Associated 21-cm absorption towards the cores of radio galaxies

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ABSTRACT
We present the results of Giant Metrewave Radio Telescope observations to detect H I in absorption towards the cores of a sample of radio galaxies. From observations of a sample of 16 sources, we detect H I in absorption towards the core of only one source, the Fanaroff–Riley type II (FR II) radio galaxy 3C 452 which has been reported earlier by Gupta & Saikia. In this paper we present the results for the remaining sources which have been observed to a similar optical depth as for a comparison sample of compact steep-spectrum (CSS) and gigahertz peaked-spectrum (GPS) sources. We also compile available information on H I absorption towards the cores of extended radio sources observed with angular resolutions of a few arcsec or better. The fraction of extended sources with detection of H I absorption towards their cores is significantly smaller (7/47) than the fraction of H I detection towards CSS and GPS objects (28/49). For the cores of extended sources, there is no evidence of a significant correlation between H I column density towards the cores and the largest linear size of the sources. The distribution of the relative velocity of the principal absorbing component towards the cores of extended sources is not significantly different from that of the CSS and GPS objects. However, a few of the CSS and GPS objects have blueshifted components \( \gtrsim 1000 \text{ km s}^{-1} \), possibly due to jet–cloud interactions. With the small number of detections towards cores, the difference in the detection rate between FR I (4/32) and FR II (3/15) sources is within the statistical uncertainties.

Key words: galaxies: active – galaxies: evolution – galaxies: jets – galaxies: nuclei – radio lines: galaxies.

1 INTRODUCTION
It is widely believed that the source of energy of active galactic nuclei (AGN) is the accretion of matter on to a supermassive black hole with an accretion disc, located in the centre of the galaxy. While there have been many theoretical and numerical studies of accretion flows (e.g. Hawley 2011), observational studies of the gaseous components in the circumnuclear regions could provide useful insights towards understanding the dynamics and properties of the gas that might be fuelling the AGN. At radio frequencies, an important method of probing this region is via 21-cm H I absorption towards compact radio sources, such as the cores of radio galaxies and quasars (QSOs), and the compact steep-spectrum (CSS) and gigahertz peaked-spectrum (GPS) sources. The CSS and GPS objects (O’Dea 1998) typically have sizes of \( \lesssim 15 \) and 1 kpc, respectively, and are believed to be the young (\(<10^7 \text{ yr}\)) progenitors of the larger radio galaxies and QSOs which extend up to a few Mpc, with the largest sources being typically \(~10^8 \text{ yr}\) old (Jamrozy et al. 2008; Konar et al. 2008). Such studies could also help us study the evolution of the gaseous component with the age of the radio source and also test consistency of these properties with the unified schemes for AGN (Pihlström, Conway & Veermeulen 2003; Gupta & Saikia 2006b; Curran & Whiting 2010).

Studies of H I absorption towards radio galaxies and QSOs have shown that the absorption lines are more often detected towards CSS and GPS objects, with previous studies (Pihlström et al. 2003; Gupta et al. 2006; Chandola, Sirothia & Saikia 2011) showing an apparent anticorrelation between the integrated optical depth and source size. For an assumed fixed value of the covering fraction and spin temperature, this corresponds to an anticorrelation with the neutral hydrogen column density. Gupta & Saikia (2006b) found the 21-cm absorption detection rate to be higher towards the CSS and GPS sources identified with galaxies than with QSOs. They find that there is a tendency for the detection rate as well as the column density for galaxies to increase with core prominence, a statistical indicator of the orientation of the jet axis to the line of sight. This can be understood in a scenario where radio sources are larger

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than the scale of the circumnuclear \( H I \) disc so that the lines of sight to the lobes at very large inclinations do not intersect the disc. On the other hand, Curran & Whiting (2010) and more recently Allison et al. (2012) have investigated the effect of UV luminosity on the \( 21\text{-cm} \) absorption detection rate. They found that after excluding the sources with UV luminosities, \( L_{\text{UV}} \geq 10^{23} \text{ W Hz}^{-1} \), the \( 21\text{-cm} \) absorption detection rate for compact radio sources is only marginally higher than for other radio sources. Curran & Whiting suggest that higher \( 21\text{-cm} \) absorption detection rate amongst compact objects is probably due to their generally low UV luminosity rather than their compact sizes or orientation.

Compared with the studies of \( H I \) absorption towards CSS and GPS objects, the extended radio sources have received less attention. However, there have been a few notable exceptions like van Gorkom et al. (1989), Morganti et al. (2001) and more recently Emonts et al. (2010). To understand any evolution in the \( H I \) component of the circumnuclear gas as the radio source grows from the GPS and CSS scales to larger dimensions, it is necessary to probe the gas on similar scales from radio observations probing the compact regions with comparable optical depths. This can be achieved via \( 21\text{-cm} \) observations towards the radio cores of large radio sources with resolutions of about a few arcsec or better so that the core is resolved from the more extended emission and can be unambiguously identified. Such observations will also enable us to determine any differences in the \( H I \) properties of Fanaroff–Riley type I (FR I) and FR II sources. There have been suggestions that the mode of fuelling the nucleus and the structure of the torus/disc may be different for the FR I and FR II radio sources, with those in FR Is being geometrically thin (e.g. Morganti et al. 2001).

In this paper we present the results of \( 21\text{-cm} \) \( H I \) absorption observations towards the cores of FR I and FR II radio galaxies with the Giant Metrewave Radio Telescope (GMRT), and combine our results with those in the literature to examine any evolution in the \( H I \) properties in the circumnuclear region with source size. Possible differences between FR I and FR II radio galaxies, and the distribution of the velocities of the absorbing components relative to the systemic velocities have also been examined. The observations are described in Section 2. The discovery of \( 21\text{-cm} \) absorption towards the core of the FR II radio galaxy J2245+3941 (3C452), which is a part of our sample, has been reported earlier (Gupta & Saikia 2006a). In this paper we present the results for the remaining 15 sources. In Section 3 we combine our results with those of similar searches and discuss the statistical trends in gas properties with respect to radio-source characteristics. The results are summarized in Section 4.

## 2 Observations

Table 1 lists the 16 FR I and FR II radio galaxies which we observed with the GMRT over the period of 2004-2010. Table 1 also lists some of their observed properties. With the available

| Source name | Alt. name | Redshift | \( S_{1.4} \) (mJy) | \( P_{1.4} \) \( \times 10^{25} \) (W Hz\(^{-1} \)) | Type | LAS (arcsec) | LLS (kpc) | LAS ref. | VLBI ref. |
|-------------|------------|----------|------------------|-------------------|------|--------------|----------|-----------|-----------|
| J0209+3547  | 4C 35.03   | 0.0377   | 2087             | 0.70              | FR I | 83           | 61       | 0         | 1         |
| J0223+4259  | 3C 66B     | 0.0213   | 6217             | 0.65              | FR I | 678          | 288      | 1         | 2         |
| J0313+4120  | S4         | 0.1340   | 487              | 2.38              | FR II| 570          | 1340     | 2         | 3         |
| J0334+3921  | 4C 39.12   | 0.0206   | 1183             | 0.12              | FR I | 402          | 165      | 1         | 2         |
| J0418+3301  | 3C 111     | 0.0485   | 15121            | 8.59              | FR II| 195          | 182      | 0         | 4         |
| J0566+4237  | 4C 42.2    | 0.0590   | 937              | 0.80              | FR I | 67           | 76       | 0         | –         |
| J0748+5548  | DA240      | 0.0357   | 2237             | 0.67              | FR II| 2040         | 1428     | 3         | 5         |
| J0758+3747  | 3C 189     | 0.0428   | 2637             | 1.16              | FR I | 144          | 120      | 0         | 2         |
| J1147+3501  |            | 0.0631   | 815              | 0.80              | FR I | 780          | 936      | 4         | 2         |
| J1628+3933  | 3C 338     | 0.0304   | 3595             | 0.78              | FR I | 112          | 67       | 0         | 2         |
| J1744+5542  | NGC 6454   | 0.0312   | 810              | 0.18              | FR I | 200          | 123      | 5         | 3         |
| J1835+3241  | 3C 382     | 0.0579   | 5548             | 4.55              | FR II| 171          | 189      | 6         | 2         |
| J1836+1942  | PKS        | 0.0161   | 1458             | 0.09              | FR I | 316          | 102      | 1         | –         |
| J1842+7946  | 3C 390.3   | 0.0555   | 11537            | 8.73              | FR II| 235          | 250      | 0         | 6         |
| J2245+3941  | 3C 452     | 0.0811   | 10383            | 17.25             | FR II| 256          | 386      | 7         | 2         |
| J2328+3745  | 3C 465     | 0.0302   | 7590             | 1.63              | FR I | 487          | 290      | 1         | 7         |

Column 1: source name; column 2: alternative name; column 3: redshift; column 4: flux density at 1.4 GHz in mJy; column 5: luminosity at 1.4 GHz; column 6: radio morphology, i.e. FR I or FR II; columns 7 and 8: largest projected angular (LAS) and linear (LLS) size in arcsec and kpc, respectively, where LAS has been estimated from the outer hotspots in the FR II sources, and from the outermost contours in the FR I sources; column 9: references for the LAS; column 10: references for the VLBI structure.

References for the largest angular sizes – 0: this paper; 1: NRAO VLA Sky Survey (NVSS; Condon et al. 1998), 2: de Bruyn (1989), 3: Willis, Strom & Wilson (1974), 4: Giovannini et al. (1999), 5: Bridle & Fomalont (1978), 6: Leahy & Perley (1991), 7: Gupta & Saikia (2006a).

All redshift information is from the NASA Extragalactic Database (NED) except for J1744+552 and J1842+7946. The redshift for J1744+552 has been taken from Bridle & Fomalont (1978) and for J1842+7946 has been taken from Eracleous & Halpern (2004).

Flux densities at 1.4 GHz are determined using the maps from NVSS. Luminosities have been calculated from these flux densities assuming a spectral index of 1.

References for the VLBI structure – 1: Lara et al. (1997); 2: Giovannini et al. (2001); 3: Britzen et al. (2007); 4: Linfield (1987); 5: Saripalli et al. (1997); 6: Alef et al. (1996); 7: Ventura et al. (1995).
Table 2. Observational details and results of the search for associated H I absorption.

| Source       | Date      | Obs. freq (MHz) | BW (MHz) | $t_{int}$ (h) | Beam (arcsec x arcsec) | Comp. | Peak flux (mJy beam$^{-1}$) | $\sigma$ (mJy beam$^{-1}$) | $\tau$ (10$^{-3}$) | $N$(H I) (10$^{20}$ cm$^{-2}$) |
|--------------|-----------|----------------|----------|---------------|------------------------|-------|--------------------------|---------------------------|----------------|-----------------------------|
| J0209+3547   | 2006 Jan  | 1368.76        | 4        | 3.5           | 2.41 x 1.91 +20       | Core  | 102                      | 0.91                      | <26.7          | <5.15                       |
| J0223+4259   | 2006 Jan  | 1390.84        | 4        | 4.6           | 2.64 x 2.25 -83       | Core  | 170                      | 1.10                      | <19.5          | <3.77                       |
| J0313+4120   | 2004 Jan  | 1252.56        | 8        | 3.0           | 2.62 x 2.15 -53       | Core  | 383                      | 1.12                      | <8.7           | <1.68                       |
| J0334+3921   | 2006 Jan  | 1391.75        | 4        | 4.9           | 2.70 x 1.99 +53       | Core  | 304                      | 0.85                      | <8.4           | <1.62                       |
| J0418+3801   | 2006 Jan  | 1354.70        | 4        | 5.2           | 3.15 x 2.38 +34       | Core  | 1393                     | 0.90                      | <2.1           | <0.41                       |
| J0565+4237   | 2010 Jan  | 1341.27        | 4        | 4.9           | 3.63 x 2.80 +64       | Core  | 222                      | 0.53                      | <6.9           | <2.95                       |
| J0748+5548   | 2010 Jan  | 1371.49        | 4        | 4.4           | 2.70 x 2.16 +25       | Core  | 209                      | 0.38                      | <5.4           | <2.78                       |
| J0758+3747   | 2006 Jan  | 1362.06        | 4        | 5.2           | 3.12 x 2.07 +43       | Core  | 184                      | 1.01                      | <16.5          | <3.19                       |
| J1147+3501   | 2010 Jan  | 1336.06        | 4        | 4.4           | 3.69 x 2.38 +38       | Core  | 351                      | 0.57                      | <4.8           | <1.96                       |
| J1628+3933   | 2010 Jan  | 1378.56        | 4        | 4.8           | 3.42 x 2.17 +61       | EP    | 67.6                     | 0.93                      | <4.1           | <7.99                       |
| J1744+5542   | 2010 Jan  | 1377.43        | 4        | 4.0           | 4.24 x 3.18 -75       | Core  | 313                      | 1.18                      | <11.4          | <2.20                       |
| J1835+3241   | 2006 Mar  | 1342.70        | 4        | 4.5           | 2.68 x 2.10 +35       | EHS   | 203                      | 1.05                      | <15.6          | <3.01                       |
| J1836+1942   | 2004 Jan  | 1397.84        | 4        | 2.0           | 3.04 x 2.10 -70       | Core  | 224                      | 2.10                      | <28.2          | <5.44                       |
| J1842+7946   | 2010 Jan  | 1345.72        | 4        | 4.9           | 3.88 x 2.32 +17       | NHS   | 177                      | 1.02                      | <17.4          | <3.34                       |
| J2245+3941   | 2005 Dec  | 1313.85        | 4        | 5.6           | 3.14 x 2.25 +52       | EHS   | 94                       | 1.10                      | <35.1          | <6.77                       |
| J2338+2701   | 2004 Jan  | 1378.74        | 4        | 4.0           | 2.89 x 2.24 -50       | Core  | 302                      | 1.63                      | <16.2          | <3.13                       |

Column 1: source name; column 2: year and month of observations; column 3: redshifted 21-cm frequency; column 4: baseband bandwidth (BW); column 5: observing time in hour (excluding calibration overheads); columns 6, 7 and 8: restoring beam, radio component (EHS = eastern hotspot, WHS = western hotspot, NHS = northern hotspot, EP = eastern peak, WP = western peak and Core = radio core) and peak brightness in mJy beam$^{-1}$ for the continuum image made using line-free channels, respectively; column 9: rms noise in the spectrum; column 10: optical depth estimate, and column 11: H I column density in units of 10$^{20}$ cm$^{-2}$, assuming $T_e$ = 100 K and a covering factor, $f_c$, of unity; upper limits are 3$\sigma$ values, assuming $\Delta v = 100$ km s$^{-1}$.

The 21-cm absorption towards J2245+3941 (3C 452) has a velocity of $-2.8$ km s$^{-1}$ relative to its optical systemic velocity.

observing time, these 16 were selected largely from the 3CR and B2 samples to have a core flux density at 1400 MHz $\geq 100$ mJy with resolutions of a few arcsec or better so that the core could be distinguished from the more extended bridge/jet emission. The 16 sources observed with the GMRT consist of 10 FR I and 6 FR II radio sources. Their projected linear sizes range from $\sim 61$ kpc to as large as $\sim 1.4$ Mpc ($H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27, \Omega_{vac} = 0.73$; Spergel et al. 2003).

The observations were made with a baseband bandwidth (BB BW) of 4 MHz (velocity range $\sim 800$ km s$^{-1}$) split into 128 channels (resolution $\sim 7$ km s$^{-1}$), except for J0313+4120 for which a BB BW of 8 MHz (resolution $\sim 15$ km s$^{-1}$) was used (see Table 2). For the observations of J2245+3941 (3C 452) on 2005 December 11, the then new high-resolution mode (resolution $\sim 3.6$ km s$^{-1}$) of the GMRT correlator was used (cf. Gupta & Saikia 2006a). The expected redshifted 21-cm frequency was placed at the centre of the BB BW by tuning the local oscillator chain. The standard flux density and bandpass calibrators (3C 48, 3C 147 and 3C 286) were usually observed every 3 h to correct for variations in amplitude and bandpass. Observations of the target source were preceded and followed by observations of a phase calibrator, a compact radio source, typically every 35 min.

The Astronomical Image Processing System (AIPS) package was used to reduce the data. After flagging bad data, including those affected by radio frequency interference, and calibrating the data, a continuum image of the source was made by averaging $\sim 60$ line-free channels. The images were made with the highest resolution, which was typically $\sim 2$ arcsec with the GMRT at the L band, because of our interest in detecting absorption towards the compact components such as the radio cores. The data were self-calibrated to produce a satisfactory continuum image, after which the complex gains were applied to all the frequency channels and the continuum image was subtracted from the visibility data cube. Spectra were extracted at the pixels of maximum brightness in the cores and the hotspots. This was done independently for both Stokes RR and LL to check for consistency. The two polarization channels were later combined to produce the final Stokes I spectrum which was shifted to the heliocentric frame. The results for all the 16 sources, including the radio galaxy J2245+3941 (3C 452) are summarized in Table 2.

The final radio continuum images, i.e. the ones used for continuum subtraction, and the 21-cm H I absorption spectra for the 15 galaxies with non-detections are presented in Appendix A (Figs A1–A15). The large-scale structure is seen in most of the images except for J0313+4120, J0748+5548, J1147+3501, J1744+5542 and J1836+1942 where the diffuse emission is largely resolved out in our GMRT images. For all sources the rms noise in the spectra, the column density for the lone detection, 3C 452, and 3$\sigma$ upper limits to the optical depth towards all the other cores, and also towards the hotspots or peaks in 5 of the 16 sources are presented in
Table 2. The H\textsc{i} column density, \(N(\text{H}\textsc{i})\), has been estimated using the relation
\[
N(\text{H}\textsc{i}) = 1.823 \times 10^{18} T_e \int \tau(v)dv f_e \text{ cm}^{-2}
\]
and assuming \(T_e = 100 \text{ K}\) and \(f_e = 1.0\), where \(T_e\) and \(f_e\) are the spin temperature, optical depth at a velocity \(v\) and the fraction of background emission covered by the absorber, respectively. In this paper wherever we mention \(N(\text{H}\textsc{i})\) column density, it refers to the pseudo-H\textsc{i} column density with the above assumptions. The upper limits to \(N(\text{H}\textsc{i})\) are \(3\sigma\) values and have been estimated, as stated above, assuming \(T_e = 100 \text{ K}\), \(\Delta v = 100 \text{ km s}^{-1}\) and \(f_e = 1.0\).

3 DISCUSSION

In order to estimate reliably the fraction of sources with 21-cm \(\text{H}\textsc{i}\) detection, it is important to consider surveys of sources which report the detections as well as the non-detections. In our sample of 16 radio galaxies observed with the GMRT, we detect 21-cm absorption associated with the core of only 1 radio galaxy, i.e. J2245+3941 (3C 452) (Gupta & Saikia 2006a). To improve upon the statistics, we have considered the observations of large (>15 kpc) sources by van Gorkom et al. (1989), Morganti et al. (2001) and Emonts et al. (2010) who have reported both the detections and non-detections in their samples, and have summarized their results in Table 3 which has a total of 31 sources. We have included only those sources which have been observed with a resolution of a few arcsec (corresponding to a beam size of \(\lesssim 15 \text{ kpc}\) for our redshift range) in order to minimize the effect of large-scale structures on our estimates. We have also avoided inclusion of QSOs, BL Lacs, Spirals or Seyferts in the sample as we wanted to have a sample of radio galaxies with their hosts being ellipticals. Thus, combining our observations of 16 sources listed in Table 1 and the 31 sources listed in Table 3, we obtain a sample of 47 radio sources, called the ‘cores sample’. We also list nine sources in Table 4 for which \(\text{H}\textsc{i}\) 21-cm absorption has been reported towards their core from observations with an angular resolution of a few arcsec but not included in our ‘cores sample’ for statistical analysis since in these cases non-detections were not published.

3.1 Frequency of occurrence

A comparison of the results of \(\text{H}\textsc{i}\) 21-cm absorption observations towards the cores of radio galaxies with those obtained for CSS and GPS objects could help explore possible evolution of the content of \(\text{H}\textsc{i}\) gas in the host galaxies of radio sources as the sources evolve. The column densities or upper limits to these in our ‘cores sample’ range from \(~0.5 \times 10^{20}\) to \(6.9 \times 10^{20} \text{ cm}^{-2}\). The median column density sensitivity of our ‘cores sample’ including the upper limits is \(3.1 \times 10^{20} \text{ cm}^{-2}\). For comparison, we consider the compilation of CSS and GPS sources from Gupta et al. (2006). From this compilation of 62 CSS and GPS sources we consider 60 sources. We exclude J1415+1320 and J1945+7055 as these were reported as individual detections. To enlarge this sample further we also consider 21-cm absorption searches based on samples of steep-spectrum sources reported in the literature since 2006. We consider measurements of 17 sources from Chandola et al. (2011), 5 compact sources (B0258+35, B0648+27, B1122+39, B1447+27 and B1557+26) with steep spectrum from Emonts et al. (2010) and 2 sources from Carilli et al. (2007). The measurements of 10 compact sources with steep spectrum are available from Allison et al. (2012) but detailed size information is not available for these. So we are not able to include these in our sample. Thus, we have a sample of 84 CSS and GPS sources. This sample has column densities or upper limits to these ranging from \(~0.06 \times 10^{20}\) to \(125 \times 10^{20} \text{ cm}^{-2}\) with a median value of \(1.9 \times 10^{20} \text{ cm}^{-2}\) assuming that the values for the non-detections are close to the upper limits. To ensure that the sources are observed to similar sensitivity limits so that the distributions of column densities are similar for both the ‘cores’ and the ‘CSS and GPS’ samples, we considered all the sources from ‘CSS and GPS sample’ with a column density estimate or an upper limit to it which is at least \(1.5 \times 10^{20} \text{ cm}^{-2}\). This leaves us with a sample of 49 CSS and GPS sources with a median column density sensitivity of \(3.8 \times 10^{20} \text{ cm}^{-2}\), assuming again that the values for the non-detections are close to the upper limits.

The detection rate for the ‘cores sample’ is rather low (7/47; ~15 per cent; see Fig. 1) compared with the detection rate for compact CSS and GPS sources (28/49; ~57 per cent; see Fig. 2, lower panel). Considering the entire sample of 84 CSS and GPS objects, the detection rate (31/84; ~37 per cent; see Fig. 2, upper panel) is again significantly higher than for the ‘cores sample’. All but three of the sources from the ‘CSS and GPS sample’ with column density values \(\lesssim 1.5 \times 10^{20} \text{ cm}^{-2}\) represent sensitive observations of CSS and GPS objects with no detection of \(\text{H}\textsc{i}\) in absorption. We have also examined the very long baseline interferometry (VLBI) scale structure (references given in Tables 1 and 3) of the cores of the larger sources (‘cores sample’) and found that they tend to have a core-jet structure where most of the flux density is from the VLBI-scale core component which is usually smaller than the CSS and GPS objects suggesting that the difference in the \(\text{H}\textsc{i}\) absorption detection rate is not due to different covering factors. Although it would be useful to confirm it from a larger sample, clearly the detection rate of \(\text{H}\textsc{i}\) in absorption towards the cores of larger sources is smaller than for the CSS and GPS objects, suggesting an evolution in the gaseous content of the host galaxies.

It is also interesting to examine the \(\text{H}\textsc{i}\) detection rate for FR I and FR II radio sources in case this reflects any differences in either the torus/disc or fueling processes (e.g. Morganti et al. 2001; Emonts et al. 2010). In the ‘cores sample’ \(\text{H}\textsc{i}\) is detected in absorption towards 4 out of 32 (~13 per cent) FR I objects, compared with 3 out of 15 (~20 per cent) for the FR II sources. Within statistical errors, there is no significant difference in the detection rate towards the cores for FR I and FR II radio sources. These have been observed with similar sensitivity.

3.2 Column density versus size

As mentioned earlier, the \(\text{H}\textsc{i}\) column density in CSS and GPS objects appears to be anticorrelated with source size (Pihlström et al. 2003; Gupta et al. 2006; Chandola et al. 2011), but shows no evidence of any dependence on either redshift or luminosity (Gupta et al. 2006). On sub-galactic scales, the observed anticorrelation has been interpreted by Pihlström et al. (2003) to be due to gas distributions with a radial power-law density profile. It is also relevant to note here that Emonts et al. (2010) observed a sample of radio galaxies to detect \(\text{H}\textsc{i}\) in emission and found an inverse relation between \(\text{H}\textsc{i}\) mass and source size.

In Fig. 3 we plot the 21-cm \(\text{H}\textsc{i}\) column density towards the cores against the projected linear size in kpc for the sample of 47 radio galaxies. In this figure, we also plot an additional nine sources where \(\text{H}\textsc{i}\) detection has been reported from observations with angular resolutions of a few arcsec for single sources (see Table 4), giving a total of 16 detections. The linear sizes range from tens of kpc to over a Mpc while the column densities vary from \(0.5 \times 10^{20}\) to
9.39 M_⊙ 1.74 G 2.51 G
12.32 M_⊙ 3.7 E 162 G
19.24 458 316 7 4 FR II 19.24 458 316 7 4 FR II
2.21 276 215 6 – FR I 12.33 4153 45 0.01 123 49 10 – FRI
2.15 47.7 47 1 5 FR I 12.34 4261 0.0167 130 5 11 – FR I
2.79 259.8 215.9 1 – FR II 12.34 4261 0.0167 130 5 11 – FR I
4.50 M_⊙ 9.39 M_⊙ 1.90 M 8.63 M
10.06 5493 152.7 5 4 FR II 10.06 5493 152.7 5 4 FR II
19.24 458 316 7 4 FR II 19.24 458 316 7 4 FR II
2.15 47.7 47 1 5 FR I
17.82 M_⊙ 8.06 M_⊙ 1.90 M 8.63 M
19.32 686 81.5 3 5 FR II 19.32 686 81.5 3 5 FR II
2.79 259.8 215.9 1 – FR II 11.46 M_⊙ 2.79 259.8 215.9 1 – FR II
69 \times 10^{20} \text{ cm}^{-2}. There does not seem to be any significant relation between the H\textsc{i} column density towards the cores and the largest projected linear sizes of the sources.

### 3.3 Relative velocity of absorbing gas

The relative velocity of the absorbing gas could be significantly blueshifted if it is due to gas which has been accelerated by interaction with the radio jet, while infalling material fueling the central engine would appear redshifted. An important component of the unification scheme for FR II radio galaxies is the presence of a circumnuclear disc/torus. H\textsc{i} gas associated with this and rotating around the nucleus may appear both blue- and redshifted relative to the systemic velocity. It is worth noting that CSS and GPS objects often show complex line profiles with both blue- and redshifted H\textsc{i} absorption components.

We compare the relative velocity of the principal absorbing component for the 16 detections towards cores of larger sources with the 33 detections [including 2 sources from Gupta et al. (2006) which we left out earlier while doing statistical analysis of detection rates] towards CSS and GPS objects. While making these comparisons it is also relevant to note that different ionization lines...
Table 4. Sources reported in the literature for cores with H\textsubscript{I} detection but not included in our ‘cores sample’.

| Source name | Alt. name | Redshift | LAS (arcsec) | LLS (kpc) | LAS Ref. | Type | \(N(\text{H}\textsubscript{I})\) \(\times 10^{20}\) cm\textsuperscript{-2} | \(V_{\text{shift}}\) (km s\textsuperscript{-1}) | Ref. |
|-------------|-----------|----------|--------------|-----------|----------|------|-----------------|-------------|-----|
| J0319+4130  | NGC 1275  | 0.0176   | 198          | 70        | 1        | FR I  | 2.34            | 2797        | YRS|
| J0840+2949  | 4C29.30   | 0.0647   | 520          | 639       | 2        | FR I  | 47              | 84          | CSG|
| J0918−1205  | Hydra A   | 0.0549   | 310          | 326       | 3        | FR I  | 42              | −180        | D   |
| J1219+0549  | NGC 4261  | 0.0875   | 492          | 75        | 4        | FR I  | 7.2             | −3          | J   |
| J1247+6723  |          | 0.1073   | 671          | 1301      | 5        | FR II | 6.73            | 57          | S   |
| J1325−4301  | Cen A     | 0.0018   | 30.564       | 563       | 6        | FR I  | 50.1            | 6           | VGH|
| J1352+3126  | 3C 293    | 0.0450   | 216          | 189       | 7        | FR I  | 78.9            | 3           | B   |
| J1351+2404  | 3C 321    | 0.0961   | 286          | 503       | 8        | FR II | 92.3            | 235         | CSDN|
| J1959+4044  | Cygnus A  | 0.0561   | 127          | 137       | 9        | FR II | 25.4            | 165         | C   |

Column 1: source name; column 2: alternative name; column 3: redshift; columns 4 and 5: largest projected angular (LAS) and linear (LLS) size in arcsec and kpc, respectively; column 6: references for the LAS; column 7: H\textsubscript{I} column density; column 8: radio morphology classification; column 9: the shift of the primary H\textsubscript{I} component relative to the systemic velocity as measured from the optical emission lines, with a negative sign indicating a blueshift, and column 10: references for the H\textsubscript{I} observations.

References for the structural information and LLS – 1: Pedlar et al. (1990), 2: Chandola, Saikia & Gupta (2010) 3: Ekers & Simkin (1983), 4: Condon & Broderick (1988), 5: Lara et al. 2001; 6: Junkes et al. (1993), 7: Bridle, Fomalont & Cornwell (1981), 8: Chandola et al. (2012), 9: Perley, Dreher & Cowan (1984b).

References for H\textsubscript{I} observations – D: Dwarakanath, Owen & van Gorkom (1995), J: Jaffe & McNamara (1994), S: Saikia, Gupta & Konar (2007), C: Conway & Blanco (1995), YRS: De Young, Roberts & Saslaw (1973), VGH: van der Hulst, Golisch & Haschick (1983), CSDN: Chandola et al. (2012), CSG: Chandola et al. (2010), B: Beswick, Pedlar & Holloway (2002).

Figure 1. H\textsubscript{I} column density distribution of the ‘cores sample’. The shaded areas represent the detections while the unshaded areas represent 3\(\sigma\) upper limits.

Figure 2. Upper panel: H\textsubscript{I} column density distribution of the ‘CSS and GPS sources’ from Gupta et al. (2006). Lower panel: H\textsubscript{I} column density distribution of CSS and GPS sources with \(N(\text{H}\textsubscript{I})\) or upper limits to it greater than 1.5 \(\times 10^{20}\) cm\textsuperscript{-2}. The shaded areas represent the detections while the unshaded areas represent 3\(\sigma\) upper limits.
cm absorption is detected towards $4\sim 10$ column density towards the cores to $69\times 10^{20}$ cm$^{-2}$. The distribution of velocities for the principal H\textsc{i} absorption towards the cores of larger column density as a function of the projected linear source size. The arrows mark the 3$\sigma$ upper limit to the column density. The unfilled symbols denote FR I sources while the filled symbols denote FR II sources. The circles denote the sources from our GMRT observations while the squares, the triangles with vertex up and the triangles with vertex down denote sources from Emonts et al. (2010), van Gorkom et al. (1989) and Morganti et al. (2001), respectively. The rhombuses correspond to sources which are not included in our cores sample but have detection towards the cores of larger radio sources with ~arcsec resolution.

Figure 3. H\textsc{i} column density as a function of the projected linear source size. The arrows mark the 3$\sigma$ upper limit to the column density. The unfilled symbols denote FR I sources while the filled symbols denote FR II sources. The circles denote the sources from our GMRT observations while the squares, the triangles with vertex up and the triangles with vertex down denote sources from Emonts et al. (2010), van Gorkom et al. (1989) and Morganti et al. (2001), respectively. The rhombuses correspond to sources which are not included in our cores sample but have detection towards the cores of larger radio sources with ~arcsec resolution.

Figure 4. The distribution of velocities for the principal H\textsc{i} absorption components with respect to the systemic velocity estimated from optical lines. The bold boxes represent the distribution for CSS and GPS sources, while the shaded areas denote the cores of FR I and FR II radio sources. In the cores, Perseus A (NGC 1275), where the principal relative velocity is $2797$ km s$^{-1}$, has been put in bin at $2000$ km s$^{-1}$.

4 SUMMARY

We have presented the results from a search for 21-cm absorption towards the cores of 16 FR I and FR II radio galaxies. From our search we have reported earlier one new detection, i.e. towards the core of the radio galaxy J2245+3941 (3C 452) (Gupta & Saikia 2006a), and have now presented the upper limits on N(H\textsc{i}) for the remaining 15 sources. We have combined our results with those of similar 21-cm absorption searches in the literature to obtain a larger sample, called the ‘cores sample’, of 47 radio galaxies and have summarized our results here.

(i) The upper limits to the H\textsc{i} column density towards the cores of large sources presented here range from $\sim 0.5 \times 10^{20}$ to $69 \times 10^{20}$ cm$^{-2}$.

(ii) Considering observations of similar sensitivity, we find that the detection rate of H\textsc{i} absorption towards the cores of larger (>15 kpc) sources is only ~15 per cent, compared with ~57 per cent for CSS and GPS objects, suggesting an evolution in the gaseous content of the host galaxies as the radio sources age and grow in size.

(iii) The H\textsc{i} column density towards the core versus the largest linear size plot for the large sources shows no significant correlation between these parameters.

(iv) The distribution of the relative velocity of the principal absorbing component towards the cores of large sources is not significantly different from that of the CSS and GPS objects, although a few of the CSS and GPS objects show large blueshifted velocities ($\gtrsim 1000$ km s$^{-1}$) possibly due to jet–cloud interactions.

(v) For the ‘cores sample’, H\textsc{i} absorption is detected towards 4 out of 32 (~13 per cent) FR I objects, and 3 out of 15 (~20 per cent) FR II sources. Although there have been suggestions of differences in the torus/disc structure and fuelling mechanisms between FR I and FR II sources, with the small number of detections there does not appear to be a significant difference in the detection rate between these two types of radio sources.

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APPENDIX A: MAPS AND 21-CM SPECTRA OF THE ‘CORES SAMPLE’ FROM OUR GMRT OBSERVATIONS

Figure A1. Image of J0209+3547 (4C+35.03) with an rms noise of 0.2 mJy beam$^{-1}$. The contour levels are 0.6 $\times (-1, 1, 2, 4, 8, 16, 32, 64, 128)$ mJy beam$^{-1}$. In all the images the restoring beam is shown as an ellipse while the position of the optical host galaxy is marked with a (+) sign. The dashed contours represent the negative flux density values while the solid contours represent the positive flux density values. The spectra at the peak intensity pixel [shown with a ($\times$) sign] for the different components are shown below each image and the components have been indicated in the spectra. For all the spectra, x- and y-axes represent the heliocentric velocity in km s$^{-1}$ and the normalized intensity, respectively. The spectra have been normalized using the flux density corresponding to the peak intensity pixel.
Figure A2. Image of J0223+4259 (3C 66B) with an rms noise of 0.6 mJy beam$^{-1}$. The contour levels are $3 \times (-1, 1, 2, 4, 8, 16, 32, 45)$ mJy beam$^{-1}$.

Figure A3. Image of J0313+4120 with an rms noise of 0.5 mJy beam$^{-1}$. The contour levels are $2.5 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128)$ mJy beam$^{-1}$.

Figure A4. Image of J0334+3921 (4C+39.12) with an rms noise of 0.1 mJy beam$^{-1}$. The contour levels are $0.8 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam$^{-1}$.

Figure A5. Image of J0418+3801 (3C 111) with an rms noise of 0.6 mJy beam$^{-1}$. The contour levels are $6 \times (-1, 1, 2, 4, 8, 16, 24, 32, 64, 128)$ mJy beam$^{-1}$.
Figure A6. Image of J0656+4237 (4C 42.22) with an rms noise of 0.24 mJy beam$^{-1}$. The contour levels are $0.8 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128)$ mJy beam$^{-1}$.

Figure A7. Image of J0748+5548 (DA 240) with an rms noise of 0.37 mJy beam$^{-1}$. The contour levels are $2.40 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam$^{-1}$.

Figure A8. Image of J0758+3747 (3C 189) with an rms noise of 0.5 mJy beam$^{-1}$. The contour levels are $2.0 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128)$ mJy beam$^{-1}$.

Figure A9. Image of J1147+3501 with an rms noise of 0.54 mJy beam$^{-1}$. The contour levels are $2.057 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam$^{-1}$.
Figure A10. Image of J1628+3933 with an rms noise of 0.46 mJy beam⁻¹. The contour levels are $5 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128)$ mJy beam⁻¹.

Figure A11. Image of J1744+557 with an rms noise of 0.48 mJy beam⁻¹. The contour levels are $4 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam⁻¹.

Figure A12. Image of J1835+3241 (3C 382) with an rms noise of 0.5 mJy beam⁻¹. The contour levels are $2.35 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam⁻¹.

Figure A13. Image of J1836+1942 (PKS 1834+196) with an rms noise of 0.8 mJy beam⁻¹. The contour levels are $4.0 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam⁻¹.
Figure A14. Image of J1842+7946 (3C 390.3) with an rms noise of 0.59 mJy beam$^{-1}$. The contour levels are $2.35 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256)$ mJy beam$^{-1}$.

Figure A15. Image of J2338+2701 (3C 465) with an rms noise of 0.5 mJy beam$^{-1}$. The contour levels are $2.5 \times (-1, 1, 2, 4, 8, 16, 32, 64, 128)$ mJy beam$^{-1}$.

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