ON THE (NON)EVOLUTION OF H\textsc{i} GAS IN GALAXIES OVER COSMIC TIME

J. Xavier Prochaska\textsuperscript{1} and Arthur M. Wolfe\textsuperscript{2}

\textsuperscript{1} Department of Astronomy and Astrophysics, UCO/Lick Observatory; University of California, 1156 High Street, Santa Cruz, CA 95064, USA; xavier@ucolick.org
\textsuperscript{2} Department of Physics, and Center for Astrophysics and Space Sciences, University of California, San Diego, Gilman Dr., La Jolla; CA 92093-0424, USA; awolfe@ucsd.edu

Received 2008 November 12; accepted 2009 February 26; published 2009 April 24

\begin{abstract}
We present new results on the frequency distribution of projected H\textsc{i} column densities \( f(N_{\text{HI}}, X) \), total comoving covering fraction, and integrated mass densities \( \rho_{\text{HI}} \) of high-redshift, H\textsc{i} galactic gas from a survey of damped Ly\( \alpha \) systems (DLAs) in the Sloan Digital Sky Survey, Data Release 5. For the full sample spanning \( z = 2.2 - 5 \) (738 DLAs), \( f(N_{\text{HI}}, X) \) is well fitted by a double power law with a break column density \( N_d = 10^{15.55 \pm 0.04} \text{ cm}^{-2} \) and low/high-end exponents \( \alpha = -2.00 \pm 0.05, -6.4^{+1.1}_{-1.6} \). The shape of \( f(N_{\text{HI}}, X) \) is invariant during this redshift interval and also follows the projected surface density distribution of present-day H\textsc{i} disks as inferred from 21 cm observations. We conclude that H\textsc{i} gas has been distributed in a self-similar fashion for the past 12 Gyr. The normalization of \( f(N_{\text{HI}}, X) \), in contrast, decreases by a factor of 2 during the \( \approx 2 \) Gyr interval from \( z = 4 - 2.2 \) with coincident decreases in both the total covering fraction and \( \rho_{\text{HI}} \). At \( z \approx 2 \), these quantities match the present-day values suggesting no evolution during the past \( \approx 10 \) Gyr. We argue that the evolution at early times is driven by “violent” processes that removes gas from nearly half the galaxies at \( z \approx 3 \) establishing the antecedents of current early-type galaxies. The perceived constancy of \( \rho_{\text{HI}} \), meanwhile, implies that H\textsc{i} gas is a necessary but insufficient precondition for star formation and that the global star formation rate is driven by the accretion and condensation of fresh gas from the intergalactic medium.

\textbf{Key words:} galaxies: evolution – intergalactic medium – quasars: absorption lines
\end{abstract}

\textbf{Online-only material:} color figures

\section{1. INTRODUCTION}

In the current paradigm of galaxy formation within cold dark matter (CDM) cosmology, baryons accrete, dissipate, and settle to the centers of dark matter halos. Gas with a non-\textsuperscript{1}negligible angular momentum will form an H\textsc{i} disk with typical surface densities exceeding 1 \( M_\odot \text{ pc}^{-2} \) (or H\textsc{i} column densities, \( N_{\text{HI}} > 10^{20} \text{ cm}^{-2} \)). Various processes (e.g., merger-induced shocks, secular evolution) inspire the formation of molecular clouds that cool, fragment, and initiate star formation. Finally, stellar feedback (e.g., winds, supernovae), active galactic nuclei (AGNs) activity, galaxy interactions, and even magnetic fields (Wolfe et al. 2008) may inhibit star formation, perhaps driving the gas from the galaxy.

The H\textsc{i} gas of galaxies, therefore, serves as a barometer of recent star formation activity and a record of prior processing. The mass, metallicity, velocity field, surface density profile, etc. reflect both the underlying dark matter potential and also the star formation history of the galaxy. In the local universe, H\textsc{i} gas is mapped in the 21 cm line with radio telescopes. These data reveal the mass, surface density profiles, and kinematics of modern H\textsc{i} disks (e.g., Zwaan et al. 2005a; Walter et al. 2008). With current facilities, unfortunately, it is impossible to survey galactic H\textsc{i} gas in 21 cm emission at high redshift. Such analysis awaits the construction of facilities like the proposed Square Kilometer Array.

In lieu of 21 cm observations, one may observe H\textsc{i} gas through electronic transitions, e.g., the Lyman, Balmer, and Paschen series. Although these lines can be studied in emission, they arise via recombination processes in ionized gas. Furthermore, detectable fluxes require a strong (i.e., local) excitation/ionization source associated with special, isolated regions of the galaxy. To study the bulk of H\textsc{i}, one may probe the gas in absorption via the Lyman series (Wolfe et al. 1986). At the characteristic column densities of H\textsc{i} disks, the Ly\( \alpha \) transition is damped and astronomers refer to the observed profiles as damped Ly\( \alpha \) systems (DLAs; Wolfe et al. 2005). These DLA profiles are mainly revealed in the spectra of distant quasars, yet they also manifest in the spectra of GRB afterglows (e.g., Chen et al. 2005). Unfortunately, these intrinsically luminous sources cover only a small fraction of the sky such that one rarely intersects a given galaxy with multiple sightlines (e.g., Ellison et al. 2007). Therefore, galactic H\textsc{i} gas\footnote{The connection between DLA absorption and high \( z \) galaxies is suggested by numerous lines of circumstantial evidence (e.g., metal abundances, their high gas surface densities, the detection of molecules, their kinematic properties and also analysis of cosmological simulations Prochaska et al. 2003; Noterdaeme et al. 2008; Prochaska & Wolfe 1997; Katz et al. 1996; Wolfe et al. 2005) although the direct detection of starlight remains rare (Möller et al. 2002).} at high \( z \) must be studied statistically through the observation of thousands of quasars across the sky.

This experiment has been realized over the past few years as an unintended consequence of the Sloan Digital Sky Survey (SDSS) for high-redshift quasars (Prochaska & Herbert-Fort 2004; Prochaska et al. 2005, hereafter PHW05). In this paper, we report on the results from a survey of the SDSS Data Release 5 (SDSS-DR5; Adelman-McCarthy et al. 2007). We place new constraints on the projected H\textsc{i} column density distribution, total covering fraction, and integrated mass density of galactic H\textsc{i} gas at \( z > 2 \). We search for evolution in these quantities from \( z = 2 \) to 4 and also compare the measurements with H\textsc{i} disks from the local universe (Zwaan et al. 2005b). These results offer new insight on the evolution of galactic H\textsc{i} gas and its role in the processes of galaxy formation. Throughout the paper, we adopt a \( \Lambda \text{CDM} \) cosmology with \( \Omega_m = 0.7, \Omega_{\Lambda} = 0.3 \), and \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \).
2. RESULTS

We have surveyed damped Lyα systems at \( z \geq 2.2 \) using the database of quasar spectroscopy from the SDSS-DR5. We have implemented the algorithms developed in PHW05 to search for DLA candidates, measure the survey path, eliminate strong BAL quasars, and to fit Voigt functions to candidate DLAs. Tables and figures for the Lyα fits are provided online (http://www.ucolick.org/~xavier/SDSS). The full statistical sample now comprises 738 DLAs with \( N_{\text{HI}} \geq 10^{20.3} \text{ cm}^{-2} \) over a total redshift path \( \Delta z = 3082.5 \), each located at velocity \( \delta v > 3000 \text{ km s}^{-1} \) from the background quasar.

In Figure 1(a) we present the \( N_{\text{HI}} \) frequency distribution \( f(N_{\text{HI}}, X) \) of the full statistical sample. This measure describes the projected column density distribution of H I gas in galaxies at high \( z \) per comoving absorption path length \( dX \) (Wolfe et al. 1995; Storrie-Lombard & Wolfe 2000; Péroux et al. 2003). Similar to our result from the SDSS-DR3 (PHW05), \( f(N_{\text{HI}}, X) \) is well described by a power law at low \( N_{\text{HI}} \) values \( f(N_{\text{HI}}, X) \sim N_{\text{HI}}^{\alpha_1} \) with \( \alpha_1 \approx -2 \), but transitions to a steeper function at \( N_{\text{HI}} \approx 10^{21.5} \text{ cm}^{-2} \). This break in \( f(N_{\text{HI}}, X) \) is required to yield a finite H I mass density, \( \rho_{\text{HI}} = (m_\text{HI} N_{\text{HI}}/c) f(N_{\text{HI}}, X) dX dN \). Following the formalism in PHW05, we fitted a double power law to \( f(N_{\text{HI}}, X) \); the best-fit model is overlapped on the data in Figure 1(a) and tabulated in Table 1 for a series of redshift intervals. The table also lists the zeroth and first moments of \( f(N_{\text{HI}}, X) \) which give the line density \( \ell(X) \) and \( \rho_{\text{HI}} \), values respectively. The former quantity represents the covering fraction per \( dX \) for the integrated population of galactic H I gas at a given epoch. The latter quantity is the comoving mass density of H I gas in high \( z \) galaxies.

A principal result of our survey is that the shape of the H I distribution function does not evolve in cosmic time. Figure 1(b) shows the cumulative \( f(N_{\text{HI}}, X) \) distributions for a series of redshift intervals from \( z = 2.2 \) to 5. We have performed a series of two-sided Kolmogorov–Smirnov (KS) test comparisons and find that the null hypothesis cannot be ruled out at greater than 90% confidence for any pair. Table 1 also reveals that the parameters of a double power-law fit to the data show no significant (> 2\( \sigma \) ) variations with redshift.

In Figure 1(b), we also present the cumulative \( f(N_{\text{HI}}, X) \) function for H I disks in the local universe, as estimated from 21 cm observations (Zwaan et al. 2005b). Remarkably, the \( z \sim 0 \) distribution function is a near perfect match to the high \( z \) universe. This is a stunning result noted first and independently by Zwaan et al. (2005b) and PHW05. Although the universe and the galaxies within it have evolved substantially over the \( \approx 10 \text{ Gyr} \) interval from \( z = 3 \) to today, the combined distribution of H I surface densities is invariant. Stated differently, the population of galaxies at any epoch shows a self-similar projected H I surface density distribution.

Although the shape of \( f(N_{\text{HI}}, X) \) is invariant, its normalization decreases with time. This is revealed in Figure 2 where we present \( \ell(X) \) and \( \rho_{\text{HI}} \), from \( z = 5 \) to 2. Both the co-moving covering fraction and the mass density of H I disks decreases by 50% in this \( \approx 2 \text{ Gyr} \) interval. This sharp decline in both \( \ell(X) \) and \( \rho_{\text{HI}} \) is a surprising and profound result. Before discussing its origin, we emphasize that the evolution must occur at all column densities of the DLAs such that the shape of \( f(N_{\text{HI}}, X) \) remains invariant. Therefore, one should focus on processes that affect the inner and outer regions of H I disks together.

Table 1

| \( z \) | \( \Delta X \) | \( \Delta z \) | \( m_{\text{DLA}} \) | \( \ell_{\text{HI}} \) | \( \rho_{\text{HI}} \) |
|-------|-------|-------|-------|-------|-------|
| 2.2, 2.5 | 10872.8 | 3082.5 | 739 | 3.05 | \( 23.95 \times 10^{20} \) |
| 2.2, 2.4 | 1652.7 | 5144.2 | 79 | 2.31 | \( 24.68 \times 10^{20} \) |
| 2.4, 2.7 | 2405.8 | 717.5 | 132 | 2.57 | \( 23.64 \times 10^{20} \) |
| 2.7, 3.0 | 2304.5 | 723.7 | 169 | 2.86 | \( 24.17 \times 10^{20} \) |
| 3.0, 3.5 | 2702.5 | 732.2 | 227 | 3.22 | \( 23.84 \times 10^{20} \) |
| 3.5, 4.0 | 1319.2 | 291.3 | 86 | 3.70 | \( 24.16 \times 10^{20} \) |
| 4.0, 5.5 | 432.8 | 103.6 | 46 | 3.49 | \( 23.76 \times 10^{20} \) |

Notes. The frequency distribution for DLA absorption is modeled as a double power law \( f(N_{\text{HI}}, X) = k_3 (N_{\text{HI}}/N_d)^{\alpha_3} \) with \( \alpha_3 = \alpha_1 \) for \( N_{\text{HI}} \leq N_d \) and \( \alpha = \alpha_4 \). See PHW05 for further details.

a Mean absorption redshift of the DLA sample.

b Line density of DLAs per absorption length \( dX \). Also written as \( dN/dX \) in the literature.

c Note that we recover the same estimate for \( \rho_{\text{HI}} \) whether we sum the discrete \( N_{\text{HI}} \) values or integrate the best fitting double power law (see also PHW05).

Figure 1. Left: integrated frequency distribution \( f(N_{\text{HI}}, X) \) of projected H I column densities for galaxies at \( z = 2 \) to 4. The overplotted curve represents the best-fit, double power law which has a break column density \( N_d = 10^{21.5} \text{ cm}^{-2} \), a "faint-end" exponent \( \alpha_3 \approx -2.00 \pm 0.05 \), and a high-end exponent \( \alpha_4 \approx -4.4 \) (95% c.l.). Right: cumulative distribution functions of \( f(N_{\text{HI}}, X) \) for galaxies in a series of redshift intervals. For \( z > 2 \), the shape of \( f(N_{\text{HI}}, X) \) is invariant and, remarkably, matches with the observed function for local H I disks (Zwaan et al. 2005b).

(A color version of this figure is available in the online journal.)
of galaxies. The results presented in Figure 1(b) suggest that the outer regions of H I galaxies are not especially sensitive to these processes nor to the underlying dark matter halo mass. We note that this is actually a prediction of viscous models of galactic disk formation (Lin & Pringle 1987; Olivier et al. 1991). We await explorations of this topic within the context of cosmological simulations of galaxy formation.

Secular and feedback processes may be expected to have greater effect on the gas toward the inner regions, i.e., at the highest surface densities. We have also searched for variations in $f(N_{HI}, X)$ at large $N_{HI}$, but identify none. At the 95% c.l., all of the redshift intervals have $f(N_{HI}, X)$ distributions consistent with a break column density of $N_{HI} = 10^{1.6} \text{cm}^{-2}$. Furthermore, restricting the frequency distributions to $N_{HI} > 10^{11} \text{cm}^{-2}$, all give satisfactory KS-test probabilities. We conclude there is no evolution at these column densities, but caution that the full sample includes only 105 DLAs. The data also reveal, for the first time, that $f(N_{HI}, X)$ is steeper than $\alpha = -3$ beyond the break. For the full sample, this result is robust even if we only consider DLAs with $N_{HI} > 10^{11} \text{cm}^{-2}$. The steep break cannot be attributed only to the effects of projection (e.g., inclination of disks) alone which predict $\alpha = -3$ (see Wolfe & Chen 2006). We predict that the break is also associated with the conversion of atomic gas to molecules (Schaye 2001; Zwaan & Prochaska 2006, but see Noterdaeme et al. 2008).

Now consider the sharp decrease in the total comoving covering fraction and H I mass density from $z = 4$ to 2 (Figure 2, Table 1). One’s initial reaction may be to interpret this decline in terms of active star formation, i.e., the conversion of the H I gas in DLAs to stars via in situ star formation. This interpretation is problematic for several reasons. First, one expects star formation to mainly influence gas at high H I surface densities; this is revealed, in part, by the form of the Schmidt law, $\Sigma_{SFR} = K \times \Sigma_g^{1.4}$, where $\Sigma_{SFR}$ is the SFR per unit area and $\Sigma_g$ is the gas mass surface density (Schmidt 1959; Kennicutt 1998). But the invariant shape of $f(N_{HI}, X)$ suggests that in situ star formation in DLAs is unlikely to consume gas according to the Schmidt law. This is illustrated in Figure 3(a), which shows how an initial single power-law approximation for $f(N_{HI}, X)$ steepens with time if stars form according to the Schmidt law (Lanzetta et al. 1995). We find that the absence of changes in the shape of $f(N_{HI}, X)$ implies that the star formation efficiency is less than 1/10 that in local galaxies.

Second, Wolfe & Chen (2006) used the infrequent detection of extended, low surface-brightness galaxies in the Hubble Ultra Deep field to set an upper limit on the comoving SFR density $\dot{\rho}_g < 10^{-2.7} \text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-3}$. We used this limit to set an upper limit on the decrease in $\rho_{HI}$ due to in situ star formation. We fitted a conservative expression for $\rho_{HI}(z)$ to be consistent with (1) this upper limit at $z \sim 3$ and (2) observations of star-forming galaxies in the redshift interval $z = [0. 8]$ (e.g., Bouwens et al. 2008). We then computed the decrease in $\rho_{HI}(z)$ by integrating $\rho_{HI}(z)$ from $z = 6 \text{ to } 3$. The resulting dip in $\rho_{HI}$ is shown as the dotted curve in Figure 3(b). Clearly the decrease in $\rho_{HI}$ predicted by in situ star formation is too small to account for the factor of 2 decrease observed. Specifically, the total mass density of stars formed in situ gas traced by H I is less than a few percent of the observed $\rho_{HI}$ at $z = 4$.

Third, to markedly change the covering fraction of H I galaxies, in situ star formation would have to lower $\approx 50\%$ of those regions below the DLA criterion. At the DLA threshold, star formation is likely very weak (if not absent) and should not affect this gas. We conclude, therefore, that in situ star formation...
formation on its own it is possible to explain the sharp decline in \(\ell(X)\) and \(\rho_{\text{HI}}\) at high \(z\). By similar arguments, one rules out an interpretation where the majority of \(\text{H I}\) gas is simply converted into molecular gas. Furthermore, observational biases (e.g., dust obscuration, gravitational lensing) are most important at high \(N_{\text{HI}}\) values and can be ruled out as dominant factors. Finally, the extragalactic UV background (EUVB) will modify the distribution of neutral gas in the outer parts of \(\text{H I}\) galaxies but the DLA threshold is sufficiently large that variations in the EUVB should play only a minor role for \(\ell(X)\) and a negligible role for \(\rho_{\text{HI}}\) (e.g., Viegas 1995).

On the other hand it is possible that the gas in DLAs fuels star formation (Wolfe & Chen 2006; Wolfe et al. 2008). In that case, the Schmidt law would not apply to DLA gas. Rather, secular processes could drive the gas to the center where it would be consumed by star formation in compact star-forming regions. To compute the decrease in \(\rho_{\text{HI}}(z)\) we fitted analytic functions to the intrinsic values of \(\rho_{\text{HI}}(z)\) derived by Bouwens et al. (2008) and computed \(\rho_{\text{HI}}(z)\) by integrating the under the \(\rho_{\text{HI}}(z)\) curve. The results are well-matched to the data at \(z = [2.5, 4.5]\) (Figure 3(b)). Although we obtained this fit by arbitrarily increasing the “initial” \(\rho_{\text{HI}}(z)\) at \(z = 6\) by 10% above our highest data point at \(z = 4.0\), the decrease in \(\rho_{\text{HI}}(z)\) predicted by this model for \(\rho_{\text{HI}}(z)\) provides a good match to the data for a wide range of initial values of \(\rho_{\text{HI}}\). However, this simple model breaks down at \(z < 2.4\), where the predicted \(\rho_{\text{HI}}(z)\) falls below the constant value set by \(\rho_{\text{HI}}(z) = [0, 2.4]\). But the leveling off of \(\rho_{\text{HI}}\) at \(z < 2.4\), could be explained by delayed infall of gas from the IGM at a rate that balances gas consumption by star formation, a phenomenon observed in some numerical simulations of galaxy formation (Kereš et al. 2005). Of course, a crucial challenge to this idea is how to transport gas from the extended regions comprising DLAs to the center, i.e., by a factor of 15 or more in radius (see Wolfe et al. 2008), without substantially affecting the shape of \(f(N_{\text{HI}}, X)\), but by reducing its normalization by a factor of 2.

The other extremum is that the sharp decline in covering fraction and mass density of \(\text{H I}\) gas results from “violent” feedback processes. By violent, we envision processes that altogether remove the \(\text{H I}\) gas from a galaxy. These may include AGN activity, galactic-scale winds, tidal effects, and ram-pressure stripping. To match the observed evolution in \(\ell(X)\) and \(\rho_{\text{HI}}\), one would require that approximately half of the galaxies exhibiting \(\text{H I}\) at \(z \approx 4\) have lost their gas by \(z = 2\). This implies a dramatic evolution in the fraction of \(\text{H I}\)-rich to \(\text{H I}\) poor galaxies in the 2 Gyr interval centered at \(z \approx 3\). The resulting galaxies, if unable to accrete new \(\text{H I}\) gas for subsequent star formation, would passively evolve into “red and dead” galaxies. We speculate, therefore, that \(z \sim 3\) marks the critical epoch for the formation of stars in the ancestors of modern, early-type galaxies.

The data in Figure 2 provide another surprising result. The red bands in the figure show \(z \approx 0\) estimates of \(\ell(X)\) and \(\rho_{\text{HI}}\), as inferred from 21 cm observations (Ryan-Weber et al. 2003; Zwaan et al. 2005a). We find that \(\rho_{\text{HI}}\) at \(z = 2.2\) matches the present-day value. A brazen, but reasonable, assertion by interpolation is that \(\rho_{\text{HI}}\) has not evolved over the past 10 Gyr of our universe. If confirmed (see Rao et al. 2006, for an estimate at \(z \approx 1\) that is likely to be biased high), this result has several important implications. First, if processes remove \(\text{H I}\) gas from galaxies at \(z < 2\), these must be matched by the formation of new galaxies. Because the assembly of dark matter halos of galactic-scale masses (\(< 10^{12}M_\odot\)) is expected to be nearly complete at \(z \sim 2\), we contend that the complete removal of \(\text{H I}\) gas from individual galaxies is also nearly complete. Second, the accretion of gas into existing \(\text{H I}\) galaxies must be balanced...
by the consumption of that gas into stars and/or its removal from the galaxy by feedback processes. This suggests that H\textsubscript{i} gas plays a special, but subservient role in the formation of stars. In essence, H\textsubscript{i} disks represent a bias level of gas that is a necessary but insufficient condition for star formation. In this scenario, the global star formation rate at any given epoch is driven predominantly by the accretion rate of fresh material onto existing H\textsubscript{i} disks, an inference also drawn from cosmological simulations of galaxy formation (Kere\v{s} et al. 2005). It further suggests that galaxies with H\textsubscript{i} gas have been critically unstable to star formation over the past 10 billion years.

The observations presented here will be supplemented by future data releases of the SDSS and next generation surveys. The key open empirical issues include: (1) is there even a mild evolution in the break column density with redshift? (2) what is the functional form of \( f(N_{\text{H} \text{i}}, X) \) beyond the break? (3) what are the values of these quantities at \( z \approx 6 \)? and (4) how does one reconcile the observed evolution in the kinematic characteristics of DLAs from \( z = 2 \) to today with the absence of evolution in \( f(N_{\text{H} \text{i}}, X) \) (Prochaska & Wolfe 1997; Prochaska et al. 2002; Zwaan et al. 2008)? Of great interest will be to compare the observational constraints presented here against theoretical models for the buildup and evolution of H\textsubscript{i} galactic gas over cosmic time.

J.X.P. and A.M.W. are supported by NSF grant (AST-0709235). We are grateful for the tremendous effort put forth by the SDSS team to produce and release the SDSS survey. We acknowledge helpful discussions with M. Fumagalli, S. Faber, and J. Primack. We thank H.-W. Chen for first suggesting we draw comparisons with the local universe. We also acknowledge the efforts of S. Herbert-Fort who helped build the algorithms for the DLA survey.

REFERENCES

Adelman-McCarthy, J. K., et al. 2007, ApJS, 172, 634  
Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2008, ApJ, 686, 230  
Chen, H.-W., Prochaska, J. X., Bloom, J. S., & Thompson, I. B. 2005, ApJ, 634, L25  
Ellison, S. L., Hennawi, J. F., Martin, C. L., & Sommer-Larsen, J. 2007, MNRAS, 378, 801  
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda Escude, J. 1996, ApJ, 457, L57  
Kenneicutt, R. C., Jr. 1998, ARA&A, 36, 189  
Kere\v{s}, D., Katz, N., Weinberg, D. H., & Dav\'e, R. 2005, MNRAS, 363, 2  
Lanzetta, K. M., Wolfe, A. M., & Turnshek, D. A. 1995, ApJ, 440, 435  
Lin, D. N. C., & Pringle, J. E. 1987, ApJ, 320, L87  
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319  
Moeller, P., Warren, S. J., Fall, S. M., Fynbo, J. U., & Jakobsen, P. 2002, ApJ, 574, 51  
Nagamine, K., Springel, V., & Hernquist, L. 2004, MNRAS, 348, 421  
Noterdaeme, P., Ledoux, C., Petitjean, P., & Srianand, R. 2008, A&A, 481, 327  
Olivier, S. S., Primack, J. R., & Blumenthal, G. R. 1991, MNRAS, 252, 102  
Péroux, C., McMahon, R. G., Storrie-Lombardi, L. J., & Irwin, M. J. 2003, MNRAS, 346, 1103  
Pouzet, A., et al. 2008, MNRAS, 390, 1349  
Prochaska, J. X., Gawiser, E., Wolfe, A. M., Castro, S., & Djorgovski, S. G. 2003, ApJ, 595, L9  
Prochaska, J. X., & Herbert-Fort, S. 2004, PASP, 116, 622  
Prochaska, J. X., Herbert-Fort, S., & Wolfe, A. M. 2005, ApJ, 635, 123  
Prochaska, J. X., Ryan-Weber, E., & Staveley-Smith, L. 2002, PASP, 114, 1197  
Prochaska, J. X., & Wolfe, A. M. 1997, ApJ, 487, 73  
Rao, S. M., Turnshek, D. A., & Nestor, D. B. 2006, ApJ, 636, 610  
Razoumov, A. O., Norman, M. L., Prochaska, J. X., & Wolfe, A. M. 2006, ApJ, 645, 55  
Ryan-Weber, E. V., Webster, R. L., & Staveley-Smith, L. 2003, MNRAS, 343, 1195  
Schaye, J. 2001, ApJ, 562, L95  
Schmidt, M. 1959, ApJ, 129, 243  
Storrie-Lombardi, L. J., & Wolfe, A. M. 2000, ApJ, 543, 552  
Viegas, S. M. 1995, MNRAS, 276, 268  
Walter, F., Brinks, E., de Blok, W. J. G., Bigiel, F., Kennicutt, R. C., Jr., Thornley, M. D., & Leroy, A. K. 2008, AJ, 136, 2563  
Wolfle, A. M., & Chen, H.-W. 2006, ApJ, 652, 981  
Wolfle, A. M., Gaviser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861  
Wolfle, A. M., Jorgenson, R. A., Robishaw, T., Heiles, C., & Prochaska, J. X. 2008, Nature, 455, 638  
Wolfle, A. M., Lanzetta, K. M., Foltz, C. B., & Chaffee, F. H. 1995, ApJ, 454, 698  
Wolfle, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJS, 61, 249  
Zwaan, M. A., Meyer, M. J., Staveley-Smith, L., & Webster, R. L. 2005a, MNRAS, 359, 30  
Zwaan, M. A., & Prochaska, J. X. 2006, ApJ, 643, 675  
Zwaan, M. A., van der Hulst, J. M., Briggs, F. H., Verheijen, M. A. W., & Ryan-Weber, E. Y. 2005b, MNRAS, 364, 1467  
Zwaan, M., Walter, F., Ryan-Weber, E., Brinks, E., de Blok, W. J. G., & Kennicutt, R. C. 2008, AJ, 136, 2886