HI}})/(1 + z_{\text{OH}})$, where $F = g_p(\alpha^2/\mu)^{1/2}$ (Uzan 2011). The centers of components fitted to the OH and H I are $z_{X_1} = 0.051498 \pm 0.000007$, $z_{Y_1} = 0.051561 \pm 0.000007$, $z_{X_2} = 0.051497 \pm 0.000002$, and $z_{Y_2} = 0.051551 \pm 0.000002$. This yields for the two components $(\Delta F/F)_x = (0.95 \pm 0.3) \times 10^{-6}$ and $(\Delta F/F)_y = (9.5 \pm 6.3) \times 10^{-6}$. The weighted average...
of these provides \((\Delta F/F) = (5.2 \pm 4.5) \times 10^{-6}\). Taking the case of \(\alpha\) as it has strongest dependence on \(F\), and assuming that \(\mu\) and \(g_p\) are constant, we get \(\Delta \alpha/\alpha = (1.7 \pm 1.4) \times 10^{-6}\). This is among the stringent constraints on the variation of \(\alpha\) (Rahmani et al. 2012; Kanekar et al. 2018).

The constraints on \(\mu\) and \(g_p\) will be weaker but more importantly, here we have assumed that the components \(X\) and \(Y\) for OH and HI absorption are tracing the gas with same physical conditions and internal motions within the cloud. The same is implicitly assumed for the component \(Z\), which is only detected in the higher S/N HI spectrum. This, and the uncertainty due to \(f_{i,\text{OH}}^i = f_{i,\text{HI}}^i\) caused either by the different sizes of HI and OH clouds or the proper motion of the radio source components between the epochs of HI and OH observations, are the major unaccounted sources of errors in our analysis. More sensitive near-simultaneous observations of this absorber, especially using the VLBI, are planned to address these uncertainties.

### 4. Implications of OH Non-detections

Li et al. (2018) recently published observations of OH main lines from the Galaxy toward 44 extragalactic continuum sources. The HI and OH column densities derived by them from the Gaussian component-by-component analysis, along with the measurements from our survey, are presented in Figure 3. The top panel of Figure 3 provides detection rate \(R_{\text{Gal}}\) for different limiting values of OH and HI column densities, \(N(\text{OH})_{\text{lim}}\) and \(N(\text{HI})_{\text{lim}}\), respectively. For given values of these, \(R_{\text{Gal}}\) is estimated by determining the number of OH detections with OH and HI column densities larger than the limiting values, and dividing it by total number of sight lines with \(N(\text{HI}) \geq N(\text{HI})_{\text{lim}}\), but considering only those that are sensitive to detect OH down to \(N(\text{OH})_{\text{lim}}\). It is apparent from the figure that (i) \(R_{\text{Gal}}\) is smaller for larger \(N(\text{OH})_{\text{lim}}\), i.e., absorbers with larger \(N(\text{OH})\) are rarer. In particular, none that are similar to known absorbers from Gravitational lenses are detected, and (ii) \(R_{\text{Gal}}\) does not depend on \(N(\text{HI})_{\text{lim}}\). In general, the trends in \(R_{\text{Gal}}\) with respect to \(N(\text{OH})_{\text{lim}}\), or \(N(\text{HI})_{\text{lim}}\) can shed light on the nature of OH absorbers and the conditions in which they are likely to be detected. Due to large statistical errors we are unable to draw any substantial conclusions. At this point, these Galactic measurements provide the minimal context in which to view the detections/non-detections from our survey.

The \(N(\text{OH})\) upper limits from our sample are in the range \((0.4-7.7) \times 10^{14} \text{ cm}^{-2}\). These are sensitive to the detection of OH at the higher end of column densities observed in the diffuse ISM (refer to Galactic measurements in Figure 3). We also note that the highest \(N(\text{HI})\) absorber in our sample is a non-detection in OH. The associated AGN (J0942+0632) in this case is resolved into multiple components extending over 89 pc (Srianand et al. 2015). The OH non-detection could be
due to $f_c^{\text{OH}} < 1$, or that there is no molecular gas along the sight line.

Next we use the method used to estimate $R_{\text{Gal}}$ to obtain the detection rate, $R_{\text{det}}$, for our OH survey. For this we adopt $\log N(\text{OH})_{\text{lim}}(\text{cm}^{-2}) = 13.7$ and $\log N(\text{H})_{\text{I}} = N(\text{HI})_{\text{lim}}(\text{cm}^{-2}) = 19.0$. We estimate $R_{\text{sur}} = 1/4 = 25\%$. Note that this does not include the measurements for three gravitational lens systems that have column densities in the range of dense molecular gas. From Gupta et al. (2012), $n_{21}$ for integrated 21 cm optical depths of 0.1-0.5 km s$^{-1}$ are available. We note that for 70K, 0.1 km s$^{-1}$ corresponds to $\log N(\text{H})_{\text{c}}(\text{cm}^{-2}) = 19.1$. Adopting $n_{21}(0.5 < z < 1) = 0.03^{+0.03}_{-0.02}$ from Gupta et al. (2012) for $\log N(\text{H})_{\text{I}} > N(\text{HI})_{\text{lim}}(\text{cm}^{-2}) = 19.0$ and assuming no redshift evolution in $n_{21}$, we get the number per unit redshift range of OH absorbers, $n_{\text{OH}} = R \times n_{21} = 0.008^{+0.008}_{-0.008}$.

Although they have been derived for somewhat arbitrarily chosen limiting values of $N(\text{H})_{\text{I}}$ and $N(\text{OH})$ to include most of the measurements from our survey, the adopted limits are relevant for the upcoming MeerKAT Absorption Line Survey (MASS: Gupta et al. 2017a) which will have the sensitivity to detect cold atomic and molecular gas with $N(\text{H})_{\text{I}} > 10^{19}$ cm$^{-2}$ and $N(\text{H})_{\text{I}} > 10^{14}$ cm$^{-2}$. Based on the derived $n_{\text{OH}}$ and the total MALS redshift path of $\sim$1000 toward on-axis (primary) strong radio sources, we expect to detect $10^{-2} - 10^{-3}$ OH absorbers from the diffuse ISM of external galaxies.

5. Concluding Remarks

We have used GMRT, VLA, and WSRT to perform the first survey of OH absorption from cold atomic gas in galaxies. The survey has led to first detection of OH from diffuse molecular gas ($N(\text{OH}) \sim 10^{13-14}$ cm$^{-2}$) at $z > 0$. This absorber is the first to enable further detailed studies through VLBI spectroscopy to improve our understanding of the physical extent of both cold atomic and molecular gas, and also the first to directly address the systematics affecting the constraints on fundamental constants of physics through radio absorption lines. The three previously known intervening OH absorbers are at higher $z$ and, due to unavailability of suitable low-frequency receivers, cannot be observed through VLBI spectroscopy. A substantial number of OH absorbers may be detected from large surveys with Square Kilometer Array (SKA) pathfinders, allowing these to be used as an effective tool to probe complex gas physics and variations of fundamental constants. The majority of radio absorption line surveys up to this point have been based on sight lines from optical spectroscopic surveys, which are biased against dust. They are indeed tracing diffuse ISM. This will change with upcoming blind radio absorption line surveys, which will trace both diffuse and dense ISM. The results from the survey presented here will still be applicable to the part of the survey(s) tracing dense ISM.

We thank the referee for useful comments. N.G., P.N., P.P.J., and R.S. acknowledge support from the Indo-French Centre for the Promotion of Advanced Research under Project 5504-B. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. The VLA is run by the National Radio Astronomy Observatory which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. WSRT is operated by the ASTRON (Netherlands Institute for Radio Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO). This paper makes use of ARTIP—the Automated Radio Telescope Imaging Pipeline developed by IUCAA (http://www.iucaa.in/) and ThoughtWorks (https://www.thoughtworks.com/).