THE ALFALFA H\textsc{i} ABSORPTION PILOT SURVEY: A WIDE-AREA BLIND DAMPED Ly\textalpha SYSTEM SURVEY OF THE LOCAL UNIVERSE

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ABSTRACT

We present the results of a pilot survey for neutral hydrogen (H\textsc{i}) 21 cm absorption in the Arcibo Legacy Fast Arcibo L-Band Feed Array (ALFALFA) Survey. This project is a wide-area “blind” search for H\textsc{i} absorption in the local universe, spanning \(-650 \, \text{km} \, \text{s}^{-1} < c \, z < 17,500 \, \text{km} \, \text{s}^{-1}\) and covering 517.0 \, \text{deg}^2 (7\% of the full ALFALFA survey). The survey is sensitive to H\textsc{i} absorption lines stronger than 7.7 mJy (8983 radio sources) and is 90\% complete for lines stronger than 11.0 mJy (7296 sources). The total redshift interval sensitive to all damped Ly\textalpha (DLA) systems ($N_{\text{HI}} \geq 2 \times 10^{20}$\,\text{cm}\textsuperscript{-2}) is $\Delta z = 7.0$ (129 objects, assuming $T_e = 100$ \,K and covering fraction unity); for super-DLAs ($N_{\text{HI}} \geq 2 \times 10^{21}$\,\text{cm}\textsuperscript{-2}) it is $\Delta z = 128.2$ (2353 objects). We re-detect the intrinsic H\textsc{i} absorption line in UGC 6081 but detect no intervening absorption line systems. We compute a 95\% confidence upper limit on the column density frequency distribution function $f(N_{\text{HI}}, X)$ spanning four orders of magnitude in column density, $10^{19} (T_e/100 \, \text{K}) (1/\text{f})$\,\text{cm}\textsuperscript{-2} < $N_{\text{HI}}$ < $10^{21} (T_e/100 \, \text{K}) (1/\text{f})$\,\text{cm}\textsuperscript{-2}, that is consistent with previous redshifted optical DLA surveys and the aggregate H\textsc{i} 21 cm emission in the local universe. The detection rate is in agreement with extant observations. This pilot survey suggests that an absorption line search of the complete ALFALFA survey—or any higher redshift, larger bandwidth, or more sensitive survey, such as those planned for Square Kilometer Array pathfinders or a low-frequency lunar array—will either make numerous detections or will set a strong statistical lower limit on the typical spin temperature of neutral hydrogen gas.

Key words: methods: observational – quasars: absorption lines – radio lines: galaxies – surveys

1. INTRODUCTION

The neutral hydrogen (H\textsc{i}) 21 cm (1420.405725 MHz) spin-flip transition has long been employed as an emission line tracer of the neutral gas content, surface density profile, kinematics, and dark matter halos of spiral galaxy disks in the local universe. H\textsc{i} 21 cm absorption, however, is rarely observed at low redshift outside of the Galaxy because it relies on the chance alignment of a bright radio source with foreground gas, and the covering fraction of cold neutral gas is low. The very slow Einstein rate coefficient for spontaneous emission, $A_{21 \text{cm}} = 2.87 \times 10^{-15}$\,\text{s}^{-1}, means that a detectable 21 cm line requires either a large gas mass for emission or a high column density for absorption; the latter operationally limits H\textsc{i} 21 cm absorption line studies to damped systems ($N_{\text{HI}} > 2 \times 10^{20}$\,\text{cm}\textsuperscript{-2}). But the comoving density of damped Ly\textalpha (DLA) absorption systems is only $dN/dz = 0.045 \pm 0.006$ per unit redshift at $z = 0$ (Zwaan et al. 2005), so identifying such systems in the local universe ($z < 0.1$) requires examination of many hundreds of sightlines. If they can be found, H\textsc{i} 21 cm absorption lines complement emission lines; while emission line surveys are flux-limited (mass-limited at a fixed distance), absorption line surveys are column-density-limited (at fixed illuminating continuum), independent of distance, and can identify very low mass collections of neutral gas. H\textsc{i} 21 cm absorption line surveys can potentially identify primordial atomic gas, infalling or outgoing gas in the vicinity of galaxies, or spiral disks themselves in a distance- and dust-extinction-independent fashion.

The Arcibo\textsuperscript{7} Legacy Fast Arcibo L-Band Feed Array (ALFALFA) Survey is a 7000 \,\text{deg}^2 extragalactic H\textsc{i} 21 cm emission line survey. Compared to the H\textsc{i} Parkes All Sky Survey (Meyer et al. 2004), the ALFALFA survey is eight times more sensitive, has four times the angular resolution, three times the spectral resolution, and a factor of 1.4 more bandwidth (Giovanelli et al. 2005), and provides the first data set approaching the sensitivity and areal coverage required for a truly “blind” H\textsc{i} 21 cm absorption line search. Such a search is effectively a search for DLAs that does not rely on UV-bright quasar sightlines (and thus can detect dusty DLAs).

In this paper, we describe the ALFALFA H\textsc{i} 21 cm absorption pilot survey, a test of the notion that DLA systems can be detected “blindly” in the local universe in a shallow, large area spectroscopic survey for H\textsc{i} emission from galaxies. We present the methods and results of our survey, along with follow-up observations conducted at the Green Bank Telescope\textsuperscript{8} (GBT), and demonstrate that it is possible to place meaningful upper limits on the column density frequency distribution function. The pilot survey results suggest that a search of the full 7000 \,\text{deg}^2 of the ALFALFA survey for H\textsc{i} 21 cm absorption would be worthwhile, both for understanding cold neutral gas

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in the local universe and in preparation for planned absorption line surveys at high and low redshifts with upcoming new radio telescopic facilities.

2. SEARCHING FOR ABSORPTION LINES IN THE ALFALFA SURVEY

The ALFALFA survey offers the combined sensitivity, areal coverage, and redshift span to make a “blind” H$\text{I}$ 21 cm absorption line search feasible and astrophysically interesting. The complete ALFALFA survey will cover $\sim 7000$ deg$^2$ and is expected to detect more than 25,000 galaxies in H$\text{I}$ 21 cm emission (Giovanelli et al. 2005). The data products of the survey are dual-polarization $2.4 \times 2.4$ 1024-channel spectral data cubes spanning 25 MHz each. There are four spectrally overlapping cubes per sky position spanning the range $-2000 < cz < 17,900$ km s$^{-1}$ (Giovanelli et al. 2005). The rms noise per spectral channel after smoothing to 10 km s$^{-1}$ is 2.2 mJy (Saintonge 2007).

Our ALFALFA H$\text{I}$ absorption pilot survey examines a 517 deg$^2$ subset of the mature ALFALFA data product in the northern Virgo Cluster region, spanning $10.9^h < \alpha < 14.95^h$ and $+7^\circ \leq \delta < +16^\circ.3$ (122 spectral cubes). We omit a 1.6 deg$^2$ region centered on M87; the strong radio source in M87 (220 Jy at 1.4 GHz) creates spectral standing waves that render this region inaccessible to weak line spectroscopy with Arecibo (Giovanelli et al. 2007).

Figure 1 shows the survey area and distribution of radio sources with 8.4 mJy $< S(1.4$ GHz $) < 5.3$ Jy. We searched a velocity range $-650$ km s$^{-1} < cz < 17,500$ km s$^{-1}$, with notable gaps due to radio frequency interference or Galactic H$\text{I}$ emission at $cz = 0$, 2200, 3300, and 8800 km s$^{-1}$ of about 200 km s$^{-1}$ width plus a large gap at 15,000–16,000 km s$^{-1}$ (Giovanelli et al. 2007). The gaps in the spectral coverage render $\sim 10\%$ of the line velocity range unsearchable. The net search covers $\Delta z = 0.054$ along each line of sight plus the range $-650$ km s$^{-1} < cz < -100$ km s$^{-1}$. This translates into a comoving path length of $\Delta X = 0.0571 \Delta z$.9

Our line search relies on the optimized matched filter detection methods developed by Saintonge (2007): we multiply the continuum-subtracted data cubes by $-1$ and run the line-finding algorithm as if we were searching for narrow Gaussian H$\text{I}$ emission lines. Saintonge (2007) obtains matched filter search completeness (all lines are detected) of 5.5 and 6.5, respectively, for narrow lines in the ALFALFA survey. Our absorption line search used the conventional ALFALFA matched filter $S/N$ of 4.6 to search for lines with central depth greater than $7.7$ mJy toward continuum$^{10}$ sources with flux densities greater than 8.4 mJy (this continuum threshold corresponds to a line center optical depth of 2.5 and a neutral hydrogen column density of $1.4 \times 10^{22}$ cm$^{-2}$ assuming hydrogen spin (21 cm line excitation) temperature $T_\text{L} = 100$ K, a source covering fraction $f$ of unity, and a 30 km s$^{-1}$ FWHM line width). We chose this continuum threshold to allow for the possibility of detecting very large column densities; while expected to be very rare, the number of sources probing such regimes on the sky is large. Our low S/N threshold does identify many spurious absorption lines, which we subsequently assess using five criteria: (1) association with NVSS radio sources (the 45$^\circ$ NRAO VLA Sky Survey (NVSS) beam is well matched to the 1$'$ ALFALFA pixels), (2) similar line properties in both linear polarizations, (3) unresolved angular size, (4) no association with radio frequency interference, and (5) no association with spectral standing waves. Possible absorption lines that meet these criteria were subsequently re-observed with the GBT (Section 3).

The vast majority of lines detected using our S/N threshold of 4.6 were obviously spurious in large part because we were searching below the reliability threshold. For the calculation of column density statistics (Section 5), we require confidence that detected lines are real (reliability) and that a non-detection is in fact a non-detection (completeness), so we impose the more severe S/N cut of 6.5, corresponding to the Saintonge (2007) estimate of the 90% completeness limit. For the Gaussian narrow line template with FWHM of 30 km s$^{-1}$, this corresponds to a line peak of 11.0 mJy. Allowing for opaque lines, we make a continuum cut at the same level. For the full line search, there are 8983 radio sources with $S(1.4$ GHz $) > 8.4$ mJy, but for the restricted column density statistics, we reduced the sample to 7296 sources with $S(1.4$ GHz $) > 11.0$ mJy. The distribution of continua for the full sample is shown in Figure 2.

Supplemental observations were required for two samples: candidate H$\text{I}$ absorption systems and strong continuum sources. Strong sources create spectral standing waves between the primary reflector and the superstructure blocking the aperture of Arecibo, frustrating the detection of weak lines. It is possible that a technique can someday be developed which replicates

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9 We assume $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$ cosmology (Komatsu et al. 2011). Making no assumptions about global curvature, $\Omega_k = 1 - \Omega_\Lambda - \Omega_m$, the comoving path length is $\Delta X = \int_{cz}^{cz_{max}} dz(1+z)^2 / \sqrt{(1+z)^2c^2(1+z\Delta z) - (z_0+2\Delta z) \Omega_k}$, where $\Delta z = 0.054$ along each line of sight plus the range $-650$ km s$^{-1} < cz < -100$ km s$^{-1}$. We use the $\Delta X$ quantity only in the calculation of the column density frequency distribution function (Section 5); otherwise, $\Delta z$ is used to describe the survey.

10 All radio continua used in the selection of sources and the analysis of survey results were obtained from the NRAO VLA Sky Survey (NVSS) catalog and represent integrated flux densities (Condon et al. 1998).
the “double position-switching” mode of Arecibo in software using continuum templates within the survey data. But in the meantime, it was necessary to observe strong continuum sources, \( S(1.4\, \text{GHz}) > 220\, \text{mJy} \), individually (Section 3). The strong sources in our sample span the range 220 mJy < \( S(1.4\, \text{GHz}) < 5.3\, \text{Jy} \) (and exclude M87 at 220 Jy), but the majority fall in the range 220–500 mJy.

3. OBSERVATIONS AND DATA REDUCTION

We observed 13 candidate absorption systems and 250 “strong” sources (NVSS flux density greater than 220 mJy) with the GBT in 2008 April through August. The GBT is particularly well suited for weak spectral line detection toward strong continuum sources thanks to its unblocked aperture. Observations of all sources were designed to mimic the spectral resolution, spectral coverage, and sensitivity of the ALFALFA survey.

For the follow-up observations of line candidates, we observed for a total of 10 minutes on-source in a 5 minute position-switched mode using two linear polarizations, 9 level sampling, 6 s records, and a 50 MHz bandwidth centered on the tentative line. The strong sources were observed in a search mode using two overlapping 50 MHz bands spanning 95 MHz from 1335.4 to 1430.4 MHz (\( cz = -2090 \) to 19,080 km s\(^{-1}\)) for 5 minutes on-source with a reference “Off” spectrum recorded roughly every fifth source. We used two linear polarizations, 9-level sampling, and 3 s records. For all observations, a calibration diode signal was injected for half of each record.

Each individual off-source-flattened and calibrated spectral record was manually examined and flagged for RFI, then averaged in time and polarization. After polynomial baseline subtraction, we achieved 1.3 mJy rms noise in 10.4 km s\(^{-1}\) channels (at 1400 MHz) toward the candidate absorbers after Hanning and Gaussian smoothing and averaging polarizations. We reached 2.2 ± 0.2 mJy rms noise toward the 151 strong sources with continua in the range 220–370 mJy, 2.5 ± 0.3 mJy toward the 83 sources of 370–1000 mJy, 2.8 ± 0.3 mJy toward the 12 sources of 1.0–2.0 Jy, and 4.3 ± 1.2 mJy toward the 4 sources of 2.0–5.3 Jy (the quoted uncertainties span the range of rms noise values in each source grouping). All GBT data reduction and analysis was performed with GBTIDL.\(^{11}\)

4. RESULTS

4.1. Column Density Limits

We made no new detections of H\(^\text{I}\) 21 cm absorption (intrinsic or intervening) in the pilot survey: no ALFALFA absorption line candidates were confirmed by GBT observations, and no strong sources observed with the GBT show absorption lines. Despite the lack of new detections, the uniform data set and large number of continuum sources in the survey allow us to place limits on the column density frequency distribution function \( f(N,X) \) (Section 5). Each non-detection of H\(^\text{I}\) absorption toward a radio continuum source places an upper limit on the H\(^\text{I}\) column density of

\[
N(\text{H}\, ^{\text{I}}) < 1.8 \times 10^{18} \left( \frac{T_s}{f} \right) 1.064 \, \text{FWHM} \cdot \tau \, \text{cm}^{-2},
\]

where the limit on optical depth is set by \( S/N = 6.5 \) corresponding to the completeness limit,

\[
\tau < -\ln \left( 1 - \frac{11 \, \text{mJy}}{S(1.4\, \text{GHz})} \right).
\]

and we assume the minimum FWHM matched filter template line width used for the search, 30 km s\(^{-1}\). For the strong sources observed independently at the GBT, we adjust the 11 mJy line limit above according to the rms noise: it is unchanged for the 220–370 mJy sources (2.2 mJy rms), but increases to 28 mJy for the strongest source at 5.3 Jy. We can generally detect any DLA toward the strong sources. Figure 3 shows the redshift path searched for each column density limit.

For a source covering fraction of unity and a spin temperature \( T_s = 100 \, \text{K} \), the total redshift interval sensitive to all DLA systems (\( N_{\text{HI}} \geq 2 \times 10^{20} \, \text{cm}^{-2} \)) is \( \Delta z = 7.0 \) (129 objects); for super-DLAs (\( N_{\text{HI}} \geq 2 \times 10^{21} \, \text{cm}^{-2} \)) it is \( \Delta z = 128.2 \) (2353 objects). The lowest detectable column density under these assumptions is \( 3 \times 10^{19} \, \text{cm}^{-2} \) (but see Figure 3).

4.2. Re-detection of Intrinsic H\(^\text{I}\) Absorption in UGC 6081

We have re-detected the strong intrinsic H\(^\text{I}\) absorption line in the interacting system UGC 6081 at \( cz = 10,800 \, \text{km s}^{-1} \), previously detected by Bothun & Schommer (1983) and Williams

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\(^{11}\) GBTIDL (http://gbtidl.nrao.edu/) is the data reduction package produced by NRAO and written in the IDL language for the reduction of GBT data.
of the two merging components are consistent with both H\textsubscript{I} absorption lines and cannot resolve the H\textsubscript{I} provenance (Geller et al. 1984). The stronger H\textsubscript{I} component must originate in the stronger (NW) component of UGC 6081 because the line is deeper than the flux density of the SE continuum source. The weaker, blueshifted H\textsubscript{I} component, however, could arise in either radio continuum source. We compute optical depths assuming that all H\textsubscript{I} absorption originates in the NW radio source, and we obtain a very large total H\textsubscript{I} column density of \( N(\text{H}\textsubscript{I}) = 1.13(1) \times 10^{22} \, (T_s/100 \, \text{K}) \, (1/f) \) cm\textsuperscript{-2} by direct integration of the observed spectrum (rather than from the Gaussian fits). This column density is a factor of 1.4 and 2.8 larger than the values obtained by Williams & Brown (1983) and Bothun & Schommer (1983), respectively, due in large part to larger and confused continua employed in the previous calculation of optical depths. Note that if \( T_s > 100 \, \text{K}, \, f < 1 \), or the blue line were associated with the SE component, then the already very large column density would be even larger.

Our re-detection of H\textsubscript{I} absorption in UGC 6081 illustrates the power of the ALFALFA survey—designed as an H\textsubscript{I} emission line survey—to detect H\textsubscript{I} absorption (intrinsic and intervening) in a new completely “blind” survey mode.

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**Table 1**

Intrinsic H\textsubscript{I} Absorption Lines toward UGC 6081

| Line | \( \nu \) (MHz) | \( \nu \) (km s\textsuperscript{-1}) | \( z \) | FWHM Depth (km s\textsuperscript{-1}) | Depth (mJy) | \( \int \tau \, dv \) (km s\textsuperscript{-1}) | \( N_{\text{H}\textsubscript{I}} \) (cm\textsuperscript{-2}) |
|------|----------------|----------------|------|--------------------------|-----------|-----------------------------|------------------|
| 1    | 1370.943(4)    | 10816.3(0.9)   | 0.036079(3) | 73(3) | -46.7(1.6) | 0.40(2) | 31.5(1.6) | 0.57(3) \times 10^{22} \, (T_s/100 \, \text{K}) \, (1/f) |
| 2    | 1371.14(3)     | 10770.8(5.8)   | 0.03593(2) | 220(10) | -17.1(1.4) | 0.13(1) | 30.4(2.7) | 0.55(5) \times 10^{22} \, (T_s/100 \, \text{K}) \, (1/f) |
| Total | 1370.91(3)     | 10823.1(5.5)   | 0.03610(2) | 86(2) | -66.5(2.2) | 0.64(3) | 62.1(0.7) | 1.13(1) \times 10^{22} \, (T_s/100 \, \text{K}) \, (1/f) |

**Notes.** H\textsubscript{I} absorption properties of UGC 6081. We list the observed line center frequencies, velocities, and redshifts (barycentric, optical definition), the line widths and depths, apparent and integrated optical depths (see Section 4.2), and H\textsubscript{I} column density. Values in parentheses indicate uncertainties in the final digit(s). The FWHM and integrated optical depth values are in the rest frame of UGC 6081. The first two rows in the table indicate measured and derived quantities obtained from Gaussian fits to the spectrum, while the last row in the table lists numerical values for the entire absorption system obtained without Gaussian fits.
5. ANALYSIS

We compute the column density frequency distribution function \( f(N_{\text{HI}}, X) \) following Cooksey et al. (2010) using the limiting column density sensitivity estimates shown in Figure 3:

\[
f(N_{\text{HI}}, X) \propto \frac{\lambda_{\text{max}}}{\Delta N_{\text{HI}} \Delta X},
\]

where \( \lambda_{\text{max}} \) is the Poisson upper limit on the detection rate of absorption systems with column density \( N_{\text{HI}} \) in interval \( \Delta N_{\text{HI}} \) and \( \Delta X \) is the comoving absorption path length searched. In this case, the search interval is uniform for all sources, so \( \Delta X = \delta X \cdot n_{\text{sens}} \), where \( \delta X = 0.0571 \text{ is the corrected redshift interval } \), \( \delta z = 0.0545 \text{ and } n_{\text{sens}} \text{ is the number of sources toward which observations were sensitive enough to detect a column density equal to or greater than } N_{\text{HI}} \). (Figure 3 shows the nearly identical quantity \( \Delta z = \delta z \cdot n_{\text{sens}} \text{ versus the column density sensitivity} \). A 95% confidence upper limit on the Poisson rate is \( \lambda_{\text{max}} = 3.00 \text{ when no detections are made.} \)

Figure 6 shows the column density frequency distribution 95% confidence limits calculated for a range of \( T_s/f \) values, but in each case a single value is assumed for the entire survey. To address this, we also calculated the 95% confidence limits on \( f(N_{\text{HI}}, X) \) for 1000 trials in which \( T_s/f \) is uniformly randomly distributed for each sight line in the range 100–1000 K. Figure 7 compares the result of a randomly distributed \( T_s/f \) to the mean of the distribution (550 K), showing little difference between the two distributions except in the lowest column density bins. This demonstrates that despite the unconstrained nature of the spin temperature and covering factor, a distribution of values is well represented in the \( f(N_{\text{HI}}, X) \) upper limit locus by a mean value. Also, although \( T_s/f \) is unconstrained source by source, the prior on this quantity can still produce a useful constraint on \( f(N_{\text{HI}}, X) \), increasingly so as surveys get larger or more sensitive (Section 6).

Figures 6 and 7 compare our column density frequency distribution limits to measured \( f(N_{\text{HI}}, X) \) distributions from the Zwaan et al. (2005) \( z \approx 0 \) Hz 21 cm emission line analysis and from the optical surveys of redshifted DLAs at \( z = 2–4 \) by Prochaska & Wolfe (2009) and Noterdaeme et al. (2009), showing them to be consistent in all cases.

The calculation of \( f(N_{\text{HI}}, X) \) is influenced by the choice of column density interval \( \Delta N_{\text{HI}} \) because we are calculating upper limits: the numerator in Equation (3) is independent of the number of sources whereas the denominator grows with \( \Delta N_{\text{HI}} \). We chose \( \Delta N_{\text{HI}} = 0.5 \text{ dex as a compromise between good statistics in most bins and resolution of } f(N_{\text{HI}}, X) \text{ along the column density axis, but it should be borne in mind that these limits do depend on this choice. With coarser sampling, } f(N_{\text{HI}}, X) \text{ moves lower but does not become inconsistent with the fits to } f(N_{\text{HI}}, X) \text{ obtained by Zwaan et al. (2005), Prochaska & Wolfe (2009), and Noterdaeme et al. (2009).} \)

The column density sensitivity is proportional to the combination of factors \( \text{FWHM} \cdot \frac{T_s}{f} \); if this quantity decreases, the sources are redistributed into lower column bins, driving the \( f(N_{\text{HI}}, X) \) values lower. A line FWHM smaller than the assumed 30 km s\(^{-1}\) is likely in many DLAs, suggesting that an average value of \( T_s/f = 100 \text{ K is probably too low (Figure 6).} \)

A source of systematic uncertainty in our calculation of \( f(N_{\text{HI}}, X) \) is the unknown redshift distribution of the illuminating radio sources. We have assumed for this analysis that all radio sources lie at \( cz > 17, 500 \text{ km s}^{-1} \), but there are certainly cases to the contrary (e.g., UGC 6081). This error operates in one direction: it diminishes the total redshift search path of the survey, driving our \( f(N_{\text{HI}}, X) \) limit upward. The size of this effect, however, is very small: using the redshift distribution of NVSS sources with \( S(1.4 \text{ GHz)} > 10 \text{ mJy determined by} \text{Brookes et al. (2008) and fit by de Zotti et al. (2010), we calculate that no more than about 60 sources in the } 517 \text{ deg}^{2} \text{ pilot survey lie within the observed redshift range, which is 0.8% of the sample. The redshift distribution of these sources will also be skewed toward the high-redshift side of the survey, so the effect of this incomplete redshift coverage is truly negligible.} \)
Since we obtain only upper limits on the column density frequency distribution $f(N_{\text{HI}}, X)$, its moments, such as the H\textsc{i} mass density ($\rho_{\text{HI}}$) or equivalently $\Omega_{\text{HI}}$) and the comoving covering fraction $\ell(X)$, are dominated by the endpoint limits and thus not well constrained by our observations. It is likely that such moments can be computed from future surveys (Section 6.1). Our lack of detections is perfectly consistent with expectations and recent work on DLA lines and H\textsc{i} 21 cm emission (Section 6).

6. DISCUSSION

Our upper limits on the column density frequency distribution function are consistent with previous determinations of $f(N_{\text{HI}}, X)$, both at high redshift (Prochaska & Wolfe 2009; Noterdaeme et al. 2009, via Ly$\alpha$ absorption) and at low redshift (Zwaan et al. 2005, via H\textsc{i} 21 cm emission). Figures 6 and 7 show that an expanded survey would either start making absorption line detections or will place a strong statistical limit on the hydrogen spin temperature to source covering fraction ratio ($T_s/f$). We suspect that it will be the latter, but in any case, our results provide strong motivation for a more sensitive or a larger area survey. For example, a search for absorption lines in the full ALFALFA survey would increase the comoving search path $\Delta X$ by a factor of 14 (1.15 dex) in each $N_{\text{HI}}$ bin, which will place the $f(N_{\text{HI}}, X)$ 95% confidence limits in conflict with previous measurements of the distribution over the range $10^{20}$ cm$^{-2} < N_{\text{HI}} < 10^{22}$ cm$^{-2}$ unless either DLAs are detected or $T_s/f \gtrsim 500$ K on average.

Clearly a more productive approach to obtain the column density frequency distribution $f(N_{\text{HI}}, X)$ at $z = 0$ is via H\textsc{i} 21 cm emission lines (e.g., Zwaan et al. 2005), but beyond $z \lesssim 0.2$, where the emission line flux density becomes prohibitively weak for anything less than a square kilometer of collecting area, one would use a distance-independent absorption line survey such as the pilot survey presented here. Furthermore, “blind” 21 cm based detections of DLAs can identify dusty sightlines that would otherwise be missed by optical/UV surveys, which is key to identifying exceptionally rare molecular absorption systems and addressing the fraction of dusty DLAs.

6.1. Future Surveys

As Figures 3, 6, and 7 demonstrate, even incremental improvements in survey sensitivity would lead to large improvements in column density sensitivity and statistics because the source population grows as a power law as the 1.4 GHz flux density decreases (Figure 2). But for strong sources, which provide probes of low column density, areal coverage remains important.

The first step should be to search the full ALFALFA survey for 21 cm absorption lines; this pilot survey covered 7% of the full survey, so an order-of-magnitude increase in search path is possible using extant data. This will either produce detections of intervening absorption line systems or lower the limits on the column density frequency distribution function, indicating a statistical lower bound on spin temperature (modulo covering fraction). It is already clear from Figure 6 that the typical spin temperature of H\textsc{i} gas at $z \sim 0$ cannot be less than $T_s/f \simeq 100$ K.

Future facilities that could perform commensal or dedicated 21 cm absorption line surveys include Square Kilometer Array (SKA) prototypes, including the 256 element Allen Telescope Array, the SKA Molonglo Prototype, the Australian SKA Pathfinder, and the Karoo Array Telescope (MeerKAT), as well as Epoch of Reionization (EoR) and Dark Ages telescopes, such as a lunar far-side array, the Low Frequency Array, the Precision Array to Probe the EoR, and the Murchison Widefield Array. These facilities will provide various combinations of areal coverage, bandwidth ($\delta z$ per source), and sensitivity. As we have demonstrated here, sensitivity is key because it determines the number of sightlines available per solid angle of sky surveyed, and the power-law increase in radio source counts with decreasing flux density means that even slight improvements in sensitivity will lead to large gains in the size of absorption line surveys. Bandwidth and areal coverage, in comparison, grow absorption line surveys linearly.

While absorption line detection is distance independent, which is an enormous advantage over redshifted emission line surveys, future H\textsc{i} absorption line surveys will have to contend with the issue of unknown redshifts of the continuum population and the loss of foreground sources in the total redshift search path.

7. CONCLUSIONS

Our “blind” pilot survey for H\textsc{i} 21 cm absorption lines in a 517 deg$^2$ section of the ALFALFA survey spanning $-650$ km s$^{-1} < cz < 17,500$ km s$^{-1}$ detected no new absorption line systems, but re-detected the intrinsic absorption in UGC 6081. We calculate column density sensitivity limits toward a sample of 7296 radio sources and construct upper limit envelopes for the column density frequency distribution function $f(N_{\text{HI}}, X)$ that are consistent with previous work at high and low redshifts (e.g., Zwaan et al. 2005; Prochaska & Wolfe 2009; Noterdaeme et al. 2009). Our results suggest that higher redshift, larger solid angle, larger bandwidth, and especially more sensitive surveys will be an astrophysically worthwhile pursuit in terms of constraining the 21 cm spin temperature and detecting dusty DLA systems as well as DLAs toward optically faint but radio-loud illumination sources. A subset of these H\textsc{i} 21 cm absorption systems will also host the exceptionally rare and elusive molecular absorption systems, which can be employed to study cold molecular gas at high redshift and to constrain the cosmic evolution of fundamental physical constants.

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