SMALL-SCALE PROPERTIES OF ATOMIC GAS IN EXTENDED DISKS OF GALAXIES

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ABSTRACT

We present high-resolution H i 21 cm observations with the Karl G. Jansky Very Large Array for three H i rich galaxies in absorption against radio quasars. Our sample contains six sightlines with impact parameters from 2.6 to 32.4 kpc. We detected a narrow H i absorber of FWHM 1.1 km s$^{-1}$ at 444.5 km s$^{-1}$ toward SDSS J122106.854+454852.16 probing the dwarf galaxy UCG 7408 at an impact parameter of 2.8 kpc. The absorption feature was barely resolved and its width corresponds to a maximum kinetic temperature, $T_k \approx 26$ K. We estimate a limiting peak optical depth of 1.37 and a column density of $6 \times 10^{19}$ cm$^{-2}$. The physical extent of the absorber is 0.04 kpc and covers $\sim$25%–30% of the background source. A comparison between the emission and absorption strengths suggests the cold-to-total H i column density in the absorber is $\sim$30%. Folding in the covering fraction, the cold-to-total H i mass is $\sim$10%. This suggest that condensation of warm H i ($T_s \sim 1000$ K) to cold phase ($T_s < 100$ K) is suppressed in UGC 7408. The unusually low temperature of the H i absorber also indicates inefficiency in condensation of atomic gas into molecular gas. The suppression in condensation is likely to be the result of low metal content in this galaxy. The same process might explain the low efficiency of star formation in dwarf galaxies despite their huge gas reservoirs. We report the non-detection of H i in absorption in five other sightlines. This indicates that either the cold gas distribution is highly patchy or the gas is much warmer ($T_s > 1000$ K) toward these sightlines.

Key words: galaxies: dwarf – galaxies: ISM – ISM: abundances – ISM: structure – quasars: absorption lines – radio lines: ISM – ultraviolet: ISM

Online-only material: color figures

1. INTRODUCTION

The accretion and subsequent condensation of inflowing ionized gas, with temperatures of $10^4$–$10^5$ K, from the intergalactic medium and circumgalactic medium (CGM) into the interstellar medium (ISM) of galaxies, with temperatures of $10^4$–$10^5$ K, is a crucial aspect of the baryon cycle. While our theoretical understanding of gas inflow into galactic halos has progressed considerably in the last couple of decades (including work by Birnboim & Dekel 2003; Maller & Bullock 2004; Kereš et al. 2005; Ford et al. 2014), the processes that enable the gas to actually condense and achieve physical conditions where stars can form are not yet well understood. On the observational front, several studies have confirmed the presence of vast reservoirs of cool gas ($10^{4}$ $M_\odot$ of gas at $10^{4}$–$5$ K; Werk et al. 2014) and metals (Wakker & Savage 2009; Prochaska et al. 2011; Tumlinson et al. 2011; Borthakur et al. 2013; Bordoloi et al. 2014) in the CGM of galaxies of all types. Several studies have found correlations between the kinematics of cooler and hotter CGM gas phases (Tripp et al. 2008, 2011; Meiring et al. 2013). Similarly, evidence of extended cool rotating disks has been seen using probes such as Mg ii absorbers (Steidel et al. 2002; Kacprzak et al. 2010).

Where does the infalling/circumgalactic gas condense into ISM? How is that process regulated? And what do the properties of neutral gas in extended disks or extraplanar gas teach us about this process? In order to answer these questions and to understand the connection between the process of condensation and the properties of the ISM, detailed surveys of cold gas properties in the outer disks of galaxies are needed. For this purpose, H i 21 cm absorbers have been used by multiple teams to study properties of cold gas over a wide range of redshifts (e.g., Kanekar & Chengalur 1997; Lane & Briggs 2001; Vermeulen et al. 2003; Darling et al. 2004; Keeney et al. 2005; Gupta et al. 2007, 2009, 2010, 2013; Borthakur et al. 2010, 2011; Srianand et al. 2013, and references therein).

In the last 5 yr two low-$z$ surveys by Gupta et al. (2010) and Borthakur et al. (2011, 2011 hereafter) attempted a census of cold gas detection rate as a function of impact parameter from the host galaxy. These studies used radio-bright quasars to probe low-$z$ galaxies at impact parameters ranging from 11 to 53 kpc and 2 to 100 kpc, respectively. Due to the rarity of small impact parameter quasar–galaxy pairs, the sample included a wide variety of galaxies with majority of them being sub-L*$$. Despite the inhomogeneity in their galaxy properties, the two studies have provided independent estimations of the covering fraction of cold gas to be $\approx$50% within $\sim$20 kpc. The detection of cold gas beyond that distance is exceedingly rare. However, it is worth noting that these surveys sparsely sampled the impact parameter range and did not take into account the effects of galaxy orientation. On the other hand, the number density and cross-section of damped Ly$\alpha$ (DLA; i.e., absorbers with $N$(H i) $\geq 2 \times 10^{20}$ cm$^{-2}$) systems suggests a covering fraction of H i to be around 50% within 20 kpc of a galaxy (see Section 4.1 in B11; Section 6.1 in Schaye et al. 2007). Interestingly, the Milky Way’s atomic gas disk with H i column densities
Figure 1. GBT H\textsubscript{i} spectra toward background quasars probing three foreground galaxies from the survey by B11. The GBT beam covered the quasar sightline along with the foreground galaxy. The spectra show strong H\textsubscript{i} emission features believed to be associated with the ISM of the foreground galaxy. The spectra toward quasar J122106+454852 probing galaxy UGC 7408 show the data at original resolution. The spectra toward the other two sightlines probing galaxies J141629+372120 (labeled as J141629) and J160659+271642 (labeled as J160659) are smoothed by 30 pixels (\(\equiv 10.6 \text{ km s}^{-1}\)) to increase signal-to-noise ratio. No clear indication of 21 cm H\textsubscript{i} absorption were seen in the raw or the smoothed data. The large GBT beam of FWHM 9.1 makes it impossible to interpret the physical significance of the non-detections of H\textsubscript{i} absorption toward these quasar sightlines. One explanation could be that there is an absence of gas in the region probed by the sightlines. However, it is also possible that 21 cm absorption produced toward the quasar sightlines is being filled in by H\textsubscript{i} emission associated with gas elsewhere in the galaxies. Higher spatial resolution is warranted to distinguish between the two possible scenarios, thus our motivation for obtaining higher spatial resolution VLA observations.

2. OBSERVATION

2.1. Targets

2.1.1. Targets for High Spatial Resolution 21 cm H\textsubscript{i} Imaging with the VLA

We carried out follow-up VLA observations of three galaxies with radio-bright background sources. Properties of the target galaxies such as their redshifts, stellar and H\textsubscript{i} masses, central metallicities, H\textsubscript{i} velocity centroids, and widths are provided in Table 1. The GBT spectrum of the three galaxies obtained by B11 shows strong H\textsubscript{i} emission. The measured H\textsubscript{i} masses indicate that these galaxies have more H\textsubscript{i} than stars. Based on the H\textsubscript{i} mass to disk size relationship derived by Swaters et al. (2002), these galaxies are expected to have extended H\textsubscript{i} disks well beyond their optical disks.

These three galaxies are probed by six sightlines corresponding to six radio-bright background sources. Information on each of the sightlines including their IDs from the study by B11, position of the background radio sources, their 20 cm fluxes, and impact parameters is provided in Table 2. Three of the sightlines are QSOs with optical spectroscopic data from the Sloan Digital
Table 1

| Foreground Galaxy | Redshift | Stellar Mass \( (\log M_\odot) \) | Metallicity\(^a\) \( (12+\log(O/H)) \) | H\(_i\) Mass \( (\log M_\odot) \) | \( v_{\text{HI peak}} \)\(b\) (\( \text{km s}^{-1} \)) | \( \Delta v_{\text{HI}} \)\(c\) (\( \text{km s}^{-1} \)) |
|------------------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| J122115.22+454843.2\(^d\) | 0.0015 | 7.4 | 8.3\(^e\) | 8.3 | 460 | 417–507 |
| J141629.25+372120.4 | 0.0341 | 9.3 | 8.6 | 9.4 | 10235 | 10070–10300 |
| J160659.13+271642.6 | 0.0462 | 9.3 | 8.4 | 9.9 | 13860 | 13500–14030 |

Notes.
\( ^a\) Metallicity based on N\(_2\) index (Pettini & Pagel 2004). The metallicity was measured from emission lines from the central region of the galaxy and may be considered as the upper limit for the gas probed by the quasar sightlines.
\( ^b\) Velocity corresponding to the peak of the H\(_i\) profile.
\( ^c\) Velocity width (full) of the emission profile.
\( ^d\) Also known as UGC 7408.
\( ^e\) Based on values published by Kennicutt et al. (2008).

Table 2

| No. B11 | No.\(^a\) | Foreground Galaxy | Redshift | Background Radio Source | S\(_{\text{FIRST}}\)\(b\) (mJy) | \( \rho \) (kpc) | \( \Sigma_{\text{sfr}} \)\(c\) (M\(_\odot\) yr\(^{-1}\) kpc\(^{-2}\)) |
|---------|--------|------------------|----------|-------------------------|-----------------|------------|-----------------|
| 1 | 12 | J122115.22+454843.2\(^d\) | 0.0015 | 122105.480+454838.80 | 122105.480+454838.80 | 53.69 | 3.3 |
| 2 | 13 | " " | " " | 122106.854+454852.16 | 122106.854+454852.16 | 21.46 | 2.8 |
| 3 | 14 | " " | " " | 122107.811+454908.02 | 122107.811+454908.02 | 12.82 | 2.6 |
| 4 | 21 | J141629.25+372120.4 | 0.0341 | 141631.039+372203.01 | 141631.039+372203.01 | 30.71 | 32.4 |
| 5 | 22 | " " | " " | 141630.672+372137.09 | 141630.672+372137.09 | 30.53 | 16.2 |
| 6 | 23 | J160659.13+271642.6 | 0.0462 | 160658.315+271705.86 | 160658.315+271705.86 | 141.01 | 23.3 |

Notes.
\( ^a\) Sightline ID from Borthakur et al. (2011).
\( ^b\) Flux density from the VLA Faint Images of the Radio Sky at Twenty Centimeters Survey (Becker et al. 1995).
\( ^c\) SFR estimated from H\(_\alpha\) emission toward the optical QSO using SDSS3 spectra.
\( ^d\) Also known as UGC 7408.

Table 3

| Field | Duration (hr) | Bandwidth (MHz) | Bandwidth (km s\(^{-1}\)) | Channel Width (arcsec \( \times \) arcsec) | Beam Size\(a\) (arcsec \( \times \) arcsec) | \( \sigma_{\text{channel}} \) (mJy beam\(^{-1}\)) | \( \sigma_{\text{cont爝up}} \) (mJy beam\(^{-1}\)) |
|-------|--------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| J122115.22+454843.2\(^e\) | 2.0 | 1.0 | 211 | 0.8 | 7.45 \( \times \) 5.58 | 3.96 | 0.292 |
| J141629.25+372120.4 | 8.0 | 2.0 | 436 | 1.7 | 7.13 \( \times \) 5.22 | 1.0 | 0.078 |
| J160659.13+271642.6 | 8.0 | 4.0 | 883 | 3.4 | 8.35 \( \times \) 5.94 | 0.9 | 0.102 |

Notes.
\( ^a\) Reported for the line image. The variation in beam size between continuum and the line image is less than 10%.
\( ^b\) Average of all channels.

Sky Survey (SDSS). The non-detection of any H\(_\alpha\) in emission at the redshift of the foreground galaxy in the QSO spectra provides us with an upper limit on the star formation rate (SFR) surface density (\( \Sigma_{\text{sfr}} \)). Since all the galaxies were found to have strong 21 cm H\(_i\) emission in the GBT spectra, it is impossible to rule out absorption being filled in by emission from a different spatial location. Hence, we carried out high spatial resolution VLA observations to confirm the non-detections at the location of the background radio sources. The VLA in B-configuration is most appropriate for such a study as the size of the synthesized beam (\( \sim 8'' \times 6'' \)) matches the extent of the background continuum sources and is hence most conducive to detecting absorption features. For example, the spatial resolution achieved in our imaging (Column 6 of Table 3) is better than that prescribed by Dickey et al. (2000, resolution of \( <10'' \)) for extragalactic sources.

2.1.2. Targets for Follow-up Ultraviolet Spectroscopy with the HST

We obtained UV spectra for two of the QSO sightlines from our original sample that had confirmed 21 cm absorbers. The purpose of these observations was to detect and measure the Ly\(_\alpha\) (\( \lambda 1215.670 \)) transition associated with the 21 cm absorbers and hence provide a measure of the H\(_i\) column density independent of any assumption regarding the spin temperature of the gas. The combination of H\(_i\) absorption properties from the 21 cm hyperfine transition and the Ly\(_\alpha\) transition can be used to measure the column density and spin temperature of the absorber simultaneously. The QSOs were observed with the Cosmic Origins Spectrograph (COS) aboard the HST under programs 12467 and 12486. One of the sightlines, SDSS J122115.22+454843.2, is the optical/UV counterpart of the radio sightline #2 (see Table 1). The other sightline is toward SDSS J104257.58+074850.5, probing galaxy GQ1042+0747 at an impact parameter of 1.7 kpc (Borthakur...
et al. 2010). The setups for the HST observations are presented in Table 4.

Unfortunately, the COS spectra for both the targets had insufficient flux at the rest-frame wavelength of Lyα for the targeted galaxies. As a result no measurements could be made. The drop in UV flux of the QSOs is consistent with the presence of Lyman limit systems at higher redshift toward these sightlines that have consumed most of the flux at shorter wavelengths. Therefore, for the remainder of the paper, we concentrate on the analysis and results from the 21 cm follow-up observations.

### 2.2. Data Acquisition and Analysis

#### 2.2.1. Very Large Array Observations

We carried out a total of 18 hr of observations with the VLA in B-configuration under program 10C-120. We observed the field toward SDSS J122115.22+454843.2 (UCG 7408 hereafter) for 2 hr and the fields toward SDSS J141629.25+372120.4 (J141629 hereafter) and SDSS J160659.13+271642.6 (J160659 hereafter) for 8 hr each. The observations were carried out in dual polarization mode with a bandwidth of 1, 2, and 4 MHz, respectively. This setup was chosen to yield velocity coverage of 211, 436, and 883 km s\(^{-1}\) respectively. WIDAR, the correlator, was set up to deliver 256 spectral channels for each of the used bandwidths, resulting in a velocity width of 330 km s\(^{-1}\) and a channel width of 2.6 km s\(^{-1}\), respectively. The data were reduced and calibrated following the standard calibration and imaging procedures using NRAO’s Astronomical Image Processing Software. The spatial resolution achieved with uniform weighting of the data is 52.17×38.11, which is not enough to resolve the background radio source into three individual sources. And hence, detailed spatial information on the associated H\(\text{I}\) absorption could not be made with these data, thus requiring the need for higher spatial and spectral resolution B-configuration data.

#### 2.2.2. Archival Very Large Array Data

We also present existing VLA D-configuration data that were obtained under legacy ID AY190 and were first published by B11. The data were obtained in 2008 in dual polarization mode with a bandwidth of 1.5 MHz and 128 spectral channels using the old VLA correlator. These correspond to a velocity coverage of 330 km s\(^{-1}\) and a channel width of 2.6 km s\(^{-1}\), respectively. The data were reduced and calibrated following the standard calibration and imaging procedures using NRAO’s Astronomical Image Processing Software. The spatial resolution achieved with uniform weighting of the data is 52.17×38.11, which is not enough to resolve the background radio source into three individual sources. And hence, detailed spatial information on the associated H\(\text{I}\) absorption could not be made with these data, thus requiring the need for higher spatial and spectral resolution B-configuration data.

### 3. RESULTS AND DISCUSSION

In this section we present the continuum images and H\(\text{I}\) spectra from our VLA observations. The left panels of Figures 2–4 show 21 cm radio continuum images overlaid as red contours on the SDSS r-band images in grayscale. The flux density measured for each of the background radio sources (continuum) is provided in Column 4 of Table 5. Figure 2 also shows the VLA D-configuration H\(\text{I}\) emission map overlaid as yellow contours (first published by B11). Spectra extracted from each of the sightlines are shown in black on the right panels. The standard deviation in flux density per channel is plotted in green. The errors are plotted in negative units (i.e., \(-\sigma\)) for easy visual identification of significant absorption features.

### 3.1. Cold Gas in UGC 7408

We detected a narrow absorption feature associated with UGC 7408 in our VLA B-configuration spectra toward sightline #2. The absorption feature peaks at a velocity of 444.5 km s\(^{-1}\) and was measured to have an FWHM of 1.1 km s\(^{-1}\). The width of the feature is comparable with our spectral resolution. No

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### Table 4

**HST Cosmic Origins Spectrograph Follow-up Observations of UV-bright Background QSOs**

| Field          | Program ID | Grating\(^a\) | Exposure (s) |
|----------------|------------|----------------|--------------|
| J104257.58+074850.5 | 12467      | G140L         | 2221         |
| J122115.22+454843.2 | 12486      | G130M         | 8085         |

**Notes.**
- \(^a\) The far-ultraviolet detector of the COS is sensitive to wavelengths between 900 and 2150 Å and has medium-resolution (R \(\sim\) 20,000) and low-resolution (R \(\sim\) 3000) gratings.

### Table 5

**Optical Depth and Column Density Measurements**

| No. | Background Radio Source | \(\rho\) (kpc) | \(S_{1.4\text{GHz}}\) (mJy) | \(\sigma_{4\text{km}\cdot s^{-1}}\) (mJy) | Abs Strength (mJy) | \(\tau_{3\sigma}\) | \(N(\text{H}_1)_{3\sigma}\) \(\times 10^{19} \text{cm}^{-2}\) |
|-----|-------------------------|---------------|-----------------|----------------|-----------------|-------------|-----------------|
| 1   | 122105.480+454838.80    | 3.3           | 65.18           | 1.42           | <4.26          | <0.07       | <2.55           |
| 2   | 122106.854+454852.16\(^b\) | 2.8         | 24.72           | 1.42           | …              | …           | …               |
| 3   | 122107.811+454908.02    | 2.6           | 13.44           | 1.42           | <4.26          | <0.39       | <14.22          |
| 4   | 122106.854+454852.16\(^b\) | 2.8         | 13.98           | …              | 10.41\(^c\)   | 1.39\(^c\) | 6.47            |
| 5   | 122107.811+454908.02    | 2.6           | 13.44           | 1.42           | <4.26          | <0.39       | <14.22          |
| 6   | 122107.811+454908.02    | 2.6           | 13.44           | 1.42           | <4.26          | <0.39       | <14.22          |

**Notes.**
- \(^a\) Assuming a line width of 4 km s\(^{-1}\), a spin temperature \(T_s = 50\) K, and a covering fraction, \(f = 1\).
- \(^b\) Region where the absorption was detected (see Figure 2 for details).
- \(^c\) At the intrinsic resolution of the data (channel width of \(0.84\) km s\(^{-1}\)).
significant absorption features were seen toward sightlines #1 and #3. Previously, B11 had found an H\textsubscript{i} absorption feature associated with UGC 7408 toward the background quasar encompassing sightlines #1–3. The absorption was found as dip on an otherwise Gaussian emission profile. The VLA D-configuration spectrum extracted from a region the size of the synthesized beam centered at the quasar is shown in Figure 5. B11 concluded that the atomic gas that filled in the beam contributed to the broad Gaussian emission feature, whereas the gas toward the quasar sightline, covering a small fraction of the D-configuration beam, produced the superimposed absorption. By subtracting the emission, as modeled by a Gaussian profile, these authors found the absorption feature to have an FWHM of 4.75 km s\textsuperscript{-1}, as measured from the assumed Gaussian model. Therefore, the D-configuration data are consistent with lower spectral resolution observations of an intrinsically narrow and deep absorption feature such as the one detected in B-configuration. While the two detections are consistent, the narrowness of the absorber clearly demonstrates the need for higher spectral resolution to obtain precise constraints on the physical conditions and kinematics of 21 cm absorbers.

Similar narrow H\textsubscript{i} features have been detected in absorption in the Large Magellanic Cloud (LMC; 1.4 km s\textsuperscript{-1} by Dickey et al. 1994), and Small Magellanic Cloud (SMC; 1.2 km s\textsuperscript{-1} by Dickey et al. 2000). However, unlike emission, H\textsubscript{i} absorption can only be measured in absorption surveys, owing to their low spectral resolution, detected only absorbers with large widths. Therefore, it is possible that these studies might have missed absorbers such as this.

3.1.1. Covering Fraction of Cold Gas in UGC 7408

We present the H\textsubscript{i} map from the channel corresponding to the velocity of the absorption feature (444.5 km s\textsuperscript{-1}) seen toward sightline #2 in Figure 6. The background radio source is shown in black contours. The map is color coded to show absorption in blue, noise (±1σ) in green, and emission in yellow/red. However, unlike emission, H\textsubscript{i} absorption can only be measured in the region covered by the background radio source.

Absorption associated with sightline #2 can be seen in blue in Figure 6, covering the northeast quadrant of the background source. The physical size (area) of the H\textsubscript{i} cloud responsible for the absorption is ~0.04 kpc\textsuperscript{2}. The implied covering fraction, f, of the background source by the cloud is ~25%–30%.
Figure 3. Left: SDSS $r$-band image of SDSS J141629.25+372120.4 in grayscale overlaid with contours of VLA B-configuration continuum map shown in red. The target galaxy, J141629, is marked with a dashed rectangle in white and the sightlines are labeled. The red contours are at flux density levels of 5, 10, 15, and 20 mJy beam$^{-1}$. The beam is shown at the bottom right corner in red and the physical scale at the rest frame of the target galaxy is shown on the top right-hand corner. Right: spectra extracted at the position of the background sources (sightlines #4 and 5) are presented. The standard deviation in flux density ($-1\sigma$) in each of the channel maps are plotted in green. We do not see any absorption feature at strength $3\sigma$ or higher for both the sightlines.

(A color version of this figure is available in the online journal.)

Figure 4. Left: SDSS $r$-band image of SDSS J160659.13+271642.6 in grayscale overlaid with contours of VLA B-configuration continuum map shown in red. The target galaxy, J160659, is marked with a dashed rectangle in white and the sightlines are labeled. The red contours are at flux density levels of 50, 100, 150, and 170 mJy beam$^{-1}$. The VLA beam is shown at the bottom right corner in red and the physical scale at the rest frame of the target galaxy is shown on the top right-hand corner. Right: spectrum extracted at the position of the background sources (sightline #6) is presented. The standard deviation in flux density ($-1\sigma$) in the channel maps is plotted in green. We do not see any absorption feature at strengths $3\sigma$ or higher toward this sightline. This being the background source with the largest integrated flux among the six sightlines discussed in this paper, we estimate the most stringent optical depth limit of $\tau_{6} \leq 0.03$ for this target.

(A color version of this figure is available in the online journal.)
and the flux density of the background source at the same region is 13.98 mJy. The absorption feature is unresolved and the limiting FWHM was measured to be

\[ \sigma_{\text{pixel}} = 1.1 \text{ km s}^{-1} \]

The data show a Gaussian H\textsc{i} emission feature with an absorption feature (FWHM = 4.75 km s\textsuperscript{-1}) superimposed at the peak of emission. B11 concluded that the broad Gaussian emission feature was produced by the atomic gas that filled in the beam, whereas the gas toward the quasar sightline, covering only a small fraction of the beam, produced the superimposed absorption.

(A color version of this figure is available in the online journal.)

3.1.2. Physical Properties of the H\textsc{i} Absorber

A spectrum extracted from the position of the absorber (identified as a white oval of same size as the beam) is shown on the right. We measured the peak depth in flux density for the feature to be 10.41 mJy. For comparison, we also present in Figure 6 the D-configuration absorption spectrum that was obtained by subtracting the H\textsc{i} emission model from the spectrum in Figure 5. The region of the galaxy from which the D-configuration spectrum was extracted is shown as the white dashed rectangle on the image in the left panel of Figure 6. As noted earlier, the absorption feature seen in the B-configuration data is deeper and narrower than that seen in the VLA D-configuration data. The B-configuration data have higher spectral and spatial resolution; however, they have lower signal-to-noise ratio than the D-configuration data. Nevertheless, the feature was confirmed at >5\sigma at that channel or at >3\sigma average, the average noise over all channel.

From our B-configuration data, we estimated the peak optical depth of this absorber to 1.37 using the following relation:

\[ \tau = -\ln \left( \frac{I_o - I_{abs}}{I_o} \right) , \]  

where \( I_o \) is the flux density of the background quasar at the position of the absorber of 13.98 mJy and \( I_{abs} \) is the peak strength of the absorption feature of 10.41 mJy (see Figure 6, left panel). If we assume the width of the line is due to collisional excitation of the hydrogen atoms, we can relate the kinetic temperature of the gas to the width of the line as

\[ T_k \leq 21.855 (\Delta \nu)^2 \]

where \( \Delta \nu \) is the FWHM of the line in km s\textsuperscript{-1}. In this case, \( \Delta \nu = 1.1 \text{ km s}^{-1} \) and implies a kinetic temperature, \( T_k \leq 26.4 \text{ K} \). This indicates that the temperature of this absorber is similar to that observed in cold neutral medium (CNM) of the LMC and SMC (Dickey et al. 1994, 2000).

Assuming the kinetic temperature as a proxy for spin temperature (i.e., \( T_k = T_s = 26.4 \text{ K} \)), we estimate the column density

Figure 5. VLA D-configuration H\textsc{i} spectrum extracted from a region the size of the synthesized beam centered at the quasar (first published by B11). The data show a Gaussian H\textsc{i} emission feature with an absorption feature (FWHM = 4.75 km s\textsuperscript{-1}) superimposed at the peak of emission. B11 concluded that the broad Gaussian emission feature was produced by the atomic gas that filled in the beam, whereas the gas toward the quasar sightline, covering only a small fraction of the beam, produced the superimposed absorption.

(A color version of this figure is available in the online journal.)

Figure 6. Left: 21 cm H\textsc{i} absorption map of UCG 7408 corresponding to the channel at velocity, \( v = 444.5 \text{ km s}^{-1} \). The colors show the observed flux densities such that blue represents pixels with negative flux density, i.e., absorption, yellow/red represents pixels with positive flux density, i.e., emission, and green indicate pixels within the observed noise (±1\sigma) in the data. The background source is shown in black contours at flux density levels of 5, 10, 20, 30, 40, and 50 mJy beam\textsuperscript{-1}. It is worth noting that we are sensitive to absorption only against the background radio source. However, we are sensitive to emission in the entire region. The synthesized beam size (=230 pc × 173 pc in physical units) is shown in the lower left-hand corner. The red contours show the VLA D-configuration H\textsc{i} emission map with contour levels indicating 14.4, 21.7, and 28.9 × 10\textsuperscript{19} cm\textsuperscript{-2}. Spectra extracted from the regions marked in white are shown in the right panel. Right: VLA B-configuration H\textsc{i} spectrum extracted from the region marked in the white oval, the size of the beam, is shown in the top panel in black. The absorption has a peak depth of 10.41 mJy and the flux density of the background source at the same region is 13.98 mJy. The absorption feature is unresolved and the limiting FWHM was measured to be 1.1 km s\textsuperscript{-1}. This corresponds to a kinetic temperature, \( T_k \leq 26 \text{ K} \). The VLA D-configuration H\textsc{i} spectrum extracted from the white dashed rectangular region (similar in size to the D-configuration beam) is shown in the lower panel in blue. The feature has an FWHM of 4.75 km s\textsuperscript{-1} and a centroid at 442.2 km s\textsuperscript{-1}. The absorption spectrum was obtained by subtracting out the Gaussian emission profile from the raw spectrum as discussed in detail by B11.

(A color version of this figure is available in the online journal.)
of H I in this absorber to be $6.3 \times 10^{19}$ cm$^{-2}$ using the following expression:

$$N(H\,I) = 1.823 \times 10^{18} \frac{T_{\text{f}}}{f} \int \tau(v)dv \text{ cm}^{-2},$$  

(3)

where $\tau(v)$ is the 21 cm optical depth as a function of velocity in km s$^{-1}$. From the Gaussian fit to the absorber, we estimate $\int \tau(v)dv = 1.3$. In this case, the covering fraction is unity, $f = 1$, as we are measuring optical depth, $\tau(v)$, at the region of the background source where the absorber was detected.

The column density of cold gas as derived from the absorption feature is significantly lower than the total H I column density seen in emission. By comparing the two, we find the ratio of cold-to-total H I column density associated with the absorber to be $\approx 30\%$. Folding in the covering fraction, we find that only $\approx 10\%$ of the total H I by mass exists in the cold phase. The non-detections of H I in absorption toward sightlines #1 and #3 provide upper limits on the column densities of 2.9 and $14.2 \times 10^{19}$ cm$^{-2}$, respectively. The same exercise of comparing these column densities to that observed in emission implies that the cold-to-total H I toward sightlines #1 and #3 are $\approx 20\%$ and $\approx 50\%$, respectively.

3.1.3. Nature of H I in UCG 7408

Our results suggest that the process of condensation is suppressed in UGC 7408. We found that a large fraction of atomic gas in the extended disk of this galaxy is warm with a temperature much larger than a few 100 K. Therefore, we conclude that most of the atomic gas in the extended disk of UCG 7408 failed to condense into the atomic gas clouds of 100–50 K (typically found in the Milky Way ISM). We did detect a small fraction of gas in the cold phase with temperature $\approx 25$ K. This is much lower than the temperatures commonly seen in the CNM of the Milky Way (Heiles & Troland 2003; Strasser et al. 2007). In fact, at such low temperatures most of the gas in the Milky Way is in the molecular phase. The existence of such cold atomic gas suggests that the fraction of H I that was able to condense into the cold phase remains in the atomic state and avoids the transition to molecular phase.

The atomic hydrogen in the SMC also exhibits very similar properties. For instance, Dickey et al. (2000) found that less than 15% of the total H I in the SMC is in the cold phase. They also found the temperature of cold phase to be typically 40 K or less. They suggested that the difference in the properties of the CNM between the SMC and the Milky Way is a consequence of the difference in the metallicity in their ISM. Low metallicity implies lower radiative cooling. In particular for clouds where cooling is dominated by fine-structure line emission, the thermal equilibrium between the warm and the cold phase requires higher pressures with decreasing metal abundance (Wolfire et al. 1995). This limits the existence of cold clouds to regions of higher pressure, and hence the reduction in the cold gas fraction. Similar effects are observed in DLAs where the spin temperatures are inversely proportional to the metallicity of the DLA (Kanekar et al. 2009). Again, this emphasizes the inefficient cooling of gas at lower metallicities.

On the other hand, the lower metallicity would imply lower dust content and therefore, the fraction of atomic gas that is able to cool does not suffer from photoelectric heating by dust grains. However, the lack of dust grains is likely to impede the production of molecules. Dust plays a crucial role in shielding gas clouds against ionization thus aiding in atomic-to-molecular transition. Therefore, a drop in metallicity/dust content requires a much larger column of neutral gas to shield the clouds and form molecules (see Figure 1 in Krumholz et al. 2009). Observationally, this is evident from the variation in the minimum neutral gas column densities required to detect molecules in galaxies as a function of metallicity. For example, in the Milky Way the transitions occurs when the neutral gas column density is $10^{20.7}$ cm$^{-2}$ or higher (Savage et al. 1977). The same for LMC and SMC was found to be at $N(H\,I) > 10^{21.3}$ cm$^{-2}$ and $> 10^{22.0}$ cm$^{-2}$, respectively (Tumlinson et al. 2002).

Therefore, it is likely that UCG 7408 has a very low molecular gas fraction as compared to its neutral gas content. This would explain the small physical extent of the stellar component in this galaxy unlike its extended H I distribution as well as the suppression in star formation (as indicated by the limiting SFR surface density in Table 2) in the vicinity of the absorber despite its low temperature.

3.2. Extended H I Disks of J141629 and J160659

We did not detect any H I absorbers toward the sightlines #4 and #5 probing galaxy J141629 at impact parameters of 16.2 and 32.4 kpc and sightline #6 probing galaxy J160659 at an impact parameter of 23.3 kpc. The limiting optical depths and column densities estimated from 3$\sigma$ noise in the spectra are presented in Table 5.

Both these galaxies have large H I reservoirs (log$[M(H\,I)]$ = 9.4 and 9.9, respectively) and hence are expected to have extended H I distributions. The empirical H I mass to size relationship derived for dwarf galaxies from the WHISP Survey (Swaters et al. 2002) predicts that the H I detection in J141629 and J160659 have radii, $R_{H\,I}$, of 15.3 and 30.1 kpc, respectively. This implies that J160659 is probed by sightline #6 ($\rho = 23.3$ kpc) within the $R_{H\,I} = 30.1$ kpc. However, no H I was observed in absorption. The 3$\sigma$ limit on the absorption column density toward this sightline is $3.6 \times 10^{18}$ cm$^{-2}$. However, the expected H I surface density within $R_{H\,I}$ is $\geq 1 \times 10^{20}$ pc$^{-2}$, which is equivalent to a column density of $\geq 1.3 \times 10^{20}$ cm$^{-2}$. This implies that the limiting column density is 35 times lower than the column density predicted at $R_{H\,I}$. Similarly, sightline #5 probes J141629 at the edge of its H I disk ($\rho = 16.2$ kpc and $R_{H\,I} = 15.3$ kpc) and the upper limit on its H I column density is an order of magnitude below that expected at $R_{H\,I}$. This suggest that cold-to-average H I column densities could be lower than 10% toward these sightlines. A similar argument based on the empirically observed ratio between H I to optical radius of $\approx 3$ for dwarf galaxies also implies an unusually low cold H I ($T \approx 100$ K or less) content at the position of these sightlines.

There could be two likely causes for the non-detection of H I in these sightlines. The first possibility is that the H I distribution is highly patchy and the covering fraction of gas with column density $\approx 10^{20}$ cm$^{-2}$ is significantly smaller than 1. If that were the case, then it would also imply that true column density of the patchy H I is much higher than $1.3 \times 10^{20}$ cm$^{-2}$ within $R_{H\,I}$. The second possibility is that the atomic gas is warm ($T_{\text{spin}} > 1000$ K) and produces a broad (due to Doppler broadening) and shallow (i.e., low optical depth because $T_{\text{spin}} \propto (\tau)^{-2/3}$; see Equation (5) from B11) absorption feature. Such features would remain hidden in our data due to the limited signal-to-noise ratio. This is a disadvantage that impacts most 21 cm absorption studies.
4. CONCLUSION

We presented follow-up VLA B-configuration observations of six quasar sightlines from the GBT 21 cm H I absorption sample of B11. The sightlines probed three foreground galaxies. This includes three sightlines probing dwarf galaxy, UGC 7408. Strong H I emission was detected toward these sightlines in the GBT spectra and hence a reliable limit on the optical depth based on the non-detection of absorption could not be made. Therefore, we obtained high spatial resolution imaging with the VLA and found the following.

1. A narrow H I absorber was detected toward sightline J122106.854+454852.16 (#2) at 444.5 km s\(^{-1}\). The absorber is associated with the extended H I disk of UGC 7408 at an impact parameter of 2.8 kpc. This absorber was tentatively detected by B11 in their low spatial and spectral resolution VLA D-configuration data. Our higher resolution data showed the absorber to be narrow and unresolved. A Gaussian fit to our data gives an FWHM of 1.1 km s\(^{-1}\) and a corresponding kinetic temperature of \(T_K \approx 26\) K. Assuming the kinetic temperature as a proxy for the spin temperature, we estimated the column density of the absorber to be \(6.3 \times 10^{19}\) cm\(^{-2}\).

2. The area of the cloud associated with the absorber was measured to be 0.04 kpc\(^2\). This implies a covering fraction of the background source \(\sim 25\% – 30\%\).

3. The cold-to-total H I column density in the absorbing cloud toward this sightline was estimated to be \(\sim 30\%\). In terms of mass, the cold phase is about \(10\%\) of the total H I.

4. The low fraction of cold-to-total H I and the existence of cold H I at extremely low temperatures, where gas normally transitions to molecular phase, suggests that the process of condensation is suppressed in this galaxy. The likely explanation for the suppression is the low metal content in this galaxy. Similar properties of the CNM were seen in the SMC. Together, these two cases are consistent with the effects of low metallicity in suppressing condensation.

5. We reported non-detection of H I in absorption for the remaining five sightlines. The limiting optical depths range from \(\tau \lesssim 0.01–0.39\). These limits are about three times better than those measured by B11 toward most sightlines.

6. One of the sightlines is expected to probe the extended H I disk (\(\rho < R_{HI}\)) of the foreground galaxy J160659.13+271642.6. The non-detection of H I in absorption toward that sightline indicates an extremely low column density of cold gas (\(T_{\text{spin}} < 100\) K). Two likely interpretations are that either the cold gas distribution is highly patchy or the H I is at much higher temperature (\(T_{\text{spin}} > 1000\) K).

7. The non-detection of H I puts stringent limits on H I optical depth. This lends support to the conclusions from the B11 survey that the covering fraction of cold gas at column densities greater than that of DLA is very small beyond \(\lesssim 15\) kpc.

Based on our results, we emphasize the need for a statistically larger sample to probe gas within 20 kpc of galaxies. Currently, plans are underway for two such surveys—the First Large Absorption Survey in H I (PI: Sadler; Allison et al. 2012) with the Australian Square Kilometre Array Pathfinder and the MeerKAT Absorption Line Survey (PIs: Gupta & Srianand) with the South African MeerKAT radio telescope. Both of them are pathfinder missions for the Square Kilometer Array (SKA). The high sensitivity of SKA will make it the ideal telescope for mapping cold gas in absorption against fainter background sources. These upcoming facilities and the planned surveys promise to substantially improve our understanding of small-scale properties of cold gas as a function of radial distance within their host galaxies. A large sample will also facilitate a census of variations in cold gas properties and the process of condensation as a function of galaxy properties such as stellar mass, gas content, metallicity, SFR, etc. That will be the crucial step in understanding the physics behind the process of condensation, its regulation, and how that translates to evolution of galaxies across the full stellar mass spectrum.

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