Atomic Hydrogen in Star-forming Galaxies at Intermediate Redshifts

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Abstract

We have used the upgraded Giant Metrewave Radio Telescope to carry out a deep (117 on-source hours) L-band observation of the Extended Groth Strip, to measure the average neutral hydrogen (H I) mass and median star formation rate (SFR) of star-forming galaxies, as well as the cosmic H I mass density, at 0.2 < z < 0.4. This was done by stacking the H I 21 cm emission and the rest-frame 1.4 GHz radio continuum from 445 blue star-forming galaxies with MB < −17 at zmean ≈ 0.34. The stacked H I 21 cm emission signal is detected at ~7σ significance, implying an average H I mass of ⟨MHI⟩ = (4.93 ± 0.70) × 109 M⊙. We also stacked the rest-frame 1.4 GHz radio continuum emission of the same galaxies to obtain a median SFR of (0.54 ± 0.06) M⊙ yr−1; this implies an atomic gas depletion timescale of ΔH I = (≈9) Gyr, consistent with values in star-forming galaxies in the local universe. This indicates that the star formation efficiency does not change significantly over the redshift range 0–0.4. We used the detection of the stacked H I 21 cm emission signal to infer the normalized cosmic H I mass density (ρH I/µH,O) in star-forming galaxies at z ≈ 0.34. Assuming the local relation between H I mass and absolute B-magnitude, we obtain ρH I/µH,O = (4.81 ± 0.75) × 10−3, implying no significant evolution in ρH I/µH,O from z ≈ 0.4 to the present epoch.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Radio interferometry (1346); Radio spectroscopy (1359); Star formation (1569); H I line emission (690); High-redshift galaxies (734)

1. Introduction

Understanding galaxy evolution requires us to understand evolution in the two main baryonic constituents of galaxies, the stars and the gas. Over the past two decades, much progress has been made in understanding the evolution of the stellar properties of galaxies (e.g., the star formation rate (SFR), the main sequence, etc; Hopkins & Beacom 2006; Noeske et al. 2007), via optical and near-infrared studies of the so-called “deep fields.” Our understanding of molecular gas in high-z galaxies has also improved, via blind and targeted CO studies (e.g., Pavesi et al. 2018; Tacconi et al. 2018; Decarli et al. 2019). In contrast, little is known about atomic gas, primarily neutral hydrogen (H I), in high-z galaxies, although this is the primary fuel reservoir for star formation. Understanding the redshift evolution of the H I content of star-forming galaxies is essential to obtain a complete picture of galaxy evolution.

In the local universe, H I 21 cm emission surveys have yielded the H I masses of thousands of galaxies (e.g., Zwaan et al. 2005; Jones et al. 2018), providing accurate measurements of the H I mass function and the cosmic H I mass density. Unfortunately, it is difficult to detect the weak H I 21 cm line from galaxies at z > 0.2 with current telescopes (e.g., Jaffé et al. 2013; Catinella & Cortese 2015), with only one galaxy detected at z > 0.25, at z ≈ 0.376 in the Very Large Array CHILES survey of the COSMOS field (Fernández et al. 2016).

While detecting individual galaxies in H I 21 cm emission at z > 0.3 will require very deep integrations in the foreseeable future, one can measure the average H I content of samples of galaxies within the primary beam of a radio interferometer, by “stacking” their H I 21 cm emission signals (e.g., Chengalur et al. 2001). Of course, such stacking requires large galaxy samples with accurate redshifts, usually from optical spectroscopy. This requirement has meant that, despite multiple studies, there are still no statistically significant detections of the stacked H I 21 cm emission signal at z > 0.2 (e.g., Lah et al. 2007; Kanekar et al. 2016; Rhee et al. 2018).

The paucity of information on the H I content of galaxies at even relatively low redshifts, z > 0.25, has motivated us to begin an H I 21 cm “deep field” with the upgraded Giant Metrewave Radio Telescope (uGMRT). We chose the Extended Groth Strip (EGS) as the target field, due to the outstanding ancillary data in the EGS over a wide range of wavelengths, as well as the excellent spectroscopic coverage in this field from the DEEP2 and DEEP3 surveys (Newman et al. 2013; Cooper et al. 2012). In this Letter, we present results from the first part of this uGMRT H I 21 cm emission survey.

2. Observations and Data Analysis

We used the uGMRT L-band receivers to carry out a deep integration on the EGS between 2017 March and 2018 April (proposals 31_038 and 34_083). The total integration time was ≈175 hr, with an on-source time of ≈117 hr. The pointing center was chosen to be R.A. = 14h20m00′′, decl. = +52°54′00″, close to the center of the region with the richest multiwavelength coverage. The GMRT Wideband Backend was used as the correlator, with a bandwidth of 400 MHz, subdivided into 8192 channels, and two polarizations. The 400 MHz band covers the frequency range 970–1370 MHz, corresponding to z ≈ 0.037–0.46, with a velocity resolution of ≈10–15 km s−1 across the band.

The initial analysis, including data editing, gain and bandpass calibration was carried out using “classic” AIPS, following standard procedures. After the initial calibration, the...
A 400 MHz data set was split into four 100 MHz subbands, and a standard self-calibration procedure (e.g., Kanekar et al. 2016) was then run independently in AIPS on each subband. The self-calibrated data of the four subbands were then stitched together, and the combined visibilities imaged in CASA, using TCLEAN. An area of \( \approx 1^{\circ} \times 1^{\circ} \) was imaged, out to the first null of the uGMRT primary beam. A single final amplitude-and-phase self-calibration was then carried out to bring the different subbands onto the same flux density scale, and a final continuum image was then made from the self-calibrated data, using TCLEAN, with Briggs weighting (\( \text{robust} = 0.5 \)). This image, shown in Figure 1, has a resolution of \( \approx 3^{\prime}.9 \times 2^{\prime}.7 \) and an rms noise of \( \approx 2.3 \mu \text{Jy Bm}^{-1} \) near the image center.

The gain solutions obtained from the self-calibration procedure were then applied to the spectral visibilities, and the continuum image was subtracted out, before a final round of RFI excision was carried out on the residual data. The residual multichannel visibilities were then shifted to the barycentric frame and imaged in CASA, using natural weighting. This spectral cube was corrected for the (frequency-dependent) shape of the uGMRT primary beam. Small subcubes were extracted at the location of each target galaxy, shifted to velocity, in the rest frame of the galaxy, and smoothed to, and resampled at, a velocity resolution of 60 km s\(^{-1}\).

### 3. Stacking the H\textsc{i} 21 cm Emission and the Radio Continuum

To obtain a clean interpretation of the H\textsc{i} 21 cm stacking results, it is important to use a uniformly selected sample of galaxies, with accurate redshifts (redshift errors \( \lesssim 100 \text{ km s}^{-1} \)). For the EGS, the DEEP2 and DEEP3 surveys have a redshift accuracy of \( \approx 30 \text{ km s}^{-1} \) (Newman et al. 2013), sufficient for H\textsc{i} 21 cm stacking. We restricted our target sample to “blue” star-forming galaxies, using the color division of Coil et al. (2008) between red and blue galaxies, \( \left[ (U-B) = -0.032 \times (M_B + 21.62) + 1.035 \right] \). We also used a uniform absolute B-magnitude limit to select our targets, with \( M_B \leq -17 \); with the DEEP2 and DEEP3 spectroscopic criteria, this yields a near-complete, absolute-magnitude-limited sample of galaxies at \( 0.2 < z < 0.4 \). Finally, the galaxies were selected to lie within the FWHM of the uGMRT primary beam at the frequency of the redshifted H\textsc{i} 21 cm line to have a redshift quality code \( > 3 \) (i.e., reliable redshifts; Newman et al. 2013), and to not be classified as active galactic nuclei in either the DEEP2/DEEP3 catalogs (based on the best-fit template to the optical spectral energy distribution; Cooper et al. 2012; Newman et al. 2013) or detected in our radio continuum image, with a 1.4 GHz luminosity \( \gtrsim 2 \times 10^{23} \text{ W Hz}^{-1} \) (e.g., Condon et al. 2002).
We do not a priori know the optimal spatial resolution at which to extract the spectrum for each galaxy. Using too high a resolution would resolve out some of the HI 21 cm emission, thus reducing the signal-to-noise ratio (S/N). Conversely, using too coarse a resolution would imply that only some of the interferometric baselines (the shorter ones) are being used to extract the spectrum, again lowering the S/N. We hence extracted spectra at a range of spatial resolutions, 20–100 kpc, at the redshift of each galaxy and stacked the spectra at each resolution to determine the optimal spatial resolution. At each resolution, an error spectrum was also extracted for each galaxy, by measuring the rms noise per channel in the subcube of the galaxy, from an annular region that excludes the galaxy itself. A second-order baseline was then fitted to each spectrum, using the velocity range ±1500 km s⁻¹ around the galaxy redshift, and subtracted out.

Before stacking, we used the Kolmogorov–Smirnov and Anderson–Darling tests to test the spectra for Gaussianity, excluding spectra with p-values <0.002 in either test. Our final sample contains 445 blue star-forming galaxies with $M_\text{HI} \leq -17$, at 0.2 < z < 0.4, and with an average redshift of $\langle z \rangle = 0.34$.

The stacking was carried out in units of HI 21 cm line luminosity (rather than flux density) to account for the spread in the luminosity distances of the target galaxies. While the uGMRT sensitivity is approximately constant (within ≈10%) across the observing band, the rms noise on the flux density spectra varies due to both the galaxy locations in the primary beam and frequency-dependent data flagging. In addition, the rms noise in the luminosity density spectra increases with increasing redshift. The optimal approach of weighting by the inverse of the variance of the luminosity density spectra would imply significantly lower weights for the higher-redshift galaxies, i.e., a bias toward lower redshifts. We hence chose to weight each spectrum by the inverse of its variance in flux density, so that the effective redshift of the stacked spectrum remains the average redshift of the sample, $\langle z \rangle = 0.34$.

Our final stacked H I 21 cm spectrum, at a resolution of 40 kpc, is shown in Figure 2. The spectrum shows a clear detection of H I 21 cm emission, with an integrated luminosity density of $L_{\text{HI}} = (2.10 \pm 0.30) \times 10^4$ Jy Mpc⁻² km s⁻¹. The signal was also detected in the stacks at resolutions of 20 kpc and 30 kpc, but with a lower integrated luminosity density, indicating that the total H I 21 cm emission has not been recovered. Using a spatial resolution coarser than 40 kpc does not significantly change the integrated luminosity density, but lowers the S/N due to an increased rms noise.

We also stacked the radio continuum images of our 445 galaxies to measure their average SFR from the 1.4 GHz radio luminosity (e.g., Yun et al. 2001). We followed the procedure of Bera et al. (2018), using “median stacking” to stack the 1.4 GHz radio luminosity images of the sample. A radio spectral index of $\alpha = -0.8$ (with flux density $S_\nu \propto \nu^\alpha$) was assumed to shift each galaxy’s image from the observing frequency of 1.2 GHz to a rest-frame frequency of 1.4 GHz. Figure 3[A] shows the stacked 1.4 GHz continuum image of the 445 galaxies. A marginally resolved source is clearly detected, with a 1.4 GHz luminosity of $L_{1.4\text{GHz}} = (1.45 \pm 0.18) \times 10^{21}$ W Hz⁻¹. No emission was seen in a stack of positions offset by 50″ from the sample galaxies to test for possible systematic effects (see Figure 3 [B]; e.g., Bera et al. 2018).

4. Results and Discussion

4.1. The Atomic Gas Mass and Gas Fraction

For optically thin H I 21 cm emission, the H I mass of a galaxy is related to its velocity-integrated H I 21 cm line luminosity density by the relation

$$M_{\text{HI}} = 2.343 \times 10^5 \times \int L_{\text{HI}}dv,$$

where $M_{\text{HI}}$ is in units of $M_\odot$ and $L_{\text{HI}}$ in Jy Mpc⁻² km s⁻¹. Our measured stacked H I 21 cm line luminosity density of $L_{\text{HI}} = (2.10 \pm 0.30) \times 10^4$ Jy Mpc⁻² km s⁻¹ then yields an average H I mass of $M_{\text{HI}} = (4.93 \pm 0.70) \times 10^9 M_\odot$, for the galaxies of the sample. The line FWHM is ≈200 km s⁻¹.

In the local universe, the H I mass of a galaxy is correlated with its H I diameter, $D_{\text{HI}}$ (e.g., Wang et al. 2016). If the local $D_{\text{HI}} = M_{\text{HI}}$ relation applies to galaxies at $z = 0.34$, our average H I mass of $\approx 5 \times 10^9 M_\odot$ implies an average diameter of $\approx 40$ kpc. This is consistent with our finding that a spatial resolution of 40 kpc recovers all the H I 21 cm emission.

To estimate the effect of source confusion on the measured average H I mass, we identified galaxies in our sample with...
“close companion(s),” defined as a neighbor separated by \( \lesssim 40 \text{ kpc} \) and \( \lesssim 300 \text{ km s}^{-1} \) in the DEEP2/DEEP3 catalogs. Only \( \lesssim 10\% \) of the galaxies of our sample have such “close companion(s);” excluding these from the stack does not significantly change the average HI mass. Source confusion thus has little effect on our measurement.

The average stellar mass of the galaxies of our sample is \( M_\ast = 4.1 \times 10^9 M_\odot \) (Mostek et al. 2012; Stefanon et al. 2017), implying a ratio of HI mass to stellar mass, \( M_{\text{HI}}/M_\ast \approx 1.2 \). This is somewhat larger than values of \( M_{\text{HI}}/M_\ast \) in blue star-forming galaxies in the local universe: for example, applying our stellar mass function to blue galaxies in the xGASS sample (with NUV–r \( \lesssim 4 \); Catinella et al. 2018) yields \( M_{\text{HI}}/M_\ast \approx 0.5 \) (although we note that the xGASS sample has \( M_\ast \gtrsim 10^9 M_\odot \), which is somewhat larger than the stellar mass of our sample).

4.2. The Atomic Gas Depletion Timescale

The atomic gas depletion timescale, \( t_{\text{dep}}(\text{HI}) = M_{\text{HI}}/\text{SFR} \), is the time taken by a galaxy to consume its HI reservoir at its current SFR and is a measure of its star formation efficiency. A short HI depletion timescale suggests that star formation is likely to soon be quenched, in the absence of gas inflow. In the local universe, studies of stellar-mass-selected samples of star-forming galaxies (with, typically, \( M_\ast \gtrsim 10^9 M_\odot \)) have obtained \( t_{\text{dep}}(\text{HI}) \approx 3–10 \text{ Gyr} \), with little evidence for dependence on galaxy properties like stellar mass, galaxy color, etc. (e.g., Schiminovich et al. 2010; Wong et al. 2016; Saintonge et al. 2017; Catinella et al. 2018). However, stacking the HI 21 cm emission and the radio continuum of star-forming galaxies at \( z \approx 1.3 \) (with \( M_B \lesssim -21 \)) yielded a far lower average HI depletion time, \( \langle t_{\text{dep}} \rangle < 0.87 \text{ Gyr} \) (Kanekar et al. 2016; Bera et al. 2018). This suggests evolution in the HI depletion time for star-forming galaxies from \( z \approx 1.3 \) to \( z \approx 0 \).

Our stack of the 1.4 GHz radio continuum emission of 445 blue star-forming galaxies yielded a median 1.4 GHz radio luminosity of \( L_{1.4 \text{GHz}} = (1.45 \pm 0.18) \times 10^{21} \text{ W Hz}^{-1} \). Using the relation SFR = \( 3.7 \times 10^{-22} \text{ W Hz}^{-1} \) (assuming a Chabrier initial mass function; Yun et al. 2001) gives a median SFR of \( (0.54 \pm 0.06) M_\odot \text{yr}^{-1} \). Combining this with the average HI mass yields \( \langle t_{\text{dep}}(\text{HI}) \rangle \approx 9 \text{ Gyr} \), consistent with the values of \( t_{\text{dep}} \) in the local universe, but far lower than that at \( z \approx 1.3 \). This suggests either evolution in the star formation efficiency of galaxies between \( z \approx 1.3 \) and \( z \approx 0.34 \), soon after the epoch of galaxy assembly, or a much higher efficiency in brighter galaxies at \( z \approx 1.3 \).

4.3. The Cosmic HI Density

Our estimate of the average HI mass, \( \langle M_{\text{HI}} \rangle = (4.93 \pm 0.70) \times 10^9 M_\odot \), of an absolute-magnitude-limited sample of galaxies can be used to infer the cosmic mass density of HI in galaxies, \( \rho_{\text{HI}}/\rho_c \), at \( z \approx 0.34 \), where \( \rho_c \) is the comoving critical density at \( z = 0 \). To estimate \( \rho_{\text{HI}}/\rho_c \) in galaxies with \( M_B \leq -17 \), we simply integrate over the B-band luminosity function at \( z \approx 0.3 \) for \( M_B \leq -17 \) and multiply by \( \langle M_{\text{HI}} \rangle \). The B-band luminosity function at \( z \approx 0.3 \) is (Willmer et al. 2006)

\[
\phi(L_B) = \left( \frac{\phi_\ast}{L_{B\ast}} \right) \left( \frac{L_B}{L_{B\ast}} \right)^\alpha e^{-L_B/L_{B\ast}},
\]

where \( \phi_\ast = (32 \pm 2) \times 10^{-4} \text{ Mpc}^{-3} \), \( L_{B\ast} = (1.77 \pm 0.09) \times 10^9 L_B \odot \), and \( \alpha = -1.30 \). Integrating over this luminosity function for \( M_B \leq -17 \) yields a comoving galaxy number density of \( 0.013 \text{ Mpc}^{-3} \). This yields \( \rho_{\text{HI}} = (6.41 \pm 0.91) \times 10^7 M_\odot \text{ Mpc}^{-3} \) and \( \rho_{\text{HI}}/\rho_c = (4.75 \pm 0.67) \times 10^{-4} \) for galaxies with \( M_B \leq -17 \) at \( 0.2 < z < 0.4 \). We emphasize that this estimate of \( \rho_{\text{HI}}/\rho_c \) does not include contributions from galaxies fainter than \( M_B = -17 \).

The total \( \rho_{\text{HI}}/\rho_c \) in blue galaxies at \( z \approx 0.3 \) may be estimated by combining the B-band luminosity function at \( z \approx 0.3 \) with the relation between \( M_{\text{HI}} \) and \( M_B \) (e.g., Dénes et al. 2014),

\[
\frac{M_{\text{HI}}}{M_B} = K \left( \frac{L_B}{L_{B\ast}} \right)^{\beta},
\]

where \( K \) is a constant equal to \( M_{\text{HI}}/L_B \) for \( L_B = L_{B\ast} \). Combining the above equations, and integrating over the...
Figure 4. Evolution of $\rho_{H I}/\rho_{c,0}$ with redshift, with all values in a 737 cosmology (Neelam et al. 2016). The black square is from blind H I 21 cm emission surveys in the local universe (Jones et al. 2018), the red triangles from earlier low-emission surveys in the local universe measured, at $(z = 0.2 - 0.4)$ by stacking their H I 21 cm line and 1.4 GHz continuum emission. We obtain $\langle M_{HI} \rangle = (4.93 \pm 0.70) \times 10^9 M_\odot$ and SFR = $(0.54 \pm 0.06) M_\odot yr^{-1}$, implying an H I depletion timescale of $\langle t_{dep} (HI) \rangle \approx 9 Gyr$. This is comparable to the H I depletion timescale in local star-forming galaxies, but far larger than the timescale at $z \approx 1.3$. We obtain a gas fraction of $M_{HI}/M_B \approx 1.2$, larger than typical values in local star-forming galaxies. Finally, we obtain a cosmic H I mass density of $\rho_{HI}/\rho_{c,0} = (4.81 \pm 0.75) \times 10^{-3}$, consistent with the value of $\rho_{HI}/\rho_{c,0}$ in the local universe, and with $\approx 90\%$ arising from bright galaxies, with $M_B \lesssim -17$.

5. Summary

We have used a deep uGMRT 970–1370 MHz observation of the EGS to measure the average H I mass and the median total SFR of a sample of 445 blue star-forming galaxies at $z \approx 0.2 - 0.4$ by stacking their H I 21 cm line and 1.4 GHz continuum emission. We obtain $\langle M_{HI} \rangle = (4.93 \pm 0.70) \times 10^9 M_\odot$ and SFR = $(0.54 \pm 0.06) M_\odot yr^{-1}$, implying an H I depletion timescale of $\langle t_{dep} (HI) \rangle \approx 9 Gyr$. This is comparable to the H I depletion timescale in local star-forming galaxies, but far larger than the timescale at $z \approx 1.3$. We obtain a gas fraction of $M_{HI}/M_B \approx 1.2$, larger than typical values in local star-forming galaxies. Finally, we obtain a cosmic H I mass density of $\rho_{HI}/\rho_{c,0} = (4.81 \pm 0.75) \times 10^{-3}$, consistent with the value of $\rho_{HI}/\rho_{c,0}$ in the local universe, and with $\approx 90\%$ arising from bright galaxies, with $M_B \lesssim -17$.

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Figure 4 shows $\rho_{HI}/\rho_{c,0}$ versus redshift, from a range of measurements at $z \approx 0.2 - 0.4$. It is clear that our estimate of $\rho_{HI}/\rho_{c,0}$ at $z \approx 0.34$ is consistent with the value in the local universe (Jones et al. 2018), indicating no significant evolution in $\rho_{HI}/\rho_{c,0}$ over $0 < z < 0.4$.

B-band luminosity function (this time, for all $M_B$), we obtain

$$\rho_{H I}/\rho_{c,0} = \frac{K_{B,0}}{\rho_{c,0}} L_{B,0} \phi_{s} \Gamma (\alpha + \beta + 2, L_{min}/L_{B,0}). \tag{4}$$

where $L_{min}$ is the faint-end cutoff of the B-band luminosity function. The result is insensitive to the choice of $L_{min}/L_{B,0}$ as long as this value is $\lesssim 10^{-3}$.

There is currently no direct estimate of $\beta$ at $z \approx 0.3$. We hence assume that the local $M_{HI}-M_B$ relation ($\beta = -0.15$; Dénès et al. 2014) is valid at $z \approx 0.3$. We then obtain $K = (0.73 \pm 0.11) M_{B,0}/L_{B,0}$. We also include the effect of cosmic variance by using the estimated cosmic variance of 18% in the luminosity density $\phi_{s}$ at $z \approx 0.3$ for the EGS (Willmer et al. 2006). Replacing for $K$ in Equation (4), with $L_{min}/L_{B,0} = 10^{-4}$, we obtain $\rho_{H I} = (6.5 \pm 1.1 \times 10^{-4} \times 10^3 M_{B,0} \text{Mpc}^{-3}$ and $\rho_{HI}/\rho_{c,0} = (4.81 \pm 0.75 \pm 0.87) \times 10^{-4}$, where the second uncertainty in the two expressions stems from cosmic variance. Note that using the $M_{HI}-M_B$ relation to estimate $\rho_{HI}/\rho_{c,0}$ in galaxies with $M_B \approx -17$ yields values of $\rho_{HI}/\rho_{c,0}$ consistent (within the statistical errors) with our estimate above.

In the local universe, $\rho_{HI}/\rho_{c,0}$ has long been accurately estimated via blind H I 21 cm emission surveys (e.g., Zwaan et al. 2005; Jones et al. 2018). Conversely, at high redshifts, $z > 2$, the incidence of damped Ly$\alpha$ absorbers (DLAs) in QSO spectra from the Sloan Digital Sky Survey has been used to infer $\rho_{HI}/\rho_{c,0}$ (e.g., Prochaska et al. 2005; Noter daeme et al. 2012). These studies have shown that $\rho_{HI}/\rho_{c,0}$ declines by only a factor of $\approx 2$ from $z = 2.2$ to $z \approx 0$. However, the need for ultraviolet spectroscopy to detect DLAs at $z < 1.7$ and the weakness of the H I 21 cm line has meant that it has been difficult to study the evolution of $\rho_{HI}/\rho_{c,0}$ at intermediate redshifts, $z \approx 0.2 - 2.2$. Our result, $\rho_{HI}/\rho_{c,0} = (4.81 \pm 0.75) \times 10^{-4}$, is the first statistically significant estimate of $\rho_{HI}/\rho_{c,0}$ at these redshifts.
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