The Giant Metrewave Radio Telescope Cold-HI AT $z \approx 1$ Survey

Aditya Chowdhury, Nissim Kanekar, and Jayaram N. Chengalur
National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune, India; chowdhury@ncra.tifr.res.in

Received 2022 April 6; revised 2022 June 16; accepted 2022 June 28; published 2022 October 3

Abstract

We describe the design, data analysis, and basic results of the Giant Metrewave Radio Telescope Cold-HI AT $z \approx 1$ (GMRT-CAT$z1$) survey, a $510 \text{ hr}$ upgraded GMRT HI 21 cm emission survey of galaxies at $z = 0.74–1.45$ in the DEEP2 survey fields. The GMRT-CAT $z1$ survey is aimed at characterizing HI in galaxies during and just after the epoch of peak star formation activity in the universe, a key epoch in galaxy evolution. We obtained high-quality HI 21 cm spectra for 11,419 blue star-forming galaxies at $z = 0.74–1.45$, in seven pointings on the DEEP2 subfields. We detect the stacked 21 cm HI emission signal of the 11,419 star-forming galaxies, which have an average stellar mass of $M_* \approx 10^{10} M_\odot$, at $7.1\sigma$ statistical significance, obtaining an average HI mass of $\langle M_{\text{HI}} \rangle = (13.7 \pm 1.9) \times 10^9 M_\odot$. This is significantly higher than the average HI mass of $\langle M_{\text{HI}} \rangle = (3.96 \pm 0.17) \times 10^9 M_\odot$ in star-forming galaxies at $z \approx 0$ with an identical stellar-mass distribution. We stack the rest-frame 1.4 GHz continuum emission of our 11,419 galaxies to infer an average star formation rate (SFR) of $8.07 \pm 0.82 M_\odot \text{ yr}^{-1}$. Combining our average HI mass and average SFR estimates yields an HI depletion timescale of $1.70 \pm 0.29 \text{ Gyr}$, for star-forming galaxies at $z \approx 1$, $\approx 3$ times lower than that of local galaxies. We thus find that, although main-sequence sequences at $z \approx 1$ have a high HI mass, their short HI depletion timescale is likely to cause quenching of their star formation activity in the absence of rapid gas accretion from the circumbulge medium.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Radio spectroscopy (1359); Neutral hydrogen clouds (1099); High-redshift galaxies (734)

1. Introduction

Over the past seven decades, the HI 21 cm transition has played a fundamental role in our understanding of galaxies and galaxy evolution. Studies of HI 21 cm emission from galaxies in the local universe, using both single dishes (e.g., Zwaan et al. 2005; Catinella et al. 2018; Haynes et al. 2018) and radio interferometers (e.g., Verheijen 2001; Begum et al. 2008; Walter et al. 2008; Heald et al. 2011; Hunter et al. 2012), have provided information on the nature of dark matter halos in nearby galaxies (e.g., Bosma 1981; Casertano & van Gorkom 1991; Begum et al. 2008; de Blok et al. 2008), the mass distribution of HI in the local universe (the HI mass function; e.g., Zwaan et al. 1997, 2005; Jones et al. 2018), the connection between rotation velocity and baryonic mass (e.g., Tully & Fisher 1977; McGaugh et al. 2000; Verheijen 2001; Lelli et al. 2019), the dependence of the global HI properties of galaxies on their stellar properties (e.g., Saintonge & Catinella 2022), the relation between the HI mass and the size of the HI disk (e.g., Broeils & Rhee 1997; Wang et al. 2016), the role of HI in regulating star formation in galaxies (e.g., Leroy et al. 2008; Roychowdhury et al. 2009), the impact of environment and galaxy interactions on the HI disks of galaxies (e.g., Cayatte et al. 1990; Hibbard et al. 2001; Chung et al. 2009), the cosmological mass density of neutral hydrogen (e.g., Zwaan et al. 2005; Jones et al. 2018), and a variety of other issues.

Unfortunately, the low Einstein A-coefficient of the HI 21 cm transition implies that the HI 21 cm line is very weak. This makes HI 21 cm emission studies of galaxies at cosmological distances challenging, even with sensitive modern-day telescopes. Indeed, while deep searches for HI 21 cm emission at high redshifts have been carried out for more than 30 years (e.g., Subrahmanyan & Anantharamaiah 1990; Uson et al. 1991; Wieringa et al. 1992), often with integrations of hundreds of hours (e.g., Jaffé et al. 2013; Catinella & Cortese 2015; Fernández et al. 2016; Gogate et al. 2020), the highest redshift at which HI 21 cm emission has been detected from an individual object remains $z \approx 0.376$ (Fernández et al. 2016). Detecting HI 21 cm emission from galaxies at significantly higher redshifts, $z \gtrsim 1$, is one of the main goals of next-generation telescopes like the Square Kilometre Array.

The prohibitively large integration times required on today’s radio telescopes to detect HI 21 cm emission from galaxies at $z \gtrsim 1$ has meant that, until very recently, nothing was known about the HI masses of high-$z$ galaxies or their evolution, or relations to other galaxy properties such as stellar mass, star formation rate (SFR), molecular gas mass, environment, etc. This lack of information about HI, the primary fuel for star formation, in high-$z$ galaxies is in stark contrast with the spectacular progress made in measuring their stellar properties (e.g., Madau & Dickinson 2014), and, more recently, their molecular gas properties (e.g., Tacconi et al. 2020).

Progress in understanding the HI properties of high-$z$ galaxies can be made by using the HI 21 cm stacking approach (Zwaan 2000; Chengalur et al. 2001). Here, the average HI properties of a sample of galaxies can be determined by coadding, i.e., stacking, the HI 21 cm emission signals of the individual galaxies, as long as their positions and redshifts are accurately known. Applying this technique to determine the average HI mass of galaxies at $z \gtrsim 1$ requires a large number of galaxies with spectroscopic redshifts, located within the field of view of the telescope, and with their redshifted HI 21 cm line frequencies covered by a single frequency setting. Further, HI 21 cm stacking experiments critically require accurate spectroscopic redshifts, with redshift errors $\lesssim 100 \text{ km s}^{-1}$, to prevent...
the stacked signal from being smeared in velocity (e.g., Maddox et al. 2013; Elson et al. 2019).

In the local universe, HI 21 cm stacking has been used to probe the dependence of the HI properties of galaxies on their stellar properties and environments (Fabello et al. 2011, 2012; Brown et al. 2015, 2017; Meyer et al. 2016), as well as to measure the cosmological HI mass density at z ≈ 0 (e.g., Hu et al. 2020). The results of these studies have been consistent with those from direct HI 21 cm emission surveys of individual galaxies. At low redshifts, z ≲ 0.2, successful HI 21 cm stacking experiments have been carried out using both single dishes (Delhaize et al. 2013) and radio interferometers (Rhee et al. 2013). At intermediate redshifts, z ≈ 0.2–0.4, the early HI 21 cm stacking experiments, all using the Giant Metrewave Radio Telescope (GMRT), obtained only tentative (∼2σ–3σ) detections of the stacked HI 21 cm emission signal (Lah et al. 2007, 2009; Rhee et al. 2016, 2018). Recently, Bera et al. (2019) used a 175 hr upgraded GMRT1 survey of the Extended Groth Strip (EGS) at z ≈ 0.2–0.4 to obtain the first statistically significant detection of the stacked HI 21 cm emission from galaxies at intermediate redshifts. At even higher redshifts, Kanekar et al. (2016) used 60 hr with the GMRT to search for the stacked HI 21 cm emission from star-forming galaxies at z ≈ 1.3 in the DEEP2 survey fields (Newman et al. 2013), obtaining an upper limit on the average HI mass of the galaxies.

Recently, Chowdhury et al. (2020) used the upgraded GMRT to carry out an HI 21 cm emission survey of galaxies in the DEEP2 survey fields (Newman et al. 2013), covering the redshift range z = 0.74–1.45. Chowdhury et al. stacked the HI 21 cm signal from 7653 blue star-forming galaxies at z = 0.74–1.45 to measure, for the first time, the average HI mass of galaxies at z ≈ 1. They found that the average HI mass of blue star-forming galaxies at z ≈ 1, with an average stellar mass of M* ≈ 1010 M⊙, is a factor of ∼3 higher than that of galaxies at z ≲ 0 with the same average stellar mass. However, they also found that the HI reservoir can sustain the high SFR in these galaxies for only ≲2 Gyr, in the absence of fresh gas accretion. Subsequently, Chowdhury et al. (2021) reported results from another GMRT HI 21 cm emission survey of the DEEP2 fields, using the original GMRT receivers and a 33-MHz bandwidth to cover the narrow redshift range z = 1.18–1.39. They stacked the HI 21 cm emission from 2841 blue star-forming galaxies to obtain an independent ≈5σ detection of the stacked HI 21 cm signal, at z ≈ 1.3. Again, the HI reservoir was found to be sufficient to sustain the galaxy SFRs for only ≈2 Gyr, in the absence of fresh gas accretion. Chowdhury et al. (2020) suggested that the observed decline in the star formation activity of the universe at z ≲ 1 arises due to insufficient gas accretion onto star-forming galaxies from the circumgalactic medium (CGM; see also Bera et al. 2018; Chowdhury et al. 2021).

We present here the GMRT Cold-HI AT z ≈ 1 (GMRT-CATz1) survey, a 510 hr upgraded GMRT HI 21 cm emission survey of galaxies at z = 0.74–1.45 in the DEEP2 survey fields, aimed at characterizing the HI properties of galaxies at z ≈ 1. The survey covers a crucial epoch where the cosmic SFR density becomes to decline after its peak at z ≈ 1.3 (e.g., Madau & Dickinson 2014); the GMRT-CATz1 survey is thus uniquely suited to investigate the role of HI in the decline of the SFR density at z ≲ 1. This paper describes the survey design, the observations, and the data analysis of the GMRT-CATz1 survey, along with an accurate measurement of the average HI mass and the HI depletion timescale of star-forming galaxies at z ≈ 1. A study of the role of HI in the decline of the cosmic SFR density is presented in Chowdhury et al. (2022a), while Chowdhury et al. (2022b) compare the contributions of atomic gas, molecular gas, and stars to the baryonic content of star-forming galaxies at z ≲ 1. Future papers will discuss other results from the GMRT-CATz1 survey, including the HI scaling relations at these redshifts, a comparison between the properties of the ionized gas and the neutral atomic gas in star-forming galaxies at z ≈ 1, and the cosmological HI mass density at z ≈ 1.

This paper is organized as follows: Section 2 provides a brief summary of the DEEP2 Galaxy Redshift Survey, focusing on the aspects relevant for our GMRT HI 21 cm survey; Section 3 discusses the design of the GMRT-CATz1 survey and provides information on the upgraded GMRT observations; Section 4 presents the analysis of the GMRT data in detail; Section 5 describes the procedures used to stack the HI 21 cm emission luminosities and the rest-frame 1.4 GHz continuum luminosities; Section 6 provides detailed information on the main sample of galaxies; Section 7 presents our measurements of the average HI mass as a function of spatial resolution and our final choice of the optimal spatial resolution for all subsequent HI 21 cm stacking; Section 8 presents the GMRT-CATz1 detection of the stacked HI 21 cm line emission and stacked rest-frame 1.4 GHz continuum emission from our full sample of galaxies at the optimal spatial resolution, along with the main results of this paper concerning the average HI properties of star-forming galaxies at z ≈ 1; Section 9 provides a discussion on the average HI properties of red galaxies and galaxies hosting active galactic nuclei (AGNs) at z ≈ 1; Section 10 discusses possible systematic effects, and shows that our average HI mass measurements are unlikely to be affected by such systematics; Section 11 presents a search for HI 21 cm emission from the individual DEEP2 galaxies covered by the GMRT-CATz1 survey; and, finally, Section 12 summarizes our key conclusions. We refer the reader who is interested in the key science results of this paper to Sections 8 and 12.

Throughout this paper, we use a flat $\Lambda$CDM cosmology, with ($H_0$, $\Omega_m$, $\Omega_\Lambda$) = (70 km s$^{-1}$ Mpc$^{-1}$, 0.3, 0.7). We also assume a Chabrier initial mass function (IMF) in all estimates of stellar masses and SFRs. SFR estimates from the literature that assume a Salpeter IMF were converted to a Chabrier IMF by subtracting 0.2 dex (e.g., Madau & Dickinson 2014). All magnitudes are in the AB system.

2. The DEEP2 Galaxy Redshift Survey

The DEEP2 Galaxy Redshift Survey (Newman et al. 2013) used 90 nights with the DEIMOS spectrograph on the Keck II telescope to measure the spectroscopic redshifts of ≈38,300 galaxies in four near-contiguous regions of the sky, with a sky area of 2.8 deg$^2$. The survey covered the wavelength range 6500–9100 Å with a high spectral resolution (R = 6000), allowing a clean identification of the [OIII]λ3727 doublet from the redshift range z ≈ 0.7–1.45. The limiting apparent magnitude of the survey is $R_{AB} = 24.1$, and the typical redshift
accuracy, for objects with redshift quality \( \geq 3 \), is \( \lesssim 62 \text{ km s}^{-1} \) (Newman et al. 2013).

The DEEP2 Data Release 4 (DR4) catalog (Newman et al. 2013) contains 27,966 galaxies with spectroscopic redshifts of quality \( \geq 3 \) at \( z = 0.7–1.45 \) in the four DEEP2 fields. 21,561 of these galaxies are located in DEEP2 fields 2, 3, and 4, which consist of seven subfields of size \( \approx 28' \times 52' \). The FWHM of the GMRT Band-4 receivers is \( \approx 43' \) at 610 MHz, implying that each of the above seven subfields can be reasonably covered with a single GMRT Band-4 pointing (see Figure 1). Further, the HI 21 cm line from galaxies at \( z = 0.74–1.45 \) is redshifted to the frequency range \( \approx 580–820 \text{ MHz} \), i.e., into the frequency coverage of the GMRT Band-4 receivers. DEEP2 fields 2, 3, and 4 are thus ideal targets for a GMRT HI 21 cm emission survey of galaxies at \( z \approx 0.74–1.45 \) (e.g., Kanekar et al. 2016; Chowdhury et al. 2020, 2021). We note that, although DEEP2 Field 1, the EGS, has excellent multivavelength coverage (e.g., Davis et al. 2007), we did not observe it as the narrowness of the EGS (\( \approx 16' \); Newman et al. 2013) implies that a significant fraction of the GMRT Band-4 primary beam would contain almost no galaxies with spectroscopic redshifts.

The stellar masses of the DEEP2 galaxies were estimated via a relation between the \( (U−B) \) and \( (B−V) \) color, and the ratio of the stellar mass to the B-band luminosity (Weiner et al. 2009). This relation was calibrated at \( z \approx 1 \) using the subset of DEEP2 galaxies that have direct K-band estimates of the stellar mass. The scatter of the individual stellar masses estimated using this relation is \( \approx 0.3 \text{ dex} \) (Weiner et al. 2009).

### 3. The Upgraded GMRT Observations

We used the upgraded GMRT (Swarup et al. 1991; Gupta et al. 2017) Band-4 550–850 MHz receivers to observe DEEP2 fields 2, 3, and 4 for a total time of \( \approx 510 \text{ hr} \), over three GMRT cycles between 2018 October and 2020 October (proposals 35_087, 37_063, and 38_033; PI: Aditya Chowdhury). The total time was divided approximately equally between seven pointings in the three DEEP2 fields. This was motivated by (a) minimizing the effect of cosmic variance on our measurements, by increasing the sky area, and (b) reducing the risk of the rms noise on the spectra of individual galaxies not decreasing \( \propto 1/\sqrt{\Delta t} \) on a single field, due to systematic effects such as dynamic range issues.

The DEEP2 sky area of \( \approx 2 \text{ deg}^2 \) covered by the GMRT-CAT\(_{1}\) survey (sky volume of \( \approx 10^7 \text{ comoving Mpc}^3 \)) is sufficient to ensure that the effects of cosmic variance are negligible (Newman & Davis 2002; Newman et al. 2013). Driver & Robotham (2010) find that these effects would be \( \lesssim 10\% \) for a single contiguous survey volume of \( \gtrsim 10^7 \text{ cMpc}^3 \).

The total survey volume of \( \approx 10^7 \text{ cMpc}^3 \) of the GMRT-CAT\(_{1}\) survey consists of three separate contiguous regions (DEEP2 fields 2, 3, and 4); the effects of cosmic variance are hence expected to be even lower than \( \lesssim 10\% \), by a factor of \( \approx \sqrt{3} \) (Driver & Robotham 2010).

The initial 90 hr of observations were carried out between 2018 October and 2019 March (GMRT Cycle 35), with five pointings\(^5\) on DEEP2 fields 3 and 4; the analysis of these data was presented in Chowdhury et al. (2020). Between 2019 October and 2020 March (GMRT Cycle 37), we used 170 hr of observations to observe all three DEEP2 fields with seven pointings. The remaining 250 hr were obtained between 2020 May and 2020 October (GMRT Cycle 38), again with seven pointings on the three DEEP2 fields. The total on-source observing time for each of the seven DEEP2 subfields was \( \approx 50–60 \text{ hr} \). We note that the pointing center on DEEP2 subfield 31 was shifted by \( \approx 8' \) between our observations of Cycle 35 and those of Cycles 37 and 38; this was done to reduce the deconvolution errors from bright radio-continuum sources at the edge of the pointing. Table 1 provides a summary of the 510 hr of observations, while Figure 1 shows the different pointings on the three DEEP2 fields.

We used the GMRT Wideband Backend (Reddy et al. 2017) as the correlator, covering the frequency range 530–930 MHz with a total bandwidth of 400 MHz, divided into 8192 spectral channels. In each observing run, we used observations of one or more of the standard calibrators 3C48, 3C147, or 3C286 to calibrate the flux-density scale, and observations of the nearby compact sources 0022 + 002, 0204 + 152, or 1609 + 266 to calibrate the antenna complex gains and antenna bandpass shapes.

### 4. Data Analysis, Sample Selection, and Statistical Tests

#### 4.1. The Data Analysis

All data were analyzed in the Common Astronomy Software Applications package (CASA version 5; McMullin et al. 2007) following standard procedures. The same procedures, described in detail below, were used for the data from all observing cycles. We note that the analysis of the initial 90 hr of data from Cycle 35 was presented by Chowdhury et al. (2020). The new analysis described here contains a few minor improvements over that of Chowdhury et al. (2020).

The GMRT consists of 30 antennas, with 14 of these in a central 1 km\(^2\) region (the central square) and the remaining 16

\(^5\) The allocated time for the project in Cycle 35 was 100 hr; we lost an entire 10 hr run on DEEP2 field 41 due to severe radio frequency interference.
| DEEP2 Subfield | R.A. (J2000) | Decl. (J2000) | GMRT Cycle | On-source Time (hr) | Number of Galaxies | $\sigma_{\text{HI}}$ ($\mu$Jy beam$^{-1}$) |
|----------------|-------------|--------------|-------------|---------------------|-------------------|-------------------------------|
| 21             | 16°47′59.7″ | +34°55′40.4″ | 37          | 32.7                | 1547              | 201                           |
|                | 38          |              | 17.9        | 1545               | 313               |
| 22             | 16°51′28.9″ | +34°56′58.9″ | 37          | 22.8                | 1623              | 274                           |
|                | 38          |              | 26.9        | 1663               | 293               |
| 31             | 23°26′52.8″ | +00°08′25.7″ | 35          | 14.3                | 1390              | 328                           |
| 23°27′26.2″    | +00°08′22.9″| 37          | 12.8        | 1405               | 338               |
|                | 38          |              | 33.9        | 1226               | 232               |
| 32             | 23°29′49.9″ | +00°12′12.7″ | 35          | 14.5                | 1403              | 304                           |
|                | 37          |              | 10.7        | 1268               | 319               |
|                | 38          |              | 26.7        | 1431               | 288               |
| 33             | 23°32′58.7″ | +00°08′22.7″ | 35          | 15.3                | 1227              | 293                           |
|                | 37          |              | 14.8        | 1140               | 338               |
|                | 38          |              | 33.9        | 1062               | 195               |
| 41             | 02°28′24.0″ | +00°35′27.6″ | 35          | 7.5                 | 1878              | 355                           |
|                | 37          |              | 31.4        | 1899               | 286               |
|                | 38          |              | 31.1        | 1903               | 268               |
| 42             | 02°30′48.0″ | +00°35′15.0″ | 35          | 15.0                | 1813              | 362                           |
|                | 37          |              | 17.2        | 1780               | 308               |
|                | 38          |              | 28.0        | 1790               | 291               |

**Table 1**

Summary of the GMRT Observations and Results

| DEEP2 Subfield | R.A. (J2000) | Decl. (J2000) | GMRT Cycle | On-source Time (hr) | Number of Galaxies | $\sigma_{\text{HI}}$ ($\mu$Jy beam$^{-1}$) |
|----------------|-------------|--------------|-------------|---------------------|-------------------|-------------------------------|
| 21             | 16°47′59.7″ | +34°55′40.4″ | 37          | 32.7                | 1547              | 201                           |
|                | 38          |              | 17.9        | 1545               | 313               |
| 22             | 16°51′28.9″ | +34°56′58.9″ | 37          | 22.8                | 1623              | 274                           |
|                | 38          |              | 26.9        | 1663               | 293               |
| 31             | 23°26′52.8″ | +00°08′25.7″ | 35          | 14.3                | 1390              | 328                           |
| 23°27′26.2″    | +00°08′22.9″| 37          | 12.8        | 1405               | 338               |
|                | 38          |              | 33.9        | 1226               | 232               |
| 32             | 23°29′49.9″ | +00°12′12.7″ | 35          | 14.5                | 1403              | 304                           |
|                | 37          |              | 10.7        | 1268               | 319               |
|                | 38          |              | 26.7        | 1431               | 288               |
| 33             | 23°32′58.7″ | +00°08′22.7″ | 35          | 15.3                | 1227              | 293                           |
|                | 37          |              | 14.8        | 1140               | 338               |
|                | 38          |              | 33.9        | 1062               | 195               |
| 41             | 02°28′24.0″ | +00°35′27.6″ | 35          | 7.5                 | 1878              | 355                           |
|                | 37          |              | 31.4        | 1899               | 286               |
|                | 38          |              | 31.1        | 1903               | 268               |
| 42             | 02°30′48.0″ | +00°35′15.0″ | 35          | 15.0                | 1813              | 362                           |
|                | 37          |              | 17.2        | 1780               | 308               |
|                | 38          |              | 28.0        | 1790               | 291               |

**Note.** The columns are: (1) the DEEP2 subfield, (2), (3) the J2000 R.A. and decl. of the GMRT pointing center, (4) the observing cycle in which the observations were carried out, (5) the on-source time, in hours, (6) the final number of galaxies whose HI 21 cm subcubes were stacked, and (7) the median rms noise on the HI 21 cm subcubes at a velocity resolution of 30 km s$^{-1}$ and a spatial resolution of 90 kpc. See main text for discussion. Note that all observations had the same correlator setup, covering the frequency range 530–930 MHz, with 8192 spectral channels.

Arranged along three arms, forming a Y shape and providing baselines out to $\approx 25$ km. Terrestrial radio frequency interference (RFI) is typically stronger on the shorter central-square baselines, and decorrelates on the longer baselines. To reduce the effects of RFI, we entirely excluded the 91 baselines between pairs of central-square antennas, and restricted our analysis to the remaining 344 baselines. The 91 central-square baselines that were excluded have UV distances of $0.08–3.8$ k$\lambda$ at an observing frequency of $650$ MHz; these correspond to angular scales of $0.9–43'$, far larger than the angular scales of interest in this work.

The data for each DEEP2 subfield from the three GMRT observing cycles were analysed independently. The result of the analysis is thus either two or three independent spectral cubes for each DEEP2 subfield, one each for the data of each cycle. This was done to prevent systematic errors, such as those due to low-level RFI, imperfect deconvolution, etc., in the data of one GMRT cycle on a given field from affecting the overall data quality for that field. The independent spectral cubes allow us to separately examine the quality of the spectra from all DEEP2 galaxies from each GMRT cycle. For example, if the spectrum of a particular DEEP2 galaxy from Cycle 37 is affected by RFI, our approach ensures that the spectra of the galaxy from Cycles 35 and 38 can be used, if these are clean.

Conversely, if the data from all three cycles were combined to generate a single spectral cube for the pointing, we would have had to entirely exclude the DEEP2 galaxy in question from our sample.

For each observing run, after initially removing data from nonworking antennas, the AOFLAGGER (Offringa et al. 2012) package was used to excise data affected by RFI. The antenna gains and bandpass shapes were determined using the data on the calibrator sources, and these solutions were applied to the target source visibilities. All antenna-based gain and bandpass calibration, as well as self-calibration, was performed using the calR$^3$ package (Chowdhury et al. 2020), a collection of robust calibration routines within the CASA framework. Following this, all visibility data on each pointing from each cycle were combined together to produce a single multichannel data set for each pointing. A standard iterative self-calibration procedure, along with further excision of data affected by low-level RFI, was then separately performed on the data of each pointing, again for each observing cycle. For each subfield, the data of the first observing cycle were calibrated using 3–4 rounds of imaging and phase-only self-calibration, followed by 2–3 rounds of imaging and amplitude-and-phase self-calibration.

---

8 The package is publicly available at https://github.com/chowdhuryaditya/calR (Chowdhury 2021).
For observations of the same subfield in later cycles, the continuum image obtained from the first observing cycle was used as the initial self-calibration model (solving for both amplitude and phase), followed by at least two rounds of imaging and amplitude-and-phase self-calibration. The imaging was done with the CASA task TCLEAN, with w-projection (Cornwell et al. 2008), multifrequency synthesis (second-order expansion; Rau & Cornwell 2011), and Briggs weighting (Briggs 1995), with a robust parameter of $-0.5$. For each field, the self-calibration procedure was continued until no improvement was seen in either the image or in the residuals after subtracting the image from the calibrated visibilities. At the end of the self-calibration procedure, the calibrated visibilities of each DEEP2 subfield of each cycle were separately imaged with the task TCLEAN, again using w-projection, multifrequency synthesis (second-order expansion), and Briggs weighting with a robust parameter of 0.0.

We next used the final continuum images of each target field to subtract out all detected continuum emission from the self-calibrated spectral-line visibilities. For each field, the continuum subtraction was performed separately for the data in each observing cycle, using the continuum image of that cycle. We then used AOFLAGGER (Offringa et al. 2012) to perform one final round of RFI excision on the continuum-subtracted spectral-line visibilities.

The fraction of data on each target field that was lost due to time-variable issues such as RFI, temporary problems with antennas, etc., but not including the antennas that were not available throughout the observing run and the 91 baselines among the central-square antennas that were excited at the outset of the analysis, was $\approx 26\%$, $\approx 32\%$, and $\approx 19\%$ for Cycles 35, 37, and 38, respectively. Figure 2 shows, separately for each observing cycle, the fraction of data excised due to such time-dependent issues as a function of observing frequency.

The CASA task TCLEAN was then used to make spectral cubes from the continuum-subtracted visibilities of each target field, and from each cycle; this yielded a total of 19 spectral cubes. The cubes were made in the barycentric frame, with w-projection and Briggs weighting with a robust parameter of $+1$. We experimented with various values of the robust parameter, and found Briggs weighting with a robust parameter of $+1$ to be the optimal choice; this results in reducing the effect of deconvolution errors around bright radio-continuum sources, without causing a significant increase in the spectral rms noise of the cubes. Each cube covers a sky area of $0.8 \times 0.8$, larger than the FWHM of the GMRT primary beam at the lowest observing frequency of the band; this allowed us to obtain HI 21 cm spectra for all DEEP2 primary beams within the FWHM of the GMRT primary beam at the redshifted HI 21 cm line frequency of each galaxy. The channel width of the spectral cubes is 48.8 kHz, corresponding to a velocity resolution of $18$–$25$ km s$^{-1}$ across the frequency band. The synthesized beams of the cubes have FWHMs of $4''0$–$7''5$, corresponding to spatial resolutions of $29$–$63$ kpc for the redshift range $z = 0.74$–$1.45$.

4.2. Radio-continuum Images

The final 655 MHz radio-continuum images of each DEEP2 subfield were made after combining all available data on each pointing. For each pointing, we first combined the calibrated visibilities from all cycles into a single data set, and then performed a few iterations of self-calibration on the combined data set. The self-calibrated visibilities of each subfield were then imaged, with w-projection, multifrequency synthesis (second-order expansion), and Briggs weighting with a robust parameter of 0.0. For each pointing, we imaged a region of $\approx 1.5 \times 1.5$ around the pointing center, extending well beyond the null of the GMRT primary beam at these frequencies. The median of the rms noise values in each continuum image is $\approx 5$–$10$ µJy beam$^{-1}$, while the FWHMs of the synthesized beams are $\approx 3''$–$4''$. Table 2 lists the FWHMs of the synthesized beams and the rms noise values of these final radio-continuum images. The rms noise values listed in the table were obtained by taking the median of the local rms noise computed on regions of size $\approx 84'' \times 84''$, without primary beam correction. The final continuum images of the seven DEEP2 subfields are shown in Figure 3. We note that the GMRT pointing on subfield 31 in Cycle 35 was slightly different from the pointing used in Cycles 37 and 38 (see Figure 1). The final radio-continuum image of subfield 31 in Figure 3 is from the data obtained in Cycles 37 and 38.

4.3. Sample Selection

Our upgraded GMRT observations cover the redshifted HI 21 cm line for 16,250 DEEP2 galaxies with accurate redshifts (redshift quality, $Q \geq 3$ in the DEEP2 DR4 catalog; Newman et al. 2013) at $z = 0.74$–$1.45$, lying within the FWHM of the GMRT primary beam at the redshifted HI 21 cm frequency of
the galaxy. The FWHM of the GMRT primary beam is $\approx 43^\prime$ at 610 MHz, and scales with frequency ($\nu$) as FWHM $\propto 1/\nu$. The HI 21 cm lines of the 16,250 galaxies at $z = 0.74$--1.45 are redshifted to frequencies $\approx 580$--820 MHz, where the Band-4 receivers have their highest sensitivity.

The DEEP2 survey is magnitude-limited in the $R$ band ($R < 24.1$), and this preferentially picks out blue objects at $z > 0.7$ (Willmer et al. 2006; Newman et al. 2013). Indeed, only 2222 out of the 16,250 DEEP2 objects covered by our observations are part of the red cloud in the color–magnitude diagram (Willmer et al. 2006). Figure 4 shows the distribution of 16,250 DEEP2 galaxies in the rest-frame ($U$–$B$) versus rest-frame $M_B$ color–magnitude diagram. We ensure the homogeneity of our sample by restricting our study to the 14,028 objects with $M_B > 21.63$ $- 1.014$ (Willmer et al. 2006).

Some of the above 14,028 blue DEEP2 galaxies may host AGNs, which could affect the gas properties of the galaxy. We hence used our radio-continuum images of the DEEP2 subsamples to exclude all detected radio AGNs from our sample. Radio-continuum studies show a bimodality in the distribution of rest-frame 1.4 GHz radio luminosity ($L_{1.4, \text{GHz}}$), with objects having $L_{1.4, \text{GHz}} > 2 \times 10^{23}$ W Hz$^{-1}$ being predominantly radio-bright AGNs, and objects with $L_{1.4, \text{GHz}} < 2 \times 10^{23}$ W Hz$^{-1}$ being predominantly star-forming galaxies (Condon et al. 2002). We use this criterion to exclude the 882 DEEP2 objects that are detected at $\geq 4\sigma$ statistical significance in our radio-continuum images, with $L_{1.4, \text{GHz}} > 2 \times 10^{23}$ W Hz$^{-1}$. After excluding these 882 radio-bright AGNs, our sample contains 13,146 blue star-forming galaxies at $z = 0.74$--1.45.

Finally, we excluded from the sample the 487 galaxies that have stellar masses $M_\ast < 10^9 M_\odot$. This was done in order to ensure that our results can be directly compared with results for the xGASS survey (Catinella et al. 2018), which has measured the HI properties of galaxies at $z \approx 0$ with $M_\ast > 10^9 M_\odot$. Our note that only $\approx 4\%$ of our galaxies have $M_\ast < 10^9 M_\odot$, and their exclusion from the sample does not affect the results presented in this work (within the statistical uncertainties). After excluding the 487 galaxies with $M_\ast < 10^9 M_\odot$, our sample contains 12,659 blue star-forming galaxies at $z = 0.74$--1.45.

### 4.4. Hi 21 cm Spectral Cubes

We obtain multiple Hi 21 cm spectra, with uncorrelated statistical noise, for nearly every blue star-forming DEEP2 galaxy in our sample. Specifically, for each DEEP2 galaxy, we obtain two or three independent Hi 21 cm spectra from the observations in the different GMRT cycles. We also obtain additional independent Hi 21 cm spectra for the galaxies that lie in the overlap regions of our pointings on the DEEP2 subsamples. A total of 33,640 independent Hi 21 cm spectra were obtained for the 12,659 galaxies in our sample, with up to six independent Hi 21 cm spectra per DEEP2 galaxy.

For each DEEP2 galaxy, we extracted an Hi 21 cm subcube centered on the galaxy from each spectral cube that covered its Hi 21 cm line. Each subcube covers an angular extent of $\pm 76^\prime 8$ around the galaxy location, and a velocity range of $\pm 1500$ km s$^{-1}$ around its redshifted Hi 21 cm line frequency. We convolved each of the 33,640 independent Hi 21 cm subcubes with Gaussian beams such that the FWHMs of the final beams of each convolved subcube are identical.

Next, the spatial extent of the Hi 21 cm emission from galaxies at these redshifts is not known. We hence initially convolved each subcube to a range of spatial resolutions, 60, 70, 80, 90, 100, 110, 120, 150, and 200 kpc. The analysis of the subcubes was carried out at each of the above resolutions. Our final choice of the spatial resolution is described in Section 7 below.

During the process of convolution, care was taken to normalize the convolved subcubes such that the peak of the convolved point-spread function (using the same kernel) is unity (Chowdhury et al. 2020). Any spectral channel where the intrinsic beam has a FWHM $> 60$ kpc was excised at this stage. Next, we regirded each subcube to a uniform spatial and spectral grid, with 10 kpc spatial pixels covering $\pm 500$ kpc around the position of the DEEP2 galaxy, and 30 km s$^{-1}$ velocity channels covering $\pm 1500$ km s$^{-1}$ around its redshifted Hi 21 cm line frequency. Finally, we fitted a second-order polynomial to the spectrum at each spatial pixel of the subcubes, and subtracted this out. This was done to remove any residual spectral baselines due to deconvolution errors from bright radio-continuum sources.

### 4.5. Statistical Tests for Systematic Effects in the Spectral Cubes

We carried out a series of tests on the subcubes, aiming to remove any subcubes affected by non-Gaussian systematic effects. This was done to ensure that the noise properties of the stacked Hi 21 cm subcubes are not limited by such systematics. Initially, we discarded any Hi 21 cm subcube that has $> 15\%$ of its spectral channels excised due to RFI; this resulted in the excision of 3721 Hi 21 cm subcubes, i.e., $\approx 11\%$ of the full sample.

Next, we tested whether the noise properties of the Hi 21 cm subcubes are consistent with their arising from a Gaussian distribution. The tests were carried out on the subcubes with a spatial resolution of 60 kpc; performing these tests at coarser

---

**Table 2**

Properties of the GMRT 655 MHz Continuum Images of Each DEEP2 Subfield

| DEEP2 Subfield | Synthesized Beam | $F_{\text{max}}$ (mJy beam$^{-1}$) | $\sigma_{\text{cont}}$ (mJy beam$^{-1}$) |
|---------------|------------------|-------------------------------|-------------------|
| 21            | $3^\prime 7 \times 3^\prime 1$ | 152.3                        | 4.5               |
| 22            | $3^\prime 3 \times 2^\prime 6$ | 158.5                        | 8.0               |
| 31            | $4^\prime 1 \times 3^\prime 3$ | 82.4                         | 6.2               |
| 32            | $4^\prime 1 \times 3^\prime 3$ | 29.7                         | 5.0               |
| 33            | $4^\prime 1 \times 3^\prime 3$ | 34.4                         | 4.6               |
| 41            | $3^\prime 7 \times 2^\prime 9$ | 284.0                        | 10.3              |
| 42            | $4^\prime 1 \times 3^\prime 2$ | 75.6                         | 5.9               |

---

Note. The columns are (1) the DEEP2 subfield, (2) the FWHM of the synthesized beam, (3) the peak flux density of the brightest source in the field, uncorrected for the primary beam response, and (4) the rms noise on the image, obtained by taking the median of the local rms noise computed on regions of size $\approx 84^\prime \times 84^\prime$. Note that the continuum image of DEEP2 subfield 31 uses data from Cycles 37 and 38 only (see main text for details).
spatial resolutions yielded similar results. We excluded spectra based on the following criteria:

1. Any HI 21 cm subcube having a spectral feature of \( \geq 6.0\sigma \) significance, either at the native velocity resolution \( (30 \text{ km s}^{-1}) \) or after smoothing to resolutions of 60 km s\(^{-1}\) and 120 km s\(^{-1}\), was rejected.

2. Each HI 21 cm subcube was tested for the presence of correlations between neighboring spectral channels (e.g., due to a residual spectral baseline) by examining the decrease in the rms noise after smoothing to coarser velocity resolutions. Specifically, each HI 21 cm subcube was smoothed by a factor of 10 to a spectral resolution of 300 km s\(^{-1}\); any subcube whose rms noise was found to decrease by a factor \( >0.47 \) after the smoothing was excluded from the sample.

These tests resulted in our excluding 926 HI 21 cm subcubes, i.e., \( \approx 3\% \) of the remaining 29,919 HI 21 cm subcubes. Our final sample, after excising 4647 subcubes in all, contains a total of 28,993 independent HI 21 cm subcubes for 11,419 blue star-forming galaxies at \( z = 0.74 - 1.45 \). Table 1 lists the final number of galaxies (i.e., HI 21 cm subcubes) obtained from the observations of each subfield in each GMRT cycle. We emphasize that the results of this paper are not sensitive to the exact choice of the thresholds used in the above tests.
4.6. The rms Noise on the Individual HI 21 cm Subcubes

The presence of systematic effects in the data, such as deconvolution errors, residual low-level RFI, etc., can limit the final spectral rms noise obtained on the HI 21 cm spectra. To test for such effects, we computed the rms noise on our final sample of 28,993 independent HI 21 cm subcubes, at a spatial resolution of 90 kpc, and compared this to the spectral rms noise expected for upgraded GMRT observations. For a given observation of a DEEP2 subfield, we compute the expected spectral rms noise taking into account (1) the sensitivity of the upgraded GMRT Band-4 receivers (as measured by the observatory), (2) the total on-source time obtained on the DEEP2 subfield in that GMRT cycle, (3) the fraction of data excised due to RFI, nonworking antennas, power failures, etc., (4) the effect of spectral smoothing to obtain a velocity resolution of 30 km s$^{-1}$, and (5) the effect of spatial smoothing to obtain a resolution of 90 kpc.

Figures 16, 17, and 18 in the Appendix compare the spectral rms noise obtained on the HI 21 cm subcubes of the DEEP2 galaxies with the expected rms noise for each observation. We find that the actual rms noise obtained on our HI 21 cm subcubes is within $\approx 10\%$ of the rms noise predicted using the GMRT sensitivity curve for the Band-4 receivers. We note that the GMRT sensitivity curve is itself only accurate to $\approx 10\%$, while the typical flux-scale uncertainty for upgraded GMRT observations (such as the ones presented here) is also $\approx 10\%$. We thus find no evidence for systematic effects that might affect the spectral rms noise on our sample of 28,993 independent HI 21 cm subcubes. We also repeated the above analysis at other spatial resolutions (>60 kpc) and find similar results. Overall, we find no evidence suggesting that the final rms noise obtained on our HI 21 cm subcubes might have been limited by systematic effects.

5. The Stacking Analysis

5.1. Stacking the HI 21 cm Emission

For each HI 21 cm subcube, we first corrected the measured flux density to take into account the position of the DEEP2 galaxy in the GMRT primary beam, and then converted the flux density to the corresponding HI 21 cm line luminosity density, $L_{HI}$ (in units of Jy Mpc$^{-2}$), using the relation $L_{HI} = 4\pi S_{HI} D_L^2/(1 + z)$, where $S_{HI}$ is the HI 21 cm line flux density (in units of janskys), and $D_L$ is the luminosity distance of the galaxy (in units of megaparsecs). The stacked HI 21 cm spectral cube for the DEEP2 galaxies was obtained by taking an average, across all HI 21 cm subcubes of the final sample, of the HI 21 cm line luminosity densities in the corresponding spatial pixels and velocity channels of the individual subcubes. We then fitted a second-order spectral baseline to the spectrum of each spatial pixel of the stacked cube, excluding the central $\pm 250$ km s$^{-1}$ velocity range, and subtracted out this baseline from each spatial pixel to obtain the final stacked HI 21 cm spectral cube.

We determined the rms noise on the stacked cube by using Monte Carlo simulations in which we shifted the central velocity of each DEEP2 galaxy in the range $\pm 1500$ km s$^{-1}$, and then stacked the velocity-shifted HI 21 cm subcubes. Spectral channels that were shifted outside the $\pm 1500$ km s$^{-1}$ velocity range were wrapped around to the other side of the spectrum, before the stacking. We repeated the above procedure to obtain $10^4$ realizations of the stacked HI 21 cm subcube. For each spatial and velocity pixel of the stacked HI 21 cm subcube, we computed the rms of the HI 21 cm luminosities across the $10^4$ realizations to obtain an estimate of the rms noise on the pixel.

Finally, we used a boxcar kernel to smooth the stacked HI 21 cm subcubes, including those derived via the Monte Carlo simulations, to a velocity resolution of 90 km s$^{-1}$. This was done in order to increase the signal-to-noise ratio ($S/N$) per channel, to clearly identify the velocity range with HI 21 cm emission. We used these subcubes to estimate the average HI mass of the DEEP2 galaxies, and the error on the average HI mass. We note that our results are not sensitive to the exact choice of the final velocity resolution of the stacked HI 21 cm cubes. The average HI masses derived from the stacked HI 21 cm spectra at other resolutions (e.g., 60, 120 km s$^{-1}$, etc.) are consistent with those reported in this paper, for a velocity resolution of 90 km s$^{-1}$.

We also computed the errors on the stacked HI 21 cm subcube via two other methods: (i) bootstrap resampling with replacement, and (ii) computaion of the rms noise from the image plane of the stacked subcube. The errors derived via these methods are very similar to those derived via our Monte Carlo approach.

The average HI mass of our sample of DEEP2 galaxies was obtained as follows: (i) the central velocity channels of the final stacked cube were integrated to produce an image of the HI 21 cm emission, (ii) the stacked HI 21 cm spectrum was obtained by taking a cut through the location of the peak luminosity density in this HI 21 cm image, (iii) a contiguous range of central velocity channels in the stacked HI 21 cm spectrum, each containing emission at $>1.5\sigma$ statistical significance, was selected, (iv) the signal in these channels was integrated to obtain the average velocity-integrated HI 21 cm line luminosity density ($\int L_{HI}dv$), in units of Jy Mpc$^{-2}$ km s$^{-1}$, and (v) the average HI mass of the sample was obtained via the expression $M_{HI} = [1.86 \times 10^4 \times \int L_{HI}dv] M_\odot$.

We note that the average HI mass obtained by integrating the stacked HI 21 cm spectrum over a wide velocity range of $\pm 250$ km s$^{-1}$ is consistent with that obtained from the above approach, integrating over a contiguous range of central density.
velocity channels with emission at $\geq 1.5\sigma$ statistical significance.

5.2. Stacking the Rest-frame 1.4 GHz Continuum Emission

Measurements of the rest-frame 1.4 GHz radio luminosity of a star-forming galaxy can be used to infer its SFR via the known correlation between the radio and the far-infrared (FIR) luminosities (Condon 1992; Yun et al. 2001). We use our radio-continuum images of the DEEP2 subfields, along with the FIR–radio correlation, to estimate the average SFR of our galaxies (e.g., White et al. 2007; Bera et al. 2018; Leslie et al. 2020).

The synthesized beams of our radio-continuum images correspond to a physical scale of $\approx 24–35$ kpc over the redshift range $z = 0.74–1.45$. We extracted $\approx 84^\circ \times 84^\prime$ subimages around each DEEP2 galaxy of our sample and convolved each subimage with a Gaussian kernel such that the final synthesized beam has a FWHM of 40 kpc (again normalizing the subimages such that the peak of the convolved point-spread function is unity; Chowdhury et al. 2020). We then regridded the subimages to a uniform grid with 5.2 kpc pixels and extending over $\pm 260$ kpc. Next, for each DEEP2 galaxy, we converted the observed flux density in each pixel to the rest-frame 1.4 GHz luminosity at the galaxy redshift, assuming a spectral index of $\alpha = -0.8$ (Condon 1992), with $S_\nu \propto \nu^{-\alpha}$. We note that the central frequency of our radio-continuum images corresponds to rest-frame frequencies of $\approx 1.14–1.61$ GHz for the galaxies of our sample, quite close to 1.4 GHz; our results are hence insensitive to the exact choice of $\alpha$. A median-stacking approach was then used to estimate the average rest-frame 1.4 GHz luminosity of our sample (White et al. 2007).

In this approach, we compute the median of the 1.4 GHz luminosities of each spatial pixel, across the sample of galaxies. The median rest-frame 1.4 GHz luminosity is then converted to a median SFR using the relation SFR ($M_\odot$ yr$^{-1}$) = $(3.7 \pm 1.1) \times 10^{-22} \times L_{1.4}$ GHz (W Hz$^{-1}$) (Yun et al. 2001; after scaling to a Chabrier IMF).

In order to test for systematic effects and to compute the rms noise on our stacked continuum image, we repeated the above procedure for subimages at locations offset by $100^\prime$ from the DEEP2 galaxies. The stack at the offset locations shows that the mean of the distribution of luminosity density values is slightly shifted to negative values; in flux-density units, the offset is $\approx -0.4 \mu$Jy, more than an order of magnitude lower than the rms noise on each of our radio-continuum images. This weak bias in the mean of the distribution is likely to be due to negative sidelobes of very faint sources in our continuum maps, i.e., those with flux densities comparable to or lower than our cleaning thresholds. For the rest-frame 1.4 GHz continuum stack of a given subsample of galaxies, we correct for this effect by (i) computing the mean luminosity density of the stack at locations offset by $100^\prime$ from the target galaxies, and (ii) subtracting this mean luminosity density from all pixels of the stacks at both the galaxy locations and the offset locations. Effectively, this amounts to a small zero-point correction in our continuum stacked images; the correction is at the level of $\approx 4\%–5\%$ of the detected 1.4 GHz luminosity in the stacked radio-continuum images.

We note that uncertainties in the flux-density scale of our radio-continuum images would affect our radio-derived SFR estimates. These systematic uncertainties are typically $\lesssim 10\%$ for the GMRT, for our calibration procedure. We have very conservatively treated this as a $1\sigma$ error on the flux-density estimates. Thus, the errors on our SFR values include both a 10% systematic uncertainty and the $1\sigma$ statistical uncertainty.

In passing, we note that we are unlikely to miss any radio-continuum emission from the star-forming regions of the galaxies of our sample because the 40 kpc beam of the stacked radio-continuum images is much larger than the observed sizes of star-forming regions in galaxies at these redshifts (Trujillo et al. 2004). Indeed, the FWHM of the $R$-band emission is less than 10 kpc for $\approx 98\%$ of the 11,419 DEEP2 galaxies in our sample (Coil et al. 2004).

6. The Sample of 11,419 Blue, Star-forming Galaxies

Our main sample consists of 11,419 blue star-forming galaxies at $z = 0.74–1.45$ in the seven uGMRT pointings on DEEP2 fields 2, 3, and 4, after excluding AGNs, red galaxies, galaxies with stellar masses $M_\star < 10^9 M_\odot$ (see Section 4.3), and galaxies whose HI 21 cm subcubes were affected by discernible systematic effects (see Section 4.5). Our upgraded GMRT observations provide up to six independent measurements of the HI 21 cm spectrum of each galaxy of our sample (see Section 4.4). Approximately 57% of the galaxies have $\geq 3$ independent measurements of their HI 21 cm spectra, with at least one from each GMRT cycle. In all the analyses presented in this paper, we have treated the independent HI 21 cm spectra as arising from separate objects. This effectively implies that, in computing the average quantities of the sample, each of the 11,419 sample galaxies has a weight proportional to the number of independent measurements of its HI 21 cm spectrum.

6.1. Redshifts and Stellar Masses

The redshift distribution of the 11,419 galaxies of our sample, after accounting for the number of independent HI 21 cm spectra per galaxy, is shown in Figure 5(A). The sample spans the redshift range $z = 0.74–1.45$, with a mean redshift ($\bar{z}$) = 1.04.

Our sample of 11,419 galaxies has stellar masses in the range $M_\star = 10^9 – 10^{11.4} M_\odot$. The stellar-mass distribution of the 11,419 galaxies, after factoring in the number of independent HI 21 cm spectra per galaxy, is shown in Figure 5(B). The mean stellar mass of the sample is $\langle M_\star \rangle = 9.9 \times 10^9 M_\odot$.

Finally, we note that both the redshift and the stellar-mass distributions of the 28,993 HI 21 cm subcubes (shown in Figure 5) are similar to those of the 11,419 galaxies.

6.2. The Star-forming Main Sequence

An important question is whether our sample is dominated by main-sequence galaxies, or whether it contains a significant population of starburst systems. To test this, we binned the sample of galaxies into multiple stellar-mass subsamples, and measured the average SFR in each of the stellar-mass bins to test whether the average SFR and average stellar mass are consistent with the star-forming main sequence at these redshifts. Further, the star-forming main sequence has been shown to evolve within our redshift range, $z = 0.74–1.45$ (e.g., Whitaker et al. 2014; Leslie et al. 2020). We hence divided our sample into two redshift ranges, $z = 0.74–1.00$ and $z = 1.00–1.45$, and in each redshift bin, we measured the average SFR of galaxies in stellar-mass subsamples of width 0.5 dex. This was done by separately stacking the rest-frame 1.4 GHz
luminosities of the galaxies in each stellar-mass subsample to determine their average SFR, using the procedure described in Section 5.2. The stacking was performed using weights such that the redshift distributions of the stacked subimages in the stellar-mass subsamples are identical. Finally, for each redshift bin, we compared our measurements of the average stellar mass and the average SFR with the star-forming main-sequence relation of Whitaker et al. (2014). We note there were fewer than 35 galaxies with \( M_*=10^{11} M_\odot \) in both redshift intervals; the average SFRs of these highest-stellar-mass subsamples may thus be affected by small number statistics and are hence not used for this comparison.

Figure 6 shows our measurements of the average SFR of galaxies in the four stellar-mass subsamples, for the two redshift bins, \( z = 0.74-1.00 \) and \( z = 1.00-1.45 \). For comparison, we also plot the star-forming main-sequence relations obtained for a stellar-mass-complete sample of star-forming galaxies at similar redshifts (Whitaker et al. 2014). These authors provide the star-forming main-sequence relation for the redshift ranges \( z = 0.5-1.0 \) and \( z = 1.0-1.5 \); we have interpolated between these measurements to infer the main-sequence relations at \( z = 0.74-1.00 \) and \( z = 1.00-1.45 \). Figure 6 shows that our average SFR values in each of the four stellar-mass bins are consistent with the star-forming main-sequence relations in the two redshift intervals.

7. The Average HI Mass and the Optimum Spatial Resolution

We used the procedure described in Section 5.1 to stack the 28,993 HI 21 cm subcubes of the 11,419 blue star-forming galaxies of our sample, at the nine different spatial resolutions (60, 70, 80, 90, 100, 110, 120, 150, and 200 kpc) at which we obtained HI 21 cm subcubes of the DEEP2 galaxies. For each resolution, the HI 21 cm stacking was carried out with identical weights assigned to each HI 21 cm subcube. Figure 7 shows the stacked HI 21 cm spectra of the 11,419 galaxies at the nine different spatial resolutions. We clearly detect the average HI 21 cm emission signal at all spatial resolutions, with \( \approx 4.2\sigma -7.4\sigma \) significance.

We integrated the detected HI 21 cm emission signals of Figure 7 over the velocity range \([-150, +210 \text{ km s}^{-1}]\) to infer the average HI mass of the DEEP2 galaxies, within the central spatial beam; these measurements are listed in Table 3. Figure 7 shows the average HI mass of the galaxies as a function of spatial resolution. The average HI mass is seen to increase from \( (10.0 \pm 1.5) \times 10^9 M_\odot \) at a resolution of 60 kpc to \( (15.4 \pm 3.7) \times 10^9 M_\odot \) at 200 kpc. Further, the increase in the average HI mass shows clear evidence of flattening at coarser resolutions (see Figure 8). Increasing the size of the spatial beam of the HI 21 cm subcubes comes at the cost of down-weighting the longer GMRT baselines, and consequently
raising the rms noise on the stacked spectrum. We find that the rms error on the stacked HI 21 cm cube increases approximately linearly with spatial resolution over $60 - 200$ kpc, with the S/N of the detections peaking at a resolution of $\approx 80$ kpc (see Table 3). The Astrophysical Journal, 937:103 (23pp), 2022 October 1 Chowdhury, Kanekar, & Chengalur

7.1. The Optimal Spatial Resolution

The choice of spatial resolution is important in terms of both accurately measuring the average HI mass of the DEEP2 galaxies and maximizing the S/N of the final HI 21 cm spectrum. As can be seen from Table 3 and Figure 8, using too narrow a spatial resolution resolves out some of the HI 21 cm emission signal, and results in underestimating the average HI mass. Conversely, using too coarse a spatial resolution would include all the HI 21 cm emission but at the cost of increasing the rms noise on the signal. Ideally, the spatial resolution would be matched to the spatial extent of the HI 21 cm emission. However, the spatial extent of the HI 21 cm emission from galaxies at $z \approx 1$ is not a priori known. We hence aimed to identify the optimal spatial resolution by measuring the average HI mass at different resolutions, and finding the resolution above which the measured average HI mass does not continue to increase.

An important subtlety in measuring the average HI mass at different spatial resolutions arises from the fact that the mass measurements are correlated, as a subset of the interferometer visibilities is common to the measurements. Thus, one cannot assume independent errors when taking the difference between the values of the average HI mass measured at different spatial resolutions. We hence measured the difference between the
average H\textsubscript{I} masses at each pair of spatial resolutions by stacking the difference of the H\textsubscript{I} 21 cm spectra at the location of each galaxy at the two resolutions. For example, to estimate the excess H\textsubscript{I} mass at 80 kpc resolution relative to 60 kpc resolution, we first subtracted the H\textsubscript{I} 21 cm spectrum of each individual subcube at 60 kpc resolution from that of the same subcube at 80 kpc resolution to obtain a difference spectrum for the subcube. We then stacked these difference spectra to measure the excess H\textsubscript{I} 21 cm emission signal. The error on the stacked difference spectrum for each pair of resolutions was obtained via the Monte Carlo approach described in Section 5.1. The above procedure was carried out for every pair of the spatial resolutions at which we obtained the H\textsubscript{I} 21 cm subcubes, i.e., every pair of 60, 70, 80, 90, 100, 110, 120, 150, and 200 kpc.

We find evidence at $\gtrsim 2.5 \sigma$ statistical significance for an increase in the average H\textsubscript{I} mass of our sample of 11,419 galaxies out to a resolution of 90 kpc. However, the difference between the average H\textsubscript{I} mass measured at a spatial resolution of 90 kpc and at any coarser resolution has $< 2 \sigma$ significance. In other words, the average H\textsubscript{I} mass of our galaxies, measured at a resolution of 90 kpc, is consistent, within statistical uncertainties, with that measured at coarser resolutions. We thus identify 90 kpc as the optimal spatial resolution for the H\textsubscript{I} 21 cm stacking.

Unless otherwise mentioned, all subsequent results of the H\textsubscript{I} 21 cm emission stacking of this survey are at a spatial resolution of 90 kpc.

8. The Average H\textsubscript{I} Properties of Star-forming Galaxies at $z \approx 1$

In this section, we present the main results of this study, from stacking the H\textsubscript{I} 21 cm line emission and the rest-frame 1.4 GHz continuum emission signals of the full sample of 11,419 blue star-forming galaxies. Possible systematic effects are considered in Section 10; we note here, in passing, that we find no evidence in Section 10 for systematic effects that might affect our results.

8.1. The Average H\textsubscript{I} Mass and the Average SFR of the Sample

The stacked H\textsubscript{I} 21 cm emission image and the stacked H\textsubscript{I} 21 cm spectrum of the 11,419 blue star-forming galaxies, obtained by stacking the 28,993 independent H\textsubscript{I} 21 cm subcubes at a spatial resolution of 90 kpc, are shown in Figure 9. A clear detection of the stacked H\textsubscript{I} 21 cm emission signal can be seen in both the stacked spectrum and the stacked H\textsubscript{I} 21 cm emission image. The velocity-integrated average H\textsubscript{I} 21 cm signal has $7.1 \sigma$ statistical significance. Integrating the stacked H\textsubscript{I} 21 cm spectrum over the velocity range $[-150, +210 \text{ km s}^{-1}]$, we find that the average velocity-integrated H\textsubscript{I} 21 cm line luminosity of the 11,419 galaxies at $\langle z \rangle = 1.04$ is $(7.33 \pm 1.03) \times 10^9$ Jy Mpc$^2$ km s$^{-1}$. This yields an average H\textsubscript{I} mass of $\langle M_{\text{HI}} \rangle = (1.37 \pm 0.19) \times 10^{10}$ $M_\odot$ for the blue star-forming galaxies at $\langle z \rangle = 1.04$. This is consistent with the earlier measurement of $\langle M_{\text{HI}} \rangle = (1.19 \pm 0.26) \times 10^{10}$ $M_\odot$ at $\langle z \rangle \approx 1.0$ by Chowdhury et al. (2020), from the 90 hr of observations in GMRT Cycle 35.

The average SFR of the 11,419 galaxies of our sample was determined from their stacked rest-frame 1.4 GHz continuum luminosities, following the procedures of Section 5.2. Figure 10(A) shows the image obtained by stacking the rest-frame 1.4 GHz luminosities of the 11,419 galaxies, while Figure 10(B) shows the stack at positions offset from the DEEP2 galaxies: a clear detection of the stacked 1.4 GHz continuum emission, at $\approx 67 \sigma$ significance, is visible in the left panel, while no systematic effects can be seen in the right panel. Using the SFR calibration of Yun et al. (2001), adjusted to a Chabrier IMF, the detection yields an average SFR of $(8.07 \pm 0.82) \ M_\odot \ yr^{-1}$ for the sample. The average properties of the blue, star-forming galaxies of our sample are summarized in Table 4.

The H\textsubscript{I} mass of blue galaxies in the local universe, with near-UV $r < 4$ and with a stellar-mass distribution identical to the 11,419 galaxies at $z \approx 1$, is $(3.96 \pm 0.17) \times 10^9$ $M_\odot$ (Catinella et al. 2018).\footnote{The errors on the average H\textsubscript{I} mass of the xGASS galaxies from Catinella et al. (2018) were computed using bootstrap resampling with replacement.} We emphasize that the average H\textsubscript{I} mass of the blue galaxies in the xGASS sample was computed with weights such that their effective stellar-mass distribution is identical to that of the 11,419 blue star-forming galaxies at $z = 0.74\text{--}1.45$. As can be seen in Figure 11(A), we find clear evidence, at $5.1 \sigma$ significance, for redshift evolution in the average H\textsubscript{I} mass of blue galaxies between $z \approx 1$ and $z \approx 0$. Specifically, we find...
that the blue star-forming galaxies at \( z \approx 1 \), i.e., at the end of the epoch of peak cosmic SFR density, have HI reservoirs that are larger by a factor of \((3.5 \pm 0.5)\) than those of blue galaxies with an identical stellar-mass distribution in the local universe.

8.2. The HI Depletion Timescale

The availability of neutral gas, the fuel for star formation, determines the time for which a galaxy can sustain its current SFR. The gas depletion timescale, defined as the ratio of the gas mass (HI or H\(_2\)) to the SFR, is an important metric to understand how long a galaxy can sustain its current SFR. We define the characteristic HI and H\(_2\) depletion timescales of the galaxies of a given sample as, respectively, \( \langle t_{\text{dep,HI}} \rangle \equiv \langle M_{\text{HI}} \rangle / \langle \text{SFR} \rangle \) and \( \langle t_{\text{dep,H}_2 \rangle} \equiv \langle M_{\text{H}_2} \rangle / \langle \text{SFR} \rangle \). In the local universe, blue galaxies with the same stellar-mass distribution as the 11,419 galaxies in our sample have \( \langle t_{\text{dep,HI}} \rangle = (4.5 \pm 0.2) \) Gyr (Catinella et al. 2018) and \( \langle t_{\text{dep,H}_2 \rangle} = (0.45 \pm 0.04) \) Gyr (Saintonge et al. 2017).\(^6\) The HI depletion timescale of galaxies with \( M_* \approx 10^{10} \) M\(_\odot\) in the local universe is thus much longer than

---

\(^6\) We have divided the molecular gas masses of Saintonge et al. (2017) by a factor of 1.36 to obtain the H\(_2\) masses of their galaxies. Further, we note that the characteristic gas depletion timescales in this paper are all calculated consistently by taking the ratio of the weighted-average gas mass to the weighted-average SFR of the sample, with weights such that the stellar-mass distribution of the sample is identical to that of Figure 5(B).
having identical stellar-mass distributions, with smaller than the characteristic HI depletion timescale of sustain their current SFR for a long timescale, the H2 depletion timescale. Local universe galaxies can thus Figure 11. Redshift evolution of (A) the average HI mass, \( \langle M_{\text{HI}} \rangle \), and (B) the characteristic HI depletion timescale, \( \langle t_{\text{dep},\text{HI}} \rangle \), for blue star-forming galaxies, having identical stellar-mass distributions, with \( \langle M_\ast \rangle \approx 10^{10} M_\odot \). In both panels, the blue circle shows the result from the xGASS survey of local universe galaxies (Catinella et al. 2018), while the red square shows the measurement at \( z \approx 1 \) from the current work.

| Parameter                          | Value          |
|------------------------------------|----------------|
| Number of Galaxies                 | 11,419         |
| Number of HI 21 cm subcubes        | 28,993         |
| Redshift range                     | 0.74–1.45      |
| Average redshift, \( \langle z \rangle \) | 1.04           |
| Stellar-mass range                 | \( 1.0 \times 10^{7.2} \times 10^{11} M_\odot \) |
| Average stellar mass, \( \langle M_\ast \rangle \) | \( 9.9 \times 10^8 M_\odot \) |
| Average radio-derived SFR          | \( 8.07 \pm 0.82 M_\odot \text{ yr}^{-1} \) |
| Average HI mass, \( \langle M_{\text{HI}} \rangle \) | \( (13.7 \pm 1.9) \times 10^9 M_\odot \) |
| HI depletion timescale, \( \langle t_{\text{dep},\text{HI}} \rangle \) | \( (1.70 \pm 0.29) \text{ Gyr} \)

Note. The rows are (1) the number of galaxies, (2) the number of independent HI 21 cm subcubes, (3) the redshift range of the galaxies, (4) their average redshift, \( \langle z \rangle \), (5) the stellar-mass range of the galaxies, (6) their average stellar mass, \( \langle M_\ast \rangle \), (7) the average SFR derived from the rest-frame average 1.4 GHz radio luminosity density, (8) the average HI mass, \( \langle M_{\text{HI}} \rangle \), and (9) the characteristic HI depletion timescale, \( \langle t_{\text{dep},\text{HI}} \rangle \equiv \langle M_{\text{HI}} \rangle / \langle \text{SFR} \rangle \). See main text for discussion.

the H2 depletion timescale. Local universe galaxies can thus sustain their current SFR for a long timescale, \( \langle t_{\text{dep},\text{HI}} \rangle \approx 4.5 \text{ Gyr} \), even without the accretion of fresh gas from the CGM or via mergers. In other words, the availability of HI is not a bottleneck in the star formation process in local universe galaxies.

For the DEEP2 galaxies, we combine the average HI mass of \( \langle M_{\text{HI}} \rangle = (13.7 \pm 1.9) \times 10^9 M_\odot \) with the average SFR of \( (8.07 \pm 0.82) M_\odot \text{ yr}^{-1} \) to obtain a characteristic HI depletion timescale of \( \langle t_{\text{dep},\text{HI}} \rangle = (1.70 \pm 0.29) \text{ Gyr} \), for blue star-forming galaxies with \( \langle M_\ast \rangle \approx 10^{10} M_\odot \) at \( \langle z \rangle = 1.04 \). Our measurement of \( \langle t_{\text{dep},\text{HI}} \rangle \) of blue galaxies at \( z \approx 1 \) is three times smaller than the characteristic HI depletion timescale of \( \langle t_{\text{dep},\text{HI}} \rangle \approx 4.5 \pm 0.2 \text{ Gyr} \) of blue galaxies with an identical stellar-mass distribution in the local universe (see Figure 11(B)). Further, the HI depletion timescale at \( z \approx 1 \) is only a factor of \( \approx 3 \) higher than the H2 depletion timescale of \( \approx 0.5 \text{ Gyr} \) in main-sequence galaxies at similar redshifts (Tacconi et al. 2013). Our results thus clearly establish, consistent with the findings of Chowdhury et al. (2020), that blue star-forming galaxies at the end of the epoch of peak cosmic SFR density can sustain their SFR for a short timescale, only \( \approx 1.5 \text{ Gyr} \), in the absence of gas accretion from the CGM. This supports the hypothesis that the accretion of gas from the CGM may have been insufficient to sustain the high SFR of galaxies at \( z \approx 1 \), causing the observed decline in the star formation activity of the universe at lower redshifts (Bera et al. 2018; Chowdhury et al. 2020, 2021). Further, using HI 21 cm data from the present GMRT-CATz1 survey, Chowdhury et al. (2022a) find direct evidence that the average HI mass of star-forming galaxies at \( z \approx 1 \) is a factor of \( \approx 3.2 \) lower than that of galaxies with the same stellar-mass distribution at \( z \approx 1.3 \), indicating that the accretion was insufficient to replenish the gas reservoirs of massive galaxies.

In passing, we note that there are a number of possible causes for the decline in the gas accretion onto massive galaxies at \( z \lesssim 1 \), including (1) a transition in the mode of accretion from cold mode at high redshifts to hot mode at \( z \lesssim 1 \), which would slow down the accretion process (e.g., Kereš et al. 2005; Dekel et al. 2009), (2) AGN or stellar feedback, especially in massive galaxies (e.g., Weiner et al. 2009; Steidel et al. 2010; Kakkad et al. 2020; Valentino et al. 2021), and (3) heating of the gas reservoir in the CGM (e.g., Schawinski et al. 2014). The current HI 21 cm (and ancillary) data on the DEEP2 fields do not allow us to distinguish between these (and other) possibilities. Further, it is also possible that environmental effects (e.g., Tal et al. 2014) might contribute to the decline in the star formation activity at \( z \lesssim 1 \). Deeper HI 21 cm data should allow us to separate the galaxies into isolated systems and groups, and enable us to study such environmental effects.

\footnote{We note that this is the H2 depletion timescale, after dividing the molecular gas depletion timescale by a factor of 1.36.}
9. The Average HI Mass of Red Galaxies and AGNs at $z \approx 1$

9.1. Red Galaxies

The DEEP2 survey targeted galaxies down to a limiting magnitude of $R_{AB} = 24.1$; this results in a bias against the red galaxies at $z > 0.7$, with the bias becoming stronger at higher redshifts (see Section 6; Willmer et al. 2006; Newman et al. 2013). Indeed, only $\approx 14\%$ of the DEEP2 galaxies at $z = 0.74 - 1.45$ that lie within our uGMRT pointings are part of the red cloud (see Section 6), and only $\approx 26\%$ of these are at $z > 1$. In order to ensure the homogeneity of our sample, we had excluded the red DEEP2 galaxies from our main sample of blue star-forming galaxies. Here, we examine the average HI mass and the average SFR of the red DEEP2 galaxies at $z = 0.74 - 1.45$, lying within our uGMRT pointings, and compare their average properties to those of the blue DEEP2 galaxies of our main sample.

Our GMRT observations cover the redshifted HI 21 cm line for 2222 red galaxies at $z = 0.74 - 1.45$. After excluding the galaxies hosting radio-bright AGNs (see Section 4.3) and galaxies whose HI 21 cm subcubes were affected by systematic effects (identified using the procedures of Section 4.5), our sample contains 4346 independent HI 21 cm subcubes of 1738 red galaxies at $z = 0.74 - 1.45$.

We stacked the 4346 HI 21 cm subcubes of the 1738 red galaxies at $z = 0.74 - 1.45$, following the procedures of Section 5.1. Figure 12(A) shows the stacked HI 21 cm emission signal of the 1738 red galaxies. We obtain a tentative detection, at $2.9\sigma$ statistical significance, of the average HI 21 cm emission from the 1738 red galaxies at $\langle z \rangle = 0.94$. Integrating the average HI 21 cm emission signal over the velocity range $[-150, +210 \, \text{km s}^{-1}]$ yields an average HI mass of $\langle M_{\text{HI}} \rangle = (12.4 \pm 4.2) \times 10^{10} M_\odot$. The average HI mass of the red galaxies is thus consistent with $\langle M_{\text{HI}} \rangle = (13.7 \pm 1.9) \times 10^{10} M_\odot$, the average HI mass of the 11,419 blue star-forming galaxies of our main sample (Section 8). However, we note that the average stellar mass of the 1738 red galaxies is $\langle M_* \rangle \approx 6 \times 10^{10} M_\odot$, far higher than the average stellar mass of the blue galaxies, $\langle M_* \rangle \approx 10^{10} M_\odot$. The ratio of the average HI mass to the average stellar mass, $\langle M_{\text{HI}} \rangle / \langle M_* \rangle = 0.21 \pm 0.07$, for the red galaxies is thus far lower than the same ratio, $\langle M_{\text{HI}} \rangle / \langle M_* \rangle = 1.38 \pm 0.19$, for the blue star-forming galaxies.

However, we note that both the stellar-mass and the redshift distributions of the samples of blue galaxies and red galaxies are different, with the red sample having both higher stellar masses and lower redshifts. Chowdhury et al. (2022a) find that the average HI properties of blue galaxies depend on both their average redshift and their average stellar mass; these dependences would affect the above comparisons between the red and blue galaxies. The differences in the redshift and the stellar-mass distributions of the two galaxy samples should be taken into account by using appropriate weights in future comparisons.

We estimate the average SFR of the 1738 red galaxies by median-stacking their rest-frame 1.4 GHz continuum luminosities, following the procedures of Section 5.2. Figure 12(B) shows the stacked rest-frame 1.4 GHz continuum emission of the red galaxies. We clearly detect the stacked 1.4 GHz continuum emission from the sample of red galaxies, at $\approx 25\sigma$ significance, obtaining an average SFR of $6.05 \pm 0.65 M_\odot \, \text{yr}^{-1}$. As noted above, the sample of red galaxies has a high average stellar mass, $\langle M_* \rangle \approx 6 \times 10^{10} M_\odot$; the average SFR of $6.05 \pm 0.65 M_\odot \, \text{yr}^{-1}$ for these galaxies is $\approx 4.5$ times lower than that of the main-sequence galaxies with $\langle M_* \rangle \approx 6 \times 10^{10} M_\odot$ at similar redshifts (Whitaker et al. 2014). Combining the average HI mass and the average SFR yields a characteristic HI depletion timescale of $\langle t_{\text{dep,HI}} \rangle = (2.03 \pm 0.73) \, \text{Gyr}$ for the red galaxies at $\langle z \rangle = 0.94$.

Overall, we find that the red galaxies in the DEEP2 survey are massive, but have an average SFR far lower than that of blue galaxies with similar stellar masses; this suggests that most of the red objects are not dusty star-forming galaxies. The red galaxies also have a lower ratio of the average HI mass to the average stellar mass than the 11,419 blue galaxies of our main sample, but also have a significantly higher stellar mass than the above blue galaxies.
9.2. Galaxies Hosting AGNs

The GMRT-CATAC survey covers the redshifted HI 21 cm line for 882 blue DEEP2 galaxies that were found to host an AGN with $L_{14 \text{ GHz}} > 2 \times 10^{33}$ W/Hz (see Section 4.3). We investigated the 2368 HI 21 cm subcubes of these 882 AGN-hosting galaxies for systematic issues, following the procedures described in Section 4.5. After excluding the HI 21 cm subcubes affected by discernible systematic effects, we stacked the 2087 HI 21 cm subcubes of the remaining 823 AGN-hosting galaxies. We do not detect the average HI 21 cm emission signal from this sample, obtaining a $3\sigma$ upper limit of $\langle M_{\text{HI}} \rangle < 24 \times 10^9 M_\odot$ on the average HI mass of the AGN-hosting galaxies, assuming an HI 21 cm line FWHM of 360 km s$^{-1}$. The upper limit on the HI mass of the AGN-hosting galaxies is consistent with the average HI mass of $\langle M_{\text{HI}} \rangle = (13.7 \pm 1.9) \times 10^9 M_\odot$ for our main sample of 11,419 blue star-forming galaxies with no AGNs.

Overall, we find no evidence for a high average HI mass in the galaxies of our sample that host AGNs. However, the number of such objects is more than an order of magnitude lower than the number of blue galaxies in our main sample, implying that we do not obtain tight constraints on the average HI mass of the AGN sample. Probing the influence of AGNs on the average HI properties of galaxies at $z \approx 1$ will require a larger AGN sample or significantly deeper observations.

10. Tests for Systematic Issues in the HI 21 cm Stacking

10.1. The Effect of the Dirty Beam

The stacked HI 21 cm emission image of Figure 9(A) is the average of the observed HI 21 cm emission images of the individual 11,419 galaxies. Further, the observed HI 21 cm emission image of each galaxy is a convolution of the true HI 21 cm emission image with the point-spread function (the dirty beam) of the GMRT observations of the galaxy. The stacked HI 21 cm emission image of Figure 9(A) thus contains the combined effect of the point-spread functions of the different observations. For normal HI images (i.e., without stacking), in the absence of deconvolution, the point-spread function would affect the noise properties of the image (yielding structures similar to those of the dirty beam). The fact that we are stacking HI 21 cm emission from different regions of the sky, with different dirty beams, implies that it is not straightforward to deconvolve the dirty beam from the stacked HI 21 cm emission image. However, the pattern of the average dirty beam is clearly visible on inspecting the stacked HI 21 cm emission image. To correct for this, we subtracted out the stacked dirty beam from the stacked HI 21 cm emission image; a similar deconvolution strategy was also used by Chen et al. (2021) in an HI 21 cm emission stacking experiment targeting galaxies at $z \approx 0$. We emphasize that the deconvolution of the dirty beam carried out here is an approximation, which is exact only for the case of identical HI masses of all the galaxies of the sample.

We obtain the stacked dirty beam by taking the average of the dirty beams of the independent HI 21 cm subcubes in the sample. Next, we scale the average dirty beam to the peak luminosity density of the stacked HI 21 cm emission image, and subtract out this scaled dirty beam from the stacked emission image to obtain the residual image. We then obtain the final restored HI 21 cm emission image by adding to the residual image a symmetric Gaussian having a FWHM of 90 kpc and the peak luminosity density of the original HI 21 cm emission image. Figure 13 shows the stacked dirty beam, the original HI 21 cm emission image (the dirty image), the residual HI 21 cm image, and the restored, stacked HI 21 cm emission image. A comparison between the original and restored HI 21 cm emission images in Figure 13 shows clearly that the subtraction of the stacked dirty beam from the stacked HI 21 cm image improves the noise properties of the image. Further, the residual map in Figure 13 shows no evidence for any extended emission at the location of the DEEP2 galaxies, consistent with the findings of Section 7 that the average HI 21 cm emission signal is unresolved at a spatial resolution of 90 kpc.

10.2. The rms Noise of the Stacked Spectra

The sensitivity of the stacking procedure critically depends on the noise properties of the individual HI 21 cm spectra that are stacked together. The spectral rms noise on the stacked HI 21 cm spectrum is expected to decrease with the number (N) of individual HI 21 cm spectra as $\text{rms} \propto N^{-0.5}$, for independent noise on the individual spectra. However, systematic issues in the data could introduce correlations between the individual spectra that may limit the sensitivity of the stacked spectrum. We tested for such issues in our sample of 28,993 HI 21 cm spectra by measuring the dependence of the rms noise on the stacked spectrum on the number of spectra that were stacked together.

This was done by randomly selecting $N$ spectra from our full sample of 28,993 HI 21 cm spectra, where $N = 100, 200, 400, 800, 1600, 3200, 6400, 12,800, \text{ and } 25,600$. For each $N$, we stacked the randomly selected HI 21 cm spectra to obtain a stacked spectrum, and then followed the Monte Carlo approach described earlier to estimate the rms noise on the stacked spectrum.

Figure 14 shows the rms noise obtained on the stacked HI 21 cm spectrum as a function of the number of stacked galaxies, $N$. It is clear from the figure that the rms noise measurements are consistent with the relation $\text{rms} \propto N^{-0.5}$. We thus find no evidence for systematic issues that might limit the sensitivity of our stacked HI 21 cm spectrum.

10.3. The Effect of Source Confusion

The stacked HI 21 cm emission signal can include, in addition to the HI 21 cm emission from our target galaxies, HI 21 cm emission from companion galaxies lying within the interferometer beam with HI 21 cm emission at the same velocities as the target galaxy. Chowdhury et al. (2020) used the S$^3$-SAX-Sky (Obreschkow et al. 2009) simulations to find that the effect of such “source confusion,” due to companion galaxies lying within their 60 kpc spatial resolution, on the stacked HI 21 cm emission of galaxies at $z \approx 1$ is small. We repeat the procedure of Chowdhury et al. (2020), but with a spatial resolution of 90 kpc, to find that the effect of source confusion on our measurement of the average HI mass is also expected to be small, with companion galaxies contributing $\lesssim 5\%$ to the observed average HI 21 cm emission signal.

We further probe the effect of source confusion on the measurement of the average HI mass of our sample galaxies, by identifying the target galaxies that have spectroscopically identified companion galaxies in the DEEP2 DR4 catalog (Newman et al. 2013), such that the companion galaxies might contribute to our measurement of the HI 21 cm emission from
the target galaxy. Our measurement of the average HI 21 cm emission is at a spatial resolution of 90 kpc, with the detected average HI 21 cm emission spanning $\approx \pm 180$ km $s^{-1}$ around the systemic velocity. We find that only 276 galaxies of the 11,419 galaxies in our main sample ($\approx 3\%$ of the sample) have spectroscopic companions in the DEEP2 DR4 catalog that lie within $\pm 45$ kpc and whose redshifts are within $\pm 200$ km $s^{-1}$ of the target galaxy; the HI 21 cm emission from these galaxies might be included in our measurement of the average HI 21 cm emission of the target galaxies. We exclude these 276 galaxies and stack the HI 21 cm subcubes of the remaining 11,143 galaxies. This yields an average HI mass for the 11,143 galaxies of $\langle M_{\text{HI}} \rangle = (1.40 \pm 0.20) \times 10^{10} M_\odot$. This is entirely consistent with the measured HI mass of the full sample, $\langle M_{\text{HI}} \rangle = (1.37 \pm 0.19) \times 10^{10} M_\odot$. We thus find no evidence that source confusion due to companion galaxies, identified in the DEEP2 spectroscopic catalog, might affect our measurement of the average HI mass of galaxies at $z \approx 1$.

The spectroscopic completeness of the DEEP2 survey is $\approx 50\%$ (Conroy et al. 2007). The analysis presented above would thus not account for any companion galaxies for which the DEEP2 survey failed to obtain a redshift measurement. We estimate here the effect of such companion galaxies, not included in the DEEP2 spectroscopic catalog, on our measurement of the average HI mass. We find that 1928 of the 11,419 galaxies in our sample have at least one object in the DEEP2 photometric catalog (Coil et al. 2004) that lies within $\pm 45$ kpc of the target galaxy and that meets the DEEP2 color and magnitude selection criteria for spectroscopic targets in Fields 2, 3, and 4 (Newman et al. 2013). Note that the redshift of the companion galaxies thus identified could be completely different from the redshift of the target galaxy. We exclude
Hi 21 cm subcubes used for the search had a spatial resolution of 90 kpc, the optimal resolution for the average HI 21 cm emission signal (see Section 7). The search for HI 21 cm emission was carried out after smoothing the subcubes, using a boxcar kernel, to ten different velocity resolutions ranging from 30 to 300 km s$^{-1}$, in steps of 30 km s$^{-1}$. The search was done at a range of velocity resolutions in order to maximize the sensitivity to HI 21 cm emission from galaxies at a range of inclinations. We searched for HI 21 cm emission, at $\geq 5 \sigma$ statistical significance, at the location of each DEEP2 galaxy and in the central $\pm 250$ km s$^{-1}$ around its redshifted HI 21 cm emission frequency. We did not detect any emission feature with $\geq 5 \sigma$ significance in the spectra of any of the 13,596 DEEP2 galaxies, at any of the ten velocity resolutions.

The 5$\sigma$ upper limits on the HI masses of the 13,596 galaxies, for an assumed typical HI 21 cm line FWHM of 300 km s$^{-1}$, are shown in Figure 15(A). We obtain a median 5$\sigma$ upper limit of $\approx 5 \times 10^{11} M_\odot$ for galaxies at $z \approx 0.74-1.0$, and $\approx (5-12) \times 10^{11} M_\odot$ for galaxies at $z \approx 1.0-1.45$. The corresponding upper limits on the HI fraction ($f_{\text{HI}}/f_*$) for each of the 13,596 galaxies are shown in Figure 15(B). Except for a few very massive galaxies, the upper limits on the HI fraction of the 13,596 galaxies are far higher than our measurement of the ratio of the average HI mass to the average stellar mass, $\langle f_{\text{HI}}/f_* \rangle = 1.38 \pm 0.19$, of the sample. Assuming that the galaxies are viewed close to face-on, with an HI 21 cm line FWHM of 60 km s$^{-1}$, yields a median 5$\sigma$ upper limit of $\approx 2.5 \times 10^{11} M_\odot$ for galaxies at $z \approx 0.74-1.0$, and $\approx (2.5-5) \times 10^{11} M_\odot$ for galaxies at $z \approx 1.0-1.45$. These 5$\sigma$ upper limits on the HI mass of the 13,596 galaxies are $\approx 10-100$ times higher than our measurement of the average HI mass of blue galaxies at $z \approx 1$ (see Section 8).

This allows us to rule out the presence of extremely large HI reservoirs, with $f_{\text{HI}} \gtrsim (3-25) \times 10^{11} M_\odot$, in any of the 13,596 DEEP2 galaxies at $z \approx 0.74-1.45$.

12. Summary

In this paper, we present the GMRT-CATz survey, a 510 hr GMRT HI 21 cm emission survey of galaxies at $z = 0.74-1.45$ in seven fields of the DEEP2 Galaxy Redshift Survey (Newman et al. 2013). We describe the GMRT observations, the data analysis, and the main results obtained from stacking the HI 21 cm emission signals of our full sample of blue star-forming galaxies. Additional key results of the survey, including the role of HI in the decline of star formation activity of the universe at $z \lesssim 1$, the contribution of HI to the baryonic mass of galaxies at $z \approx 1$, the dependence of the HI properties of star-forming galaxies at $z \approx 1$ on their stellar properties, and estimates of the cosmological HI mass density of the universe at $z \approx 1$, will be described in separate papers (e.g., Chowdhury et al. 2022a, 2022b). The following is a summary:

1. The GMRT observations cover the redshifted HI 21 cm line for 16,250 DEEP2 galaxies at $z = 0.74-1.45$, lying within the half-power point of our GMRT pointings. We excluded red galaxies, radio AGNs, galaxies with $M_\odot < 10^9 M_\odot$, and any HI 21 cm subcubes affected by discernible systematic issues to obtain our main sample of 11,419 blue star-forming galaxies with $M_\odot \geq 10^9 M_\odot$ at $z = 0.74-1.45$. The observations provide up to six figure...
independent HI 21 cm emission subcubes for each galaxy in the sample, yielding a total of 28,993 independent HI 21 cm subcubes for the 11,419 galaxies.

2. To identify the optimal spatial resolution for the stacking, we stacked the HI 21 cm spectra of the 11,419 blue star-forming galaxies at nine different spatial resolutions, 60, 70, 80, 90, 100, 110, 120, 150, and 200 kpc. We obtained clear detections of the average HI 21 cm signal at all nine resolutions, at $4.2\sigma$−$7.4\sigma$ statistical significance. We find that the average HI mass of the sample at a resolution of 90 kpc is consistent with that at all coarser spatial resolutions. This implies that 90 kpc is the optimal spatial resolution for the HI 21 cm stacking for our galaxy sample.

3. We stacked the HI 21 cm subcubes of the sample at a resolution of 90 kpc to obtain a clear detection, with $\approx 7.1\sigma$ statistical significance, of the stacked HI 21 cm emission signal. The detection yields an average HI mass of $\langle M_{\text{HI}} \rangle = (13.7 \pm 1.9) \times 10^9 M_\odot$ for blue star-forming galaxies with $\langle M_\ast \rangle \approx 10^{10} M_\odot$ at $\langle z \rangle = 1.04$.

4. We stacked subsamples of galaxies to find that the rms noise on the stacked HI 21 cm spectrum decreases with the number, $N$, of stacked spectra as $1/\sqrt{N}$, as expected if the spectra have uncorrelated Gaussian noise. We thus find no evidence for any systematic effects that might affect our final stacked HI 21 cm spectrum.

5. We investigated the effect of source confusion on our estimate of the average HI mass of the sample, by excluding all 1928 target galaxies with either spectroscopic or photometric companions, with magnitudes and colors that meet the DEEP2 selection criteria, and that lie within ±45 kpc of a target galaxy. We stacked the HI 21 cm spectra of the remaining 9491 galaxies, obtaining an average HI mass consistent with that of the average HI mass of the full sample of 11,419 galaxies. We thus find no evidence that the average HI mass estimate might be contaminated by source confusion. We further used the S3-SAX-Sky simulations (Obreschkow et al. 2009) to find that the effect of source confusion on our stacked HI 21 cm spectrum is expected to be $\lesssim 5\%$ at our spatial resolution of 90 kpc.

6. We estimated the average SFR of the galaxies of the sample from their average rest-frame 1.4 GHz luminosity, by carrying out a median stack of the rest-frame 1.4 GHz continuum emission. This yielded an average SFR of $(8.07 \pm 0.82) M_\odot$ yr$^{-1}$. We also stacked the rest-frame 1.4 GHz continuum emission in galaxy subsamples based on stellar mass and redshift, to find that the average stellar masses and the average SFRs of the galaxies in each subsample are consistent with their lying on the main sequence at their respective redshifts.

7. We find that the average HI mass of blue galaxies in the local universe, with stellar-mass distribution identical to that of our full sample of 11,419 blue star-forming DEEP2 galaxies, is $(3.96 \pm 0.17) \times 10^9 M_\odot$. We thus find clear evidence, at $\approx 5.1\sigma$ significance, that the average HI mass of blue galaxies has declined, by a factor of $(3.5 \pm 0.4)$, from $z \approx 1$ to $z \approx 0$.

8. We combine our measurements of the average HI mass and the average SFR of the 11,419 blue star-forming galaxies at $z \approx 1$ to infer a characteristic HI depletion timescale of $\langle t_{\text{dep,HI}} \rangle \equiv \langle M_{\text{HI}} \rangle / \langle \text{SFR} \rangle = (1.70 \pm 0.29)$ Gyr. This is significantly shorter than the characteristic HI depletion timescale of $4.5 \pm 0.2$ Gyr in blue galaxies with an identical stellar-mass distribution in the local universe. We thus confirm, at a high statistical significance, the result that the HI reservoir of star-forming galaxies at $z \approx 1$ can sustain their current SFRs for a short period of $\approx 1.7$ Gyr, in the absence of accretion of fresh atomic gas from the CGM or via minor mergers (Bera et al. 2018; Chowdhury et al. 2020, 2021).

9. We stacked the HI 21 cm spectra of the 1738 red galaxies at $z = 0.74$−1.45 to obtain a tentative $(2.9\sigma$ significance) detection of their average HI 21 cm emission signal. We obtain an average HI mass of $\langle M_{\text{HI}} \rangle = (12.4 \pm 4.2) \times 10^9 M_\odot$, consistent with the value of...
\( \langle M_{\text{HI}} \rangle = (13.7 \pm 1.9) \times 10^9 \, M_\odot \) for the blue star-forming galaxies. However, the red galaxies have an average stellar mass of \( 6 \times 10^{10} \, M_\odot \), far higher than the average stellar mass of \( 10^{10} \, M_\odot \) of the blue galaxies. The ratio of the average HI mass to average stellar mass of the red galaxies is \( \langle M_{\text{HI}} \rangle / \langle M_\star \rangle = 0.21 \pm 0.07 \), far lower than the value \( \langle M_{\text{HI}} \rangle / \langle M_\star \rangle = 1.38 \pm 0.19 \) of the blue galaxies. We also stacked the rest-frame 1.4 GHz luminosities of the 1738 red galaxies to estimate an average SFR of \( 6.05 \pm 0.65 \, M_\odot \, \text{yr}^{-1} \), \( \approx 4.5 \) times lower than that of main-sequence galaxies at \( z \approx 1 \) with \( M_\star \approx 6 \times 10^{10} \, M_\odot \). The low average SFR indicates that most of the red objects are unlikely to be dusty star-forming galaxies.

We thank the staff of the GMRT who have made these observations possible. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. N.K acknowledges support from the Department of Science and Technology via a Swarnajayanti Fellowship (DST/SJF/PSA-01/2012-13). All authors acknowledge the Department of Atomic Energy for funding support, under project 12-R&D-TFR-5.02-0700.

Software: CASA (McMullin et al. 2007), calR (Chowdhury 2021), AOFLAGGER (Offringa et al. 2012), numpy (Harris et al. 2020), astropy (Astropy Collaboration et al. 2013, 2018), matplotlib (Hunter 2007), scipy (Virtanen et al. 2020), numba (Lam et al. 2015), joblib (Joblib Development Team 2021).

Appendix

The rms Noise on the Individual HI 21 cm Spectra

The spectral rms noise values of the HI 21 cm subcubes in the different DEEP2 subfields are shown in Figures 16–18.

Figure 16. The spectral rms noise on the HI 21 cm subcubes of galaxies in DEEP2 subfields 21 and 22. Observations in different GMRT cycles (35, 37, and 38) are shown in separate panels, with the red dots indicating the spectral rms noise per 30 km s\(^{-1}\) channel for each galaxy as a function of observing frequency. The blue curve in each panel shows the theoretical rms noise for the amount of on-source time, taking into account the data that were excised, and also considering the spatial resolution of 90 kpc and velocity resolutions of 30–300 km s\(^{-1}\). We find no evidence for individual redshifted HI 21 cm emission from any of the DEEP2 galaxies, obtaining 5σ upper limits of \( \approx (3–25) \times 10^{11} \, M_\odot \) on the HI masses of individual galaxies.
Figure 17. The spectral rms noise on the HI 21 cm subcubes of galaxies in DEEP2 subfields 31, 32, and 33. See the caption of Figure 16 for details.
Figure 18. The spectral rms noise on the HI 21 cm subcubes of galaxies in DEEP2 subfields 41 and 42. See the caption of Figure 16 for details.

References

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Begum, A., Chengalur, J. N., Karachentsev, I. D., Sharina, M. E., & Kaisin, S. S. 2008, MNRAS, 386, 1667
Bera, A., Kanekar, N., Chengalur, J. N., & Bagla, J. S. 2019, ApJL, 882, L7
Bera, A., Kanekar, N., Weiner, B. J., Sethi, S., & Dwarakanath, K. S. 2018, ApJ, 865, 39
Bosma, A. 1981, AJ, 86, 1825
Briggs, D. S. 1995, AAS Meeting Abstracts, 187, 112.02
Broeils, A. H., & Rhee, M. H. 1997, A&A, 324, 877
Brown, T., Catinella, B., Cortese, L., et al. 2015, MNRAS, 452, 2479
Brown, T., Catinella, B., Cortese, L., et al. 2017, MNRAS, 466, 1275
Casertano, S., & van Gorkom, J. H. 1991, AJ, 101, 1231
Catinella, B., & Cortese, L. 2015, MNRAS, 446, 3526
Catinella, B., Saintonge, A., Janowiecki, S., et al. 2018, MNRAS, 476, 875
Cayatte, V., van Gorkom, J. H., Balkowski, C., & Kotanyi, C. 1990, AJ, 100, 604
Chen, Q., Meyer, M., Popping, A., et al. 2021, MNRAS, 508, 2758
Chengalur, J. N., Braun, R., & Wieringa, M. 2001, A&A, 372, 768
Chowdhury, A. 2021, calR: Robust Calibration in CASA, v3.3.1, Zenodo, doi:10.5281/zenodo.4723688
Chowdhury, A., Kanekar, N., & Chengalur, J. N. 2022a, ApJL, 935, L5
Chowdhury, A., Kanekar, N., Chengalur, J. N., Sethi, S., & Dwarakanath, K. S. 2020, Nat, 586, 369
Chowdhury, A., Kanekar, N., Das, B., Dwarakanath, K. S., & Sethi, S. 2021, ApJL, 913, L24
Chung, A., van Gorkom, J. H., Kenney, J. D. P., Crowl, H., & Vollmer, B. 2009, AJ, 138, 1741
Coil, A. L., Newman, J. A., Kaiser, N., et al. 2004, ApJ, 617, 765
Condon, J. J. 1992, ARA&A, 30, 575
Condon, J. J., Cotton, W. D., & Broderick, J. J. 2002, AJ, 124, 675
Conroy, C., Prada, F., Newman, J. A., et al. 2007, ApJ, 654, 153
Cornwell, T. J., Golap, K., & Bhatnagar, S. 2008, ISTSP, 2, 647
Davis, M., Guhathakurta, P., Konidaris, N. P., et al. 2007, ApJL, 660, L1
de Blok, W. J. G., Walter, F., Brinks, E., et al. 2008, AJ, 136, 2648
Dekel, A., Sari, R., & Ceverino, D. 2009, ApJ, 703, 785
Delhaize, J., Meyer, M. J., Staveley-Smith, L., & Boyle, B. J. 2013, MNRAS, 433, 1398
Driver, S. P., & Robotham, A. S. G. 2010, MNRAS, 407, 2131
Elson, E. C., Baker, A. J., & Blyth, S. L. 2019, MNRAS, 486, 4894
Fabello, S., Catinella, B., Giovanelli, R., et al. 2011, MNRAS, 411, 993
Fabello, S., Kauffmann, G., Catinella, B., et al. 2012, MNRAS, 427, 2841
Fernández, X., Gim, H. B., van Gorkom, J. H., et al. 2016, ApJL, 824, L1
Gogate, A. R., Verheijen, M. A. W., Deshev, B. Z., et al. 2020, MNRAS, 496, 3531
Gupta, Y., Ajithkumar, B., Kale, H. S., et al. 2017, CSci, 113, 707
Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Nature, 585, 357
Haynes, M. P., Giovanelli, R., Kent, B. R., et al. 2018, ApJL, 861, 49
Heald, G., Józsa, G., Serra, P., et al. 2011, A&A, 526, A118
Hibbard, J. E., van Gorkom, J. H., Rupen, M. P., & Schiminovich, D. 2001, in ASP Conf. Ser. 240, Gas and Galaxy Evolution, ed. J. E. Hibbard, M. Rupen, & J. H. van Gorkom (San Francisco, CA: ASP), 657
Hu, W., Catinella, B., Cortese, L., et al. 2020, MNRAS, 493, 1587
Hunter, D. A., Ficut-Vicas, D., Ashley, T., et al. 2012, AJ, 144, 134
Hunter, J. D. 2007, CSE, 9, 90
Jaffé, Y. L., Poggianti, B. M., Verheijen, M. A. W., Deshev, B. Z., & van Gorkom, J. H. 2013, MNRAS, 431, 2111
Joblib Development Team 2021, Joblib: running Python functions as pipeline jobs, https://joblib.readthedocs.io/
Jones, M. G., Haynes, M. P., Giovanelli, R., & Moorman, C. 2018, MNRAS, 477, 2
Kakkad, D., Mainieri, V., Vietri, G., et al. 2020, A&A, 642, A147
Kanekar, N., Sethi, S., & Dwarakanath, K. S. 2016, ApJL, 818, L28
Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, MNRAS, 363, 2
Lab, P., Chengalur, J. N., Briggs, F. H., et al. 2007, MNRAS, 376, 1357
Lab, P., Pracy, M. B., Chengalur, J. N., et al. 2009, MNRAS, 399, 1447
