A BLIND GREEN BANK TELESCOPE MILLIMETER-WAVE SURVEY FOR REDSHIFTED MOLECULAR ABSORPTION

N. Kanekar¹, A. Gupta¹,², C. L. Carilli¹, J. T. Stocke⁴, and K. W. Willett⁵

¹ National Centre for Radio Astrophysics, TIFR, Ganeshkhind, Pune 411007, India; nkanekar@ncra.tifr.res.in
² Indian Institute of Science Education and Research, Mohali 140306, India
³ National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM 87801, USA
⁴ CASA, Department of Astrophysical and Planetary Sciences, University of Colorado, 389-UCB, Boulder, CO 80309, USA
⁵ School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455, USA

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ABSTRACT

We present the methodology for “blind” millimeter-wave surveys for redshifted molecular absorption in the CO/HCO⁺ rotational lines. The frequency range 30–50 GHz appears optimal for such surveys, providing sensitivity to absorbers at \( z \gtrsim 0.85 \). It is critical that the survey is “blind,” i.e., based on a radio-selected sample, including sources without known redshifts. We also report results from the first large survey of this kind, using the Q-band receiver on the Green Bank Telescope (GBT) to search for molecular absorption toward 36 sources, 3 without known redshifts, over the frequency range 39.6–49.5 GHz. The GBT survey has a total redshift path of \( \Delta z \approx 24 \), mostly at \( 0.81 < z < 1.91 \), and a sensitivity sufficient to detect equivalent H₂ column densities \( \gtrsim 3 \times 10^{21} \text{ cm}^{-2} \) in absorption at 5σ significance (using CO-to-H₂ and HCO⁺-to-H₂ conversion factors of the Milky Way). The survey yielded no confirmed detections of molecular absorption, yielding the 2σ upper limit \( n(z = 1.2) < 0.15 \) on the redshift number density of molecular gas at column densities \( N(\text{H}_2) \gtrsim 3 \times 10^{21} \text{ cm}^{-2} \).

Key words: galaxies: high-redshift – molecular processes – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

Molecular gas is an important constituent of the interstellar medium, playing a critical role in galaxy evolution via its influence on star formation. However, little is known about the cosmological evolution of molecular gas in galaxies. This is primarily due to the difficulty in detecting molecular hydrogen, \( \text{H}_2 \), the dominant molecular species. Tracers of \( \text{H}_2 \) like CO, HCO⁺, and OH (e.g., Liszt & Lucas 1996; Kanekar & Chengalur 2002; Burgh et al. 2007) hence offer the best means to first detect, and then study evolution in, the molecular phase.

Emission studies of molecular gas in redshifted galaxies have mostly been carried out using CO transitions. Such studies have provided interesting information on massive objects, the submillimeter galaxies, BzK galaxies, and high-z quasars (e.g., Carilli & Walter 2013). However, the fact that emission line strengths fall like the inverse square of the luminosity distance has meant that it has so far been difficult to detect CO emission in “normal” galaxies (e.g., Wagg et al. 2009; Wagg & Kanekar 2012), except for highly lensed systems (e.g., Baker et al. 2004; Riechers et al. 2010).

In contrast to emission surveys, the sensitivity of surveys for molecular absorption against active galactic nuclei (AGNs) does not decrease with redshift. Absorption-selected galaxies are thus more likely to be representative of the normal galaxy population. The bulk of the molecular phase in typical galaxies at any redshift is also likely to be excitationally cold and easier to detect in absorption. Molecular absorption studies can also provide important probes of cosmological evolution. The wealth of radio rotational lines allows detailed characterization of physical and chemical conditions in the absorbing gas (e.g., Henkel et al. 2005, 2008; Bottinelli et al. 2009). The relative strengths of different absorption transitions of species like \( \text{H}_2\text{CN} \), where the excitation is dominated by the cosmic microwave background (CMB), can be used to determine the CMB temperature (e.g., Henkel et al. 2009; Muller et al. 2013). Comparisons between the redshifts of different molecular (and atomic) transitions in an absorber can be used to test for cosmological evolution in the fundamental constants of physics (e.g., Drinkwater et al. 1998; Kanekar et al. 2010, 2012; Kanekar 2011; Bagdonaite et al. 2013).

Searches for molecular absorption at high redshifts, \( z > 1 \), have so far been mostly carried out via optical absorption spectroscopy, targeting the redshifted ultraviolet \( \text{H}_2 \) lines in damped Lyα systems (DLAs; e.g., Wolfe et al. 2005). Such studies have obtained detection fractions of \( \approx 15\% \) for DLAs at \( z > 1.8 \), with very low derived H₂ fractions, \( f = [2N(\text{H}_2)]/[2N(\text{H}_2) + N(\text{H}_1)] \approx 10^{-6}–0.1 \) (e.g., Ledoux et al. 2003; Noterdaeme et al. 2008), with typical limits of \( f \lesssim 10^{-5} \). These results are not very surprising as a high molecular hydrogen column density would imply the presence of a large amount of dust, which would obscure the background quasar at ultraviolet and optical wavelengths, making it very hard to even determine the quasar redshift, let alone detect absorption features in the spectrum.

Surveys for molecular absorption must hence be carried out at radio wavelengths, to ensure no bias against dusty sightlines. An unbiased radio absorption survey would provide a census of molecular absorbers as a function of redshift, allowing one to study the evolution of the cosmological mass density in molecular gas, as has been possible for atomic gas through optical surveys for DLAs (e.g., Wolfe et al. 1986). Unfortunately, the narrow fractional bandwidth hitherto accessible to radio spectrometers has made it difficult to carry out such surveys for molecular absorption. As a result, only five radio molecular absorbers are currently known at cosmological distances, all at \( z < 0.9 \) (Wiklind & Combes 1995, 1996a, 1996b, 1997; Kanekar et al. 2005). Four of these were detected in targeted searches, usually based on the redshift of \( \text{H}_1 \) 21 cm absorption (e.g., Carilli et al. 1992, 1993; Kanekar & Briggs 2003). The \( z \approx 0.886 \) system toward PKS1830–21 remains the
only molecular absorber found via a blind search (Wiklind & Combes 1996b). In this paper, we report the first large “blind” survey for redshifted molecular absorption, using the wide-bandwidth capabilities of the AutoCorrelation Spectrometer (ACS) on the Green Bank Telescope (GBT).

2. A RADIO SURVEY FOR MOLECULAR ABSORPTION

The redshift sensitivity of an absorption survey is quantified by the redshift path density \( g(z) \), defined so that \( g(z)dz \) gives the number of sightlines for which optical depths above the threshold sensitivity would have been detected in the interval \( z \) to \( z + dz \) (e.g., Lanzetta et al. 1991). The total survey redshift path is given by \( \Delta z = \int_0^\infty g(z)dz \), essentially the sum over the redshift ranges for each target over which the survey is capable of detecting absorption. The primary goal in an absorption survey is to maximize \( \Delta z \) for detectable absorption, at a given sensitivity to column density or optical depth (e.g., Wolfe et al. 1986).

A radio molecular absorption survey is best done using the strong rotational lines of CO (at \( \approx 115, 230, 345, \ldots \) GHz), and HCO\(^+\) (at \( \approx 89, 178, 267, \ldots \) GHz). While CO is far more abundant (by about a factor of 1000) than HCO\(^+\) in the interstellar medium, the HCO\(^+\) rotational lines have a higher Einstein-A coefficient than the corresponding CO rotational lines, implying that the HCO\(^+\) optical depth along a sightline is typically about an order of magnitude lower than the CO optical depth. The efficiency of a millimeter-wave molecular absorption survey is thus significantly increased because observations covering a given frequency range are sensitive to absorption in multiple redshift ranges, corresponding to the different CO and HCO\(^+\) transitions. For example, an observing frequency of 40 GHz corresponds to redshifts \( z \approx 1.22 \) (HCO\(^+\) 1–0), \( \approx 1.88 \) (CO 1–0), \( \approx 3.46 \) (HCO\(^+\) 2–1), etc. One can thus choose the observing frequency band so as to maximize the redshift range toward a background source, thus increasing the survey efficiency. Taking into account the frequency dependence of the atmospheric opacity, the best observing frequency range for a radio molecular absorption survey appears to be \( \approx 31–49 \) GHz. This would be sensitive to absorption in the redshift ranges \( 0.82 < z < 1.88 \) (HCO\(^+\) 1–0), \( 1.35 < z < 2.72 \) (CO 1–0), \( 2.64 < z < 4.75 \) (HCO\(^+\) 2–1), \( 3.70 < z < 6.44 \) (CO 2–1), etc. In other words, a survey covering 31–49 GHz would be able to detect absorption by galaxies at all redshifts \( z \gtrsim 0.82 \) in the CO and HCO\(^+\) lines. Further, the relatively small frequency range implies fewer frequency settings per source and thus a high survey efficiency. We hence originally aimed to use the GBT Ka- and Q-band receivers and the ACS to search for redshifted absorption in the frequency range 31–49 GHz.

In passing, we note that a similar absorption survey is possible at higher frequencies, in the 2 mm or 3 mm bands (e.g., Wiklind & Combes 1996b). For example, the observing frequency range 70–110 GHz provides access to all redshifts \( z > 0 \) in the CO and HCO\(^+\) lines. However, a higher observing frequency implies both a larger frequency range (i.e., more frequency settings) to cover the same redshift path and weaker background sources. Further, using a high observing frequency would effectively target the high-J rotational lines for higher redshift absorbers. In normal galaxies, the lower CO/HCO\(^+\) rotational levels are likely to be highly populated (e.g., Fixsen et al. 1999), implying that the low-J rotational transitions should yield the strongest absorption lines. All of these indicate that the frequency range 31–49 GHz is likely to be the best for molecular absorption surveys, despite the fact that it only allows access to relatively high redshifts, \( z \gtrsim 0.8 \). One might extend the survey coverage to lower redshifts by additional observations in the 3 mm band.

3. THE TARGET SAMPLE

For a molecular absorption survey, it is critical that the target selection be based on radio criteria. This is because the sample should contain no bias against optically faint AGNs, which might be dim due to extinction by dust associated with a molecular absorber along the sightline. It would also be useful if the sample were selected from a radio survey as close to the observing frequency (\( \approx 40 \) GHz) as possible, to reduce uncertainties in the source flux density.

Unfortunately, at the time of the GBT observations (2006), there were no deep all-sky radio surveys at high frequencies, \( \approx 40 \) GHz, in the literature. We hence chose to construct our main target sample from the well known 1 Jy sample (Kühr et al. 1981). This covers the whole sky excluding the Galactic plane (i.e., \( b > 10^\circ \)) and the Magellanic clouds and is expected to be complete to a flux density of 1 Jy at 5 GHz. We restricted our targets to declinations \( \gtrsim -30^\circ \) so that all sources could be observed at a reasonable elevation at the GBT. Finally, we used redshift information from the literature to exclude all sources with redshifts \( z < 1.2 \), to ensure sufficient redshift path (\( \Delta z \gtrsim 0.35 \)) for even the lowest redshift targets. We emphasize that sources without known redshifts were retained in the sample. The survey is hence not biased against targets possibly obscured by dust and, hence, without optical redshifts. Finally, while the statistical analysis will be restricted to the 1 Jy sample, we also augmented the sample with six sources without known redshifts from the UCSD survey (Jorgenson et al. 2006). Our initial sample consisted of 113 targets, 93 with measured redshifts between \( z = 1.2 \) and \( z = 3.522 \) and 20 without known redshifts.

4. OBSERVATIONS, DATA ANALYSIS AND RESULTS

Before embarking on the GBT spectroscopy, we used the Very Large Array (VLA) in its D-configuration (proposal AK619) in 2005 to obtain 43 GHz flux densities for 86 sources of the sample. The VLA observations used 1 minute on-source integrations and two 50 MHz intermediate frequency (IF) bands, with the data analyzed in aIPS. The flux densities of the remaining 27 sources were obtained from the literature. These flux densities were used to plan the GBT spectroscopy, with observing times chosen so as to achieve relatively uniform optical depth sensitivity in the CO 1–0 and HCO\(^+\) 1–0 lines.

Our initial GBT observations (proposal 05C-043) used the Ka-band and Q-band receivers in 2006 to cover the frequency range 34–48 GHz, with bandpass calibration via position-switching on timescales of 1 minute. The Ka-band was found to have high system temperatures over 36–40 GHz, and data from both receivers were affected by variable structure in the passband that could not be calibrated out. After a number of tests of the system stability, we re-designed the survey in proposal 07C-018, using the Q-band receiver to cover the frequency range \( \approx 39–49 \) GHz. Position-switching on timescales of 1 minute was initially used for passband calibration, but this did not yield spectral baselines of the requisite quality. The second part of the survey hence used sub-reflector nodding, on timescales of 4.5 s, for passband calibration. This strategy was found to give smooth spectra over each 800 MHz ACS sub-band that could be fitted with a fifth- or sixth-order polynomial.
The final GBT observations for the absorption survey were carried out in 2008, using the ACS, three-level sampling, two polarizations, and two 800 MHz sub-bands, overlapped by 100 MHz to yield a total bandwidth of 1.5 GHz. Each 800 MHz sub-band was divided into 2048 channels, giving velocity resolutions of 4.7–5.9 km s\(^{-1}\) after Hanning smoothing. For each source, we used seven overlapping frequency settings, each with a net bandwidth of 1.5 GHz, to cover the frequency range 39.6–49.5 GHz. The large overheads from sub-reflector nodding meant that we were only able to observe 38 sources of the sample with this mode. Note that these were selected randomly from the full sample, based on whether they could be observed during the scheduled runs; as such, there was no bias towards brighter sources. The total integration times per source were 1–4 minutes, with 1.5 s records, with longer integrations on the fainter sources so as to obtain comparable optical depth sensitivity. The flux density scale was calibrated using online measurements of the system temperatures with a blinking noise diode.

The GBT data were initially analyzed in the package gbtdl, using standard procedures. Minor data editing was needed due to a few spectrometer failures. After flagging, gain and bandpass calibration, the 1.5 s records were averaged to produce fourteen 800 MHz spectra for each source (seven frequency settings per source, each with two 800 MHz ACS sub-bands), covering \(\approx 39.6–49.5\) GHz. In all, there were 532 such 800 MHz spectra (38 sources and 14 spectra per source), which were then analyzed independently, outside gbtdl.

A polynomial of the order of 3–6 was fitted to each 800 MHz spectrum (excluding edge channels), and subtracted out to produce a residual spectrum. Beginning with a third-order fit, the residuals were tested for Gaussianity, using an Anderson–Darling test (Anderson & Darling 1954). If the residuals were found to be non-Gaussian \((p < 0.0001\) in the Anderson–Darling test), the procedure was repeated after increasing the order, up to order 6. If even a sixth-order fit was found to yield non-Gaussian residuals, the spectrum was dropped from the later analysis. This approach was followed so as to avoid the possibility of fitting out possible absorption features. We verified in all cases that the fitted polynomials were smooth on scales \(\gg 100\) km s\(^{-1}\), implying that narrow absorption lines would not be affected by the fitting procedure. Ninety-four spectra were excluded due to the non-Gaussianity of the residuals after the sixth-order polynomial fit, mostly due to ACS failures and radio frequency interference (RFI), especially at the upper end of the frequency range. The rejected 94 spectra were also inspected by eye to ensure that the non-Gaussianity did not arise due to the presence of spectral features.

After the above procedure, 438 spectra were retained toward 36 targets (2 sources were entirely removed). The results are summarized in Table 1, whose columns are (1) the AGN name, (2) the AGN redshift, for sources with known redshifts, (3) the usable frequency range, after all data editing, (4) the median root-mean-square (rms) optical depth \(\tau_{\text{med}}\) over the usable frequency range, and (5) the redshift path for each source with a known redshift, summing over the three CO and HCO\(^+\) transitions. In passing, we note that two of the three sources without redshifts have barely been detected in deep Keck R-band images \((R = 24.5, 25.8)\), while the third has \(R > 26.1\) (Jorgenson et al. 2006); none are from the 1 Jy sample.

Figure 1 shows the distribution of rms optical depth noise values \(\tau_{\text{rms}}\) across the 438 spectra. All but one of the spectra have \(\tau_{\text{rms}} \leq 0.125\) per 6 km s\(^{-1}\), implying that absorbers with CO/HCO\(^+\) opacities \(\geq 0.625\) would have been detected at \(\geq 5\sigma\) significance. To ensure a relatively uniform lower limit to the sensitivity across the entire frequency (i.e., redshift) range, we chose \(\tau_{\text{rms}} = 0.125\) as the threshold rms optical depth noise, excluding the sole spectrum with a significantly higher \(\tau_{\text{rms}}\) from the statistical analysis.

The search for absorption features in the spectra with \(\tau_{\text{rms}} \leq 0.125\) was carried out at velocity resolutions of 5–50 km s\(^{-1}\), smoothing the spectra to the resolution of interest to maximize the signal-to-noise ratio. Nine features were detected at \(\geq 4\sigma\) significance, after integrating over all absorption channels, with four features detected at \(\geq 5\sigma\) significance. To examine whether these might be due to RFI, the spectra of other sources observed on the same day were inspected to test whether similar features were detected at the same frequency; this was not
The Astrophysical Journal, 782:56 (5pp), 2014 February 10

Kanekar et al.

5. DISCUSSION

The threshold sensitivity of \( \tau_{\text{rms}} = 0.125 \) implies that column densities of \( N(\text{CO}) \approx 5 \times 10^{15} \text{cm}^{-2} \) and \( N(\text{HCO}^+) \approx 6 \times 10^{12} \text{cm}^{-2} \) would have been detected at 5\( \sigma \) significance (assuming excitation temperatures of 10 K). These can be converted to equivalent H\(_2\) column densities using the Galactic conversion factors \( N(\text{CO}) \approx 3 \times 10^{-6} N(\text{H}_2) \) (valid for diffuse/translucent clouds; Burgh et al. 2007) and \( N(\text{HCO}^+) \approx 2 \times 10^{-9} N(\text{H}_2) \) (e.g., Liszt & Lucas 2000). Note that the former is the median value of the ratio \( N(\text{CO})/N(\text{H}_2) \) obtained by Burgh et al. (2007) for diffuse/translucent clouds; dark clouds are likely to have lower ratios, \( \approx 2-3 \times 10^{-3} \) (e.g., Lacy et al. 1994). The use of the lower conversion factor is a conservative approach, as the higher value would imply that lower H\(_2\) column densities would have been detectable in absorption in our spectra. We also note that the above implicitly assumes that the Galactic conversion factors, for gas at roughly solar metallicity, may be used in high redshift galaxies. Given these assumptions, any molecular gas along the survey sightlines with \( N(\text{H}_2) \gtrsim 3 \times 10^{21} \text{cm}^{-2} \) should have been detected at \( \geq 5\sigma \) significance.

Figure 2 plots the redshift path density \( g(z) \) of the present survey versus redshift for the 33 sources with known redshifts. The three peaks in \( g(z) \) are because the HCO\(^+\) 1–0, CO 1–0 and HCO\(^+\) 2–1 lines sample different redshift ranges, 0.80–1.21, 1.33–1.91 and 2.60–3.27, respectively. It is clear that \( g(z) \) peaks at \( z \approx 1.2 \); this is due to the selection criterion that the targets have either \( z \geq 1.2 \) or no known redshift.

The total survey redshift path is obtained by integrating the redshift path density over redshift, i.e., \( \Delta z = \int_{z_1}^{z_2} g(z) dz \). For the 33 sources with known redshifts, we obtain \( \Delta z \approx 24 \), for \( \tau_{\text{rms}} \leq 0.125 \) and \( N(\text{H}_2) \gtrsim 3 \times 10^{21} \text{cm}^{-2} \). For comparison, there have so far been two surveys for DLAs (with H\(_1\) column densities \( N(\text{H}_1) \gtrsim 2 \times 10^{20} \text{cm}^{-2} \)) based on complete radio-selected samples, the CORALS and UCSD surveys (Ellison et al. 2001; Jorgenson et al. 2006). These surveys were typically sensitive to absorbers at higher redshifts, \( z \gtrsim 2 \), with total redshift paths of \( \approx 55 \) and \( \approx 41 \), respectively, significantly larger than the redshift path of the present molecular absorption survey.

No molecular absorbers were detected in the present survey. Using small-number statistics (Gehrels 1986), the 2\( \sigma \) upper limit to the number of molecular absorbers in the survey redshift path (\( \Delta z \approx 24 \)) is then \( N < 3.7 \). The 2\( \sigma \) upper limit to the redshift number density of molecular absorbers with \( N(\text{H}_2) \gtrsim 3 \times 10^{21} \text{cm}^{-2} \) at the peak survey redshift of \( z \approx 1.2 \) is thus \( n(z) \approx 1.2 \approx (N/\Delta z) \lesssim 0.15 \).

It would be interesting to compare the redshift number density of molecular absorbers to the redshift number density of atomic absorbers at the same redshift. Unfortunately, there have so far been no DLA surveys using radio-selected quasar samples.
at $z < 1.6$. In fact, since the Ly$\alpha$ line is in the ultraviolet for these redshifts, the only information that we have on the redshift number density of atomic gas is from Ly$\alpha$ and H$\upalpha$ 21 cm absorption surveys of samples selected on the basis of strong Mg$\upiota$ absorption (e.g., Rao et al. 2006; Lane 2000; Kanekar et al. 2009). Surveys for DLAs based on strong Mg$\upiota$ absorption have yielded $n_{\text{DLA}}(z = 1.219) \approx 0.120 \pm 0.025$ (Rao et al. 2006) for the redshift number density of DLAs, comparable to our upper limit on the number density of molecular absorbers. However, the biases in the result of Rao et al. (2006) are not known, because (1) the sample of background quasars is not a complete radio sample, and is hence subject to dust obscuration bias, and (2) the effect of the initial Mg$\upiota$ selection is unclear. For example, the absorption cross-section appears higher at redshifts $z < 1.2$. The final survey redshift path was $\Delta z \approx 8$. We have used this approach to carry out the first DLAs found via Mg$\upiota$ selection, which is unlikely (Prochaska & Wolfe 2009).

One might use the upper limit on the redshift number density to derive an upper limit on the cosmological mass density of molecular gas as $\tau \approx 1.2$ (following the arguments used in DLA surveys; e.g., Wolfe et al. 2005). Of course, this would require one to assume that the conversion factors from CO/HCO$^+$ column densities to H$\upiota$ column densities remain unchanged with redshift, which may not be valid. In the present case, the lack of detections of molecular absorption implies that we have no information on the shape of the distribution function of the molecular gas column density; this makes such an exercise very speculative. Inferring the cosmological mass density of molecular gas as well as the relative spatial extents of the atomic and molecular gas must hence await similar surveys with a significantly larger total redshift path, with the VLA or the Atacama Large Millimeter Array.

For 13 of the 33 targets with known redshifts, indicated by a † in Table 1, the survey also covers the AGN redshift. The lack of detected molecular absorption from the AGN host galaxy indicates that little molecular gas is present in the host galaxies along the AGN sightlines. It would be interesting to probe the AGN environment by examining the absorption detection function as a function of AGN type, as has been done for redshifted H$\upiota$ 21 cm absorption (e.g., Vermeulen et al. 2003; Gupta et al. 2006). However, this too will have to await the advent of larger absorption surveys.

In summary, we present the methodology for “blind” millimeter-wave molecular absorption surveys in the redshifted CO/HCO$^+$ lines, and find that the 30–50 GHz frequency range is optimal for such surveys, covering absorbers at redshifts $z \gtrsim 0.8$. We have used this approach to carry out the first large “blind” survey for redshifted molecular absorption with the GBT, covering the frequency range 39.6–49.5 GHz, i.e., the redshift ranges 0.81–1.27, 1.33–1.91 and 2.61–3.27 in, respectively, the HCO$^+$ 1–0, CO 1–0 and HCO$^+$ 2–1 lines. Thirty-six sources were searched for absorption, 33 with known redshifts, $z \gtrsim 1.2$. The final survey redshift path was $\Delta z \approx 24$ at an optical depth threshold sensitivity of $\tau_{\text{rms}} \approx 0.125$. We obtained no confirmed detections of absorption, yielding the 2 $\sigma$ upper limit $n(z = 1.2) < 0.15$ on the redshift number density of molecular absorbers with equivalent molecular hydrogen column densities $N$(H$\upiota$) $\gtrsim 3 \times 10^{21}$ cm$^{-2}$.

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