Giant Metrewave Radio Telescope limits on cool HI in galaxy groups

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Abstract. We present Giant Metrewave Radio Telescope 21-cm HI observations towards a sample of compact radio sources behind galaxy groups, to search for *cool* HI. The results – from high dynamic range spectra for 8 lines-of-sight through 7 galaxy groups – do not show any evidence for absorption by cool HI. At a resolution of 20 km s^{-1}, the optical depth upper limits obtained were between 0.0075 and 0.035 (3σ); these correspond to upper limits of a few times 10^{23} m^{-2} for the column density of any cool HI along these lines of sight (assuming a spin temperature of 100 K).

Keywords : galaxies: clusters: general – intergalactic medium – radio lines: galaxies – cosmology: miscellaneous

1. Introduction

A central question in understanding galaxy evolution is how primordial gas clouds first evolve into star-forming systems. There are good reasons to expect that gas which has never been associated with star-forming galaxies still exists in the Universe today. In cold dark matter cosmologies, low-mass structures (dark matter halos and baryonic matter) are statistically the first to form. If the baryonic matter cools it will form bound clouds and structure formation proceeds hierarchically. The mass spectrum expected for primordial clouds is steep (with the number varying with mass, m, as $n(m) \propto m^{-2}$), and if the smaller clouds do not all merge, or are disrupted, such clouds may be expected to survive to the present epoch. The most likely regions in which to find such primordial extragalactic clouds are in groups dominated by late-type galaxies, for several reasons. First, the collision rate in a galaxy group is expected to be lower than in a cluster, and therefore we might expect that low-mass clouds in galaxy groups have survived to the present day. Second,

it is observed that groups rich in elliptical galaxies often show extended X-ray emission (as in centrally-condensed clusters), whereas groups dominated by late-type galaxies never show extended X-ray emission (Mulchaey et al. 1996). Nath & Chiba (1995) have suggested that this X-ray emitting gas has its origin in the disruption of low-mass, primordial clouds. This observation suggests that groups rich in late-type galaxies also contain a large mass of gas not associated with galaxies. If we interpret this lack of X-ray emission in groups dominated by late-type galaxies as evidence for the non-disruption of low-mass clouds, then provided the clouds exceed their virial temperature (so that they have not collapsed to form stars), and are neutral, these clouds may be detectable.

Detections of intra-group atomic hydrogen which may be genuinely primordial are extremely limited, but some groups do show gaseous structures that are hard to explain as interaction products or outflows. These include, the M96 group (Schneider, Saltpeter & Terzian 1986), around NGC 5291 (Malphrus et al. 1997), the environment of NGC 4532 (Hoffman et al. 1999), the Virgo cluster (Davies et al. 2004, see also Walter, Skillman & Brinks 2005), and near local group Dwarf galaxies (Bouchard, Carignan & Staveley-Smith 2006). The recent HIPASS survey has also revealed a small number of HI clouds with no optical counterparts although not specifically in groups (e.g. Kilborn et al. 2000, 2002; and also see Doyle et al. 2005). Several searches for low mass HI clouds in galaxy groups have resulted in non-detections down to thresholds as low as 3×10^6 M$_\odot$ (e.g. Zwaan & Briggs 2000; Zwaan 2001; Dahlem, Ehle & Ryder, 2001; de Blok et al. 2002).

Here we present Giant Metrewave Radio Telescope (GMRT; see Rao 2002) 21-cm observations to test whether (primordial) intra-group HI is common in groups which might in some sense be considered young. If the gas is cool and/or in low-mass clouds – as might be expected for a steep $n(m)$ spectrum – then it is likely that a lower mass detection limit could be reached by searching for absorption rather than emission from the neutral gas. Other searches for primordial HI have been, and indeed are being carried out, usually at high redshifts (e.g. Bebbington 1986; Wieringa, de Bruyn & Katgert 1992; Taramopoulos, Briggs & Turnshek 1994; Weintroub et al. 1999), but these have only probed for very massive primordial structures. A similar experiment to ours has been carried out by Kanekar & Chengalur (2003) with the GMRT, but this was aimed at detecting HI absorption towards damped Lyman alpha systems (see also Kanekar & Chengalur 2005). Details of our observations towards compact continuum sources behind groups of galaxies, which place strong limits on the existence of low-mass clouds in the local Universe, are given in Section 2, with the results and conclusions given in Sections 3 and 4

2. GMRT Observations and Data Reduction

2.1 Selected Fields

To maximise our sensitivity to *cool* atomic gas, we search for HI in *absorption* towards background radio sources. Our sample consists of seven groups (from the catalogues of Garcia 1993 and Ramella, Pisani & Geller 1997), as shown in Table 1. These satisfy the following criteria. (i)

Table 1. Observed galaxy groups. R = from Ramella et al. (1997); LGG = from Garcia (1993).

ID	Group velocity / km s^{-1}	dispersion / km s^{-1}	Position J2000 h m	° ′	Observed Bandwidth	Date Observed
R 97	6568	139	10 47.3	+26 19.0	4 MHz	2003 Jan 6th
R 110	10470	800	10 59.2	+10 00.5	8 MHz	2003 Jan 7th
R 151	6265	261	11 43.1	+10 23.0	4 MHz	2003 Jan 6th
R 168	4790	163	11 58.5	+25 08.4	4 MHz	2003 Oct 17th
R 282	6873	668	14 06.0	+09 08.0	8 MHz	2003 Jan 6th
R 331	6905	209	15 06.7	+12 44.3	8 MHz	2003 Jan 6th
LGG 413	3315	–	17 52.5	+24 29.9	4 MHz	2003 Oct 17th

The group is dominated by late-type galaxies. It is likely that such groups represent environments where fewer galaxy–galaxy interactions have taken place, and hence primordial gas is more likely to survive, and also such groups do not have X-ray emission which may originate from disrupted, low-mass primordial clouds. (ii) The group is away from the Galactic plane. (iii) There is one ore more compact continuum source brighter than 60 mJy at 1.4 GHz visible in the NVSS survey (Condon et al. 1998) close to the centre of the group, towards which 21-cm absorption measurements can be made. Given the selected galaxy groups are nearby, with velocities less than $\sim 10^4$ km s^{-1}, then it is reasonable to expect all the selected, compact NVSS sources to be more distant than the groups.

2.2 Observations and Data Reduction

These fields were observed in two sessions with the GMRT, 2003 January 6th and 7th, and October 17th. Each group was observed for between 1 and 2 hours each (depending on scheduling constraints), with appropriate correlator frequency settings. The observations were made using 128 spectral channels, with a total bandwidth of usually 4 MHz, or in some cases 8 MHz (e.g. to allow two targets to be observed with the same reference velocity, to optimise calibration time, or for a group with a high velocity dispersion), giving channels of width 6.6 or 13.2 km s^{-1} respectively. The data were observed at a fixed frequency, without Doppler correction for diurnal variations, which is small for the duration of the observations compared with the individual channel width. Independent right and left Stokes parameter spectral data were recorded. Bright, primary, calibrators 3C48, 3C147 or 3C286 were observed for each of the velocity setting used. Secondary calibrator sources close to each of the galaxy group were observed for ≈ 4 min every ≈ 30 min. During these observations typically 26 of the 30 antennas of the GMRT were available.

The data were calibrated using standard procedures using classic *AIPS* (Bridle & Greisen 1994). A few channels near the centre of the band were inspected, and obvious interference was flagged. These channels were then averaged, and the observations of the secondary calibrators were then used to measure the antenna-based amplitude and phase variations throughout the observations. The overall flux density scale of the observations was set by the observations of the

primary calibrators, which were also used to determine antenna-based bandpass corrections. For the January observations, a few correlator channels were consistently identified as not working, and these are omitted from the results shown here. The calibrated data for both the calibrator sources, and the galaxy groups, was inspected, and further interference was identified and flagged. Images of the galaxy groups were made, in order to check the positions of continuum sources, and also see if they were resolved. The GMRT consists of 30 antennas each 45-m in diameter, 12 in a central region ≈ 1 km in extent, with the others in three arms, providing baselines up to ≈ 25 km. At 1.4 GHz the primary response of the GMRT is ≈ 0.4 deg FWHM, and the full resolution of the telescope is ≈ 2 arcsec. In some cases it was found that the continuum sources were resolved at the full resolution of the telescope. H I spectra towards the continuum sources were produced using the *AIPS* task ISPEC. This coherently added the calibrated visibilities together, on a channel-by-channel basis, using appropriate shifts in position away from the phase centre of the observations. Limits were placed on the range of baselines in the *uv*-plane that were averaged together if the source was resolved. Placing *uv*-plane limits on the data averaged together increases the total flux detected, at the expense of increased noise, but allows increased signal-to-noise in the spectra to be obtained. (Ideally the expected noise in a single 6.6 km s^{-1} channel, for a 1 hour integration, is ≈ 1 mJy, and noise levels close to this value were obtained, see Table 2.)

3. Results

The resulting H I spectra towards the observed, bright continuum sources are shown in Fig. 1. These results are shown in terms of optical depth, τ, where the observed flux density, S_{obs}, is related to the mean observed, continuum flux density, S_{cont} by

$$S_{\mathrm{obs}} = S_{\mathrm{cont}}(1 - \mathrm{e}^{-\tau}), \tag{1}$$

after smoothing the spectra to a resolution of 20 km s^{-1} (cf. Manning 2002, who discusses the linewidths of clouds seen in Lyα absorption studies, and Kalberla & Huad 2006, who find typical dispersions of this value for cold H I cores in Galactic High Velocity Clouds). These spectra do not show any obvious absorption towards any of these sources. The spectra are averages of both the left and right polarisations observed, and have had a large scale (fifth order polynomial) baseline removed, to correct for residual uncertainties in the bandpass calibrations. (The amplitude of this correction was in all cases small, less than a few mJy.) For R 151, the results for two nearby lines-of-sight, to different components of the NVSS source that was resolved by these observations, are presented. A few channels at each end of the observed band are excluded, as they are noisy due to large uncertainties in the antenna-based bandpass corrections. Also, a few channels are omitted from each of the 2003 January observations, due to correlator problems. These results are also summarised in Table 2, which gives the mean observed flux density of the source, the rms deviation per channel – after the polynomial was removed – and the signal-to-noise for each spectrum, together with the rms of the smoothed spectra in terms of optical depth.
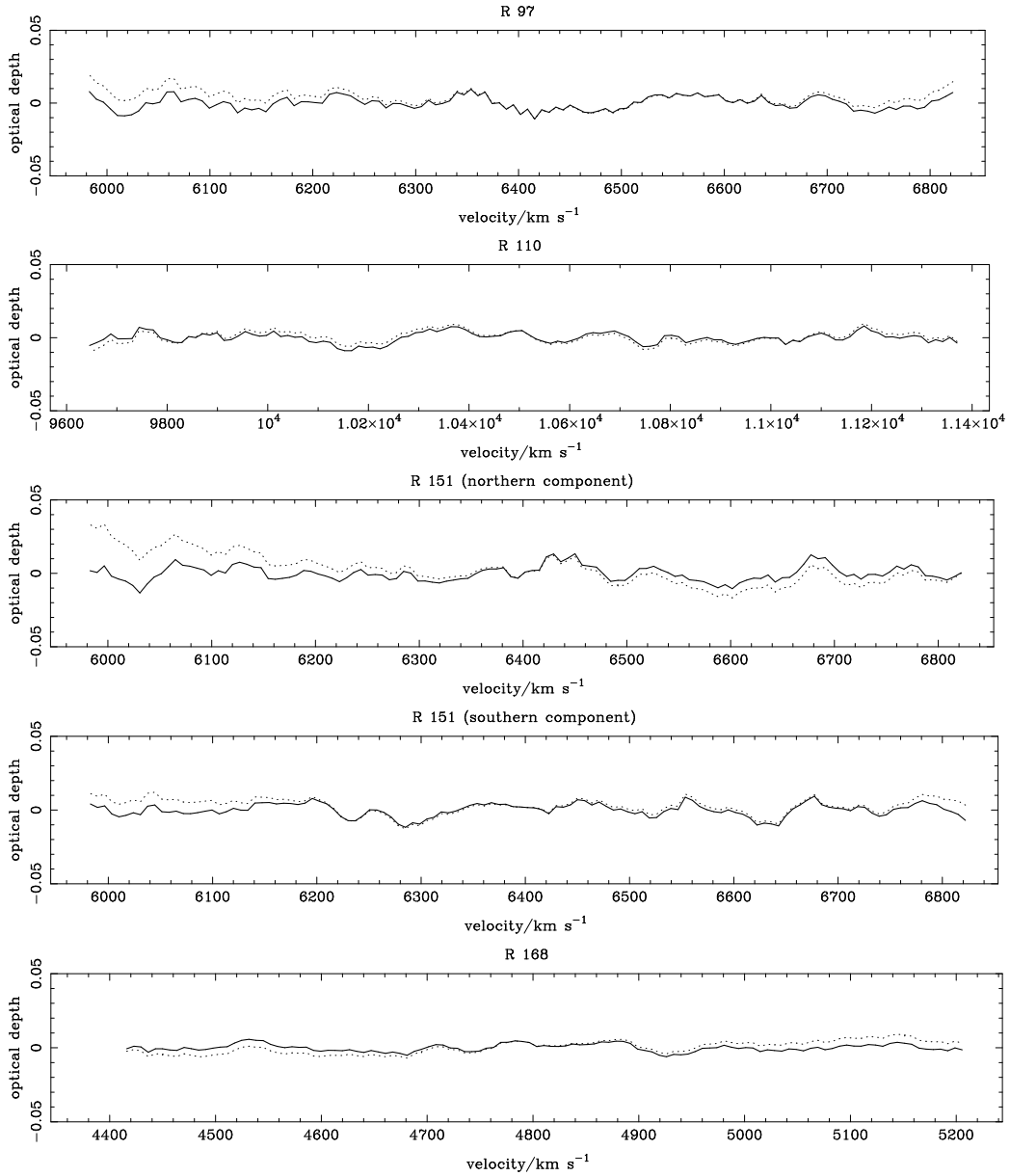
Figure 1. Observed 21-cm H I absorption spectra, in terms of optical depth, smoothed to a resolution of 20 km s^{-1}, both before (dotted line) and after (solid line) the removal of a fifth order polynomial fit.
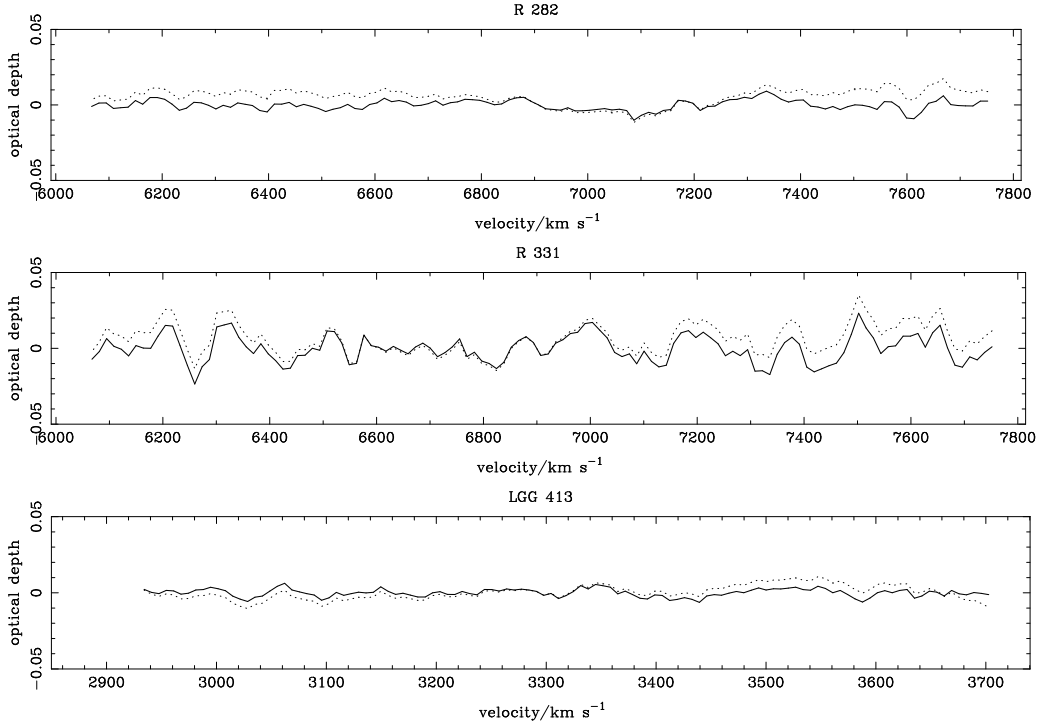
Figure 1. (continued).

Table 2. Results of HI absorption observations to background continuum sources in galaxy groups. For R 151 results for two lines-of-sight are given, as the NVSS source observed was resolved. The rms noise and signal-to-noise values are for the observed channel widths (i.e. 6.7 and 13.2 km s^{-1} for observations observed with total bandwidths of 4 and 8 MHz respectively). The optical depth rms is after smoothing to 20 km s^{-1} resolution. θ is the angular distance from the group centre.

Group ID	Source Position J2000 h m s ° ′ ″	θ /arcmin	flux density /mJy beam^{-1}	rms noise /mJy beam^{-1}	signal to noise	optical depth rms
R 97	10 48 38.5 +26 21 38	18	237	1.59	149	0.0044
R 110	11 00 29.7 +09 48 37	22	340	1.03	295	0.0036
R 151	11 42 10.6 +10 06 17	22	236	1.38	171	0.0043
	11 42 10.2 +10 06 13	22	187	1.26	148	0.0051
R 168	11 58 25.8 +24 50 19	18	468	1.45	323	0.0025
R 282	14 07 27.6 +09 17 40	24	402	1.17	344	0.0033
R 331	15 07 30.4 +12 35 49	14	90	0.76	118	0.0088
LGG 413	17 52 41.6 +24 36 03	7	208	0.97	215	0.0026

4. Discussion and Conclusions

Our observations constrain the mean column density along the sight-line. Using

$$n_{\rm HI} \simeq 1.82 \times 10^{22} T_{\rm spin} \int \tau \, dv \simeq 1.82 \times 10^{22} T_{\rm spin} \tau \Delta v \quad \text{m}^{-2} \tag{2}$$

for velocities in km s^{-1}, then the limits from our observations smoothed to $\Delta v = 20$ km s^{-1}, with typically a 3σ limit of $\tau \lesssim 0.01$, gives $n_{\rm HI} \lesssim 3.6 \times 10^{23}$ m^{-2}, for a spin temperature of 100 K. This limit is five times smaller that the peak H I column densities detected in emission by Walter et al. (2005), for the isolated H I cloud in the M81 group.

We can use this limit on the H I column density to constrain the mass distribution of clouds in virial equilibrium in these galaxy groups. For a projected area of the continuum source at the galaxy group A, and a line-of-sight through the group l, then if the volume filling factor of H I clouds in the galaxy group is f then the volume of "cloud" we expect in our surveyed volume is,

$$V = Alf. \tag{3}$$

If the number density of H I in our clouds is $\rho_{\rm HI}$ and our column density limit is $n_{\rm HI}$ then;

$$n_{\rm HI} = \frac{Alf\rho_{\rm HI}}{A} = lf\rho_{\rm HI}. \tag{4}$$

Now we can use the virial theorem to replace the dependence on $\rho_{\rm HI}$ for a dependence on $r_{\rm c}$, the cloud radius. The virial temperature is given by,

$$T_{\rm vir} = 0.13 \frac{GM\mu m_{\rm p}}{k_{\rm B} r_{\rm c}} \tag{5}$$

where μ is the mean particle mass in units of $m_{\rm p}$ (i.e. 1 for pure H I). The cloud mass M is simply

$$M = \frac{4}{3} \pi r_{\rm c}^3 \rho_{\rm HI} m_{\rm p} \tag{6}$$

which gives

$$T_{\rm vir} = 0.13 \frac{4G\pi m_{\rm p}^2 \mu}{3k_{\rm B}} \rho_{\rm HI} r_{\rm c}^2 \tag{7}$$

(for all parameters in S.I. units). Taking $T_{\rm vir} = T_{\rm spin}$, and $\mu = 1$, then

$$\rho_{\rm HI} r_{\rm c}^2 = 1.36 \times 10^{41} T_{\rm spin} \tag{8}$$

Substituting in Eq. 4 for $\rho_{\rm HI}$ gives

$$\frac{f}{r_{\rm c}^2} = \frac{n_{\rm HI}}{l T_{\rm spin} 1.36 \times 10^{41}} \tag{9}$$

Combining the observational constraint of Eq. 2 with Eq. 9 the dependence on spin temperature is eliminated, giving

$$\frac{f}{r_c^2} = \frac{1.82 \times 10^{22} \tau \Delta v}{1.36 \times 10^{41} l} = 1.34 \times 10^{-19} \frac{\tau \Delta v}{l} \tag{10}$$

or, for l and r_c are in units of pc,

$$\frac{f}{r_c^2} = 0.0041 \frac{\tau \Delta v}{l}. \tag{11}$$

Our (3σ) limits of τ of, typically, 0.01 in 20 km s^{-1}, for $l = 1$ Mpc, gives a statistical limit on f/r_h^2 of 8.3×10^{-10}. For $f = 1 \times 10^{-3}$ then $r_h = 1$ kpc, or for $f = 1 \times 10^{-6}$, $r_h = 35$ pc (although, of course, if the filling factor is low, a single line of sight may not, by chance, cross a cloud). The sense of the limit is that f/r_c^2 is less than that given in Eq.11 (i.e. for a given filling factor we constrain the lower limit for the cloud radius). As we have not considered a distribution of cloud sizes in this calculation r_c in the above refers to the mean cloud radius.

Although the present observations provide useful constraints on any cool H I in the galaxy groups studied, the results are limited due to the small number of lines of sight probed. This is due to the low density on the sky of bright enough background continuum sources. However, for more sensitive telescopes (e.g. looking forward to the SKA, see Carilli & Rawlings 2004), then this technique of searching for hydrogen by absorption will gain in competitiveness compared to searches for emission, as it will be possible to probe many more lines of sight. Any increase in sensitivity will correspondingly directly increase the detection sensitivity for emission constraints, whereas for absorption studies the improvement is not only in terms of the direct sensitivity to absorption towards any particular background source, but also the number of accessible lines of sight will be increased. Consequently, the overall usefulness of constraints provided by absorption studies will increase more rapidly than for emission studies with more sensitive instruments (see Kanekar & Briggs 2004 for further discussion).

In conclusion, these GMRT observations provide additional constraints on the amount of cool hydrogen clouds that could exist along 8 lines of sight through 7 galaxy groups. Although these results do not provide strong constraints on any *cool* H I in these galaxy groups, this method will, with the next generation of telescopes such as the SKA, allow very many lines of sight to be probed in a given group.

Acknowledgements

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