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An accurate low-redshift measurement of the cosmic neutral hydrogen density

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ABSTRACT

Using a spectral stacking technique, we measure the neutral hydrogen (HI) properties of a sample of galaxies at $z < 0.11$ across 35 pointings of the Westerbork Synthesis Radio Telescope. The radio data contain 1895 galaxies with redshifts and positions known from the Sloan Digital Sky Survey. We carefully quantified the effects of sample bias, aperture used to extract spectra, sidelobes and weighting technique and use our data to provide a new estimate for the cosmic HI mass density. We find a cosmic HI mass density of $\Omega_{\text{HI}} = (4.02 \pm 0.26) \times 10^{-4} h_{70}^{-1}$ at $\langle z \rangle = 0.066$, consistent with measurements from blind HI surveys and other HI stacking experiments at low redshifts. The combination of the small interferometer beam size and the large survey volume makes our result highly robust against systematic effects due to confusion at small scales and cosmic variance at large scales. Splitting into three sub-samples with $\langle z \rangle = 0.038, 0.067$, and 0.093 shows no significant evolution of the HI gas content at low redshift.

Key words: galaxies: evolution – galaxies: ISM – radio lines: galaxies.

1 INTRODUCTION

To fully understand the formation and evolution of galaxies, it is important to study the accretion of gas from the intergalactic medium, galaxy mergers and galaxy interaction, and the depletion of gas through galactic fountains and outflow processes (Kereš et al. 2005; Sancisi et al. 2008; Marinacci et al. 2010). Cool gas drives star formation in galaxies as shown by the correlation between star formation surface density (Σ_{SFR}) and HI surface density (Σ_{HI}) (Schmidt 1959; Kennicutt 1998), and the even tighter correlation with molecular hydrogen surface density (Σ_{H_2}) (Bigiel et al. 2008; Schruba et al. 2010). Whilst the latter provides evidence for the important role of molecular clouds in controlling star formation (Solomon & Vanden Bout 2005), because of the relatively short gas consumption time-scales, it is the large-scale net inflow and condensation of cool gas that eventually forms the massive

molecular clouds prior to star formation. Therefore, study of both the atomic and molecular phases of cool gas in galaxies is crucial for the understanding of their star formation history.

There are a number of observation techniques we can use to measure HI gas content. At high redshifts, the damped Ly α (DLA) systems seem to indicate large reservoirs of HI whose column density can be deduced from DLA absorption profiles, thereby allowing determination of the cosmic HI mass density. At $z > 1.65$, many DLA surveys have therefore been used to measure the cosmic HI gas density (Lanzetta et al. 1991; Prochaska, Herbert-Fort & Wolfe 2005; Noterdaeme et al. 2009, 2012; Songaila & Cowie 2010; Zafar et al. 2013; Crighton et al. 2015; Neeleman et al. 2016; Bird, Garnett & Ho 2017). Their results show a significant evolution of HI gas content over cosmic time and that there is more HI gas at high redshifts. At $z < 1.65$, Ly α absorption is only detected at ultraviolet (UV) wavelengths, so can only be observed with space-based telescopes. Rao, Turnshek & Nestor (2006) and Rao et al. (2017) have identified candidate DLA systems through their metal absorption lines in the redshift range $0.11 < z < 1.65$. Their results indicate no clear evolution of cosmic HI gas density. However, the

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low incidence of DLAs per unit redshift at intermediate redshifts give rise to significant statistical uncertainties.

In the local Universe, the H I content is conveniently measured through the direct detection of the 21-cm hyperfine emission line. The large instantaneous field of view provided by modern multibeam receivers has made blind, large-area H I surveys possible. The H I Parkes All-Sky Survey (HIPASS; Barnes et al. 2001) has detected H I emission from 5317 galaxies at $0 < z < 0.04$ over a sky area of $21\,341\text{ deg}^2$ (Meyer et al. 2004; Wong et al. 2006), and the Arecibo Legacy Fast ALFA (ALFALFA) survey (Giovanelli et al. 2005) has detected $\sim 31\,500$ galaxies out to $z = 0.06$ over a sky area of approximately 7000 deg^2 (Haynes et al. 2018). These large-area surveys allow for accurate measurement of the local H I mass function and the cosmic H I gas density. The measurements of H I density from these surveys are reasonably consistent with each other (Zwaan et al. 2005; Martin et al. 2010; Jones et al. 2018). However, directly measuring 21-cm emission of more distant individual galaxies is difficult with the current generation of single-dish radio telescopes, so this approach is limited to low redshift.

Individual deep 21-cm pointings have proven the feasibility of detecting H I galaxies outside the local Universe and up to $z \approx 0.3$ (Zwaan, van Dokkum & Verheijen 2001; Verheijen et al. 2007; Catinella et al. 2008; Fernández et al. 2016). However, in order to increase the chance of detection, the observed areas are often pre-selected. For example, Catinella & Cortese (2015) detected 39 galaxies up to $z = 0.25$ with the 305-m Arecibo telescope, selecting them by presence of H α emission, disc morphology and isolation. Zwaan et al. (2001) and Verheijen et al. (2007) targeted galaxies in clusters at $z \approx 0.2$ with the Westerbork Synthesis Radio Telescope (WSRT). These samples are biased towards bright galaxies with high-optical surface brightness, or in dense regions.

However, blind surveys to higher redshifts are time-consuming. For example, the Arecibo Ultra Deep Survey (AUDS; Freudling et al. 2011; Hoppmann et al. 2015) has so-far detected 103 galaxies with 400 h of integration time in the redshift range of $0 < z < 0.16$. The Cosmological Evolution Survey (COSMOS) H I Large Extragalactic Survey (CHILES) over the redshift range of $z = 0\text{--}0.45$ (Fernández et al. 2013; Fernández et al. 2016) will be able to detect up to 300 galaxies with 1000 h of observation time on the Very Large Array. However, even with such large integration times, these surveys have been limited to very small sky areas (1.35 deg^2 for AUDS and 0.3 deg^2 for CHILES), resulting in small effective volumes and large cosmic variance.

Next generation telescopes SKA pathfinder such as Australian Square Kilometre Array Pathfinder (ASKAP; Johnston et al. 2008; Meyer 2009), MeerKAT (Holwerda, Blyth & Baker 2012), Five-hundred-meter Aperture Spherical radio Telescope (FAST; Duffy et al. 2008; Nan et al. 2011), and WSRT/Aperture Tile in Focus (APERTIF; Oosterloo et al. 2009) will enable large-area surveys to significant depths. But less direct methods for measuring H I gas content at higher redshifts are also available using the technique of spectral stacking (Chengalur, Braun & Wieringa 2001). The technique combines a large number of rest-frame spectra extracted from the radio data with redshifts and positions from optical catalogues. This allows the noise to be averaged down and recovers a more significant spectral line signal, but averaged over a large sample of galaxies. By potentially accessing a larger number of galaxies, H I stacking can provide significantly large volumes, and much smaller cosmic variance.

Studies using the spectral stacking technique for galaxies outside the local Universe include those of Verheijen et al. (2007) and

Lah et al. (2009) who examined galaxies in cluster environments out to $z = 0.37$. Other observations have been used to study the properties of nearby galaxies, for example the relation between the H I content of a galaxy and its bulge (Fabello et al. 2011b) and correlations between the H I content, stellar mass and environment (Fabello et al. 2012; Brown et al. 2015, 2018), as well as the influence of an active galactic nucleus (Fabello et al. 2011a; Geréb et al. 2013). The first attempt to use stacking to calculate the cosmic H I gas density $\Omega_{\text{H I}}$ was presented by Lah et al. (2007) in the redshift range of $0.218 < z < 0.253$, using the Giant Metrewave Radio Telescope (GMRT). A more recent H I stacking experiment was carried out by Delhaize et al. (2013), using HIPASS data and new observations from the Parkes telescope combined them with $\sim 18\,300$ redshifts from the Two-Degree Field Galaxy Redshift Survey (2dFGRS) to obtain high signal-to-noise ratio (S/N) detections out to a redshift of $z = 0.13$.

Rhee et al. (2013) used data from WSRT and stacked a significantly smaller sample of 59 galaxies at $z \approx 0.1$ and 96 galaxies at $z \approx 0.2$. Rhee et al. (2016) cross-matched the zCOSMOS-bright catalogue with data from GMRT, obtaining a 474 galaxy sample at $z \approx 0.37$. With the stacking technique, they made a 3σ detection of average H I mass. Rhee et al. (2018) used observations made with the GMRT to probe the H I gas content of 165 field galaxies in the VIMOS VLT Deep Survey (VVDS) 14h field at $z \approx 0.32$, resulting in a measurement of H I mass with a significance of 2.8σ . Kanekar, Sethi & Dwarakanath (2016) used the GMRT to stack H I emission from massive star-forming galaxies at $z \approx 1.18$ to -1.34 , the highest redshift at which stacking has been attempted.

The technique of ‘intensity mapping’ can also be used to extend the H I survey limit to higher redshifts. Similar to stacking, this involves measuring the cross-power between radio and optical surveys (Pen et al. 2009), but uses the bulk emission fluctuations due to galaxy clustering over the surveyed region instead of individual galaxies. Observations conducted with the Green Bank Telescope (Chang et al. 2010; Masui et al. 2013), spanning the redshift range of $0.6 < z < 1$ have highlighted the potential power of this technique. However, the accuracy of cosmic H I density measurements remains low, and there is a dependence on simulations of the wavelength-dependent bias of galaxies at optical and radio wavelengths (Wolz, Blake & Wyithe 2017).

In this paper, we foreshadow some of the techniques that will be utilized in the future SKA pathfinder surveys to bridge the redshift gap $0.2 < z < 1.65$. We achieve this by using an interferometer in order to reduce problems arising from confusion that affect single-dish data. But we also cover a wide field of view by using multiple pointing centres in order to reduce cosmic variance, which has otherwise affected deep interferometer surveys. We obtain the radio data from WSRT (Geréb et al. 2015) and use a corresponding optical catalogue from Sloan Digital Sky Survey (SDSS; York et al. 2000), containing 1895 galaxies within the sampled redshift range. Sample selection is not biased by environment, star formation, or any particular physical characteristic other than the optical magnitude limits of the SDSS.

Section 2 presents the observational data used in this paper. In Section 3, we present the spectral extraction and stacking methodology. In Section 4, we measure average H I mass and H I mass-to-light ratio for the sample, and various sub-samples in redshift and luminosity. In Section 5, we describe our measurement of $\Omega_{\text{H I}}$ and compare with existing results in the literature. Throughout this paper, we use $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

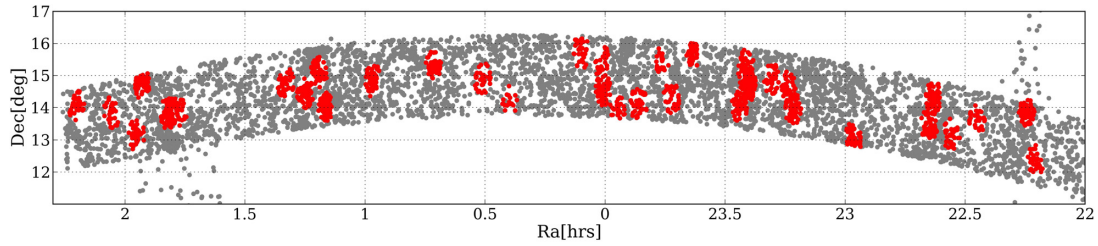


Figure 1. Positions of the galaxies contained within the 35 individual WSRT pointings observed with the WSRT (red). Other galaxies in the *GALEX*/SDSS strip are shown in grey.

2 DATA

The H I observations were made using the WSRT. Thirty six pointing positions were selected according to the overall WSRT schedule with the only main constraint being that the sky overlap with footprint of the *Galaxy Evolution eXplorer* (*GALEX*) survey (Martin et al. 2005) and SDSS South Galactic Cap region ($21^{\text{h}} < \text{RA} < 2^{\text{h}}$ and $10^{\circ} < \text{Dec.} < 16^{\circ}$). 351 h of observation time were used to observe the region, with each pointing observed for between 5 h and 12 h. Data from one of the pointings were discarded due to bad data quality. The sky region covered by the remaining 35 pointings is shown in Fig. 1.

The half-power beam width (HPBW) of the WSRT is 35 arcmin at the observing frequency, and the average synthesized beam size is $108 \text{ arcsec} \times 22 \text{ arcsec}$. Fig. 2 shows a histogram of major axis, minor axis, and position angles of the synthesized beams for the 35 pointings. The data were reduced and self-calibrated using the radio astronomy data reduction package MIRIAD (Sault, Teuben & Wright 1995). The data were flagged to reduce the contamination by radio frequency interference (RFI).

The reduced data cubes have a size of 601×601 pixels with a pixel size of $3 \text{ arcsec} \times 3 \text{ arcsec}$. The data consist of 8×20 MHz bands, each with 128 channels and two polarisations. Each channel is 0.15625 MHz wide, corresponding to $\sim 33 \text{ km s}^{-1}$ at $z = 0$ and $\sim 37 \text{ km s}^{-1}$ at $z = 0.11$. The rms was typically $0.2 \text{ mJy beam}^{-1}$ per 0.15625 MHz channel for each field, independent of frequency. Each frequency band overlaps by 3 MHz resulting in an overall frequency range of 1.406–1.268 GHz, corresponding to a redshift range of $0.01 < z < 0.12$. However, due to stronger RFI at higher redshift we set an upper redshift limit of $z = 0.11$.

Accurate measurements of redshift and spacial positions are indispensable for stacking. We use SDSS Data Release 9 (DR9), as the optical catalogue for our stacking analysis. SDSS has a typical redshift error of $\sim 60 \text{ km s}^{-1}$ and a spectral density of $60\text{--}100 \text{ deg}^{-2}$ ($z < 0.12$) in the region we selected for the H I observations. With the target selection algorithm described in Strauss et al. (2002), the SDSS sample has a completeness that exceeds 99 per cent (excluding fibre collisions). The sample appears to be complete for a star formation rate above $10^{-2} M_{\odot} \text{ yr}^{-1}$ for $z < 0.06$. The luminosities used in this paper are calculated from the SDSS *r*-band magnitudes, applying *k*-corrections (Chilingarian & Zolotukhin 2012).

By cross-matching our radio data with the SDSS catalogue, we obtain a sample of 1895 galaxies spanning the redshift range of $0.01 < z < 0.11$ (Fig. 3) and within the radius of the pointings at which the normalized primary beam response drops to 0.1. We refer to this as the magnitude-limited sample, only including galaxies with *r*-band magnitude brighter than 17.77. It has a mean redshift of $\langle z \rangle = 0.066$. To measure the H I density with a sample less biased by magnitude, we also created a volume-limited sample with $z \leq 0.0285$, which has

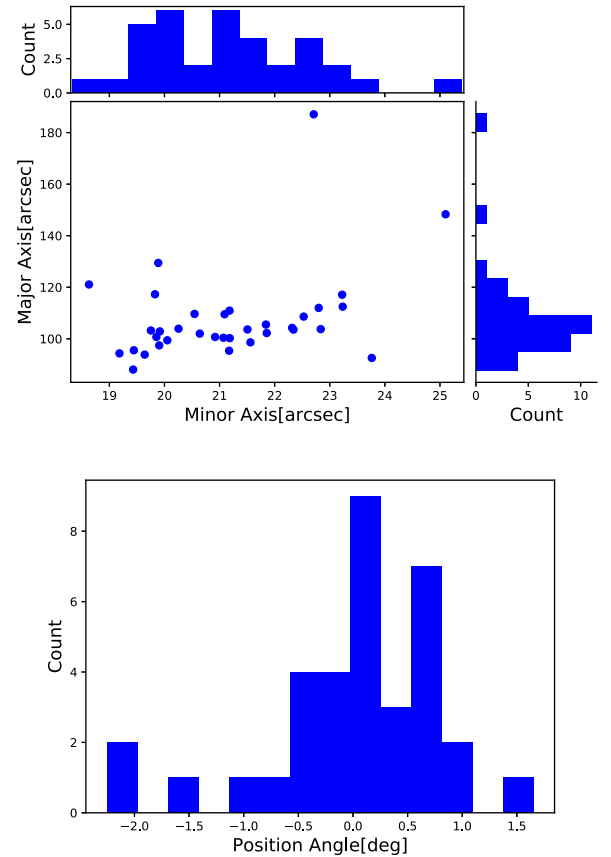


Figure 2. A histogram of the major axis, minor axis and position angle of the 35 synthesized beams, obtained from a Gaussian fit to the dirty beam point spread functions. One beam has a very large major axis ($\sim 180 \text{ arcsec}$) due to poorer uv coverage.

149 galaxies in total and a mean redshift of $\langle z \rangle = 0.024$. The volume-limited sample is complete for *r*-band luminosities $> 10^{8.68} L_{\odot}$. Fig. 4 shows the *r*-band luminosity distribution as a function of redshift with the volume-limited sub-sample highlighted.

3 STACKING ANALYSIS

3.1 H I mass spectra

The stacking technique used in this paper is similar to that described in Geréb et al. (2013). Spectra were extracted from the data cubes over an extended region around the SDSS position. After extensive tests, we find the region with aperture radius of 35 kpc gives best stacking results (see Section 3.3). The spatially-integrated spectrum

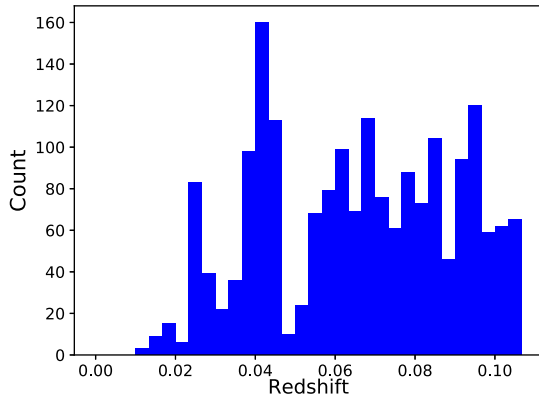


Figure 3. Redshift distribution of the SDSS spectroscopic sample contained within the 35 pointings. The width of the redshift bins is 0.003. The selected sample has an lower redshift limit of $z = 0.01$ and upper redshift limit of $z = 0.11$. The mean redshift of the sample is $\langle z \rangle = 0.066$.

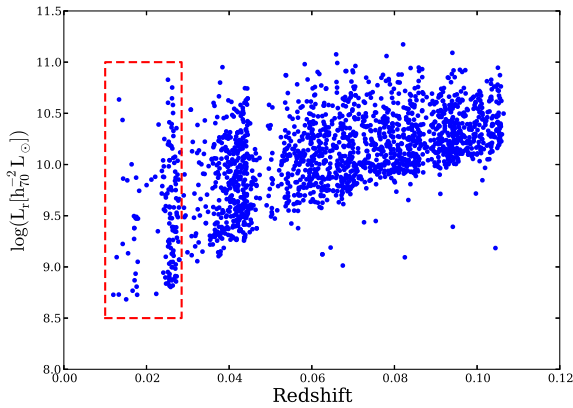


Figure 4. A plot of the r -band luminosity as a function of redshift z , for the SDSS sample. The red-dashed rectangular encloses a volume-limited sub-sample.

was calculated from

$$S_v = \frac{\sum_x \sum_y S_v(x, y)}{\sum_x \sum_y B(x, y)}, \quad (1)$$

where $S_v(x, y)$ is the flux density at pixel position (x, y) and $B(x, y)$ is the normalized synthesized beam response (centred on the SDSS position) at the same pixel position. After this, a second-order baseline was fitted to remove residual continuum (excluding a velocity range of 500 km s^{-1} around the expected spectral location of the SDSS galaxy), and the spectra were de-redshifted. The barycentric frequency is converted from the observed to the rest frame by $\nu_{\text{res}} = \nu_{\text{obs}}(1 + z)$. As the channel width is also broadened in this process, H I flux density is conserved by applying the corresponding correction:

$$S_{\nu_{\text{res}}} = \frac{S_{\nu_{\text{obs}}}}{(1 + z)}. \quad (2)$$

After shifting to the rest frame, the flux spectra were converted into mass spectra using the following relation:

$$m_{\text{HI}}(\nu) = 4.98 \times 10^7 S_{\nu} D_L^2 f^{-1}, \quad (3)$$

where S_{ν} is the de-redshifted H I flux density in Jy, D_L is the luminosity distance in Mpc, f is the normalized primary beam response, and m_{HI} is in units of $M_{\odot} \text{ MHz}^{-1}$.

We introduce a weight factor that depends on the primary beam response f , the luminosity distance D_L , as well as the rms noise of the flux density spectra σ . The weight of i th galaxy is expressed as

$$w_i = f^2 D_L^{-\gamma} \sigma^{-2}, \quad (4)$$

where large values of γ give larger weight to nearby galaxies, and small values give more weight to distant galaxies. The effect of the weight factor on the results is considered later. The averaged final stacked spectrum is obtained from

$$\langle m_{\text{HI}}(\nu) \rangle = \frac{\sum_{i=1}^n w_i m_{\text{HI},i}}{\sum_{i=1}^n w_i}. \quad (5)$$

The integrated H I mass of a stack, or $\langle M_{\text{HI}} \rangle$, is then defined as the integral along the frequency axis over the mass spectrum:

$$M_{\text{HI}} = \int_{\nu_0 - \Delta\nu}^{\nu_0 + \Delta\nu} \langle m_{\text{HI}}(\nu) \rangle d\nu, \quad (6)$$

where ν_0 refers to 1420.406 MHz and $\Delta\nu$ is large enough to capture all flux from the stack (we will later use $\Delta\nu = 1.5 \text{ MHz}$, corresponding to $\pm 317 \text{ km s}^{-1}$).

We estimate the error of the H I mass measurement through jackknife resampling. From the total sample of n spectra, $n/20$ randomly selected spectra are removed at a time to construct 20 jackknife samples, from which 20 mass spectra are obtained.

The jackknife estimate of the true variance of the measured value of the mass spectrum at a given frequency is then given by

$$\sigma^2(\langle m_{\text{HI}} \rangle) = \frac{19}{20} \sum_{j=1}^{20} \left(\langle m_{\text{HI}} \rangle - \langle m_{\text{HI}}^j \rangle \right)^2, \quad (7)$$

where the $\langle m_{\text{HI}} \rangle$ refers to the averaged H I mass spectrum from the original sample.

We can also measure $\langle M_{\text{HI}}/L \rangle$ and its error by stacking the individual M_{HI}/L spectra. We do this via equations (5) and (6), with M_{HI} replaced by M_{HI}/L .

3.2 Weighting

In order to investigate the effect of different weights on the results, we explore the range $0 \leq \gamma \leq 4$. As shown in Fig. 5 and Table 1, highly significant values for $\langle M_{\text{HI}} \rangle$ are obtained for all weighting parameters. $\langle M_{\text{HI}} \rangle$ monotonically decreases as γ increases, reflecting the lower H I mass of nearby galaxies. Similarly, $\langle M_{\text{HI}}/L \rangle$ increases with γ , although the variation is somewhat less significant. The highest overall S/N occurs when $\gamma = 1$. As shown in Table 1, the weighted mean redshift decreases with increasing γ . The measurements at $\gamma = 1$ are more representative of the entire sample: larger γ gives more weight to nearby galaxies; smaller γ gives too much weight to low S/N measurements of distant galaxies.

3.3 Aperture size

With our relatively small synthesized beam area, many SDSS galaxies will be resolved or partially resolved in H I. The extraction radius therefore needs to be carefully chosen. Too small a radius may miss H I flux, whilst too large radius will unnecessarily introduce extra noise, and increase confusion from nearby galaxies. Based on determining the maximum radius prior to confusion becoming a problem (see Fig. 6), we have chosen an aperture radius of 35 kpc , similar to the 30 kpc box size used by Geréb et al. (2015), whose observations had a somewhat smaller $\sim 10 \text{ arcsec}$ synthesized beam.

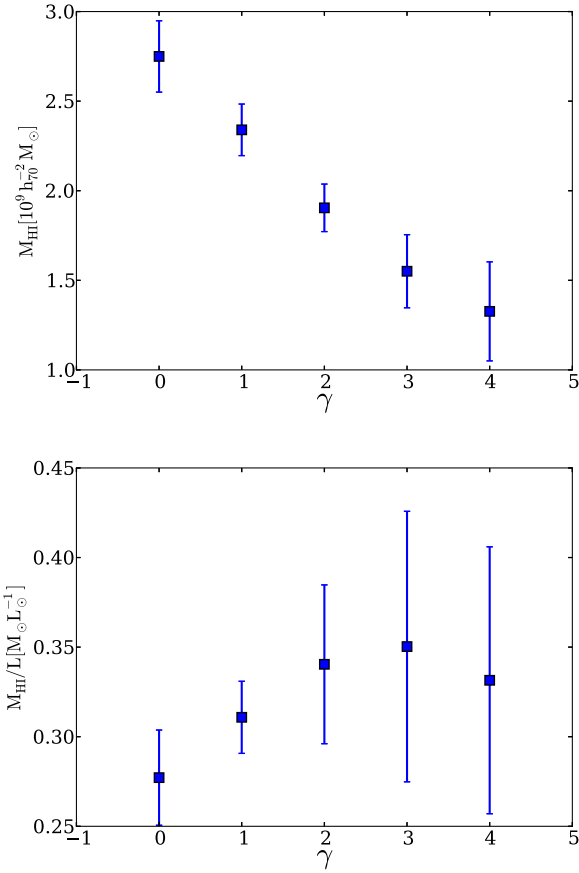


Figure 5. Average H I mass M_{HI} (top) and average H I mass-to-light ratio M_{HI}/L (bottom) as a function of weight parameter γ . The errors are obtained by jackknife sampling.

Table 1. Mean H I mass M_{HI} and mean r -band H I mass-to-light ratio M_{HI}/L_r for the magnitude-limited sample, using different values of the weight parameter γ . The weighted mean redshift is also given.

γ	$\langle z \rangle$	$\langle M_{\text{HI}} \rangle$ ($10^9 h_{70}^{-2} M_{\odot}$)	$S/N(M_{\text{HI}})$	$\langle M_{\text{HI}}/L_r \rangle$ (M_{\odot}/L_{\odot})	$S/N(M_{\text{HI}}/L)$
0	0.062	2.75 ± 0.20	13.8	0.28 ± 0.03	10.4
1	0.051	2.34 ± 0.14	16.3	0.31 ± 0.02	15.5
2	0.041	1.90 ± 0.13	14.4	0.34 ± 0.04	7.7
3	0.032	1.55 ± 0.20	7.6	0.35 ± 0.08	4.6
4	0.025	1.33 ± 0.27	4.8	0.33 ± 0.07	4.5

Fig. 6 shows that, for radii <35 kpc, the number of confused galaxies within (a) the aperture or within the synthesized beam, and (b) within 3 MHz (630 km s^{-1}) remains in the range of 120–130. However, at larger apertures, confusion increases rapidly, approximately doubling by 80 kpc. The luminosity distribution of the confused galaxies is shown in Fig. 6.

The corresponding stacked values for $\langle M_{\text{HI}} \rangle$ and $\langle M_{\text{HI}}/L \rangle$ are shown in Fig. 7. $\langle M_{\text{HI}} \rangle$ increases monotonically, reflecting the finite size of the galaxy H I discs at small apertures, and the effect of confusion at large apertures. Between 35 and 80 kpc, $\langle M_{\text{HI}} \rangle$ increases by 40 per cent. $\langle M_{\text{HI}}/L \rangle$ is less sensitive to aperture. Values for both are given in Table 2 and show that S/N for $\langle M_{\text{HI}}/L \rangle$ is maximized when the aperture radius is 35 kpc.

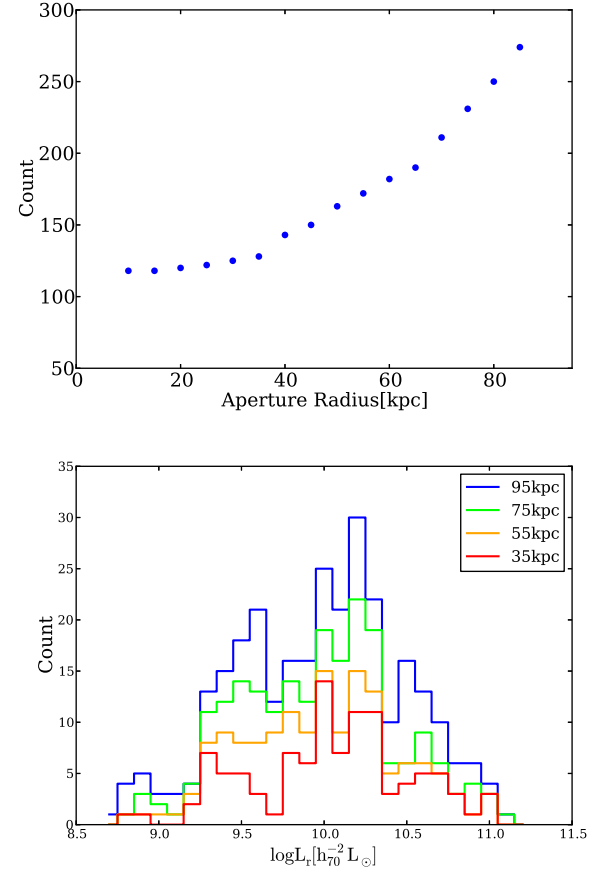


Figure 6. The top panel shows the number of confused galaxies in stacks of different aperture size. The bottom panel shows the histogram of the luminosity of the confused galaxies.

3.4 Confusion correction

As shown above, ~ 7 per cent of our sample is potentially confused with neighbouring galaxies, both catalogued and uncatalogued. Although the WSRT synthesized beam is almost an order of magnitude smaller than the Arecibo beam and two orders of magnitude smaller than the Parkes beam, we can nevertheless estimate the corresponding correction factors for $\langle M_{\text{HI}} \rangle$ and $\langle M_{\text{HI}}/L \rangle$.

We have therefore carried out a mock stacking experiment on the TAIPAN+WALLABY simulations of da Cunha et al. (2017), who employ the state-of-the-art theoretical galaxy formation model GALFORM (Cole et al. 2000), in the version presented by Lagos et al. (2012). The latter follows the cosmic evolution of galaxies using a self-consistent two-phase interstellar medium model, in which stars form from the molecular gas content of galaxies. This model provides a physical distinction between atomic and molecular hydrogen in galaxies, and thus, it is capable of predicting the evolution of these two components separately. The specific lightcones used here were produced using the N -body cold dark matter cosmological Millennium I (Springel et al. 2005) and II (Boylan-Kolchin et al. 2009) simulations, which in combination allow us to have a complete census of the H I masses of galaxies from the most H I-massive galaxies, down to an H I mass of $\approx 10^6 M_{\odot}$. Two sets of lightcones were created and presented in da Cunha et al. (2017), one mimicking the selection function of TAIPAN and another one mimicking the selection function of WALLABY, with the primary aim of assessing the overlap

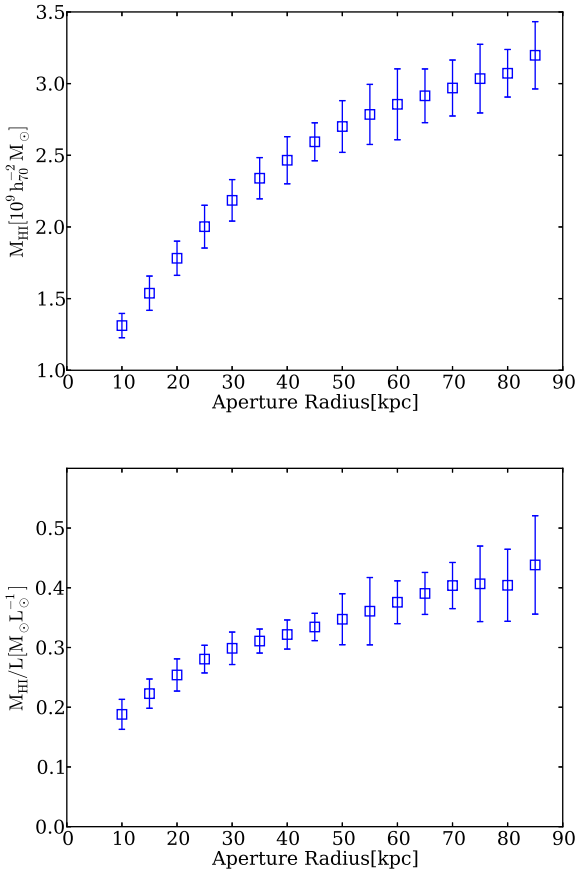


Figure 7. The measurements from stacks with different aperture size. The top panel is the for $M_{\text{H I}}$ stacks and the bottom panel is for $M_{\text{H I}}/L$ stacks.

population between the two surveys. Here, we use only the WALLABY¹ lightcones.

We extract 100 strips each of $2.5^\circ \times 40^\circ$, and in each strip, we produce 35 pointings of radii 0.5° . We select the galaxies located in these 35 pointings from $z = 0.01 \sim 0.11$ and $r \leq 17.7$. We also produce a volume-limited sub-sample as previously described. We use the same method as above to measure the $\langle M_{\text{H I}} \rangle$ and $\langle M_{\text{H I}}/L \rangle$, after locating the confused galaxies. We carry out the stacking using three methods:

- (i) Assuming that there is no confusion (i.e. stack the H I in the selected galaxies only);
- (ii) Combine the H I in the sample galaxies with that of any companions with $r < 17.77$;
- (iii) Combine the H I in the sample galaxies with that of all companions.

We follow the method in Fabello et al. (2012) to model the confusion, estimating the total signal S_i as the sum of the sample galaxy S_s and the companions (S_c) weighted with two factors:

$$S_i = S_s + \sum_c f_{1;c} f_{2;c} S_c, \quad (8)$$

where the f_1 and f_2 model the overlap between the sample galaxy and its companion in angular and redshift space.

¹This is the Extragalactic All Sky H I Survey being carried out with the Australian Square Kilometer Array Pathfinder (Johnston et al. 2008).

Table 2. Average H I mass $M_{\text{H I}}$, mass-to-light ratio $M_{\text{H I}}/L$, and corresponding S/N as a function of aperture size.

Aperture (kpc)	$\langle M_{\text{H I}} \rangle$ ($10^9 h_{70}^{-2} M_{\odot}$)	S/N($M_{\text{H I}}$)	$\langle M_{\text{H I}}/L \rangle$ ($M_{\odot} L_{\odot}^{-1}$)	S/N($M_{\text{H I}}/L$)
10	1.31 ± 0.08	15.5	0.19 ± 0.03	7.5
15	1.54 ± 0.12	12.9	0.22 ± 0.02	9.1
20	1.78 ± 0.12	14.9	0.25 ± 0.03	9.4
25	2.00 ± 0.15	13.4	0.28 ± 0.02	12.1
30	2.18 ± 0.14	15.1	0.30 ± 0.03	11.0
35	2.34 ± 0.14	16.3	0.31 ± 0.02	15.5
40	2.46 ± 0.16	15.0	0.32 ± 0.02	13.2
45	2.59 ± 0.13	19.6	0.33 ± 0.02	14.6
50	2.70 ± 0.18	15.0	0.35 ± 0.04	8.1
55	2.78 ± 0.21	13.3	0.36 ± 0.06	6.4
60	2.86 ± 0.25	11.6	0.38 ± 0.04	10.5
65	2.91 ± 0.19	15.6	0.39 ± 0.04	11.1
70	2.97 ± 0.20	15.2	0.40 ± 0.04	10.5
75	3.03 ± 0.24	12.7	0.41 ± 0.06	6.4
80	3.07 ± 0.17	18.5	0.40 ± 0.06	6.7
85	3.20 ± 0.23	13.6	0.44 ± 0.08	5.3

Table 3. Measurements of $\langle M_{\text{H I}} \rangle$ and $\langle M_{\text{H I}}/L \rangle$ from stacking galaxies in the mock catalogue. The superscript ‘m’ and ‘v’ refer to the magnitude-limited sample and volume-limited sub-sample, respectively.

	No confusion	Confused with sample galaxies	Confused with all galaxies
$\langle M_{\text{H I}}^{\text{m}} \rangle (10^9 h_{70}^{-2} M_{\odot})$	2.757	2.794	2.816
$\langle M_{\text{H I}}^{\text{m}}/L \rangle (M_{\odot}/L_{\odot})$	0.289	0.293	0.294
$\langle M_{\text{H I}}^{\text{v}} \rangle (10^9 h_{70}^{-2} M_{\odot})$	1.674	1.706	1.708
$\langle M_{\text{H I}}^{\text{v}}/L \rangle (M_{\odot}/L_{\odot})$	0.560	0.570	0.572

The results are shown in Table 3. For the magnitude-limited sample, the value of $\langle M_{\text{H I}} \rangle$ derived from stacking confused sample galaxies with $r \leq 17.77$ and stacking with all confused galaxies are 1.3 ± 0.6 and 2.1 ± 0.7 percent larger than the ‘correct’ result, respectively. For $\langle M_{\text{H I}}/L \rangle$, the increase is 1.4 ± 0.6 and 1.7 ± 0.6 percent, respectively. The increments for the volume-limited sub-samples are slightly more. For the real data, we will later utilize the confusion-included sample and use correction factors based on the ratios of method (i) and (iii) above, with 35 kpc resolution.

3.5 PSF effects

In interferometric observations, the original H I sky is convolved with the point spread function (PSF) of the telescope. The PSF is then normally removed using a deconvolution algorithm. However, such a procedure is not possible when individual galaxy signals are below the noise level. Our stacks are therefore stacks of ‘dirty’ maps. To explore the effect of this, we again employ a simulation.

We convolve a simulated H I sky with the average PSF of WSRT. The simulated sky is based on the mock catalogue of Duffy et al. (2012), in which the Theoretical Astrophysical Observatory (TAO) was used to generate a lightcone catalogue from the semi-analytic models of Croton et al. (2006). Cold gas masses in this simulation were scaled by Duffy et al. to match the local H I mass function measured by ALFALFA (Martin et al. 2010) to ensure a realistic modelling of the local H I Universe. Galaxies with H I masses $M_{\text{H I}} > 10^{8.5}$ or apparent magnitudes $m_r < 19.8$ are populated into the synthetic sky using the GALMOD routine from GIPSY.

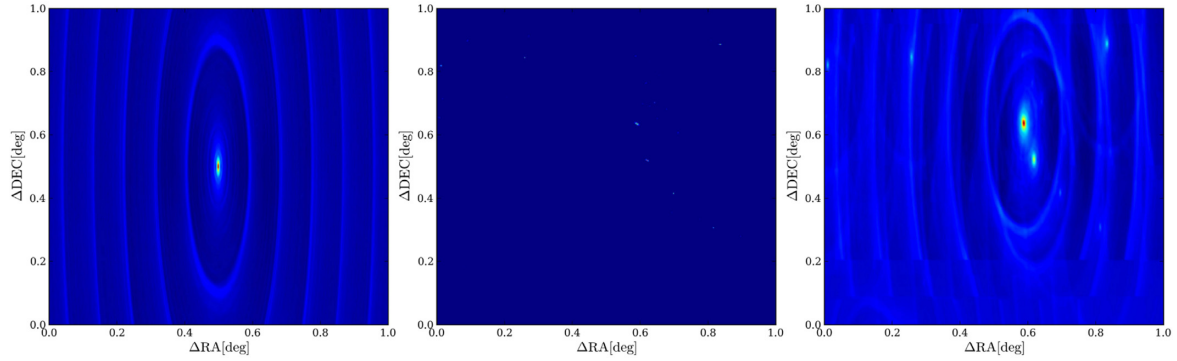


Figure 8. Left-hand panel: average PSF of WSRT observations. Central panel: a subset of a 3 MHz slice of the S^3 -SAX simulated sky at $z = 0.055$. Right-hand panel: the same slice after the convolution with the PSF.

Table 4. The results of stacking with the original catalogue, the simulated sky and the convolved sky. For the latter two, we use a aperture with a radius of 35 kpc to extract the spectra.

Data source	Aperture (kpc)	Stacked integral ($10^9 h_{70}^{-2} M_{\odot}$)
S^3 -SAX catalogue	–	3.013
Confused sky	35	3.021
Convolved sky	35	2.962

In Fig. 8, we illustrate the convolution process. The left-hand panel is the PSF of WSRT, the central panel shows a 3 MHz slice of the simulated sky at $z = 0.055$, and the right-hand panel is the same slice after the convolution with the PSF. We can see clearly see the effect of sidelobes on the surrounding sky. To quantify this effect, we apply the same stacking method to the simulated sky and the convolved sky. We stack the spectra from 2727 galaxies located in the range of $0.01 < z < 0.11$ with apparent r -band magnitudes brighter than 17.7.

In Table 4, we show the results of stacking with the original catalogue, the simulated sky and the convolved sky. For the latter two, we use an aperture with a radius of 35 kpc to extract the spectra. Directly stacking the H I mass given by the catalogue results in an averaged H I mass of $3.013 \times 10^9 h_{70}^{-2} M_{\odot}$. Stacking the spectra of the selected galaxies in the simulated sky gives $3.021 \times 10^9 h_{70}^{-2} M_{\odot}$, higher due to confusion. Stacking the spectra obtained from the convolved sky gives $2.962 \times 10^9 h_{70}^{-2} M_{\odot}$, lower due to the inclusion of negative sidelobes. Convolution makes the averaged integrated flux smaller by 1.7 per cent, meaning that sidelobes only result in a small underestimate of the true signal.

3.6 Cosmic variance

The Universe is only homogeneous on scales $\gg 100$ Mpc (Scrimgeour et al. 2012). Therefore observations in smaller regions can be affected by small-scale inhomogeneity, or cosmic variance. To assess the effect on our results, we assume the WSRT pointings are conical and we assign the ‘beam edge’ as the radius at which the normalized primary beam response equals to 0.1. At the median redshift of 0.066, the radius of this beam $r_z = 0.066, f = 0.1 = 0.5195$ deg, corresponding to 2368 kpc. This corresponds to a comoving volume of 6642 Mpc^3 per pointing with the small volume at $z < 0.01$ removed. The weighted noise-equivalent volume (square

primary beam weighting) for each beam is 1545 Mpc^3 . The number of SDSS galaxies with spectroscopic redshifts in each pointing varies between 18 and 146 (see Table 5). Combining the 35 pointings together, the weighted sampled volume is $5.4 \times 10^4 \text{ Mpc}^3$, which can be compared with the sampled volumes of HIPASS ($2.37 \times 10^5 \text{ Mpc}^3$; Zwaan et al. 2005) and the 100 per cent ALFALFA source catalogue ($10.15 \times 10^5 \text{ Mpc}^3$; Jones et al. 2018).

A simple quantifiable measure of the cosmic variance can be obtained by examining the variance of galaxy counts in the TAIPAN+WALLABY simulation. We define ξ [per cent] = $100 \times \sigma_{\text{cv}} / \langle N \rangle$, where the variance $\sigma_{\text{cv}}^2 = \sum_i (\langle N \rangle - N_i)^2 / n$, $\langle N \rangle$ is the mean galaxy count in the selected volumes, N_i is the number of galaxies in the volume i , and n is the total number of selected volumes. We randomly select 1000 strips of the same size as the WSRT strip and with the same redshift region from the simulation. In each strip, we produce 35 pointings whose distributions are same as the WSRT observations. For galaxies within 0.5° of one of the pointing centres, we find $\xi = 9.1 \pm 0.3$ per cent.

For SDSS in the main region, the mean weighted number of galaxies at Dec. near 14° across a similar 35 simulated pointings is 465 (reduced from 1485 by primary beam weighting), with a similar cosmic variance of 12 per cent. However, the weighted number of galaxies in our sample is substantially higher at 519 (reduced from 1895 by weighting). This implies that the region observed is overdense by more than the variation expected from cosmic variance. Nevertheless, the cosmic variance across a wide field of view is much lower compared with a deep single pointing. Furthermore, normalization using the SDSS luminosity function removes first-order changes to the H I density associated with optical overdensities. However, second-order environmental effects may influence the final result.

4 RESULTS

4.1 Individual pointings

The magnitude-limited sample has a mean redshift of $\langle z \rangle = 0.066$. The stacking results for each individual pointing are given in Table 5. Because of fewer galaxies and a smaller effective volume, the errors (estimated with jackknife method) are larger compared with the results from stacking the total sample. For the stacked mass spectra, only one stack (pointing 17) does not show a detection, three (pointings 12, 29, and 35) have unclear detections, whilst the remaining 30 pointings all result in clear detections. We show the stacked mass spectra in Appendix A.

Table 5. Results from stacking H I spectra in the 35 individual pointings observed with the WRST. Because of the smaller sample, the effective volume reduces and cosmic variance increases, the errors are larger compared with the results from the stacking with total sample (Section 3.2). We also show the statistical errors for stacked mass and mass-to-light spectra as $\text{noise}_{\text{stat, m}}$ and $\text{noise}_{\text{stat, m/l}}$.

Pointing	Position (J2000)	N	$\langle z \rangle$	$\langle M_{\text{H I}} \rangle$ ($10^9 h_{70}^{-2} M_{\odot}$)	Noise _{stat, m} ($10^9 h_{70}^{-2} M_{\odot}$)	$\langle M_{\text{H I}}/L \rangle$ (M_{\odot}/L_{\odot})	Noise _{stat, m/l} (M_{\odot}/L_{\odot})	Obs. time (hrs)
1	22:27:00 + 13:37:48	36	0.092	5.15 ± 3.96	0.41	1.33 ± 1.11	0.11	12.0
2	22:37:48 + 14:18:36	66	0.074	3.43 ± 0.57	0.24	0.22 ± 0.08	0.03	12.0
3	22:57:50 + 13:03:36	45	0.057	1.80 ± 0.53	0.11	0.70 ± 0.31	0.04	12.0
4	23:12:58 + 13:56:24	71	0.066	5.38 ± 0.84	0.20	0.75 ± 0.21	0.04	11.5
5	23:14:24 + 14:39:00	49	0.074	4.94 ± 1.42	0.30	0.45 ± 0.10	0.03	11.0
6	23:24:54 + 15:18:00	70	0.056	3.18 ± 0.55	0.11	0.35 ± 0.10	0.02	10.7
7	23:43:23 + 14:16:08	36	0.073	11.13 ± 4.46	0.59	0.76 ± 0.37	0.05	9.8
8	23:51:36 + 14:06:00	46	0.078	5.17 ± 1.15	0.27	0.53 ± 0.10	0.04	8.8
9	02:03:18 + 13:51:00	31	0.063	2.28 ± 1.18	0.31	0.18 ± 0.08	0.03	11.3
10	22:12:29 + 12:20:24	31	0.067	1.44 ± 0.48	0.17	0.44 ± 0.17	0.04	12.0
11	22:14:38 + 13:52:12	81	0.044	0.33 ± 0.14	0.05	–	–	9.7
12	22:33:18 + 13:11:02	35	0.089	3.98 ± 1.41	0.62	0.32 ± 0.09	0.04	12.0
13	22:39:00 + 13:26:24	57	0.079	1.58 ± 1.07	0.28	0.60 ± 0.74	0.06	12.0
14	23:18:18 + 14:55:12	39	0.081	3.41 ± 1.22	0.44	0.30 ± 0.10	0.08	10.7
15	23:26:24 + 14:03:00	55	0.054	2.11 ± 0.49	0.16	0.43 ± 0.12	0.05	10.3
16	23:38:06 + 15:45:43	60	0.066	2.53 ± 0.82	0.21	0.19 ± 0.08	0.03	8.6
17	23:45:36 + 15:22:12	26	0.087	–	–	0.06 ± 0.21	0.08	9.3
18	23:56:53 + 13:57:00	27	0.067	8.92 ± 1.93	0.29	0.70 ± 0.14	0.04	12.0
19	00:00:36 + 15:24:36	28	0.077	1.60 ± 3.55	0.38	0.05 ± 0.16	0.02	5.4
20	00:06:00 + 15:43:48	36	0.069	5.91 ± 2.71	0.29	0.32 ± 0.19	0.03	10.0
21	00:24:00 + 14:12:00	18	0.060	2.03 ± 1.79	0.21	0.15 ± 0.34	0.06	6.1
22	00:43:01 + 15:18:00	74	0.080	1.34 ± 0.71	0.17	0.10 ± 0.04	0.01	10.8
23	01:10:03 + 13:59:49	91	0.061	0.22 ± 0.68	0.09	0.07 ± 0.09	0.01	12.0
24	01:11:28 + 15:06:00	63	0.055	3.96 ± 1.28	0.20	0.47 ± 0.14	0.03	12.0
25	01:15:00 + 14:28:48	66	0.064	3.94 ± 0.60	0.23	0.46 ± 0.11	0.03	4.6
26	01:55:48 + 14:45:07	75	0.068	3.10 ± 0.69	0.23	0.64 ± 0.17	0.03	10.1
27	01:57:11 + 13:09:00	51	0.057	3.93 ± 0.97	0.20	0.43 ± 0.09	0.04	5.7
28	02:12:00 + 14:02:24	40	0.048	2.53 ± 0.84	0.11	0.84 ± 0.43	0.04	10.1
29	00:00:36 + 14:33:00	64	0.086	1.89 ± 1.43	0.43	0.18 ± 0.08	0.03	9.4
30	00:30:36 + 14:52:12	33	0.074	2.29 ± 1.68	0.37	0.09 ± 0.13	0.04	7.8
31	00:58:01 + 14:50:24	54	0.074	4.21 ± 1.19	0.35	0.26 ± 0.08	0.03	9.5
32	01:19:48 + 14:45:40	57	0.050	1.43 ± 0.36	0.14	0.36 ± 0.24	0.03	9.8
33	01:46:30 + 13:51:00	42	0.062	2.88 ± 1.04	0.25	0.35 ± 0.13	0.04	12.0
34	01:49:26 + 13:51:00	88	0.062	3.37 ± 0.52	0.14	0.41 ± 0.08	0.03	10.8
35	23:24:18 + 14:40:48	154	0.052	0.51 ± 0.30	0.11	0.08 ± 0.05	0.03	9.4

4.2 All galaxies

Stacking all mass spectra from our magnitude-limited sample results in a strong 67σ detection, where the noise level is estimated from the jackknife sampling. We measured the H I mass of the stack in the manner described in Section 3. Integrating the spectral line over the rest frequency range of $\nu = 1420.406 \pm 1.5$ MHz and applying the confusion correction results in a mean H I mass $\langle M_{\text{H I}} \rangle = (2.29 \pm 0.13) \times 10^9 h_{70}^{-2} M_{\odot}$. The mean stacked value for the ratio $\langle M_{\text{H I}}/L \rangle$ ratio results in a 56σ detection with $\langle M_{\text{H I}}/L \rangle = (0.306 \pm 0.020) M_{\odot}/L_{\odot}$. The stacked spectra are shown in Fig. 9. For the volume-limited sub-sample, we obtain $\langle M_{\text{H I}} \rangle = (0.844 \pm 0.129) \times 10^9 h_{70}^{-2} M_{\odot}$ and $\langle M_{\text{H I}}/L \rangle = (0.369 \pm 0.095) M_{\odot}/L_{\odot}$.

4.3 Redshift bins

The large redshift region and selection effects result in the sample properties changing with redshift. We split the sample into five redshift bins. The mean redshift of each bin is $\langle z \rangle = 0.024, 0.041, 0.062, 0.080$, and 0.097 . The sub-samples contain 155, 439, 453, 448, and 400 galaxies, respectively. All stacks result in significant detections. The derived average H I masses $\langle M_{\text{H I}} \rangle$ and H I

mass-to-light ratios $\langle M_{\text{H I}}/L_r \rangle$ are shown in Fig. 10 and Table 6. The H I mass increases with redshift and $M_{\text{H I}}/L_r$ decreases. Both results are explained by the fact that the samples are biased towards more luminous galaxies at higher redshift (see Fig. 11).

5 COSMIC H I DENSITY $\Omega_{\text{H I}}$

5.1 Luminosity bias

SDSS is a magnitude-limited sample and therefore many optically faint, but H I-rich galaxies are missed at higher redshift (Fig. 4). This has an influence on our results for $M_{\text{H I}}$ and $M_{\text{H I}}/L$ and means that we sample different populations of galaxies at different redshifts. To account for the missed faint, but high $M_{\text{H I}}/L$ ratio galaxies, we assume a power-law relation between $M_{\text{H I}}/L$ and luminosity given by $M_{\text{H I}}/L \sim L^{\beta}$. β is obtained from stacking galaxies binned by their r -band luminosity. We show the results in Fig. 11. There is a significant decrease of $M_{\text{H I}}/L$ with increasing L_r . We find $\log(M_{\text{H I}}/L) = (-0.587 \pm 0.046) \log L + (5.246 \pm 0.517)$. Since the sample is not complete in r -band luminosity at all redshifts, there is a selection effect in favour of low values of $M_{\text{H I}}/L$ and high values of L in this plot. However, only the slope of this line

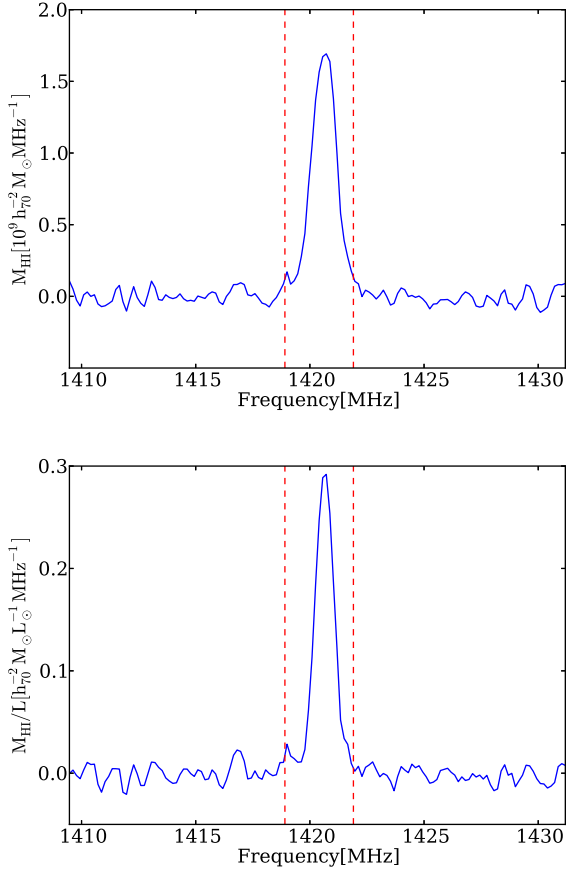


Figure 9. Stack of all galaxies in the magnitude-limited sample. Top plot: Stack of the mass spectra showing a clear 67σ detection. Integrating the spectral line and applying the confusion correction results in an H I mass of $M_{\text{H I}} = (2.29 \pm 0.13) \times 10^9 h_{70}^{-2} M_{\odot}$. Bottom plot: Stack of mass-to-light ratio spectra resulting in a clear 56σ detection with $\langle M_{\text{H I}}/L \rangle = (0.306 \pm 0.020) M_{\odot}/L_{\odot}$. The red-dashed line indicates the region of the integration.

is relevant for the current purposes and the result appears to be similar to that derived from our the volume-limited sub-sample ($\beta = -0.662 \pm 0.120$ – also shown in Fig. 11). With this relation, a suitable correction for the $\langle M_{\text{H I}}/L \rangle$ ratio is then given by Delhaize et al. (2013):

$$C1 = \frac{\langle M_{\text{H I}}/L \rangle_{\text{all}}}{\langle M_{\text{H I}}/L \rangle_{\text{obs}}} = \frac{\sum_{i=1}^N w_i}{\sum_{i=1}^N w_i (L_i/L_*)^{\beta}} \times \frac{\int (L/L_*)^{\beta} L \phi_L(L) dL}{\int L \phi_L(L) dL}, \quad (9)$$

where $\phi_L(L)$ is the luminosity function, w_i is the weight of i th galaxy, and $N = 1895$. We use L_* and $\phi_L(L)$ given by Blanton et al. (2003), where $\phi_L(L)$ is a Schechter function of the form:

$$\phi_L(L) dL = \phi^* \left(\frac{L}{L_*} \right)^{\alpha} \exp \left(-\frac{L}{L_*} \right) \frac{dL}{L_*}, \quad (10)$$

with the following parameters: $\phi^* = 5.11 \times 10^{-3} h_{70}^3 \text{ Mpc}^{-3}$, $\log(L_*/L_{\odot}) = 10.36 + \log h_{70}$, and $\alpha = -1.05$. Fig. 12 shows the original and weight-corrected distribution of SDSS galaxies in r -band luminosity bins. The weight shifts the original distribution to lower luminosity bins because nearby galaxies are given more weight than distant galaxies (most of which are bright). We find a correction factor of $C1 = 1.38$.

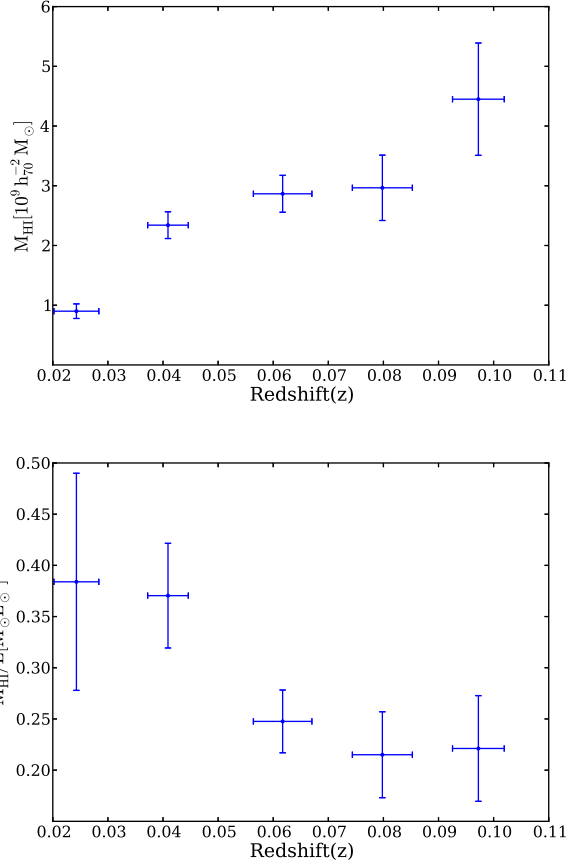


Figure 10. The results of stacking in redshift bins. The top panel is for H I mass $M_{\text{H I}}$, and the bottom panel is for $M_{\text{H I}}/L$. The data points are centred at the mean redshift of each bin. The redshift error bars represent the 1σ standard deviation within each bin.

Table 6. The results of stacking the sample in different redshift bins.

$\langle z \rangle$	Redshift range	N_g	$\langle M_{\text{H I}} \rangle$ ($10^9 h_{70}^{-2} M_{\odot}$)	$\langle M_{\text{H I}}/L \rangle$ (M_{\odot}/L_{\odot})
0.024 ± 0.004	0.01–0.03	155	0.90 ± 0.12	0.38 ± 0.11
0.041 ± 0.004	0.03–0.05	439	2.34 ± 0.22	0.37 ± 0.05
0.062 ± 0.005	0.05–0.07	453	2.87 ± 0.31	0.25 ± 0.03
0.080 ± 0.005	0.07–0.09	448	2.97 ± 0.55	0.21 ± 0.04
0.097 ± 0.005	0.09–0.11	400	4.45 ± 0.94	0.22 ± 0.05

5.2 Stacked measurement of $\Omega_{\text{H I}}$

We calculate the cosmic H I density $\rho_{\text{H I}}$ from the $\langle M_{\text{H I}}/L \rangle$ ratio of the stack and the luminosity density derived for SDSS galaxies. The luminosity density for $z = 0.1$ in the r -band is given by $\rho_L = 1.29 \times 10^8 h_{70} L_{\odot} \text{ Mpc}^{-3}$ (Blanton et al. 2003) using 147 986 galaxies. Together with the correction factor $C1$, the H I density can be calculated according to

$$\rho_{\text{H I}} = C1 \times \left\langle \frac{M_{\text{H I}}}{L} \right\rangle \times \rho_L. \quad (11)$$

We then correct confusion according to the method described in Section 3.4. The correction for $\Omega_{\text{H I}}$ is 1.7 ± 0.6 per cent. Binning the galaxies into three redshift bins gives similar factors: 1.013 ± 0.006 , 1.013 ± 0.006 , and 1.038 ± 0.010 at mean redshifts of $\langle z \rangle = 0.038$, 0.067, and 0.093, respectively.

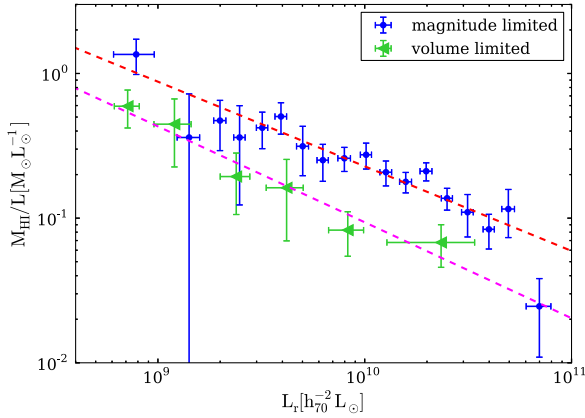


Figure 11. Stacking the magnitude-limited (blue circle) and volume-limited (green triangle) sample in luminosity bins shows that M_{HI}/L decreases with increasing luminosity. The red dashed line indicates the best fit to the magnitude-limited sample of $\log(M_{\text{HI}}/L) = (-0.587 \pm 0.046)\log L + (5.246 \pm 0.517)$; the magenta dashed line shows the best fit to the volume-limited data of $\log(M_{\text{HI}}/L) = (-0.662 \pm 0.120)\log L + (5.600 \pm 1.068)$.

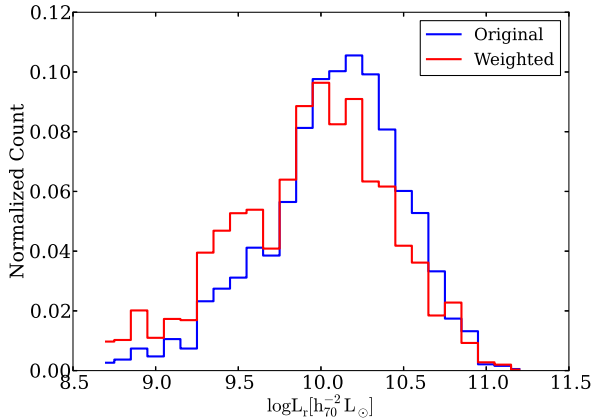


Figure 12. The distribution of SDSS galaxies from the magnitude-limited sample in r -band luminosity bins. The interval is 0.1 dex. The blue line represents the luminosities of galaxies in the sample; the red line shows the weighted number of the galaxies in the same luminosity bins.

After applying the above corrections for luminosity bias and confusion, we calculate a local density of $\rho_{\text{HI}} = (5.46 \pm 0.36) \times 10^7 h_{70} \text{ M}_\odot \text{ Mpc}^{-3}$. The error results from propagating errors in both the scaling factor and in M_{HI}/L . To convert the local density to a cosmic H I density, we divide by the $z = 0$ critical density $\rho_{c,0} = 3H_0^2/8\pi G$ and find

$$\Omega_{\text{HI}} = \frac{\rho_{\text{HI}}}{\rho_{c,0}} = (4.02 \pm 0.26) \times 10^{-4} h_{70}^{-1}. \quad (12)$$

Table 7 summarizes our measurement of Ω_{HI} with the two correction factors consecutively applied. For the smaller volume-limited sub-sample, we find $C1^v = 1.15$, and

$$\Omega_{\text{HI}}^v = (3.50 \pm 0.90) \times 10^{-4} h_{70}^{-1}, \quad (13)$$

with $\rho_L(z = 0.024) = 1.12 \times 10^8 h_{70} \text{ L}_\odot \text{ Mpc}^{-3}$ (given by equation 14). The result is consistent with the magnitude-limited sample, but with larger measurement error due to the smaller sample.

We also compute Ω_{HI} in different redshift bins, with the evolved r -band luminosity function. Using the Galaxy and Mass Assembly

Table 7. The measurement of Ω_{HI} with different methods. The K_c refers to the correction factor for confusion.

Method	Formula	$\Omega_{\text{HI}} \left(10^{-4} h_{70}^{-1} \right)$
Measured	$\langle \frac{M_{\text{HI}}}{L} \rangle \times \rho_L$	2.96 ± 0.19
Luminosity bias corrected	$C1 \times \langle \frac{M_{\text{HI}}}{L} \rangle \times \rho_L$	4.09 ± 0.27
Confusion corrected	$K_c^{-1} \times C1 \times \langle \frac{M_{\text{HI}}}{L} \rangle \times \rho_L$	4.02 ± 0.26

Table 8. The cosmic H I density Ω_{HI} in different redshift bins. The confusion correction has been applied.

$\langle z \rangle$	N_g	$\langle M_{\text{HI}} \rangle$ ($10^9 h_{70}^{-2} \text{ M}_\odot$)	$\langle M_{\text{HI}}/L \rangle$ ($\text{M}_\odot/\text{L}_\odot$)	$C1$	Ω_{HI} ($10^{-4} h_{70}^{-1}$)
0.038 ± 0.009	634	1.73 ± 0.17	0.38 ± 0.06	1.23	3.92 ± 0.63
0.067 ± 0.007	637	2.83 ± 0.34	0.21 ± 0.03	2.13	3.97 ± 0.61
0.093 ± 0.007	621	3.94 ± 0.63	0.22 ± 0.02	1.92	3.99 ± 0.36

(GAMA) II survey, Loveday et al. (2015) found the sample to be well fit with luminosity (Q) and density (P) evolution parameters introduced by Lin et al. (1999). The luminosity density ρ_L can be parametrized as

$$\rho_L(z) = \rho_L(z_0) 10^{0.4(P+Q)(z-z_0)}, \quad (14)$$

with the Schechter luminosity function parameters in terms of magnitudes evolving as

$$\alpha(z) = \alpha(z_0), \quad (15)$$

$$M^*(z) = M^*(z_0) - Q(z - z_0), \quad (16)$$

$$\phi^*(z) = \phi^*(0) 10^{0.4Pz}, \quad (17)$$

where $P = 1.0$ and $Q = 1.03$ in the r band. We use the results from Blanton et al. (2003) as the initial value for the Schechter parameters at $z_0 = 0.1$. The results in Table 8 show no measurable evolution in Ω_{HI} from $z = 0.038$ to $z = 0.093$.

5.3 Ω_{HI} in luminosity bins

We also measure Ω_{HI} more directly in r -band luminosity bins using the relation

$$\rho_{\text{HI}} = \int M_{\text{HI}}(L) \phi_L(L) dL \quad (18)$$

$$\approx \sum_i \langle M/L \rangle_i L_i \phi_L(L_i) \Delta L_i, \quad (19)$$

where i refers to the i th luminosity bin and $\phi(L)$ is the luminosity function. The $\langle M_{\text{HI}}/L \rangle_i$ can be obtained from Fig. 11. The resultant H I density in r -band luminosity bins is shown in Fig. 13. Using the fits to the data and summing the density in r -band luminosity bins from zero to infinity, we find

$$\Omega_{\text{HI}} = (4.01 \pm 0.30) \times 10^{-4} h_{70}^{-1}. \quad (20)$$

This is very close to the Ω_{HI} derived from the stacking using the previous $\langle M/L \rangle$ bias correction. Integrating the fit in Fig. 11 only in the region which has data, we have $\Omega_{\text{HI}} = (2.67 \pm 0.21) \times 10^{-4} h_{70}^{-1}$. If we directly sum up the data points from the stacked luminosity bins, rather than the fits, we find a value of

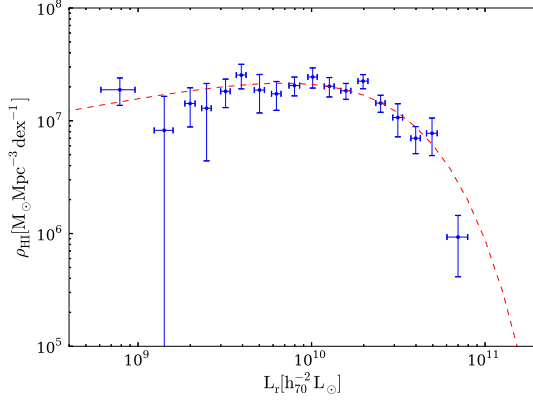


Figure 13. Values for the H I density using the measured mass-to-light ratios from the stacks as well as the luminosity density from SDSS: $\rho_{\text{H I}} = \langle M_{\text{H I}}/L \rangle \times L \times \phi(L)$. The red-dashed line indicates the estimated points using fitted relation between $\langle M_{\text{H I}}/L \rangle$ and L .

$\Omega_{\text{H I}} = (2.50 \pm 0.76) \times 10^{-4} h_{70}^{-1}$. This is lower due to the H I associated with lower and higher luminosity bins than those observed.

5.4 Comparison with previous work

We show our results for $\Omega_{\text{H I}}$ compared with other measurements at various redshifts in Figs 14 and 15. Each has been converted to a flat cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_{\text{m},0} = 0.3$. Ω_{gas} measurements using DLAs sometimes taken into account neutral Helium and contributions from Ly α absorbers with column densities $\log N(\text{H I}) < 20.3$. We convert Ω_{gas} from DLAs to $\Omega_{\text{H I}}$ using $\Omega_{\text{H I}} = \delta_{\text{H I}} \Omega_{\text{gas}} / \mu$, where $\mu = 1.3$ accounts for the mass of Helium and $\delta_{\text{H I}} = 1.2$ estimates the contribution from systems below the DLA column density threshold.

As seen in Figs 14 and 15, all measurements at lower redshift ($z < 0.5$) are in good agreement. But at the intermediate redshifts, measurements have large uncertainty. Our $\Omega_{\text{H I}}$ measurement, marked as a red star, agrees with the measurements made at zero

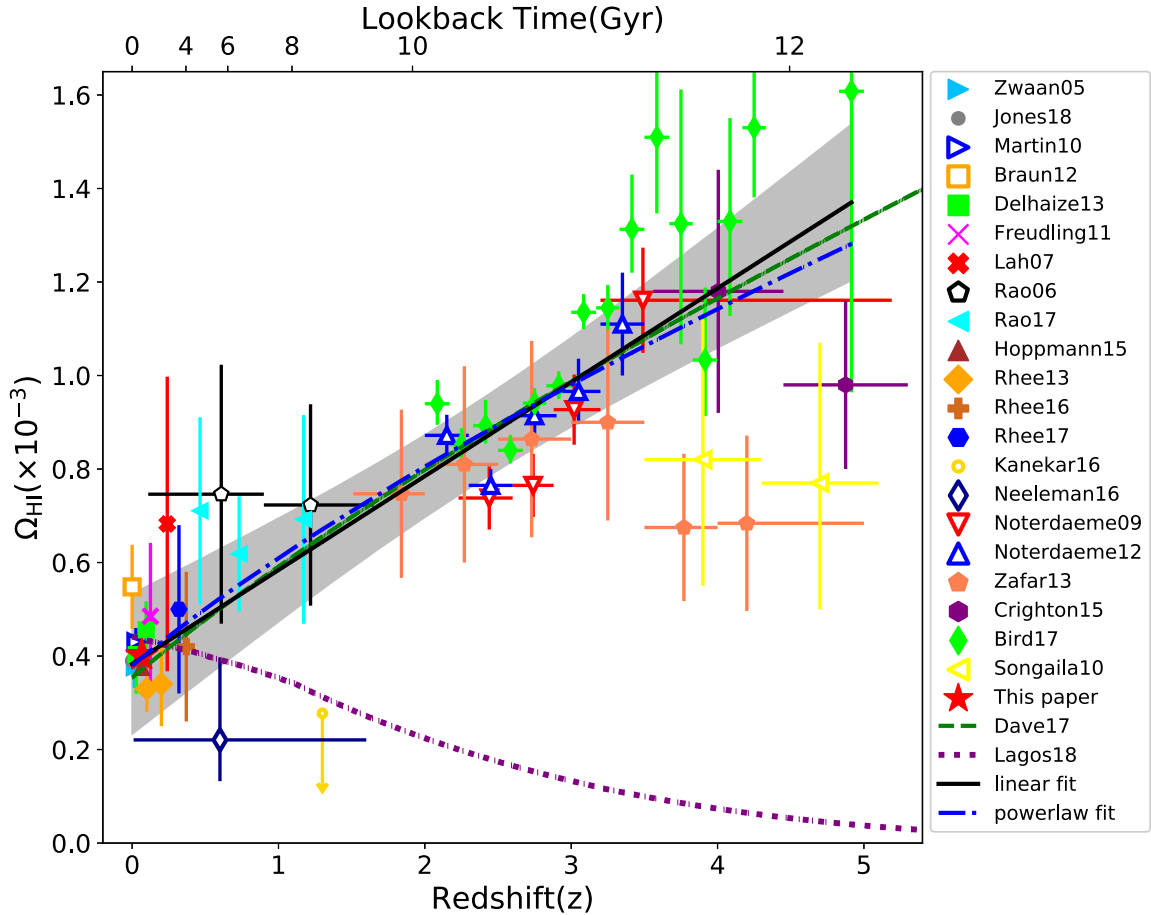


Figure 14. Cosmic H I density $\Omega_{\text{H I}}$ measurements plotted as a function of redshift from different sources: HIPASS 21-cm emission measurements (Zwaan et al. 2005); $\alpha 40$ ALFALFA 21-cm emission measurements (Martin et al. 2010); $\alpha 100$ ALFALFA 21-cm emission measurements (Jones et al. 2018); H I stacking with Parkes (Delhaize et al. 2013), AUDES (Freudling et al. 2011; Hoppmann et al. 2015); H I stacking with WSRT (Rhee et al. 2013); GMRT 21-cm emission stacking (Lah et al. 2007; Kanekar et al. 2016; Rhee et al. 2016, 2018); DLA measurements from the *HST* and the SDSS (Rao et al. 2006, 2017; Noterdaeme et al. 2009, 2012; Neeleman et al. 2016; Bird et al. 2017); self-opaque effect corrected measurement of DLAs with GBT and WSRT (Braun 2012); ESO UVES measurements of DLAs (Zafar et al. 2013); Gemini GMOS measurements of DLAs (Crighton et al. 2015); measurements of DLAs with *GALEX* and Keck (Songaila & Cowie 2010); the MUFASA cosmological hydrodynamical simulation (Davé et al. 2017); the SHARK semi-analytic model of galaxy formation (Lagos et al. 2018). Our results are shown as the red star. All of the results have been converted to a flat cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_{\text{m},0} = 0.3$, and represent the mass density from H I gas alone, without any contribution from Helium or molecules. Missing H I from column densities below the DLA threshold is also corrected. The linear weighted fit of all $\Omega_{\text{H I}}$ measurements and its 95 per cent confidence interval is shown as a black line with grey area. The blue dash-dotted line shows the power-law fit of all measurements.

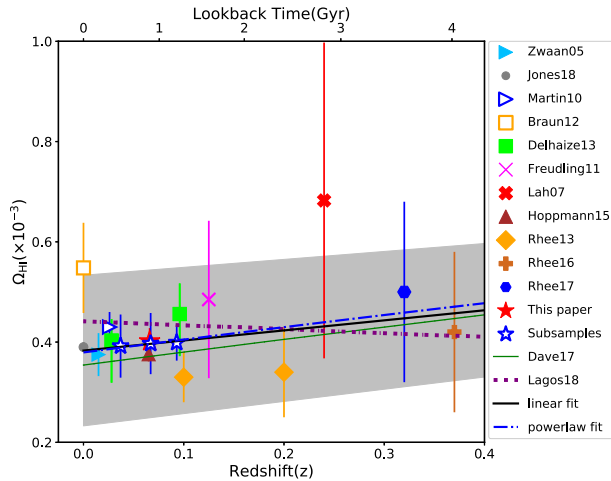


Figure 15. A zoomed-in plot showing measurements of cosmic H I density Ω_{HI} from the direct H I emission and H I stacking measurements at $z < 0.4$. The magenta stars represent our results from sub-samples at different redshifts. There is no discernible evolution in Ω_{HI} over the last ~ 4 Gyr.

redshift but has a small error bar, large signal-to-noise ratio, and low systematics. It shows the usefulness of the stacking technique applied to interferometers to bridge the redshift gap between measurements using DLA systems and estimates using direct 21-cm detections.

The value we measure for Ω_{HI} in sub-samples at different redshifts shows no evolution, within the errors of the measurements. In combination with other results, it again suggests almost no H I gas evolution from $z \approx 0.4$ to the present, a time span of over 4 Gyr. However, combining all measurements, there remains a clear increase of Ω_{HI} at higher redshift. We should note that the ‘blind’ H I 21-cm surveys are measuring the ‘true’ Ω_{HI} with the only assumption being that the H I 21-cm emission is optically thin. On the other hand, H I stacking studies require galaxy redshifts, and are hence measuring Ω_{HI} associated with galaxies detected in optical spectroscopic surveys. So high sample completeness is also required. SDSS appears to satisfy this criterion, but the under-representation of low-surface-brightness galaxies (0.1 per cent) and close pairs < 55 arcsec (6 per cent) may slightly skew the results, but this is not expected to be significant. Ω_{HI} values from DLAs are similar to those from blind surveys, in that association of the gas with a galaxy is not a pre-requisite. However, there are a number of other biases such as dust obscuration, covering factor and lensing which may contribute uncertainty (Ellison et al. 2001; Jorgenson et al. 2006).

Many simulations have trouble reproducing the observed trend with redshift due to the difficulty of resolving the various relevant gas phases (i.e. ionised, atomic and molecular gas, inside and outside galaxies). Recently, Davé et al. (2017), using a mid-size cosmological hydrodynamical simulation, MUFASA, found $\Omega_{\text{HI}} = 10^{-3.45}(1+z)^{0.74}$, which is close to the best fit we find for the observations (Fig. 14). Interestingly, previous hydrodynamical simulations have suggested that most of the H I in the Universe at $z \gtrsim 1.5$ –2 is in the circumgalactic medium rather than the interstellar medium of galaxies (van de Voort et al. 2012). Using the SHARK cosmological semi-analytic model of galaxy formation, Lagos et al. (2018) were able to predict the amount of atomic hydrogen contributed by the interstellar medium of galaxies to Ω_{HI} , across time (see Fig. 14). The contribution from the interstellar medium

of galaxies decreases with increasing redshift, in a trend that is the opposite to the overall increase deduced from observations.

The large impact parameters (42 kpc for ALMA J081740.86+135138.2, 18 kpc for ALMA J120110.26+211756.2, and 30 kpc for ALMA J123055.50–113906.4) measured for the host galaxies of high- z DLA systems provide some support for this scenario (Neeleman et al. 2017, 2018).

It also suggests that spectral H I stacking of galaxies at redshifts beyond $z \approx 0.8$ can reveal differences between the H I content of the Universe that is accounted for in galaxies and that measured through absorption lines. Future stacking experiments at higher redshifts will therefore provide unique and stringent constraints for models of galaxy formation.

We also fit the relationship between Ω_{HI} and redshift, assuming a power-law relation, and find $\Omega_{\text{HI}} = 10^{-3.42}(1+z)^{0.68}$. A simpler linear fit to all Ω_{HI} measurements, weighting all measurements according to their error, gives $\Omega_{\text{HI}}(z) = 0.000384 + 0.0002z$. The fit is shown in Figs 14 and 15. Most of the measurements are reasonably consistent with the fit, although the H I 21-cm stacking result of Kanekar et al. (2016) and the *HST* archival study of Neeleman et al. (2016) lie below the trend.

6 SUMMARY

In this paper, we use an interferometric stacking technique to study the H I content of galaxies and confirm that there is little evolution in Ω_{HI} at low redshift. Compared to previous studies, we are able to provide stronger constraints.

The data set is a 351-h WSRT H I survey covering ~ 7 deg² of the SDSS sky containing 1895 galaxies with SDSS redshifts in the range $0.01 < z < 0.11$. Using measurements of the mean H I mass-to-light ratio, we were able to bootstrap from the SDSS luminosity function to provide an accurate measurement of the cosmic H I gas content.

We have shown that interferometers such as WSRT offer significant advantages over single dish stacking measurements in terms of sensitivity, field-of-view and resolution that together maximize S/N and minimize cosmic variance and confusion.

Over all galaxies in the sample, we find an average H I mass of $\langle M_{\text{HI}} \rangle = (2.29 \pm 0.13) \times 10^9 h_{70}^{-2} M_{\odot}$ and H I mass-to-light ratio $\langle M_{\text{HI}}/L \rangle = (0.31 \pm 0.02) M_{\odot}/L_{\odot}$. For a volume-limited sub-sample, we find $\langle M_{\text{HI}} \rangle = (0.84 \pm 0.13) \times 10^9 h_{70}^{-2} M_{\odot}$ and $\langle M_{\text{HI}}/L \rangle = (0.37 \pm 0.09) M_{\odot}/L_{\odot}$.

We derived the cosmic H I density Ω_{HI} by stacking mass-to-light ratio for all galaxies. As SDSS is magnitude limited, many optically faint but H I-rich galaxies are missing. To correct for this selection bias, we derive a weight factor which accounts for the different mass-to-light ratios of the sample compared with an unbiased selection of galaxies. We find $\rho_{\text{HI}} = (5.46 \pm 0.36) \times 10^7 h_{70} M_{\odot} \text{ Mpc}^{-3}$ and $\Omega_{\text{HI}} = (4.02 \pm 0.26) \times 10^{-4} h_{70}^{-1}$ at the mean redshift of $\langle z \rangle = 0.066$. For a volume-limited sub-sample, we find $\Omega_{\text{HI}} = (3.50 \pm 0.90) \times 10^{-4} h_{70}^{-1}$ at the mean redshift of $\langle z \rangle = 0.024$. We also derive the H I density from luminosity stacking and the SDSS luminosity function, finding $\Omega_{\text{HI}} = 4.01 \times 10^{-4} h_{70}^{-1}$.

Rather than attempting to identify, then remove potentially confused targets, which has the effect of removing massive centrals and gas-rich satellites, we corrected for residual confusion using a simulation. We also explore the robustness of the result to the effect of WSRT sidelobes. For both effects, the corrections were found to be small.

Finally, we split our sample in three sub-samples with $\langle z \rangle = 0.038, 0.067$, and 0.093 and find similar results. Our results agree well with previous $\Omega_{\text{H I}}$ measurements from H I emission surveys, H I stacking, and DLA surveys. Taken together, the results confirm that there seems to be little evolution in $\Omega_{\text{H I}}$ at low redshift.

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SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](https://www.mnras.org/) online.

Figure S1. The stacked mass spectra for pointings 1–12.

Figure S2. The stacked mass spectra for pointings 13–27.

Figure S3. The stacked mass spectra for pointings 28–35.

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APPENDIX A: STACKED SPECTRA

We show the stacked mass spectra for pointings 1–9 in Fig. A1, the full 35 pointings are available online. The red-dashed lines show the region over which we do the integration to compute the average H I mass. For the stacked mass spectra, only one stack (pointing 17) does not show a detection, three (pointings 12, 29, and 35) show unclear detections, whilst the remaining 30 pointings all result in clear detections.

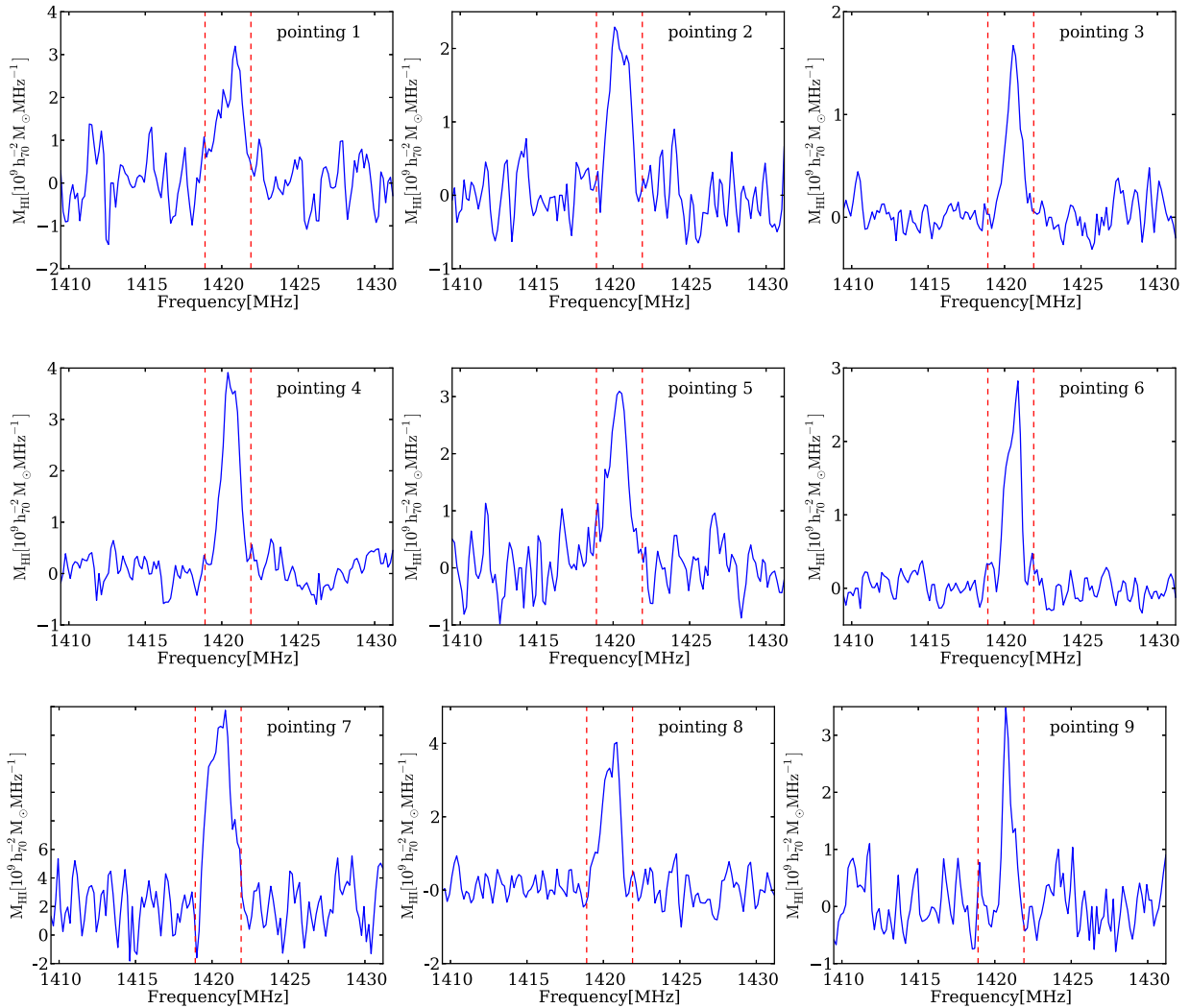


Figure A1. The stacked mass spectra for pointings 1–9.

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