Outflowing atomic and molecular gas at $z \sim 0.67$ towards 1504 + 377

Nissim Kanekar1* and Jayaram N. Chengalur2*

1 National Radio Astronomy Observatory, 1003 Lopezville Road, Socorro, NM 87801, USA
2 National Centre for Radio Astrophysics, Ganeshkhind, Pune 411007, India

ABSTRACT

We report the detection of OH 1667-MHz and wide H$\text{I}$ 21-cm absorption at $z \sim 0.67$ towards the red quasar 1504 + 377, with the Green Bank Telescope and the Giant Metrewave Radio Telescope. The H$\text{I}$ 21-cm absorption extends over a velocity range of $\sim 600$ km s$^{-1}$ blueward of the quasar redshift ($z = 0.674$), with the new OH 1667-MHz absorption component at $\sim -430$ km s$^{-1}$, nearly coincident with earlier detections of millimetre-wave absorption at $z \sim 0.6715$. The atomic and molecular absorption appear to arise from a fast gas outflow from the quasar, with a mass outflow rate $\dot{M} \sim 12$ M$\odot$ yr$^{-1}$ and a molecular hydrogen fraction $f_{\text{H}_2} \equiv (N_{\text{H}_2}/N_{\text{H}I}) \sim 0.2$. The radio structure of 1504 + 377 is consistent with the outflow arising as a result of a jet–cloud interaction, followed by rapid cooling of the cloud material. The observed ratio of HCO$^+$ and OH column densities is $\sim 20$ times higher than typical values in Galactic and high-$z$ absorbers. This could arise because of small-scale structure in the outflowing gas on sub-parsec scales, which would also explain the observed variability in the H$\text{I}$ 21-cm line.

Key words: galaxies: ISM – quasars: absorption lines – quasars: individual: 1504+377.

1 INTRODUCTION

The quasar 1504 + 377 is a rare case of a radio-loud active galactic nucleus (AGN) hosted by a disc galaxy (e.g. Perlman et al. 1996; Carilli et al. 1997). The flat-spectrum radio emission arises from a compact core and a one-sided jet to the south-west, with the jet axis aligned (within $\sim 15^\circ$) with the major axis of the host galaxy (Polatidis et al. 1995; Fomalont et al. 2000). The AGN is heavily reddened ($r - K = 5.1$) and was not detected in a deep $R$-band image, suggesting a high level of dust obscuration (Stickel et al. 1996). Consistent with this, strong redshifted millimetre-wave molecular absorption has been detected towards the radio source (Wiklind & Combes 1996a), with two absorption complexes at $z \sim 0.6734$ (system A) and $z \sim 0.6715$ (system B), close to the redshift of the host galaxy ($z = 0.674 \pm 0.001$: Stickel & Kühr 1994).

Besides the millimetre-wave transitions, H$\text{I}$ 21-cm, OH 1665-MHz and OH 1667-MHz absorption have all been detected from system A, with strong, wide profiles extending over a velocity range of $\gtrsim 100$ km s$^{-1}$ (Wiklind & Combes 1996a; Carilli et al. 1997; Kanekar & Chengalur 2002). In contrast, the millimetre-wave absorption in system B is quite narrow (FWHM $\sim 15$ km s$^{-1}$) and neither H$\text{I}$ 21-cm nor OH absorption has been detected at this redshift (Carilli et al. 1997, 1998). This is the only $z > 0.1$ millimetre-wave absorber that has not hitherto been detected in OH or H$\text{I}$ 21-cm absorption (Wiklind & Combes 1994, 1995, 1996a,b; Chengalur, de Bruyn & Narasimha 1999; Kanekar & Chengalur 2002; Kanekar et al. 2003), and is thus an excellent candidate for a deep search in these transitions. Besides studying physical conditions in the interstellar medium (ISM) of the QSO host, the detection of these lines would, in principle, also allow one to test for changes in the fundamental constants from $z \sim 0.67$ to the present epoch (Darling 2003; Chengalur & Kanekar 2003; Kanekar, Chengalur & Ghosh 2004). Unfortunately, the OH 1665-MHz line from $z \sim 0.6715$ lies at the same frequency as the known 1667-MHz absorption from $z \sim 0.6734$ (Kanekar & Chengalur 2002), implying that it (and the latter 1667-MHz line) cannot be used to probe fundamental constant evolution. We report here a search for the other three redshifted OH ground-state lines (at rest frequencies of 1667.3590, 1612.2310 and 1720.5299 MHz) and the H$\text{I}$ 21-cm line towards 1504 + 377 with the Giant Metrewave Radio Telescope (GMRT) and the Green Bank Telescope (GBT), resulting in the detection of OH 1667-MHz and H$\text{I}$ 21-cm absorption at $z \sim 0.6715$.

2 OBSERVATIONS AND DATA ANALYSIS

A search for the 1667- and 1720-MHz OH lines from $z \sim 0.6715$ was initially carried out with the GMRT on 2006 March 26 and 27, using the 256-channel mode of the correlator. Bandwidths of 1 and 4 MHz, centred at 997.37 and 1028.77 MHz, were used for the 1667- and 1720-MHz observations, respectively (also allowing a search for the 1720-MHz line from system A), yielding velocity resolutions of $\sim 2.3$ and $\sim 9.1$ km s$^{-1}$ after Hanning smoothing. 3C 286 was used to calibrate the flux density scale and the bandpass.

E-mail: nkanekar@aoc.nrao.edu (NK); chengalu@ncra.tifr.res.in (JNC)
shape; no secondary calibrator was observed as 1504 + 377 is a phase calibrator for the GMRT. The on-source times in the 1667- and 1720-MHz transitions were ~4.6 and ~1.3 h, respectively.

The GMRT data were analysed in ‘classic’ AIPS, using standard procedures. After initial editing to remove corrupted data, continuum images were made of the field at the two frequencies; both images yielded a flux density of ~1.04 ± 0.01 Jy for 1504 + 377. The radio continuum at each frequency was then subtracted out using the task UVLIN and the residual visibilities shifted to the heliocentric frame and imaged in all channels. The final spectra were then extracted by a cut through the spectral cubes at the location of 1504 + 377.

The GMRT observations resulted in the detection of a weak absorption feature at the expected frequency of the redshifted 1667-MHz line. To confirm this and to obtain a better H1 21-cm spectrum, we retrieved archival GBT data sets covering the redshifted H1 21-cm line (from 2003 December) and all four ground-state OH lines (from 2004 September). The H1 21-cm line was later re-observed with the GBT in 2006 November, to confirm the wide, weak absorption seen in the archival data.

The GBT observations were carried out in total-power, position-switched mode. The OH runs used four 12.5-MHz Auto-Correlation Spectrometer (ACS) bands, with 8192 channels, centred on the redshifted OH 18-cm frequencies. This allowed simultaneous coverage of all four OH 18-cm lines from both redshifts, with velocity resolutions of ~0.9 km s\(^{-1}\) after Hanning smoothing. The H1 21-cm observations of 2003 and 2006 used a single 12.5-MHz ACS band with 16 384 and 32 768 channels, respectively, giving resolutions of ~0.54 km s\(^{-1}\) (in 2003) and ~0.27 km s\(^{-1}\) (in 2006). The on-source times were 2.5 h for the OH lines and 0.3 and 1.5 h for the H1 21-cm line in 2003 and 2006, respectively.

All GBT data were analysed in DISH, the AIPS++ single-dish package, using standard procedures. After data editing and calibration, channels free of both absorption and radio frequency interference (RFI) were used to measure the continuum flux density. A second-order baseline was then fitted to each (typically 10 s) record and subtracted out during the process of calibration; the residual data were then averaged together to obtain the final spectrum for each transition. In the case of multiple observing epochs (e.g. the H1 21-cm line), the data from different runs were averaged together, after smoothing and interpolating to the same spectral resolution and frequency scale. The GBT 1720-MHz data set was affected by strong terrestrial RFI and will hence not be discussed further.

3 RESULTS

3.1 Spectra

The left-hand panel of Fig. 1 shows the final GBT H1 21-cm spectrum towards 1504 + 377, with optical depth (computed assuming a flux density of 1.04 Jy) plotted as a function of heliocentric velocity, in km s\(^{-1}\), relative to z = 0.674. This has a root-mean-square (rms) noise of 0.0032, in optical depth units, per ~0.54 km s\(^{-1}\) channel. The strong 21-cm absorption at ~−100 km s\(^{-1}\) (system A) was detected by Carilli et al. (1997); the dashed curve shows the three-Gaussian fit of Carilli et al. (1998) to their Westerbork Synthesis Radio Telescope (WSRT) spectrum (which we note, in passing, is ~15 times less sensitive than the GBT spectrum of Fig. 1). The right-hand panel of the figure shows a zoomed-in version of the spectrum, smoothed to a resolution of ~4.8 km s\(^{-1}\) to display the wide absorption tail clearly. The H1 21-cm absorption extends well beyond the absorption detected by Carilli et al. (1997, 1998), with a full width between nulls (FWBN) of ~600 km s\(^{-1}\). The new extended absorption can be separated into three distinct parts, a narrow component at ~−320 km s\(^{-1}\) (i.e. z = 0.6722), a broad feature at ~−430 km s\(^{-1}\) (nearly the same redshift as the z = 0.6715 millimetre-wave absorption of Wiklind & Combes (1996a)) and a smooth weak tail, extending out to ~−600 km s\(^{-1}\). The integrated H1 21-cm optical depth is \(\int \tau \ dv = 27.20 \pm 0.04\) km s\(^{-1}\), with around 15 per cent of the integrated optical depth in the new components detected here.

Weak narrow absorption was visible close to the expected frequency of the redshifted OH 1667-MHz line in both the GMRT and the GBT spectra (at ~5\(\sigma\) significance in each spectrum, after averaging all line channels). It is very unlikely that the absorption is due to local RFI, given that the spectra were taken at independent

Figure 1. Final GBT H1 21-cm absorption spectrum towards 1504 + 377 (left-hand panel; resolution ~0.54 km s\(^{-1}\)), with optical depth plotted against heliocentric velocity (relative to z = 0.674, the quasar redshift). The right-hand panel shows the spectrum smoothed to a resolution of ~4.8 km s\(^{-1}\) and zoomed-in. The dashed vertical line indicates z = 0.6715 while the dashed curves show the three-Gaussian fit of Carilli et al. (1998) to their WSRT spectrum.
3.2 H I and OH column densities

For optically thin gas, the H I and OH column densities can be derived from the H I 21-cm and OH 1667-MHz absorption profiles using the expressions

\[ N_{\text{HI}} = 1.823 \times 10^{18} \left( \frac{T_e}{f_{\text{HI}}} \right) \int \tau_{21} \, dV \]

and

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

where \( T_e \) (in K) is the H I spin temperature, \( T_e \) (in K) is the OH excitation temperature, and \( f_{\text{HI}} \) and \( f_{\text{OH}} \) are the H I and OH covering factors at the respective redshifted line frequencies. \( N_{\text{HI}} \) and \( N_{\text{OH}} \) have units of cm\(^{-2}\), while the integrals are over velocity, in km s\(^{-1}\).

Carilli et al. (1997) used 1.6- and 5-GHz very long baseline interferometry (VLBI) observations to estimate \( f_{\text{HI}} \) if only the radio core (of angular size \( \lesssim 1.4 \) mas) is covered, and \( f_{\text{HI}} \) = 0.74 if the inner jet is covered out to \( \sim 10 \) mas; this would require the absorbing material to have a spatial extent of \( \gtrsim 10 \) kpc and \( \gtrsim 70 \) kpc, respectively. Typical sizes of Galactic molecular clouds range from \( \sim 10 \) to 50 pc (Blitz 1990), somewhat smaller than the latter value; we will hence assume that at least the radio core is covered in both H I 21-cm and OH lines, i.e., \( f_{\text{HI}} \) \( \gtrsim 0.46 \) and \( f_{\text{OH}} \) \( \gtrsim 0.46 \).

Next, it is not possible to determine either \( T_e \) or \( T_e \) using only the H I 21-cm or OH 1667-MHz absorption profiles. Spin temperature estimates range from \( \sim 100 \) K in the Galaxy and local and intermediate-redshift spiral discs (e.g., Braun & Walterbos 1992) to \( \gtrsim 1000 \) K in high-redshift damped Lyman \( \alpha \) systems (Kanekar & Chengalur 2003). Assuming \( T_e \) = 100 K gives a lower limit to the H I column density. Further, following Kanekar & Chengalur (2002), we will assume \( T_e \) \( \sim 10 \) K, a typical temperature in dark clouds. We then obtain \( N_{\text{HI}} \) \( \gtrsim 1.08 \pm 0.15 \times 10^{21} \) cm\(^{-2}\) and \( N_{\text{OH}} \) \( \sim 3.26 \pm 0.15 \times 10^{22} \) cm\(^{-2}\). It should be emphasized that the above H I column density is for the entire profile, i.e., is not restricted to the absorption from system B, while the OH column density is merely for this system. Finally, we use the empirical relation \( N_{\text{HI}} \sim 10^5 \times N_{\text{OH}} \) (Liszt & Lucas 1999) to estimate the molecular hydrogen column density to be \( N_{\text{HI}} \sim 3.3 \times (T_e/100)(0.46/f_{\text{HI}}) \times 10^{21} \) cm\(^{-2}\) for system B. System A has \( N_{\text{HI}} \sim 2.3 \times (T_e/10)(0.46/f_{\text{HI}}) \times 10^{22} \) cm\(^{-2}\) (Kanekar & Chengalur 2002), giving a total H I column density of \( N_{\text{HI}} \sim 2.6 \times (T_e/10)(0.46/f_{\text{HI}}) \times 10^{23} \) cm\(^{-2}\) at \( z \approx 0.67 \).

4 DISCUSSION

4.1 Variability in the H I 21-cm profile

Fig. 3 shows a plot of the difference between the H I 21-cm optical depths in 2003 and 2006 versus heliocentric velocity, in km s\(^{-1}\), relative to \( z \approx 0.674 \). The strong features in the difference spectrum are \( \sim -100 \) and \( \sim 70 \) km s\(^{-1}\), indicating significant changes (~10% of the line depth) in the H I 21-cm profile between 2003 and 2006. Note that the difference cannot be due to a simple scaling of one or both of the spectra, as different spectral components show changes of opposite sign. While the possibility that the observed change might be due to RFI cannot be ruled out, no evidence was seen for RFI at these frequencies, in either these or our other 850-MHz GBT data sets. The profile ‘variability’ is coincident with the strongest spectral components, with the rest of the profile showing no evidence for changes within the noise.

Variability in redshifted H I 21-cm profiles has been seen earlier in two damped Lyman \( \alpha \) systems, at \( z \approx 0.524 \) towards 0235 + 164 (Wolfe et al. 1982) and \( z \approx 0.3127 \) towards 1127 – 145 (Kanekar & Chengalur 2001). While changes in the latter two profiles have been detected on far shorter time-scales (a few days) than in 1504 + 377, it is interesting that all three sources contain highly compact (~mas-scale) components. Possible explanations for the observed changes towards 1504 + 377 include refractive scintillation in the...
Galactic interstellar medium (for which the background source need not be compact: Macquart 2005), or transverse motion of a source component on VLBI scales (Briggs 1983). Both models require small-scale structure in the 21-cm optical depth of the absorbing gas.

4.2 Physical conditions in the absorbing gas

The radio core of 1504 + 377 and the nucleus of the host galaxy are coincident within the errors ($\sim$1 arcsec) in the $R$-band image of Stickel & Kühr (1994). At millimetre-wave frequencies, the core dominates the quasar flux density, with very little emission coming from the steep-spectrum jet (Wiklind & Combes 1996a). The core is also likely to be extremely compact at these frequencies, implying that both millimetre-wave absorbers arise along a single line of sight, which must also pass extremely close to the centre of the host galaxy. Wiklind & Combes (1996a) noted that it is impossible to produce two absorption components at very different velocities in such circumstances if the absorbing gas is in pure rotational motion. The large separation ($\sim$330 km s$^{-1}$) between the two observed absorption velocities is thus suggestive of the presence of strong non-circular orbits; these authors argued in favour of a scenario in which the broad absorption from system A originates close to the nucleus (in a nuclear ring or a bar), while the narrow absorption of system A arises in a more distant cloud in the disc of the host galaxy. In this picture, the systemic redshift is $z \sim 0.6715$. On the other hand, Carilli et al. (1997) used the fact that the optical emission redshift of the host galaxy ($z = 0.674 \pm 0.001$) is in excellent agreement with that of the higher redshift complex to argue that the latter is the systemic redshift. They also pointed out that the optical emission redshift is $z \sim 0.674$ out to $z \sim 0.6706$. The 21-cm absorption lies entirely blueward of the optical redshift, implying that it must arise in gas that is outflowing from the quasar.

The large velocity spread of the H I outflow in 1504 + 377 is similar to that seen in a number of low-redshift AGNs (Morganti, Tadhunter & Oosterloo 2005b). Morganti et al. (2005b) note that all known fast H I outflows have been detected in radio galaxies in early or re-started phases of their radio activity. There is also evidence that the most likely mechanism to explain such fast H I outflows is interaction between the radio jets and the surrounding interstellar medium (e.g. Morganti et al. 2005a), with rapid cooling taking place in the gas after a jet–cloud interaction, as expected from numerical simulations (e.g. Fragile et al. 2004). The fact that 1504 + 377 shows no extended radio structure (the outer jet extends to only $\sim$55 mas, i.e. $\sim$387 pc, from the nucleus; Polatidis et al. 1995) suggests that it too is in an early phase of its radio activity. Recent 5-GHz VLBI observations (Bolton et al. 2006) have found a new north-eastern extension, which was not seen in earlier (deeper) images (e.g. Fomalont et al. 2000), demonstrating that the source is currently in an active phase. Finally, the fact that the radio structure in 1504 + 377 is strongly one-sided (e.g. Fomalont et al. 2000) indicates that the jet lies close to the line of sight towards the core. The above suggestion that jet–cloud interactions are responsible for local gas cooling is consistent with the fact that millimetre-wave absorption (which takes place in cold gas and, as noted earlier, must arise towards the core) is seen at multiple velocities along the line of sight.

It thus appears that the wide H I 21-cm and molecular absorption towards 1504 + 377 arise in outflowing gas from the AGN that is cooling rapidly after an interaction with the south-western radio jet. This is the highest redshift at which such a high-velocity outflow has been observed (e.g. Morganti et al. 2005b) and, perhaps more interestingly, the first case where molecular gas has been detected in the outflow. The H$_2$ fraction is $f_{\text{H}_2} = [N_{\text{H}_2}/N_{\text{HI}}] \lesssim 2 \times (T_s/100)(T_s/10)(f_{\text{Hi}}/f_{\text{HI}})$. Morganti et al. (2005b) assume $T_s \sim 1000$ K to estimate H I column densities for sources in their sample owing to the proximity of the gas to the AGN and the likely presence of shocks. Using this value for consistency gives a molecular fraction of $f_{\text{H}_2} \sim 0.2$ in the outflowing gas.

We estimate the mass outflow rate $M$ using the model of Heckman et al. (2000), in which a constant-velocity, mass-conserving wind flows into a solid angle $\Omega$ from a minimum radius $r_s$:

$$M = 30 \left( \frac{\Omega}{4\pi} \right) \left( \frac{r_s}{1 \text{ kpc}} \right) \left( \frac{N_{\text{H}}}{10^{21} \text{ cm}^{-2}} \right) \left( \frac{v}{300 \text{ km s}^{-1}} \right) M_\odot \text{ yr}^{-1},$$

where $v$ is the outflow velocity and $N_{\text{H}}$ is the total hydrogen column density of the outflowing gas. We will assume that the minimum radius $r_s \sim 10$ pc, the size of the radio core, and, following Morganti et al. (2005b), that $\Omega = 1$ steradians and $v = \text{FWBN} / 2 \sim 300$ km s$^{-1}$. The total hydrogen column density at $z \sim 0.67$ is $N_{\text{H}} = (N_{\text{HI}} + 2 \times N_{\text{H}_2}) \sim 1.6 \times 10^{23}$ cm$^{-2}$, again assuming $T_s \sim 1000$ K. This leads to an estimated mass outflow rate of $M \sim 12 M_\odot \text{ yr}^{-1}$, comparable to estimates in nearby fast H I outflows (Morganti et al. 2005b).

Wiklind & Combes (1996a) noted that HCO$^+$ is highly abundant in system B, enhanced by at least an order of magnitude relative to expected abundances in chemical models. The ratios of HCO$^+$ to CO and HCO$^+$ to HCN column densities here are 3–5 times larger than in system A. While such large differences in relative abundances between HCO$^+$ and species such as CO, HCN, etc.,
have been observed in Galactic clouds (Lucas & Liszt 1998), the ratio of OH and HCO\(^+\) column densities in both the Galaxy and a sample of four redshifted HCO\(^+\) and OH absorbers has been found to be fairly constant, with \(N_{\text{HCO}^+}/N_{\text{OH}} \sim 0.03\) (Liszt & Lucas 1996; Kanekar & Chengalur 2002) over more than two orders of magnitude in HCO\(^+\) column density. Liszt & Lucas (2004) found this ratio to show a large spread (by a factor of \(\sim 4\)) in the clouds towards Cen A and NGC 1052, with the HCO\(^+\) and OH lines also showing very different kinematics, but argued that this could be explained by differing source structure and foreground free–free opacity at the OH and HCO\(^+\) frequencies, source variability between observing epochs, and excitation effects at high OH column densities \((\gtrsim 10^{15} \text{ cm}^{-2});\) van Langevelde et al. (1995). Conversely, system B has \(N_{\text{HCO}^+}/N_{\text{OH}} \sim 0.5 \times (T'_c/10)(0.46/f_{\text{OH}})\), discrepant by more than an order of magnitude from the expected value. However, 1504 + 377 is highly compact at both millimetre-wave and centimetre-wave frequencies (with a centimetre-wave core fraction of \(\sim 46\) per cent; Carilli et al. 1997) and the HCO\(^+\) and OH lines have very similar FWHMs \([\sim 16.5 \pm 2.2 \text{ km s}^{-1}\) (OH) and \(\sim 15.2 \pm 0.9 \text{ km s}^{-1}\) (HCO\(^+\))], making it likely that they arise from similar gas. Increasing \(T_c\) by an order of magnitude could resolve this problem but such high \(T_c\) values have never been seen in the Galaxy (e.g. Liszt & Lucas 1996). Similarly, the ratio of peak optical depths in the HCO\(^+\) and H\(_2\) 21-cm lines in system A is \(\sim 30\), far larger than that seen in Galactic clouds \((0.1 \lesssim R \lesssim 6);\) Lucas & Liszt 1996; Liszt & Lucas 1996). Carilli et al. (1997) point out that high values of \(R\) could result from either far warmer H\(_2\) or low molecular dissociation, but this would not explain the discrepancy in the ratio of OH and HCO\(^+\) column densities. If the latter is not due to real chemical differences between OH and HCO\(^+\) (which seems unlikely: Liszt & Lucas 2000), a plausible explanation is extreme small-scale structure in the opacity of the absorbing gas on sub-parsec scales, smaller than the size of the radio core at centimetre wavelengths. This could arise from internal shocks or turbulence in the rapidly outflowing gas. As noted earlier, the observed variability in the H\(_2\) 21-cm absorption at \(z \sim 0.674\) suggests similar small-scale structure at a different location in the outflow, which could also account for the large velocity difference \((\sim 15 \text{ km s}^{-1})\) in peak OH and HCO\(^+\) absorption in system A (Kanekar & Chengalur 2002). Monitoring the millimetre-wave lines for variability would be one way of testing this hypothesis.

Finally, comparisons between the OH, H\(_2\) 21-cm and HCO\(^+\) redshifts from an absorber can be used to test the evolution of fundamental constants (Darling 2003; Chengalur & Kanekar 2003). However, the above possibility of small-scale structure in the absorbing gas makes it likely that any such comparisons in the absorbing gas towards 1504 + 377 will be dominated by local systematic velocity offsets. We conclude that this absorber is unlikely to be useful for the purpose of probing fundamental constant evolution.

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