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Probable detection of HI at $z \simeq 1.3$ from DEEP2 galaxies using the GMRT

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Abstract. We analyse the redshifted HI emission from a DEEP2 field using the Giant Meterwave Radio Telescope in the frequency band of 610 MHz. There are $\simeq$ 400 galaxies in the redshift range $1.24 < z < 1.36$ and within the field of view $\simeq 44'$. We coadd the HI 21 cm-line emission at the locations of the DEEP2 galaxies. We apply stacking on three different data cubes: primary beam uncorrected, primary beam corrected (uniform weighing) and primary beam corrected (optimal weighing). We report a probable detection of the HI signal between 2–3σ level. For optimally-weighted cube, we obtain an average flux per halo: $17^{+8}_{-11}\,\mu$Jy and velocity width: $270^{+360}_{-180}\,\mathrm{km\,sec^{-1}}$ (both 90% confidence limits). The average HI mass of a halo is $M_{\rm HI} \simeq 2 \times 10^{10}\,\mathrm{M_\odot}$ and it lies in the range 0.35–8.3 $10^{10}\,\mathrm{M_\odot}$ (90% confidence limit). We compare our results with existing N-body simulations and find reasonable agreement.

Keywords : galaxies: high-redshift—radio lines: galaxies—cosmology: observations

1. Introduction

To determine the evolution of the HI content of galaxies as a function of redshift is a very important input into the understanding of the history of gas content and star formation in the universe. While the study of damped Lyman-alpha clouds in absorption gives the evolution of the aggregate HI content in the redshift range $0.5 \le z \le 5$ (Noterdaeme et al. 2012), the determination of HI content of a halo of a given mass remains elusive at high redshifts owing to the faintness of individual halos in the HI 21 cm line emission, e.g. the detection of $\simeq 10^{10}\,\mathrm{M_\odot}$ of HI at z= 1.3 would take 400 hours of observation with the Giant Meterwave Radio Telescope (GMRT). Direct observation of HI 21-cm line emission and its detailed modelling has only been possible at $z \simeq 0$ (Zwaan et al. 2005). For selected fields, the HI has been detected in emission for $z \le 0.2$ (Verheijen et al. 2010).

In this paper we report GMRT observations of one of the DEEP2 fields and attempt to estimate the HI content of the universe at $z \simeq 1.3$ using stacking of the spectra at the locations of the DEEP2 galaxies.

2. Observations and data analysis

Based on the examinations of the NVSS images of the the four DEEP2 Fields, the field centered at 1652+3455 (selected as ′Zone of very low extinction′ for DEEP2 observations) was selected for observations with the GMRT at 610 MHz. Amongst the four fields, this field contains the minimum number of bright radio sources within the primary beams (full width at half maximum $\sim 44'$) of the GMRT antennas at 610 MHz.

Based on the distribution of DEEP2 galaxies in Right Ascension and Declination and in the redshift space, and taking into account the optimum range of frequencies for observations in the 610 MHz band, a frequency range of 601 to 633 MHz was selected. This frequency range corresponds to DEEP2 sources in the redshift range $1.24 < z < 1.36$, distributed over the range of right ascensions $251^\circ.6 < \alpha < 253^\circ.2$, and declinations $+34^\circ.65 < \delta < +35^\circ.2$. This region of $79' \times 33'$ was covered in two GMRT pointings, the primary beams (FWHM) of the GMRT dishes being $\sim 44'$. Each of these pointings were observed for a total of 12 hr with a bandwidth of 32 MHz and 512 channels. This setting gives a velocity resolution of ~ 31 km s^{-1}. One of the two 12 hour pointings was completely analysed and is discussed below.

The data was analysis using AIPS which yielded a spectral line image cube (512 channels) with a spatial resolution of $10''$ and a spectral resolution of 30.7 km s^{-1}. This spectral line image cube has an RMS of 260 μJy/beam/channel, close to the expected value of ~ 200 μJy/beam/channel.

3. Results

From the image cube, we extract spectra at the positions of DEEP2 sources in the field of view. We then shift and add the spectra centered at the respective redshifts of the DEEP2 sources. In this procedure, we retain 50 channels on either side of the center of addition. If a source lies within 50 channels from the edges of the spectrum, it is excluded from the analysis. This process retains 489 sources out of a total of 539 for the entire field of view. We also apply primary beam correction to the image cube. This process increases the noise and the source flux away from the phase center. For the primary beam corrected cube, we retain sources only within 30% of the primary beam. There are 389 sources in this angular area and the procedure of coadding yields 371 sources.

In Figure 1, we show the coadded raw spectrum and the 7-channel running average spectrum, for the primary beam uncorrected, the primary beam corrected, and

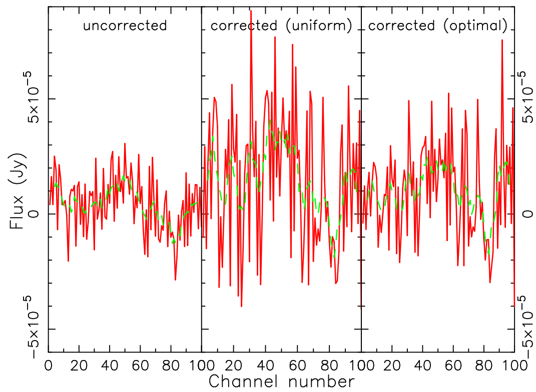

Figure 1. Co-added spectra toward DEEP2 galaxies. Left panel: The spectra are shifted and coadded at the central channel (number 50). The coadded spectrum contain 489 sources. The two curves correspond to: raw (solid, red), running average of 7 channels (dashed, green). The channel width is $\simeq 30\,\mathrm{km s^{-1}}$. Middle and Right panels: The same as the Left panel for primary beam corrected cube for uniform and optimal weighing, respectively. There are 371 sources in the coadded spectrum.

primary beam corrected optimally-weighed (each spectra is weighted with the inverse of the square of RMS) cases.

To establish the significance of a detection in the spectra shown in Fig. 1, we perform a likelihood analysis: the signal is modelled by three parameters of a Gaussian, height h, width, w and the mean x_0. In addition, we include a parameter to characterize the systematics: a constant offset of the mean of the spectrum from zero: E.

In Fig. 2, we show the posterior probability for the height and the width of the signal for the optimally-weighed spectrum in Fig. 1. The best fit x_0 and E are 50 and $6\,\mu$Jy, respectively, which means that the signal is centered at the expected position but a clear non-zero detection of E means the data suffers from systematic errors which can be modelled as a constant offset.

From the posterior probabilities shown in Fig. 2, we obtain: $h = 17^{+8}_{-11}\,\mu$Jy and $w = 9^{+12}_{-6}$ channels (90% confidence limits). This allows us to estimate the average HI mass of the halo, which lies in the range: $M_{\mathrm{HI}} = 0.35$–$8.3 \times 10^{10}\,\mathrm{M}_\odot$ (90% confidence limit).

Figure 2 suggests a 2–3σ detection of the HI signal. We get independent confirmation of this hypothesis by bootstrapping the signal by random reassignment of redshifts in the galaxy spectra and analysing the resulting coadded spectrum. The probability of a central enhancement obtained by coadding on the positions of correct redshifts is found to be smaller than 0.005, which is in general agreement with the results of the likelihood analysis.

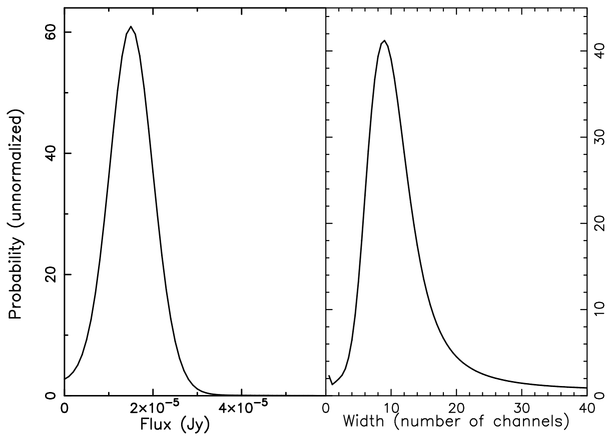

Figure 2. Posterior probabilities are shown for the optimally-weighed spectrum in Fig. 1. The width of each channel in the right hand panel is $\simeq 30\,\mathrm{km\,sec^{-1}}$.

We can directly compare our results with the simulations of Khandai et al. (2011) which showed that the stacked signal could have peak strength varying between 10–30 μJy and velocity width in the range $\simeq$ a few hundred–500 $\mathrm{km\,sec^{-1}}$ (e.g. Fig. 5 of their paper). Our results are in reasonable agreement with these simulations.

This agreement also confirms that DEEP2 galaxies are a highly biased representation of the HI distribution at $z \simeq 1.3$. If the HI content of haloes at that redshift follows the ratio of the aggregate HI content to baryon density then $M_{\rm HI} \simeq 10^{10}\,\mathrm{M_\odot}$ is contained in dark matter haloes of masses $M \simeq 2\times10^{11}\,\mathrm{M_\odot}$. On the other hand, typical damped Lyman-α clouds, which account for a large fraction of HI at $z \simeq 1$, are housed in haloes which are at least an order of magnitude lighter.

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