USING 21 cm ABSORPTION IN SMALL IMPACT PARAMETER GALAXY–QUASAR PAIRS TO PROBE LOW-REDSHIFT DAMPED AND SUB-DAMPED Lyα SYSTEMS

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ABSTRACT

To search for low-redshift damped Lyα (DLA) and sub-DLA quasar absorbers, we have conducted a 21 cm absorption survey of radio-loud quasars at small impact parameters to foreground galaxies selected from the Sloan Digital Sky Survey (SDSS). Here we present the first results from this survey based on observations of SDSS J104257.58+074850.5 (QSO = 2.66521), a quasar at an angular separation from a foreground galaxy (zgal = 0.03321) of 2′.5 (1.7 kpc in projection). The foreground galaxy is a low-luminosity spiral with on-going star formation (0.004 M⊙ yr−1 kpc−2) and a metallicity of −0.27 ± 0.05 dex. We detect 21 cm absorption from the galaxy with the Green Bank Telescope (GBT), the Very Large Array (VLA), and the Very Long Baseline Array (VLBA). The absorption appears to be quiescent disk gas co-rotating with the galaxy and we do not find any evidence for outflowing cold neutral gas. The width of the main absorption line indicates that the gas is cold, Tk ≲ 283 K, and the H i column density in DLAs shields the absorbers from photoionization by ultraviolet light, which allows the gas to cool sufficiently so that these systems can be major sites of star formation. Moreover, many studies have shown that DLAs are the dominant reservoirs of neutral gas throughout most of the history of the universe (e.g., Prochaska et al. 2005), and it has been suggested that DLAs are the progenitors of modern-day disk galaxies (Wolfe et al. 1986). The most recent DLA studies employing large statistical samples (Prochaska & Wolfe 2009; Noterdaeme et al. 2009a) indicate that the cosmological mass density of neutral gas in DLAs (Ωg,DLA) decreases with redshift from z = 4 down to z = 2.2, but there is controversy about how Ωg,DLA evolves at z ≲ 2. The decrease in Ωg,DLA could reflect the consumption of gas by conversion to stars, but Prochaska & Wolfe (2009) argue that a more complicated picture involving both inflows and outflows is suggested by the data.

1 INTRODUCTION

Damped Lyα absorbers (DLAs; defined by Wolfe et al. (1986) as N(H i) > 2 × 10²⁰ cm⁻²) and sub-DLAs (defined by Péroux et al. (2001) as 1.6 × 10¹⁷ cm⁻² < N(H i) < 2 × 10²⁰ cm⁻²) are important probes of galaxy evolution for several reasons:

First, the high H i column density in DLAs shields the absorbers from photoionization by ultraviolet light, which allows the gas to cool sufficiently so that these systems can be major sites of star formation. Moreover, many studies have shown that DLAs are the dominant reservoirs of neutral gas throughout most of the history of the universe (e.g., Prochaska et al. 2005), and it has been suggested that DLAs are the progenitors of modern-day disk galaxies (Wolfe et al. 1986). The most recent DLA studies employing large statistical samples (Prochaska & Wolfe 2009; Noterdaeme et al. 2009a) indicate that the cosmological mass density of neutral gas in DLAs (Ωg,DLA) decreases with redshift from z = 4 down to z = 2.2, but there is controversy about how Ωg,DLA evolves at z ≲ 2. The decrease in Ωg,DLA could reflect the consumption of gas by conversion to stars, but Prochaska & Wolfe (2009) argue that a more complicated picture involving both inflows and outflows is suggested by the data.

Second, the self-shielding of the DLAs facilitates accurate metallicity measurements by removing the substantial uncertainties caused by ionization corrections in lower-N(H i) absorption systems. In principle, DLAs do not suffer from any luminosity bias either; DLA metallicity measurements can be carried out equally well at any redshift as long as a higher-z background quasi-stellar object (QSO) can be found. Thus, DLAs are powerful tools for tracing the chemical enrichment history of galaxies and their progenitors. The higher H i column also enables detection of weaker lines and exotic species (e.g., Prochaska et al. 2003; Junkkarinen et al. 2004; York et al. 2006a; Pettini et al. 2008; Ellison et al. 2008), and detailed signatures of various nucleosynthetic processes can be investigated in DLAs as well as those from dust extinction.

Third, by using DLAs to select high-redshift gas-rich galaxies, the kinematics of high-z galactic gas flows can be investigated in detail, and with good statistical samples, based on the kinematics of sensitive metal absorption lines (Prochaska & Wolfe 1997; Prochaska et al. 2008). Several groups have used simulations and the observed DLA kinematics to argue that gravity-driven infall is not sufficient to produce the observed
velocity spreads of metal lines in DLAs, and some additional process (or processes) such as galactic winds appears to be required (Razoumov et al. 2008; Pontzen et al. 2008).

However, in most cases little or no information is available regarding the origin and environment in which DLA absorption arises, and this has hampered the exploitation of DLAs for probing galaxy evolution. Because the rest wavelength of the Lyα line is in the far-ultraviolet, most DLA programs have focused on high-redshift systems (z > 2) that can be detected from the ground, and at those redshifts it is very challenging to study the DLA origin and environment. At low redshifts, studies have found a wide range of galaxies associated with DLAs both in terms of morphology and luminosity (Bergeron & Boisse 1991; Steidel et al. 1995; Le Brun et al. 1997; Bowen et al. 2001; Turnshek et al. 2001; Chen & Lanzetta 2003; Rao et al. 2003), but the sample of low-z galaxies studied so far remains small. On the other hand, low-redshift 21 cm emission studies have shown that gas with \( N(\text{H}^i) > 2 \times 10^{20} \, \text{cm}^{-2} \) can be found in a variety of contexts (e.g., Hibbard et al. 2001) ranging from normal gas disks of high- and low-surface brightness galaxies to dynamically disturbed structures such as tidally stripped gas spurs and bridges or even detached intergalactic clouds. Galaxy interactions are expected to be more common at high redshifts, so an even larger proportion of high-z DLAs could originate in disturbed structures. Interpretation of, e.g., the kinematics of DLAs could be confusing if the samples are composed of a mixture of these different types of objects.

This raises a question: are there absorption signatures that can be used to distinguish gas in different environments such as quiescent galaxy disks versus dynamically disturbed extraplanar structures such as tidal tails or ram-pressure detritus? All can have \( N(\text{H}^i) > 2 \times 10^{20} \, \text{cm}^{-2} \), but how do their physical characteristics compare? Spectroscopic absorption studies of the \( \text{H}^i \) 21 cm line provide unique information to address this question for several reasons. (1) In the UV/optical, QSOs are effectively point sources, but in the radio continuum, radio-loud QSOs are often significantly extended and resolved (e.g., Lazio et al. 2009), and the absorption structure can be mapped against the extended background QSO continuum to obtain information on the spatial extent and characteristic sizes of the clouds that comprise DLAs. In addition, radio interferometers such as the Very Long Baseline Array (VLBA) can be employed to do this mapping at much higher angular resolution than is possible in other frequency bands. Thus, radio observations provide unique constraints on very small-scale structures in DLAs. Interestingly, the literature on 21 cm absorber sizes suggest vastly different sizes in different environments. For example, Keeney et al. (2005) argue that the 21 cm absorption feature associated with tidal feature of NGC 3067 (Stocke et al. 1991) shows similar profile and comparable strength over a scale of 20 mas. The authors suggest that the feature arises in an atomic gas structure of physical size >2–20 \( h_{70}^{-1} \) pc. However, based on their H\( i \) emission map and photoionization model they concluded that the absorbing cloud is uniform on a scale of 5 \( h_{70}^{-1} \) kpc. It is possible that large coherent H\( i \) clouds can contain clumpy internal structures on much smaller scales. For instance, 21 cm absorbers in the Milky Way have been shown to contain much smaller structures with sizes on the order of tens of AU (e.g., Lazio et al. 2009). Although, these scales have not yet been probed in extragalactic gas clouds; the nondetection of these small clouds can be attributed to the fact that they have a small volume filling factor as noted by Lazio et al. (2009). Very little information is available regarding the absorbing cloud sizes in other galaxies, which is one of the motivations for the study presented in this paper (see below). (2) The hyperfine 21 cm transition has a very low transition probability, so a substantial H\( i \) column is required to detect the line, and surveys designed to search for 21 cm absorbers in radio-loud QSOs automatically select systems that are DLAs or at least sub-DLAs. Thus, 21 cm absorption reveals the kinematics and physical characteristics of the neutral gas with minimal confusion from substantially ionized gas (which can confuse analyses based on metal ions such as Si \( \text{ii} \) or S \( \text{ii} \)). (3) Unlike 21 cm emission, 21 cm absorption depends on the spin temperature of the gas, and combined with the high spectral resolution available with radio spectrometers, this can provide valuable constraints on the physical conditions of the absorber. (4) H\( i \) 21 cm absorption is not affected by dust and hence, such a study can address whether optical DLA studies are biased by dust extinction (see, e.g., Ellison & Lopez 2009).

For these reasons, various groups have applied 21 cm absorption spectroscopy to the study of DLAs (e.g., Kanekar & Briggs 2004; Kanekar & Chengalur 2005; Curran et al. 2007, and references therein). Unfortunately, 21 cm absorbers are rare, and blind surveys for 21 cm absorption are very inefficient with current radio telescopes, so most previous studies have searched for 21 cm absorption in known DLAs and thus are dominated by high-z systems. For example, Macdonald et al. (2009) searched 243 possible sources for 21 cm absorbers with \( N(\text{H}^i) > 2 \times 10^{20} \, \text{cm}^{-2} \) and 3282 possible sources with \( N(\text{H}^i) > 2 \times 10^{21} \, \text{cm}^{-2} \) in the Arecibo Legacy Fast Arecibo L-Band Feed Array (ALFALFA) Survey. They re-detected one previously known intrinsic H\( i \) absorber, but no additional lines were identified. Likewise, searches for 21 cm absorption in Mg \( \text{ii} \) systems (Gupta et al. 2009; Kanekar et al. 2009a) have mostly found cases at relatively high redshifts where it is difficult to examine the environment of the absorbers.

To overcome this problem and assemble a sample of very low-redshift 21 cm absorbers suitable for environment studies, we have initiated a new survey that uses a different strategy to find the 21 cm systems. Our strategy to find low impact parameter sightlines through nearby galaxies is twofold. First, we use the Sloan Digital Sky Survey (SDSS; York et al. 2000) to directly sightlines through nearby galaxies is twofold. First, we use the Sloan Digital Sky Survey (SDSS; York et al. 2000) to directly find the 21 cm systems. Second, we search for QSO spectra that show emission lines from the DLA host galaxy. From this sample, we have selected radio-loud quasars based on data from the FIRST survey (Becker et al. 1995) or the NRAO Very Large Array (VLA) Sky Survey (Condon et al. 1998). The first part of our survey is to observe the radio-loud QSOs with the Green Bank Telescope (GBT) to determine if the foreground galaxy is a 21 cm absorber. Currently we are carrying out observations of 28 sightlines through 18 foreground galaxies from redshift 0.00154 to 0.2596 with projected distances varying from 1.7 to 109.7 kpc. The second part is to follow up the GBT detections with higher angular resolution observations with either the VLA or the VLBA.

In this paper, we present the results of the pilot study that we conducted for this survey. This initial program successfully detected 21 cm absorption from a foreground galaxy, and we have followed up this detection with high-resolution VLBA observations and optical imaging. The paper is organized as follows. We first present the spectroscopic technique used for identifying foreground galaxies from the spectra of background QSOs (Section 2). This is followed by a detailed analysis of a QSO–galaxy pair identified using our technique and the
discovery of a 21 cm absorber in the foreground galaxy. The optical imaging and foreground galaxy and environmental properties are presented in Section 3, along with estimates of the foreground galaxy’s star formation rate (SFR), metallicity, and stellar mass. In Sections 4 and 5, we describe our radio observations and analyze the properties of the 21 cm H I absorber, respectively. We discuss the physical nature and possible origin of the absorber in Section 6. Finally, in Section 7 we summarize our findings. Throughout the paper we use $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Lambda_0 = 0.7$.

2. GALAXY DISCOVERY AND REDSHIFT

The presence of a galaxy close to the line of sight of the quasar SDSS J104257.58+074850.5 ($z_{\text{QSO}} = 2.66521$) was discovered serendipitously by one of us (D.G.Y.) during the compilation of QSO absorption-line catalogs from the SDSS spectroscopic database (York et al. 2006b; Lundgren et al. 2009). In addition to the usual broad emission lines at $z = 2.665$, the SDSS spectrum of the QSO shows narrow emission lines of [O iii], Hβ, [O ii], Hα, and [S ii] at a much lower redshift. Figure 1 shows the SDSS spectrum of SDSS J104257.58+074850.5; the narrow emission lines of the foreground galaxy are readily apparent. The right ascension (R.A.) and declination (decl.) of the galaxy, which is not cataloged in SDSS, are given in Table 1. The QSO and galaxy have very similar co-ordinates of course, and to distinguish between the two in this paper, we will use the SDSS designation for the QSO, but will refer to the galaxy as “GQ1042+0747,” where GQ is an abbreviated version of “galaxy on top of QSO.” Such QSO–galaxy pairs at small impact parameters are hard to find by any technique. A recent search for “composite” Sloan QSO spectra like the one shown in Figure 1 (i.e., including emission features of lower-$z$ foreground galaxies) has unearthed 21 pairs with impact parameters $\lesssim 10$ kpc (Quashnock et al. 2008; Noterdaeme et al. 2009b) out of $\approx 74,000$ QSO candidates examined. While such pairs are rare, they deserve special attention for the purpose of studying the interstellar medium (ISM) of the foreground galaxies.

Gaussian profile fits to the seven detected narrow (foreground) emission lines in Figure 1 give an average redshift of $z = 0.0332 \pm 0.0001$, with the error derived simply as the standard deviation in the seven measurements. As SDSS spectra are always corrected to heliocentric velocities, this redshift corresponds to a heliocentric velocity of 9962 $\pm 33$ km s$^{-1}$. After reconstruction of the composite nature of the QSO spectrum, a simple visual inspection of the SDSS images of the QSO immediately revealed a galaxy close to the QSO line of sight, confirming the notion that a galaxy was contributing light to the spectrograph fiber that had been centered on the QSO.

As part of a follow-up investigation to search for interstellar Ca ii and Na i absorption lines arising from gas in the foreground galaxy, we observed the QSO using the Dual Imaging Spectrograph (DIS) on the Astrophysical Research Consortium (ARC) 3.5 m telescope at the Apache Point Observatory (APO) on 2006 January 6. The DIS was configured with the high-resolution gratings and a 0.9 slit, giving a spectral resolution of $\approx 80$ km s$^{-1}$ (FWHM) at 6700 Å. Although conditions were too poor to obtain spectra with sufficient signal-to-noise ratio (S/N) to detect absorption lines from the foreground galaxy, the Hα emission line was detected, permitting an independent measurement of the galaxy’s redshift, at a resolving power of about twice that of the SDSS data. We extracted spectra over a 5" aperture centered on the QSO and tied the zero-point of the wavelength calibration to four narrow skylines which were also covered by the observations. From the Hα line alone, we measured a redshift of $z = 0.03321 \pm 0.00003$, with the error derived from the standard deviation in the set of differences between the rest wavelengths of the four sky lines and the wavelengths we measured. After correcting the observed radial velocity to a heliocentric one, we found that the Hα emission line gave a systemic velocity of 9932 $\pm 10$ km s$^{-1}$.

### Table 1

Properties of GQ1042+0747, the Foreground Galaxy in the QSO–Galaxy Pair

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Center R.A. and decl.            | 10:42:57.74 +07:47:51.3    |
| Redshift $z_{\text{gal}}$        | 0.03321 $\pm 0.00003$, $cz = 9932 \pm 10$ km s$^{-1}$ |
| Impact parameter                 | $2.5 \equiv 1.7$ km s$^{-1}$ at $z_{\text{gal}}$ |
| Magnitudes$^b$                   | $g = 18.59, r = 18.05, i = 18.08$ |
| MW extinction                    | $g = 0.12, r = 0.08, i = 0.06$ |
| Absolute magnitudes$^a$          | $M_g = -14.75, M_r = -17.85, M_i = -17.80$ |
| Major/minor axes ratio           | 1.55                       |
| Inclination$^d$                  | 50°                        |
| Surface brightness ($r$ band) $^c$ | $\mu_g = 21.3, r_g = 21.4, \mu_r = 22.4, r_g = 0^{\prime}8$ |
| log metallicity $^a$             | $-0.27 \pm 0.05$ (N2 index); $-0.32 \pm 0.03$ (O3N2 index) |

**Notes.**

$^a$ Redshift is from APO spectrum of Hα line.

$^b$ Isophotal magnitudes from SExtractor. Formal errors on these values are $= \pm 0.2$ mag.

$^c$ Corrected for Milky Way extinction, but no k-correction applied.

$^d$ $\cos^{-1}(b/a)$, where $a$ and $b$ are the major and minor isophotal axes.
3. OPTICAL PROPERTIES AND ENVIRONMENT OF THE FOREGROUND GALAXY

3.1. SOAR Optical Imaging

Although the galaxy is clearly visible in SDSS images, little can be inferred from the SDSS photometry due to the blending of the galaxy’s image with that of the QSO. To learn more about the nature of the foreground galaxy, we obtained deeper images with better angular resolution using the SOAR Optical Imager (SOI; Schwarz et al. 2004) on the 4.1 m Southern Astrophysical Research (SOAR) telescope at Cerro Pachón in Chile. Exposures were made using g-, r-, and i-band filters for 10, 30, and 15 minutes, on 2009 March 2, February 28, and March 1, respectively. The data were processed in the conventional way, and calibrated astrometrically using the SCAMP software package (Bertin 2006). Individual frames were co-added using the SWARP software (Bertin et al. 2002), which resamples and co-adds the individual images with the derived astrometric solution based on SDSS astrometry. The final co-added g, r, and i-band images had resolutions of 1″/2, 0″/7, and 0″/8 FWHM, respectively. These were assembled into a color image following the prescription given by Lupton et al. (2004), using the data at the original resolutions, and applying an inverse hyperbolic sine (a sinh) scaling algorithm. The resulting multicolor image of the QSO–galaxy pair is shown in Figure 2.

3.2. Photometry and Surface-brightness Profile

To derive accurate measurements for the physical parameters of GQ1042+0747, we constructed a point-spread function (PSF) from a two-dimensional Moffat profile fit to stellar images in each of the g-, r-, and i-band images, and subtracted a suitably scaled PSF from the QSO profile. The galaxy, with the QSO profile removed, and again formed from a co-addition of all three colors, is shown in the inset of Figure 2.

A more detailed representation of the galaxy in the r-band image is shown in Figure 3. To better highlight the small-scale structure in the galaxy, we used the technique of unsharp masking, using the procedure outlined in Jenkins et al. (2005). We found that “gentle” unsharp masking using a Gaussian with width σ = 5 pixels most effectively enhanced the low-level morphological features of the galaxy. In Figure 3, this unsharp mask image is shown, again scaled using the a sinh scaling algorithm. The image shows that the galaxy is an inclined spiral, perhaps with a bar at its center. Some evidence of spiral arms can be seen to the SW of the center (below and to the right of the QSO’s position). A much harder stretch of the original image (the non-unsharp mask data), shown in the inset of Figure 3, clearly reveals an outer spiral arm to the NE of the galaxy (top left of the inset). The main image in Figure 3 also shows a “plume,” some 2″–3″ directly above the position of the QSO, which is not an artifact of the QSO profile subtraction. Determining whether this is simply part of the normal spiral pattern of a galaxy, or, perhaps related to what might be a companion dwarf galaxy, SDSS J104257.52+074900.5, ~10″ due north of the QSO’s position, will require higher resolution data. The companion dwarf galaxy has magnitudes measured from the SOAR data of g = 22.1, r = 21.5, and i = 21.2, with errors of 0.1 mag.

With these images, we were able to measure the galaxy properties listed in Table 1. The magnitudes of the galaxy and its major-to-minor axis ratio were derived using the SExtractor software package (Bertin & Arnouts 1996); the extinction from dust in the Milky Way was taken from the maps of Schlegel et al. (1998), and these values were used to correct the absolute magnitudes (although no k-correction was applied).

To derive a surface brightness profile, we used the ellipse routines in the STSDAS package isophote (Jedrzejewski 1987) to fit the r-band data. The results are shown in Figure 4. The profile is that observed along the semimajor axis—no other corrections have been applied, and no attempt was made to correct for the inclination of the galaxy.
made to first deconvolve the data using the PSF. As Figure 4 shows, more than a simple exponential disk model is required to explain the data, so we fit a combination of a disk model with a classical $r^{1/4}$ profile. When the intensity profile of a galaxy is converted to surface brightness, $\mu$, the profiles are given by

$$\mu_1 = \mu_e + 8.325 \left[ \left( \frac{r}{r_e} \right)^{1/4} - 1 \right],$$

(1)

$$\mu_2 = \mu_0 + 1.086 \frac{r}{r_d},$$

(2)

where $r_e$ and $r_d$ are the scale lengths of the bulge and disk components, respectively, and $\mu_e$ and $\mu_0$ are the surface brightness values at those radii. We fitted a combination of these theoretical profiles to the observed values of $\mu$ by minimizing the value of $\chi^2$ between the fit and the data, and derived the values listed in Table 1. The resulting fit is shown in Figure 4.

### 3.3. Star-formation Rate, Metallicity, and Stellar Mass

GQ1042+0747 is a low luminosity spiral with $L = 0.048L_*$ in the r-band (using $M_*= -21.2$ from Table 2 of Blanton et al. 2003). Emission-line measurements from the SDSS spectrum of the foreground galaxy are presented in Table 2. The 3″ diameter fiber used to make these measurements was centered at the QSO’s position. Most of the observed region covered the disk; some parts of the central region of the foreground galaxy were also captured. We estimated the SFR from the H$\alpha$ (Kennicutt 1998) and [O ii] transitions (Kewley et al. 2004)

using the following relationships:

$$\text{SFR}(\text{H} \alpha) = 7.9 \times 10^{-42} \times L(\text{H} \alpha, \text{erg s}^{-1}) M_\odot \text{yr}^{-1}, \quad (3)$$

$$\text{SFR}([\text{O} \ ii]) = 6.58 \times 10^{-42} \times L([\text{O} \ ii], \text{erg s}^{-1}) M_\odot \text{yr}^{-1}. \quad (4)$$

The SFR was found to be $1.26 \times 10^{-2}$ and $8.6 \times 10^{-3} M_\odot \text{yr}^{-1}$ using Equations (3) and (4), respectively, over an area of 3.1 kpc$^2$ in the rest frame of the GQ1042+0747. This corresponds to SFR surface density of $4.1 \times 10^{-3}$ and $2.8 \times 10^{-3} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$, respectively. The Balmer decrement, $I(\text{H} \alpha)/I(\text{H} \beta) = 3.0 \pm 0.4$ suggests a low dust content in this galaxy. The metallicity of the galaxy estimated using the N2 index (Pettini & Pagel 2004) is log ($O/H) + 12 = 8.42 \pm 0.05$. Assuming a solar abundance of log ($O/H) = 8.69$ (Asplund et al. 2009), the logarithmic measured metallicity is then $-0.27 \pm 0.05$ dex relative to solar. The O3N2 index yielded a similar metallicity of $-0.32 \pm 0.03$ dex relative to solar.

It is now well known that galaxies in the nearby universe follow mass–metallicity and luminosity–metallicity relationships (e.g., Tremonti et al. 2004). It is often argued that the mass–metallicity trend has important implications regarding galactic outflows, so it is of interest to consider where GQ1042+0747 is located in the mass–metallicity trend. Referring to Figure 5 in Tremonti et al. (2004), we see that GQ1042+0747 is a relatively low-luminosity galaxy and has a somewhat low metallicity compared to other SDSS galaxies of comparable absolute magnitude, but given the scatter in the relationship, the observed luminosity and metallicity of GQ1042+0747 are in good agreement with the usual luminosity–metallicity trend. To estimate the stellar mass of the galaxy, we use Equation (1) of McIntosh et al. (2008), which is based on the stellar $M/L$ ratios from Bell et al. (2003), and we obtain

$$\log \left( \frac{M_{\text{stars}}}{M_\odot} \right) \approx 9.1. \quad (5)$$

Thus, the metallicity is low for its stellar mass (see Figure 6 in Tremonti et al. 2004), but again GQ1042+0747 follows the general trend within the observed scatter. We will discuss the implications of the mass and metallicity of the galaxy compared to its absorption properties in Section 6.

### 3.4. Large-scale Environment of GQ1042+0747

A benefit of using SDSS to select low-$z$ galaxy–QSO pairs is that SDSS provides detailed information about the global context of the galaxy and its affiliated absorption. We will show below that despite the fact that GQ1042+0747 is clearly a star-forming spiral galaxy, it has a surprisingly low H$\alpha$ column density in its inner disk, and overall it has a low H$\alpha$ mass.

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**Figure 4.** r-band surface brightness profile of the galaxy in front of SDSS J104257.58+074850.5. The black dots are data points obtained using the IRAF isophote package. The final fit (solid line) is the result of co-adding an exponential disk profile (dashed line) and an $r^{1/4}$ profile (dotted line). The relevant parameters for each model are given alongside the profiles.
cause for its H\textsubscript{I} deficiency is an interesting question, and we will hypothesize that this is related to the galaxy’s environment. To set the stage for this discussion, we show the large-scale distribution of SDSS galaxies near GQ1042+0747 in Figures 5 and 6. Figure 5 shows the distribution of SDSS galaxies versus redshift along the line of sight to SDSS J104257.58+074850.5 out to $z = 0.053$; the panels show the overall (absolute) projected distance of the galaxies from the sight line (upper panel) and the projected distance in the R.A. and decl. directions only (middle and lower panels, respectively). This is a cylinder cut from SDSS spectroscopic data (up to DR7) centered on the QSO. SDSS is a magnitude-limited survey, so the galaxy points are plotted with symbol sizes that indicate the object’s luminosity based on values from NYU Value Added Catalog (Blanton et al. 2005), as shown in the legend, to give the reader a sense of the survey completeness for various galaxy luminosities. GQ1042+0747 is shown with a large red dot. We show a substantial range in redshift so that voids and large-scale structures in the galaxy distribution can be visually recognized. In order to zoom in on the more immediate vicinity of GQ1042+0747, Figure 6 shows the R.A. and decl. of only galaxies with redshifts within ±240 km s\textsuperscript{-1} of GQ1042+0747. In this figure, the symbol color indicates the velocity difference between the galaxy redshift and the redshift of the 21 cm absorption detected in GQ1042+0747 (Section 4), and the symbol size indicates the galaxy luminosity, as reflected in the figure legend.

From Figures 5 and 6, we note the following aspects of the GQ1042+0747 environment. (1) The galaxy is located near the boundary of a large-scale structure and most likely in a low density region. This is readily apparent in Figure 6—there is a paucity of galaxies southeast of GQ1042+0747, but many galaxies are found to the northwest with a prominent galaxy overdensity at R.A. $\approx 157^\circ$ and decl. $\approx 13^\circ$. (2) Qualitatively, GQ1042+0747 appears to be located within the boundaries of the large-scale structure, but nevertheless it appears to be relatively isolated—the nearest-neighbor galaxy is $>1.8$ Mpc away in projection and is offset in velocity, so the three-dimensional nearest-neighbor distance could be significantly larger. Traditionally, GQ1042+0747 would be considered a “field” galaxy; in more recent nomenclature, the galaxy might be referred to as a “wall” galaxy. A detailed spectroscopic study of the immediate environments of this galaxy would help to clarify how isolated it is. We believe that the relative isolation may have been an important factor that has affected this galaxy’s evolution, as we will discuss in Section 6.

4. 21 cm ABSORPTION SPECTROSCOPY

To search for 21 cm absorption from the ISM/halo of the foreground galaxy, SDSS J104257.58 + 074850.5 was observed with three complementary National Radio Astronomy Observatory (NRAO) telescopes: the 100 m GBT, the VLA in the B configuration, and the VLBA. The optical redshift of GQ1042+0747 was used to choose the bandpasses for the 21 cm observations. To maximize the effectiveness of our search for 21 cm absorption in the general vicinity of the foreground galaxy, the VLA was set up to provide the broadest spectral coverage that could be afforded at a reasonable spectral resolution. This resulted in sub-optimal spectral resolution for the VLA (10.6 km s\textsuperscript{-1}), but was overcome by the excellent resolution of the GBT (0.33 km s\textsuperscript{-1}). Following the detection...
of the absorber, VLBA H\textsc{i} observations were then carried out centered at the redshift of the absorber. Spectral resolution of 0.9 km s$^{-1}$ was achieved in our VLBA observations along with a superb mas spatial resolution of 22 mas $\times$ 9 mas.

4.1. Green Bank Telescope Observations

We observed SDSS J104257.58+074850.5 with the GBT for a total on-source integration time of nearly 85 minutes over two sessions on 2006 August 5–6 as part of program GBT06B-052. The source was observed in two frequencies corresponding to the H\textsc{i} 21 cm and OH 18 cm transitions at the redshift of the foreground galaxy. Unfortunately, the OH data were corrupted by severe interference and were rendered unusable, so hereafter we only discuss the 21 cm data. We used the dual polarization L-band system with a bandwidth of 12.5 MHz. Nine-level sampling and two intermediate frequency (IF) settings were employed to provide 8196 channels with 12.5 MHz. Nine-level sampling and two intermediate frequency used the dual polarization unusable, so hereafter we only discuss the 21 cm data. We note that the GBT data are corrupted by an RFI feature at $\approx$9880 km s$^{-1}$, so any absorption/emission near that velocity could be difficult to detect, and in some regards it is more effective to use the VLA or VLBA data to search for features there.

4.2. Very Large Array Observations

SDSS J104257.58+074850.5 was observed for 2 hr with the VLA in B-configuration on 2006 June 30 (project ID AT330). Only 22 antennas were available because of the expanded VLA (EVLA) conversion that was occurring at the time. The correlator was configured in the single polarization 2IF mode with 64 spectral channels at a frequency resolution of 48.8 kHz ($\sim$10.6 km s$^{-1}$) per channel to cover a total bandwidth of 3.125 MHz ($\sim$650 km s$^{-1}$). The data were calibrated following the standard VLA calibration and imaging procedure in the Astronomical Image Processing Software (AIPS). Absolute uncertainty in the resulting flux density scaling is about 15%, and this is the formal uncertainty we quote for all physical parameters derived from the flux density.

We show in Figure 9 the 1.4 GHz continuum image from the VLA (contours) overplotted on the SOAR $i$-band image (grayscale). In this figure, the synthesized beam produced using natural weighting is 5'8 $\times$ 5'5 (P.A. = $-73^\circ$). The 1.4 GHz continuum image shows a compact source, which is unresolved by the VLA, centered at $\alpha(J2000) = 10^{h}42^{m}41^{s}.58$ and $\delta(J2000) = +07^{d}48^{m}58^{s}.50$ with a peak flux density of 395 $\pm$ 59 mJy.\footnote{The 1$\sigma$ noise in the continuum image is about 0.2 mJy beam$^{-1}$, which reflects the dynamic range of the data rather than thermal noise.} This is about 3% larger than the 1.4 GHz flux density of the same source found in the archival VLA FIRST Survey (Becker et al. 1995). However, this difference is well...
within the absolute calibration uncertainty of the VLA. The unresolved radio source is centered on the QSO and is clearly offset from the center of the foreground galaxy by 2.5′ to the southwest.

The continuum-subtracted VLA H\textsc{i} spectrum of SDSS J104257.58+074850.5 covering the velocity range between 9820 km s\(^{-1}\) and 10,150 km s\(^{-1}\) is shown in Figure 7. The rms noise in each 10.6 km s\(^{-1}\) channel map is \(\sim 0.7\) mJy beam\(^{-1}\) (21 K), and no H\textsc{i} is significantly detected in emission. The narrow absorption feature seen at \(V = 9924\) km s\(^{-1}\) is spectrally unresolved with an average optical depth of \(\tau_{\text{H\textsc{i}}} = 0.0101 \pm 0.0018\) (5.6σ) over the 10.6 km s\(^{-1}\) channel width.

4.3. Very Long Baseline Array Observations

The VLBA observations of this source were carried out in two 8 hr observing sessions on the nights of 2008 June 15 and 16 under program ID BY124. Four adjacent 4 MHz baseband channel pairs were used in the observations, with both right- and left-hand circular polarizations, and sampled at 2 bits. The data were correlated at the VLBA correlator in Socorro, New Mexico in two passes. In the first pass, all the baseband channels were correlated with 32 spectral channels per 4 MHz for the purpose of imaging the radio continuum emission. The second correlation pass was performed only on the second pair of baseband channels, which were centered at 9925 km s\(^{-1}\). This produced a data cube with 1024 spectral channels and a resolution of 3.9 kHz (0.9 km s\(^{-1}\)) per channel. The total on-source integration time was 15 hr. Two of the ten VLBA antennas were rendered unusable due to technical problems (Brewster) and data corruption (Mauna Kea). The data reduction was performed using AIPS.

After a priori flagging of data affected by interference in both data sets, amplitude calibration was performed using the measurements of the antenna gains and the system temperatures for each station. Bandpass calibration was performed using 3C 273. The continuum data set was then self-calibrated and imaged in an iterative cycle. Figure 10 shows the continuum image of the background quasar SDSS J104257.58+074850.5 that was obtained using an intermediate grid weighting between pure
natural and pure uniform (Robust = 2) in the IMAGR routine of AIPS. The angular resolution of this image is 21.9 mas × 9.1 mas (P.A. = 3°) and the rms noise is 80 μJy beam⁻¹. At this resolution the source is resolved with peak and integrated flux densities of 272.0 (±0.1) mJy beam⁻¹ and 341.0 (±0.2) mJy, respectively. The spatial extent of the continuum source was fitted with a Gaussian profile that gave a nominal deconvolved size of 8.5 mas × 2.4 mas at FWHM. The radio emission associated with the QSO is core dominated with an extension toward the southwest side of the core indicative of a weak jet-like feature. The visibility amplitude decreases to 50% of the peak at baseline length of ~10 mega lambda, thus confirming the spatial extension of the QSO. The integrated flux measured in our VLBA image was 40.6 mJy less than that of the FIRST VLA survey, which suggests the presence of the faint extended structure that was detected by the VLA but was resolved out by the VLBA.

The self-calibration solutions of the continuum data set were applied to the spectral line data cube, which was then imaged using a similar weighting as the continuum. The continuum emission was then subtracted from the H\textsc{i} cube. The bottom panel of Figure 7 shows the un-smoothed VLBA 21 cm H\textsc{i} spectrum from pixels with at least 400 μJy (5σ) continuum flux. The rms noise in the VLBA spectrum is 2 mJy beam⁻¹. Again, absorption near the redshift of GQ1042+0747 is readily apparent. A comparison of the VLBA and the GBT spectra binned at the same resolution is shown in the lower panel of Figure 8. To estimate the column density, we included channels within the velocity range 9913–9930 km s⁻¹. In order to minimize the effect of noise in the optical depth cube and the column density measurement, we blanked (removed) the pixels where the continuum emission was less than 100 mJy.

5. 21 cm MEASUREMENTS

5.1. 21 cm Component Structure and Kinematics

As shown in Figure 7, the H\textsc{i} 21 cm absorber in the foreground of SDSS J104257.58+074850.5 is confirmed by our observations using the GBT, the VLA, and the VLBA. While the GBT spectra provide the highest spectral resolution, the VLBA imaging complements the GBT data by providing high angular resolution. Independent observations with the three telescopes are also helpful for overcoming systematic problems specific to one facility, e.g., the RFI problem at ν ≈ 9880 km s⁻¹ in the GBT data.

The H\textsc{i} absorber detected by the GBT has a primary component consistent with a single Gaussian profile with a centroid at

![Figure 9. VLA B-array 1.4 GHz continuum image of SDSS J104257.58+074850.5 (contours) overplotted on the SOAR i-band image (grayscale). The resolution achieved in this image is 6". The contours are plotted at 50, 100, 200, 300, and 380 mJy beam⁻¹. The quasar is unresolved, and the extent of the contours reflects the VLA beam size in this configuration.](image)

![Figure 10. Center panel: the VBLA 21 cm continuum image of the radio-bright quasar SDSS J104257.58+074850.5 (grayscale and contours). The continuum emission contours are plotted in linear increments of −4, 4, 8, 16, 32, 64, 128, 256, 512, 1024, and 2048 of the rms flux of 80 μJy beam⁻¹, and the grayscale follows the scale bar on the right side of the central panel; the beam size and orientation are shown in the inset. The quasar is modestly resolved with peak and integrated flux densities of 272 (±0.1) mJy beam⁻¹ and 341 (±0.2) mJy, respectively. Side panels: H\textsc{i} 21 cm absorption spectra from the foreground galaxy GQ1042+0747 extracted from the four independent regions to the background quasar indicated with boxes overlaid on the continuum image. Each H\textsc{i} 21 cm absorption panel is connected to the box indicating the region from which it was extracted. For purposes of comparison, all of the spectral plots are plotted with the same axis scales, and the velocity 9924 km s⁻¹ is marked for reference (the optical redshift of the foreground galaxy is 9932 ± 10 km s⁻¹).](image)
9923.97 ± 0.17 km s\(^{-1}\) or 1374.89 ± 0.0007 MHz (\(\Delta v_{\text{abs}} = 0.033103\)) and a FWHM of 3.6 ± 0.4 km s\(^{-1}\). A weaker component (∼2.3σ) can be seen at 9917.6 km s\(^{-1}\). Close inspection of Figure 8 reveals a possible third component at ∼9927 km s\(^{-1}\), but the significance of this third feature is marginal. Figure 8 shows the fit of a single Gaussian profile to the primary component of the H\(\alpha\) absorption in the continuum subtracted GBT spectrum. The width of the Gaussian could be slightly overestimated due to blending with the tentative third component at 9927 km s\(^{-1}\). Given the marginal significance of the third component, we have elected to fit the main component as shown in Figure 8 so that our line width places a conservative upper limit on the kinetic temperature of the absorbing gas (see Section 5.3). The bottom panel of Figure 8 shows a comparison of the GBT and the VLBA spectra. The profiles show similar peak absorption flux and line shapes for the primary component. However, the second component is much more prominent (4.6σ) in the VLBA spectrum and is slightly shifted in velocity (\(v = 9920\) km s\(^{-1}\)). The redshift measured from our highest resolution GBT H\(\alpha\) data is ∼8 km s\(^{-1}\) lower than the redshift derived from the H\(\alpha\) data, but is well within the uncertainty. In principle, the optical redshift could represent the systemic redshift of the galaxy. However, all of our optical spectra (from SDSS and APO) that detect the foreground galaxy emission lines are measured at the position of the QSO. As we can see from Figures 2 and 3, this position is offset from the galaxy center, and it is likely that at this location, the H\(\beta\) regions that produce the optical emission lines are rotating with the disk of the galaxy. The good agreement of the optical and 21 cm redshifts suggests that the 21 cm absorption arises in the disk and is corotating with the H\(\beta\) regions and the disk. The kinematical quiescence of the 21 cm absorbing gas warrants comment—as discussed in Section 1, high-z DLAs and sub-DLAs (e.g., Meiring et al. 2009) are noted for complex gas kinematics, which likely plays an important role in how the DLAs evolve. The 21 cm absorption traces the neutral gas, and we see no evidence of complex kinematics in the neutral gas along our sight line through GQ1042+0747. We are likely detecting an ordinary gas cloud in the disk of the galaxy.

5.2. Spatial Variability of the 21 cm Absorption

One of the broad goals of this project is to investigate the transverse spatial distribution of the absorbing gas by taking advantage of the extended nature of QSOs at radio frequencies. For this purpose, Figures 10, 11, and 12 provide more detailed presentations of the spatial structure of the 21 cm absorption. Figure 10 shows the high-resolution VLBA continuum image of the background QSO along with H\(\alpha\) absorption spectra extracted from four different regions—northwest, northeast, southwest, and southeast. Each region is roughly the size of the synthesized beams. To facilitate detailed comparisons, Figure 11 overplots the spectra from the northwest, northeast, and southeast regions on top of the spectrum from the southwest region. From these comparisons, we note the following trends: first, as the regions move from west to east, the peak absorption flux in the main component increases and the velocity centroids shift to slightly higher velocities. Second, the weaker component (at \(v \approx 9920\) km s\(^{-1}\)) is evident in all of the VLBA regions with its maximum strength in the west (3.1σ in the southeast and southwest) and weakest in the northeast (1.8σ). Both components appear to be narrower on the eastern side, but this could be simply due to more blending on the Western side if the velocity centroids of the two components are shifting closer together in the west. The spatial variation in the strength of the absorber for each spectral channel is shown in Figure 12 where the absorption feature contours are superposed on the continuum image shown in grayscale. Each velocity plane is independent and the noise should not correlate between the images.

In the main component, the absorber covers most of the background quasars at the resolution of the VLBA imaging. The extent of the H\(\alpha\) cloud as measured from the region with at least 4σ H\(\alpha\) detection is 41 mas × 21 mas on the plane of the sky, which corresponds to a physical size of 27.1 pc × 13.9 pc at the redshift of the absorber. The similarity in peak absorption flux between the GBT and VLBA profiles suggest that the absorption is associated with the same absorber. Since the GBT beam is much larger, it is possible that the GBT spectrum includes absorption from an entirely different cloud than the gas that imprints the absorption on the VLBA spectrum. However, we would intuitively expect a separate and independent cloud to have different kinematics, which in turn would cause the GBT absorption profile to have a different shape from the VLBA absorption. Also, in this case, since the QSO is not very extended...
(the VLBA flux density is just ≈40 mJy lower than the flux from VLA FIRST Survey) and the absorber is very narrow, it is unlikely that there are multiple clouds associated with the absorber.

5.3. Kinetic Temperature of the H\textsubscript{i} 21 cm Absorber

Interstellar neutral gas in disk galaxies is believed to be distributed in two distinct physical phases—the warm neutral medium (WNM) and the cold neutral medium (CNM). While the WNM is diffuse and has a temperature in the range of 5000–8000 K, the CNM exists as clumpy dense clouds with temperatures in the range of 20–250 K (Kulkarni & Heiles 1988). This has been confirmed in numerous extragalactic studies including Young & Lo (1997a, 1997b), Carilli et al. (1998), and Lane et al. (2000).

The width of an absorption line can be used to derive an upper limit on the kinetic temperature of the gas, assuming the line width is predominantly due to thermal broadening (this is an upper limit because other factors, e.g., turbulence, can also broaden the line). For neutral hydrogen, the kinetic temperature upper limit can be estimated using

\[ T_k \leq 21.855 (\Delta v)^2, \]

where \( \Delta v \) is the FWHM velocity in km s\(^{-1}\). Based on the Gaussian fitting from our high resolution GBT data, we estimate that the FWHM of the absorption feature is 3.6 km s\(^{-1}\), which indicates that

\[ T_k \leq 283 \text{ K}. \]

Thus, the temperature suggests that the 21 cm absorption arises in the CNM of GQ1042+0747.

5.4. H\textsubscript{i} Column Density and Volume Density

With the temperature constraint afforded by the high spectral resolution of the data, the H\textsubscript{i} column density can be estimated by integrating over the 21 cm absorption profile using the standard equation (e.g., Rohlfs & Wilson 1986):

\[
N(H_1) = 1.823 \times 10^{18} \frac{f}{T_s} \int \tau_{21}(v) dv, \tag{8}
\]

where \( T_s \) is the spin temperature, \( f \) is the fraction of the radio flux source that is covered by the absorbing gas and is assumed to be unity, and \( \tau_{21}(v) \) is the 21 cm optical depth in velocity space (in km s\(^{-1}\)). In the GBT spectra the peak optical depth was measured to be 0.076 ± 0.011. Given the context of the absorption (i.e., arising in the disk of a spiral galaxy), it is likely that the density is high enough so that the level populations of the H\textsubscript{i} hyperfine structure levels are set predominantly by collisions. Thus we can assume that \( T_s \approx T_k \). With \( T_k \leq 283 \text{ K} \) (Section 5.3), we obtain

\[
N(H_1)_{\text{GBT}} \leq 9.6 \times 10^{19} \text{ cm}^{-2} \tag{9}
\]

by integrating over the main absorption line detected with the GBT. This indicates that the 21 cm absorber is not quite a DLA absorber according to the usual definition. This is somewhat surprising given the small impact parameter of the sight line to an actively star-forming spiral galaxy. We discuss this further in Section 6. However, if we apply the same procedure to the VLBA data to extract the overall H\textsubscript{i} profile for pixels with continuum flux \( \geq 100 \text{ mJy} \), we obtain

\[
N(H_1)_{\text{VLBA}} \leq 1.5 \times 10^{20} \text{ cm}^{-2}. \tag{10}
\]

The difference between the GBT and the VLBA column density constraints could result from a difference in the covering fraction (\( f \)) between the two observations. Since the VLBA resolves out the source, the angular extent of the continuum source could be smaller for the VLBA than the GBT, so although the covering fraction estimated from the VLBA observations is ~1, the covering fraction for the GBT observations could be lower than 1. We note from Figure 11 that while the VLBA centroids of
the main absorption component (at \( v \approx 9924 \text{ km s}^{-1} \)) match up well with the centroid of that component indicated by the GBT data, the GBT centroid of the weaker feature (at \( 9917.6 \text{ km s}^{-1} \)) is slightly offset to shorter velocities compared to the velocity of that component in the VLBA spectra. This could also be an indication that some of the GBT absorption at \( 9917.6 \text{ km s}^{-1} \) occurs outside the continuum region detected by the VLBA.

In Section 5.2, we showed that there is some subtle spatial variability of the 21 cm absorption, but overall, similar absorption is detected in all directions probed with the VLBA data. This indicates that the dimensions of the absorbing cloud are at least 27.1 pc \( \times \) 13.9 pc. Assuming the cloud to be an ellipsoid that has a spin temperature of 283 K, the estimated \( \text{H}_i \) mass limit for this cloud is 356.10 \( M_\odot \). If we take \( \approx 14 \text{ pc} \) as the minimum line-of-sight size of the cloud and combine this with the VLBA upper limit on \( N(\text{H}_i) \), we find that the volume density of the gas is:

\[
n(\text{H}_i) < 3.5 \text{ cm}^{-3}. \tag{11}
\]

While the cloud size implied by the VLBA data is consistent with expectations for a CNM cloud, this upper limit on \( n(\text{H}_i) \) is an order of magnitude lower than expected for the CNM (compare Jorgenson et al. 2009; Tielens 2005). It is worth noting that our density values are based on the assumption that the line-of-sight length of the absorbing cloud is 14 pc. Since the VLBA absorption region of 27 pc \( \times \) 14 pc transverse to the sight line covers almost the entire continuum source with an extension in the northwest–southeast direction, it may be possible that the absorbing cloud extends beyond the region probed by the VLBA continuum data. Therefore, our size measurement is a limiting value and the line-of-sight length of 14 pc is a conservative lower limit. If the absorbing cloud is larger, then the implied number density is even lower, which further exacerbates the discrepancy with the typical density expected in CNM regions. Of course, it is possible that the cloud contains high-density internal clumps that are much smaller than the VLBA beam. In this case, the line-of-sight length could be lower and the density could be higher. However, in this situation we might expect to see more dramatic spatial variability in the VLBA absorption profiles. We do note some weak variability in the VLBA profiles, but overall the four VLBA sight lines show the same basic profile shapes (see Figure 10). This suggests that the absorbing cloud extends across the entire region probed by the VLBA data. We have not estimated the effects of ISM scintillation and microlensing on the apparent size of the emitting region. Such assessment is beyond the scope of this discussion.

5.5. Total \( \text{H}_i \) Mass of GQ1042+0747

Our 21 cm spectra show no indication of \( \text{H}_i \) emission associated with the foreground galaxy (see Figure 7). The absence of 21 cm emission provides an upper limit on the total \( \text{H}_i \) mass of GQ1042+0747. Based on the GBT noise properties and assuming a line width of 100 km s\(^{-1}\), we estimate a 3\( \sigma \) \( \text{H}_i \) mass limit of less than \( 5.1 \times 10^5 \; M_\odot \) for the foreground galaxy. This is an order of magnitude less than the \( \text{H}_i \) mass associated with a typical luminous spiral galaxy (\( L \sim L_* \)). However, GQ1042+0747 has \( L \ll L_* \), and this upper limit on \( M(\text{H}_i) \) is entirely consistent with the \( \text{H}_i \) masses measured in dwarf galaxies (e.g., Matthews et al. 1995, 1996, 1998; Swaters et al. 2002; Begum et al. 2008). Our GBT data should provide the most stringent limits on \( M(\text{H}_i) \) for any narrow features with \( \Delta V \sim 100 \text{ km s}^{-1} \). The GBT spectra suffered from sinusoidal standing waves as commonly found when observing bright continuum sources and consequently broad and faint features of the order \( \Delta V \geq 300 \text{ km s}^{-1} \) may have been missed. We also examined the ALFALFA data (R. Giovannelli 2009, private communication) which show signs of a moderate enhancement from 9775 to 10078 km s\(^{-1}\). This corresponds to an \( \text{H}_i \) mass of \( 4.5 \times 10^8 \; M_\odot \). However, the ALFALFA data also show signs of sinusoidal modulations thus adding a significantly large uncertainty to the mass estimation. We plan to observe GQ1042+0747 with the Arecibo Telescope to correctly estimate its \( \text{H}_i \) mass. The next section discusses the implications of the \( \text{H}_i \) mass of GQ1042+0747 and compares the galaxy to \( \text{H}_i \) emission from other dwarf galaxies.

6. DISCUSSION

6.1. \( \text{H}_i \) Deficiency: Evidence of Gas Consumption in an Isolated Environment?

High-resolution \( \text{H}_i \) surveys of dwarf and irregular galaxies such as the Westerbork observations of neutral hydrogen in Irregular and SPriral galaxies (WHISP) Survey (Swaters et al. 2002) or the Faint Irregular Galaxy GMRT Survey (FIGGS; Begum et al. 2008) generally find dwarf galaxies to have \( \text{H}_i \) envelopes extending over much larger area than their optical disks. However, our radio observations of the QSO sight line that pierce the inner disk of GQ1042+0747 reveal that the galaxy is surprisingly \( \text{H}_i \) deficient in several ways. Although we detect a cold \( \text{H}_i \) cloud in this galaxy, it is a sub-DLA at best, unlike what is expected from emission maps of similar galaxies from the WHISP and FIGGS surveys. Likewise, by combining the \( \text{H}_i \) column density with constraints on the size of the absorbing cloud from the VLBA data, we find that \( n(\text{H}_i) < 3.5 \text{ cm}^{-3} \), which is roughly an order of magnitude lower than expected for a CNM cloud. Here, we attempt to understand if GQ1042+0747 which appears to be an ordinary dwarf spiral in optical imaging with ongoing star formation, is consistent with \( \text{H}_i \) emission studies of dwarf galaxies or if GQ1042+0747 is a special case.

In order to understand the discrepancy between dwarf \( \text{H}_i \) galaxies and GQ1042+0747, it is important to analyze any possible bias between our selection criterion and that of the above mentioned surveys. Since GQ1042+0747 was identified using optical emission lines, our selection criteria differ from those of WHISP and FIGGS, which are \( \text{H}_i \) selected, i.e., a criterion for including the galaxies in these surveys in the first place was that they were already known to have detectable \( \text{H}_i \) emission. This could introduce a problematic bias when comparing their properties to GQ1042+0747. It is possible that galaxies such as GQ1042+0747 belong to a different population of dwarf galaxies than the \( \text{H}_i \)-rich dwarfs commonly seen in \( \text{H}_i \) surveys.

We believe the most appropriate way to understand the nature of GQ1042+0747 is to compare it with a dwarf galaxy sample which was not \( \text{H}_i \) selected. In a series of papers, Matthews and Gallagher surveyed the \( \text{H}_i \) emission properties of a sample of faint "extreme late-type" galaxies selected to have no published \( \text{H}_i \) information before their survey (e.g., Gallagher et al. 1995; Matthews et al. 1995, 1996). They found a range of modestly to highly gas-rich galaxies with \( \text{H}_i \) masses and optical properties consistent with our constraints on GQ1042+0747. In a follow-up study of isolated extreme late-type galaxies, Matthews et al. (1998) argue that these galaxies are not "scaled-down" versions of luminous gas-rich galaxies. Instead, they find that the extreme...
late-type galaxies often form stars sluggishly compared to more luminous late-type galaxies.

These results of Matthews et al. (1998) suggest a possible class of dwarf galaxies with properties similar to GQ1042+0747. In Section 3.4, we showed that GQ1042+0747 is an isolated galaxy at the edge of a large-scale structure (see Figure 6). If this dwarf galaxy is forming stars relatively slowly like the extreme late-type galaxies of Matthews et al. (1998), it may be gradually consuming its gas reservoir without being replenished with fresh gas from its intergalactic surroundings or from interactions with other galaxies.

A variation of this hypothesis is that for some reason, this galaxy is not able to efficiently transport gas into the inner region probed by the SDSS J104257.58+074850.5 sight line so that the H$_i$ is depleted in its central regions thereby creating an H$_i$ gap/hole. Interestingly, similar H$_i$ gaps/holes have been reported in H$_i$-selected dwarf galaxies such as DDO43 by Begum et al. (2008). In addition, close inspection of the WHISP H$_i$ maps reveals other galaxies with similar patchy H$_i$ distributions with lower H$_i$ intensities in some parts of their inner regions. It would be interesting to reobserve GQ1042+0747 galaxy with higher angular resolution with the upcoming Atacama Large Millimeter Array to explore the distribution and physical properties of the molecular gas. High-resolution Hubble Space Telescope (HST) imaging would also provide insight about the star-formation history in GQ1042+0747.

### 6.2. Quiescent Neutral Gas

Another possible explanation for the low amount of H$_i$ revealed by our observations is that gas in the central region of the galaxy has been partially evacuated by a galactic outflow, either a bound galactic fountain or an escaping galactic wind. Such outflows have been observed in nearby starburst galaxies (Veilleux et al. 2005, and references therein), and indications of a bound outflow have been seen in the central region of the Milky Way (e.g., Bland-Hawthorn & Cohen 2003; Keeney et al. 2006). It has long been known that there is a deficit of extraplanar H$_i$ in the inner 3 kpc of the Milky Way (Lockman 1984), which could be due to expulsion of H$_i$ from the inner Galaxy by some type of outflow (e.g., Everett et al. 2008).

If this type of outflow is driving gas out of the inner region of GQ1042+0747, then we might expect to see kinematical evidence of the outflowing gas (as was done in, e.g., Keeney et al. 2006). However, contrary to the kinematics seen in the metal-line absorption profiles of many high-$z$ DLAs (e.g., Prochaska & Wolfe 1997), the 21 cm H$_i$ line profile of GQ1042+0747 is quite simple, and we see no indications of outflowing neutral gas. However, there are some caveats. We might not detect the outflowing neutral gas if the spin temperature is too high or the covering factor is low. Conversely, the kinematics of high-$z$ galaxies are often traced by species, such as Si II, that can exist in ionized gas as well as neutral gas, and it is possible that the complex kinematics of the high-$z$ systems could be partly due to ionized gas that we would not see in 21 cm absorption. To test this possibility, it would be valuable to observe SDSS J104257.58+074850.5 in the ultraviolet with the Cosmic Origins Spectrograph (COS) on HST. Ultraviolet spectra provide sensitive probes of ionized gas, and the combination of the UV and 21 cm data would provide a direct measurement of the spin temperature of the neutral gas. It is also plausible that a WNM is present in this galaxy; if the WNM has a sufficiently large velocity dispersion and low optical depth, then such features could be lost in the process of baseline fitting. This can also be tested with COS observations using O I absorption lines, which are locked to the neutral gas by a resonant charge exchange reaction.

In Section 1, we discussed the need to probe the signatures of neutral gas that exists in different contexts. Of course, this requires a sample that is large enough to support statistically significant conclusions, but it is interesting to note that if we make the reasonable assumption that $T_G \approx T_e$ and we adopt the metallicities from the optical emission lines (Table 2), then we find that the spin temperature in GQ1042+0747 adheres to the spin temperature–metallicity relation recently presented by Kanekar et al. (2009). They discuss several hypotheses for the cause of this correlation and conclude that the increase in the number of possible radiative pathways for cooling gas with an increase in metallicity is the likely cause. Extending their argument to the case of GQ1042+0747, it seems likely that the higher metallicity in the inner disk of GQ1042+0747 causes the gas to cool more rapidly. Many high-$z$ DLAs are known to have higher spin temperatures (Kanekar & Chengalur 2005). The high-$T_e$ absorbers could originate in outer disks (or tidal/dynamical debris) where the densities and metallicities are lower and the cooling times are longer. However, it is also possible that the cooling times are longer simply because high-$z$ galaxies have substantially lower metallicities. It would be interesting to place constraints on $T_e$ in a sample of nearby galaxies probed at a range of impact parameters and with a range of galaxy properties.

### 7. SUMMARY AND CONCLUDING REMARKS

The SDSS presents a remarkable (and largely untapped) opportunity to study gas that is difficult to observe in low-redshift galaxies/groupings for observing absorption imprinted on the spectra of quasars that happen to be located in the foreground of galaxies of interest. While the SDSS obtains spectra of these background quasars, the spectra have somewhat low resolution and sensitivity for absorption spectroscopy and only cover the optical band. Thus, while the SDSS provides an invaluable database for selecting background QSO-galaxy groupings for this type of study, follow-up observations with higher resolution instruments and in other frequency bands will be required to fully exploit the technique. To demonstrate the potential of SDSS for 21 cm studies of this type, we have observed with the GBT, VLA, and VLBA the radio-loud quasar SDSS J104257.58+074850.5 that pierces a foreground star-forming spiral galaxy (GQ1042+0747) at a very small impact parameter. To complement the 21 cm observations, we have also obtained images with the SOAR telescope (which provides better angular resolution than the SDSS imaging) and follow-up spectroscopy with the APO 3.5 m telescope. From this suite of observations, we have obtained the following results.

1. The high-resolution optical imaging with SOAR shows that the foreground galaxy is a low-luminosity spiral galaxy, and the quasar sight line is at a projected distance of 2.5 from the center of the foreground galaxy, which corresponds to an impact parameter of 1.7 kpc for our assumed cosmology. The emission lines of the foreground galaxy imply a SFR surface density of 0.004 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ and a metallicity of $-0.27 \pm 0.05$ dex relative to solar. The optical Hα/HI ratio also indicates that the galaxy has a low dust content, at least in the region encompassed by the 3” SDSS fiber (3.1 kpc$^2$) centered at the position of the background QSO.
The galaxy colors indicate that its approximate stellar mass is $M_{\text{star}} \approx 10^{9.1} M_\odot$.

2. Using larger-scale information about the distribution of galaxies in the vicinity of the foreground galaxy from the SDSS, we find that this object is a relatively isolated galaxy near the boundary of a large-scale structure.

3. The spectra obtained with the GBT, VLA, and VLBA independently reveal H I 21 cm absorption in the spectrum of the background QSO at the redshift of foreground galaxy. Two components separated by $\approx 5$ km s$^{-1}$ are evident in the GBT and VLBA spectra; a third feature may be present but is only recorded at marginal significance. However, it is clear that the absorption profiles indicate simple and quiescent kinematics. The high spectral resolution of the GBT data places a strong upper limit on the kinetic temperature of the 21 cm absorbing gas in the strongest component, $T_k \leq 283$ K.

4. The background QSO is relatively compact, but nevertheless the VLBA observations resolve the continuum emission source and enable a preliminary search for small-scale spatial variability in the 21 cm absorption arising in the foreground galaxy. We find variations in the optical depth and centroids of the 21 cm absorption from four independent sight lines through GQ1042+0747 extracted from the VLBA data, but the variations are at a low level, and overall the absorption detected in the four regions shows similar optical depths and component structure. This indicates that the main absorbing cloud covers most of the continuum region detected with the VLBA and has dimensions of at least $27.1$ pc $\times 13.9$ pc.

5. Combining the upper limit on the kinetic temperature with the large covering factor indicated by the VLBA data, we obtain $N(\text{H}^+) < 9.6 \times 10^{19}$ cm$^{-2}$ from the GBT data and $N(\text{H}^+) < 1.5 \times 10^{20}$ cm$^{-2}$ from the VLBA data; the difference may be due to differences in the region probed by the large-beam single-dish telescope versus the small-beam interferometer. The lower limit on the size of the main absorbing cloud combined with the VLBA $N(\text{H}^+)$ constraint indicates that the H I volume density is less than $3.5$ cm$^{-3}$.

6. We offer some remarks about the implications of our measurements. We suggest that GQ1042+0747 provides information about how the stars and gas in an isolated galaxy evolve if left largely undisturbed. It appears that the gas in the inner region of the galaxy is being depleted (compared to other spirals) by conversion to stars without being replenished with inflowing matter. It seems unlikely that an outflow is depleting the gas; we see no evidence of outflowing material, but further observations are required to properly search for such outflows. The galaxy follows the spin temperature–metallicity relation seen in higher-redshift DLAs.

The present understanding of H I clouds and their characteristics on parsec scales outside our own galaxy is quite limited. This is pathfinding work for future 21 cm absorber investigations. With upcoming facilities like the EVLA providing higher spectral resolution, larger bandwidth, and smaller beam size, 21 cm absorbers will likely be detected in galaxies toward background QSOs much more efficiently. Moreover, the RFI environment for EVLA is expected to be different from single-dish instruments, which may be very helpful in cases affected by local RFIs. This will enable detailed studies of the nature and distribution of cold gas in galaxies at different distances from the disk. This is also a useful technique for assembling a DLA/sub-DLA sample for future UV and/or optical spectroscopic studies that is not metallicity biased. Combining our understanding of the cold component traced by 21 cm H I absorbers with the warmer component traced by Ly$\alpha$ and metal absorbers will be valuable for understanding the nature, physical conditions, dynamics, and the role of neutral clouds in galaxy evolution.

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