Molecular gas at intermediate redshifts

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Abstract. We present Giant Metrewave Radio Telescope (GMRT) observations of OH absorption in B3 1504+377 ($z \sim 0.673$) and PKS 1413+135 ($z \sim 0.247$). OH has now been detected in absorption towards four intermediate redshift systems, viz. the lensing galaxies towards B 0218+357 ($z \sim 0.685$; Kanekar et al. 2001) and 1830-211 ($z \sim 0.886$; Chengalur et al. 1999), in addition to the two systems listed above. All four systems also give rise to well studied millimetre wavelength molecular line absorption from a host of molecules, including HCO+. Comparing our OH data with these millimetre line transitions, we find that the linear correlation between $N_{\text{OH}}$ and $N_{\text{HCO+}}$ found in molecular clouds in the Milky Way (Liszt & Lucas 1996) persists out to $z \sim 1$. It has been suggested (Liszt & Lucas 1999) that OH is a good tracer of H$_2$, with $N_{\text{H}_2}/N_{\text{OH}} \approx 10^7$ under a variety of physical conditions. We use this relationship to estimate $N_{\text{H}_2}$ in these absorbers. The estimated $N_{\text{H}_2}$ is $\gtrsim 10^{22}$ in all four cases and substantially different from estimates based on CO observations.

Key words. galaxies: evolution – galaxies: formation – galaxies: ISM – cosmology: observations – radio lines: galaxies

1. Introduction

Molecular hydrogen (H$_2$) is the primary constituent of the molecular component of the interstellar medium and plays a crucial role in determining the evolution of the ISM as well as the star formation rate in galaxies. For example, in the Milky Way, $M_{\text{H}_2} \sim 5 \times 10^6 M_\odot$, comparable to the mass of the atomic component. Since it is difficult to directly detect H$_2$, its column density, $N_{\text{H}_2}$, is usually inferred from observations of other species; these are referred to as tracers of H$_2$ (see e.g. Combes 1999 for a review). The most commonly used tracer of H$_2$ is CO, which is the second most abundant molecule in the ISM. Unfortunately, despite the widespread use of CO as a tracer of H$_2$, deducing $N_{\text{H}_2}$ from CO observations remains a fairly tricky exercise (see e.g. Liszt & Lucas 1998, for a discussion).

The OH column density is known to correlate with the visual extinction $A_V$ and, hence, with the total hydrogen column density, $N_H$ (Crutcher 1979, Lucas & Liszt 1996 and Liszt & Lucas 1998, 1999) examined the variation of OH and other species (including H$_2$CO, HCN, HNC and C$_2$H) with HCO$^+$ and found that most molecules (except OH) showed a non-linear dependence on $N_{\text{HCO+}}$, with a rapid increase in their abundances at $N_{\text{HCO+}} \approx 10^{12}$ cm$^{-2}$. However, $N_{\text{OH}}$ and $N_{\text{HCO+}}$ were found to have a linear relationship extending over more than two orders of magnitude in $N_{\text{HCO+}}$ (Liszt & Lucas 1996), with

$$\frac{N_{\text{HCO+}}}{N_{\text{OH}}} \approx 0.03.$$  \hfill (1)

Further, the relative abundances of OH and HCO$^+$ to H$_2$ and each other were found to be constant in a variety of galactic clouds (Liszt & Lucas 1999), with $N_{\text{OH}}/N_{\text{H}_2} \approx 1 \times 10^{-7}$. Based on these observations, Liszt & Lucas (1999) suggested that OH and HCO$^+$ were good tracers of H$_2$.

There are presently four known molecular absorption line systems at intermediate redshifts ($z \sim 0.25–0.9$) with detected HCO$^+$ (Wiklind & Combes 1995, 1996a, 1996b, 1997). Until recently, OH absorption had been detected in only one of these objects, the $z \sim 0.886$ absorber towards PKS 1830-211 (Chengalur et al. 1999). We have now carried out a deep search for redshifted OH absorption in the remaining three absorbers with the GMRT, resulting in detections of absorption in all cases. In this letter, we describe our GMRT observations of two of these absorbers, viz. PKS 1413+135 ($z = 0.2467$) and B3 1504+377 ($z = 0.6734$); the OH observations of B 0218+357 are discussed in Kanekar et al. (2001). We also compare the OH column densities obtained in the four absorbers with their HCO$^+$ column densities and find that the linear relationship between OH and HCO$^+$ found in the Milky Way persists out to moderate redshifts. Finally, we use the conversion factor suggested by Liszt & Lucas (1999) to estimate...
\( N_{\text{H}_2} \) in all these absorbers. Throughout this paper, we use \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0.5 \).

2. Observations and Data analysis

The GMRT observations of PKS 1413+135 and B3 1504+377 were carried out in June and October 2001, using the standard 30-station FX correlator. This provides a fixed number of 128 spectral channels over a bandwidth which can be varied between 64 kHz and 16 MHz. We used a 4 MHz bandwidth for B3 1504+377, thus including both the 1665 and 1667 MHz OH transitions in the same band and yielding a resolution is \( \sim 9.4 \text{ km s}^{-1} \). However, in the case of PKS 1413+135, the HCO\(^+\) and other millimetre lines have very narrow widths. We hence used a bandwidth of 1 MHz and only observed the 1667 MHz transition (the stronger of the two lines, in thermal equilibrium), with a resolution of \( \sim 1.75 \text{ km s}^{-1} \). The standard amplitude calibrators 3C48, 3C286 and 3C295 were used for both absolute flux and system bandpass calibration in both cases. No phase calibration was necessary as both PKS 1413+135 and B3 1504+377 are unresolved on even the longest baselines of the GMRT. Only thirteen and seventeen antennas were used for the final spectra of B3 1504+377 and PKS 1413+135, respectively, due to various maintenance activities and debugging; the total on-source times were 6 hours and 5.5 hours respectively.

The data were analysed in AIPS using standard procedures. Continuum emission was subtracted using the AIPS task UVLIN; spectra were then extracted in both cases by simply averaging the source visibilities together, using a fixed number of 128 spectral channels over a bandwidth of 1 MHz, which can be varied between 64 kHz and 16 MHz. We used a 4 MHz bandwidth for B3 1504+377, thus including both the 1665 and 1667 MHz OH transitions in the same band and yielding a resolution is \( \sim 9.4 \text{ km s}^{-1} \). However, in the case of PKS 1413+135, the HCO\(^+\) and other millimetre lines have very narrow widths. We hence used a bandwidth of 1 MHz and only observed the 1667 MHz transition (the stronger of the two lines, in thermal equilibrium), with a resolution of \( \sim 1.75 \text{ km s}^{-1} \). The standard amplitude calibrators 3C48, 3C286 and 3C295 were used for both absolute flux and system bandpass calibration in both cases. No phase calibration was necessary as both PKS 1413+135 and B3 1504+377 are unresolved on even the longest baselines of the GMRT. Only thirteen and seventeen antennas were used for the final spectra of B3 1504+377 and PKS 1413+135, respectively, due to various maintenance activities and debugging; the total on-source times were 6 hours and 5.5 hours respectively.

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The final GMRT 4 MHz spectrum towards B3 1504+377 is shown in Fig. 1[A]. No smoothing has been applied; the RMS noise is 1.3 mJy per 9.4 km s\(^{-1}\) channel. Two absorption lines can be clearly seen in the spectrum, centred at heliocentric frequencies of 1337.404 MHz. This can be identified with the 1667.359 MHz OH line, with a redshift \( z = 0.24671 \pm 0.00001 \). The peak optical depth is 0.49 %.

3. Discussion

For an optically thin cloud in thermal equilibrium, the OH column density of the absorbing gas \( N_{\text{OH}} \) is related to the excitation temperature \( T_x \) and the 1667 MHz optical depth \( \tau_{1667} \) by the expression (e.g. \cite{Liszt & Lucas 1990})

\[
N_{\text{OH}} = 2.24 \times 10^{14} \left( \frac{T_x}{f} \right) \int \tau_{1667} dV ,
\]

where \( f \) is the covering factor of the absorber. In the above, \( N_{\text{OH}} \) is in \( \text{cm}^{-2} \), \( T_x \) in K and \( dV \) in \( \text{km s}^{-1} \). VLBI observations, when available, can be used to constrain the extent of the background radio continuum, and hence to estimate the covering factor \( f \). Unfortunately, the OH excitation temperature \( T_x \) cannot be directly estimated, for cosmologically distant objects. In the Galaxy, OH emission studies have shown that this temperature may be as low as \( T_x \sim T_{\text{CMB}} + 1 \text{ K} \), with similar values for the HCO\(^+\) line \((T_x (\text{HCO}^+) \sim T_{\text{CMB}})\); \cite{Lucas & Liszt 1990}. However, the excitation temperatures of the redshifted HCO\(^+\) lines in three of the four absorbers have been found to be higher than \( T_{\text{CMB}} \). OH excitation temperature; it is thus quite likely that the OH excitation temperature too will be higher in these systems. Given that all four absorption systems are believed to originate in spiral disks or in late-type galaxies \cite{Lehár et al. 2000}, these widths are similar to those in spirals disks or in late-type galaxies \cite{Lehár et al. 2000}. We note that millimetre wave molecular absorption has also been detected at \( z = 0.67343 \), in good agreement with that of the HI \((z = 0.67340; \cite{Carilli et al. 1997})\); however, the molecular absorption seen in the millimetre wave bands peaks about 15 km s\(^{-1}\) away, at \( z = 0.67335 \) \cite{Wiklind & Combes 1996a}. The integrated optical depths of the OH lines are \( \int \tau_{1665} dV = 0.257 \text{ km s}^{-1} \) and \( \int \tau_{1667} dV = 0.448 \text{ km s}^{-1} \). We note that millimetre wave molecular absorption has also been detected at \( z = 0.67150 \) \cite{Wiklind & Combes 1996a}; the 1665 MHz OH line corresponding to this redshift arises at a heliocentric frequency of 996.352 MHz, and may thus overlap with the 1667 MHz line of the \( z = 0.67343 \) absorber. We will hence use the integrated optical depth in the 1665 MHz line of the \( z = 0.67343 \) absorber to evaluate its OH column density (assuming thermal equilibrium, i.e. \( \int \tau_{1667} dV / \int \tau_{1665} dV = 1.8 \)). The integrated 1665 MHz optical depth then yields an OH column density \( N_{\text{OH}} = 1.04 \times (T_x/f) \times 10^{14} \text{ cm}^{-2} \). Carilli et al. (1997) estimate \( f \geq 0.46 \), from VLBI observations at
1.6 and 5 GHz, with the lower value obtained if only the compact core of the radio continuum (size ≈ 7.2 pc) is covered by the absorbing cloud. On the other hand, \( f = 0.74 \), if the radio jet of the source is also covered; this would require a cloud of size greater than ≈ 54 pc. Typical sizes of Giant Molecules in the Milky Way range from 10 to 50 pc (Blitz 1990); we will hence use a covering factor \( f = 0.46 \) in the analysis. This yields \( N_{\text{OH}} = 2.3 \times 10^{15} (T_{\text{r}}/10)(0.46/f) \) cm\(^{-2}\).

PKS 1413+135 : The redshift of the OH absorption towards PKS 1413+135 is in excellent agreement with that of the millimeter absorption \( (z = 0.24671; \text{Wiklind} \& \text{Combes 1997)} \). The width of the 1667 MHz line is also quite narrow, with a total spread \( \sim 14 \) km s\(^{-1}\) (slightly wider than the mm lines of Wiklind \& Combes 1997), which have a total spread \( \lesssim 10 \) km s\(^{-1}\); the integrated optical depth is \( \tau_{1667} = 0.023 \pm 0.001 \) km s\(^{-1}\). Equation \( 2 \) then yields an OH column density \( N_{\text{OH}} = 0.51 \times (T_{\text{r}}/f) \times 10^{14} \) cm\(^{-2}\).

### Table 1. Summary of OH absorption studies

| Source        | \( z_{\text{abs}} \) | \( N_{\text{OH}} \) \( \times 10^{15} \) cm\(^{-2}\) | \( N_{\text{HCO+}} \) \( \times 10^{13} \) cm\(^{-2}\) | \( N_{\text{HCO+}} \) \( \times 10^{13} \) cm\(^{-2}\) | \( N_{\text{H}_2} \) \( \times 10^{14} \) cm\(^{-2}\) | \( N_{\text{H}_2} \) \( \times 10^{14} \) cm\(^{-2}\) | \( A_V \) |
|---------------|----------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|------|
| PKS 1413+135  | 0.24671              | 1.16                            | 3.5                             | 2.9                             | 1.16                            | 0.04                            | 17.8 |
| B3 1504+377   | 0.67343              | 2.3                             | 6.9                             | 9.4                             | 2.3                             | 0.12                            | 27.1 |
| B 0218+357    | 0.68468              | 2.65                            | 7.8                             | 7.4                             | 2.65                            | 4.0                             | 28.9 |
| PKS 1830-211  | 0.88582              | 11.38                           | 34.2                            | 40                              | 11.38                           | 4.0                             | 123.2 |

* Obtained using equation \( 1 \).
† Actual measured HCO\(^{+}\) column densities, from Wiklind \& Combes 1995, 1996a, 1997, 1998 and Menten et al. 1999.
‡ Obtained using \( N_{\text{H}_2} = 1.0 \times 10^{17} \times N_{\text{OH}} \).
* Estimated from CO observations, from Wiklind \& Combes 1996a, 1996b, 1997, 1999.
We also evaluate $N_{\text{OH}}$ for the other two high redshift molecular absorbers in which OH absorption has been detected, towards B 0218+357 and PKS 1830-211 (Chengalur et al. 1999, Kanekar et al. 2001). In the case of PKS 1830-211, the integrated optical depth in the 1667 MHz line is $\int \tau_{1667} dV = 1.83 \text{ km s}^{-1}$; i.e. $N_{\text{OH}} = 4.1 \times 10^{14}(T_x/10)(0.36/f)$ cm$^{-2}$. The millimetric absorption is known to occur only towards the south-west component of the background source, which contains $\sim 36$% of the radio flux (Wiklind & Combes 1999); the covering factor is thus likely to be $f \sim 0.36$. We then obtain (again using $T_x = 10$ K) $N_{\text{OH}} = 11.4 \times 10^{15}(T_x/10)(0.36/f)$ cm$^{-2}$. Similarly, the integrated optical depth in the 1667 MHz line is $\int \tau_{1667} dV = 0.772 \text{ km s}^{-1}$, in the case of the $z = 0.6846$ absorber towards B 0218+357 (Kanekar et al. 2001); thus, $N_{\text{OH}} = 1.1 \times 10^{14} \times (T_x/f)$ cm$^{-2}$. Carilli et al. (1993) estimate the covering factor to be $f \sim 0.4$, assuming that only component A of the background continuum is covered by the absorbing cloud. The latter is reasonable since it is known that the millimetric absorption also only occurs against this component (Wiklind & Combes 1993). The OH column density is then $N_{\text{OH}} = 2.65 \times 10^{14}(T_x/10)(0.4/f)$ cm$^{-2}$.

Figure [1] shows a plot of the OH column density versus the HCO$^+$ column density for the four absorbers of our sample. The dotted line is the relationship found in the Milky Way. All four systems lie close to this line; the linear relationship between OH and HCO$^+$ column densities, seen in Galactic molecular clouds, appears to persist out to absorbers at intermediate redshift, with $N_{\text{HCO}^+} \approx 0.03 \times N_{\text{OH}}$. One may thus be able to use OH absorption lines to trace the H$_2$ content of molecular clouds at cosmological distances; all four absorbers of our sample have $N_{\text{H}_2} \gtrsim 10^{22}$ cm$^{-2}$.

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In summary, we find that the linear relationship between OH and HCO$^+$ column densities, seen in Galactic molecular clouds, appears to persist out to absorbers at intermediate redshift, with $N_{\text{HCO}^+} \sim 18$, although still somewhat smaller than that obtained from the deficit of soft X-rays ($A_V \gtrsim 30$; Stocke et al. 1992).
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