THROUGH THICK AND THIN—H I ABSORPTION IN COSMOLOGICAL SIMULATIONS

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Received 2010 December 17; accepted 2011 July 18; published 2011 August 2

ABSTRACT

We investigate the column density distribution function of neutral hydrogen at redshift z = 3 using a cosmological simulation of galaxy formation from the OverWhelmingly Large Simulations project. The base simulation includes gravity, hydrodynamics, star formation, supernovae feedback, stellar winds, chemodynamics, and element-by-element cooling in the presence of a uniform UV background. Self-shielding and formation of molecular hydrogen are treated in post-processing, without introducing any free parameters, using an accurate reverse ray-tracing algorithm and an empirical relation between gas pressure and molecular mass fraction. The simulation reproduces the observed z = 3 abundance of Lyα forest, Lyman limit, and damped Lyα H I absorption systems probed by quasar sight lines over 10 orders of magnitude in column density. Self-shielding flattens the column density distribution for NH > 10^18 cm^-2, while the transition to fully neutral gas and conversion of H I to H_2 steepen it around column densities of NH = 10^{20.3} cm^-2 and NH = 10^{21.5} cm^-2, respectively.

Key words: galaxies: formation – intergalactic medium – large-scale structure of universe – methods: numerical – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

Ground-based spectroscopic observations targeting quasars are excellent probes of z ≥ 1.7 neutral hydrogen (e.g., Rauch 1998; Wolfe et al. 2005). The Sloan Digital Sky Survey (SDSS) has produced approximately 1.5 × 10^4 moderate resolution quasar spectra (Abazajian et al. 2009). These spectra provide ample data on H I absorption lines with column densities NH > 10^{20.3} cm^-2, the so-called damped Lyα systems (DLAs; Prochaska & Wolfe 2009; Noterdaeme et al. 2009). Lines with NH < 10^{17.2} cm^-2, the so-called Lyα forest, are best discovered in high-resolution spectra of bright quasars (e.g., Kim et al. 2002). Lines with intermediate column densities, Lyman limit systems (LLSs), lie on the flat part of the curve of growth, which complicates the determination of their column densities. Traditional methods of measuring NH in DLAs can be applied to high-resolution spectra for lines with NH > 10^{19} cm^-2 when damping wings begin to appear (e.g., Péroux et al. 2005; O’Meara et al. 2007). Progress on the most difficult lines with 10^{14.5} cm^-2 < NH < 10^{19} cm^-2 has recently been made by Prochaska et al. (2010) by combining independent measurements of the Lyman limit mean free path and integral constraints over the column density distribution.

Combining the observations above, one can determine the H I column density distribution function f(NHI, z), i.e., the number of lines per unit column density dNHI per unit absorption distance dX, at redshifts z ≈ 3 from NH1 = 10^{12} cm^-2 to NH1 = 10^{22} cm^-2. Early determinations of f(NHI, z) at these redshifts were reasonably well described by a single power law, f(NHI, z) ∝ N_{HI}^η, with η = 1.5 (Tytler 1987). As the quality of observations improved, this was no longer the case. Petitjean et al. (1993) showed that a single power law and a double power law with a break at NH1 = 10^{16} cm^-2 both failed Kolmogorov–Smirnov tests at the 99% confidence level. The most recent observations are fit well by a series of six power laws which intersect at NH1 = {10^{14.5}, 10^{17.3}, 10^{19.0}, 10^{20.3}, 10^{21.75}} cm^-2 (Prochaska et al. 2010).

Attempts to explain the shape and normalization of f(NHI, z) in a cosmological context have typically focused on subsets of the full column density range. Analytic (e.g., Schaye 2001a), semi-analytic (e.g., Bi & Davidsen 1997), and numerical (e.g., Theuns et al. 1998a, 1998b) models were instrumental in identifying the Lyα forest lines with the diffuse, photoionized, intergalactic medium. Numerical work has also played a large role in determining properties of higher column density systems (e.g., Katz et al. 1996; Gardner et al. 1997; Haehnelt et al. 1998; Cen et al. 2003; Nagamine et al. 2004; Razoumov et al. 2006; Kohler & Gnedin 2007; Pontzen et al. 2008; Tescari et al. 2009; Hong et al. 2010; Cen 2010; Nagamine et al. 2010; McQuinn et al. 2011).

Although self-shielding is crucial for modeling optically thick absorbers, only Razoumov et al. (2006), Kohler & Gnedin (2007), Pontzen et al. (2008), and McQuinn et al. (2011) have used three-dimensional radiative transfer to calculate the attenuation of the UV background. Additionally, conversion of H I to H_2 is thought to determine the high end cutoff in f(NHI, z) (Schaye 2001b; Krumholz et al. 2009), yet only Cen (2010) included this process when modeling H I absorption. We present a cosmological simulation of structure formation, to which we have applied a radiative transfer self-shielding calculation and a prescription for the conversion of H I to H_2 without introducing any free parameters. We show that this simulation reproduces observational determinations of f(NHI, z) around z = 3 over the entire range in column density. In addition, we determine the typical neutral fractions and total hydrogen number densities for H I absorbers as a function of column density NH.
2. METHODOLOGY

We focus on model \textit{REF\_WMAP7\_L025N512} from the Over-Whelmingly Large Simulations (OWLS) project (Schaye et al. 2010), which is identical to \textit{REF\_L025N512} except that it was run using WMAP7 cosmological parameters. This simulation was performed with a modified version of the smoothed particle hydrodynamics (SPH) code GADGET (Springel 2005), and includes “sub-grid” models for star formation (Schaye & Dalla Vecchia 2008), chemodynamics (Wiersma et al. 2009a), galactic winds (Dalla Vecchia & Schaye 2008), and element-by-element cooling in the presence of a uniform UV background (Wiersma et al. 2009b). Gas in the interstellar medium (ISM) at densities above \(n_\text{H}^i = 0.1 \text{ cm}^{-3}\) is assumed to be multi-phase and star-forming. To compensate for this, we enforce a temperature dependence optical depth along each ray and integrate over the rate, \(\Gamma\). We then use \(\Gamma\) to calculate a new neutral fraction, \(n_{\text{H}_2}\), as opposed to the optically thin rate, \(\Gamma_{\text{thin}}\).

\(f(N_{\text{H}_1}, z) = \frac{d^2n}{dN_{\text{H}_1}dz} = \frac{d^2n}{dN_{\text{H}_1}dz} dX = \frac{d^2n}{dX} dz \) (1) is defined as the number of absorption lines \(n\), per unit column density \(dN_{\text{H}_1}\), per unit absorption distance \(dX\). The latter is related to redshift path \(dz\) as \(dX/dz = H(z)/(1+z)^2/H(z)\), where \(H(z)\) is the Hubble parameter (Bahcall & Peebles 1969).

For conversion of atomic hydrogen to molecules, we adopt a prescription based on observations by Blitz & Rosolowsky (2006) of 14 local spiral galaxies to form an \(H_2\)-fraction–pressure relation. Their sample includes various morphological types and spans a factor of five in mean metallicity. They obtain a power-law scaling of the molecular fraction, \(R_{\text{mol}} = \Sigma_{\text{H}_2}/\Sigma_{\text{H}_1}\), with the galactic mid-plane pressure, \(P_{\text{gas}} = (P_{\text{gas}}/P_0)^{\alpha}\), with \(\alpha = 0.92\) and \(P_0/k_B = 3.5 \times 10^4 \text{ cm}^{-3} \text{ K}\). Applying this relation to the simulated ISM yields \(f_{\text{H}_2} = [1 + (n_{\text{H}_1}/n_\text{H}^i)^{-\beta}]^{-1} \equiv \Lambda = (P_0/P_0)^{-\alpha}\), and \(\beta = \alpha/\nu_{\text{eff}}\).

The \(H_1\) column density distribution function, \(f(N_{\text{H}_1}, z)\) below \(N_{\text{H}_1} = 10^{17} \text{ cm}^{-2}\) is computed by generating 1000 mock spectra through each snapshot. We then apply instrumental broadening with FWHM 6.6 km s\(^{-1}\), add Gaussian noise such that we have a signal-to-noise ratio of 50 in the continuum, and fit the mock spectra using VPFIT (Carswell et al. 1987); see Theuns et al. (1998b) for more details. To obtain \(f(N_{\text{H}_1}, z)\) for the rarer systems with \(N_{\text{H}_1} < 10^{17} \text{ cm}^{-2}\), we project all 512\(^3\) gas particles along the \(z\)-axis onto a grid with 16,384\(^2\) pixels using Gaussian approximations to their SPH smoothing kernels. This leads to hypothetical lines of sight with a transverse spacing of 381 proper \(h^{-1}\) pc or about 3/4 the gravitational softening length at \(z = 3\). We have verified that our results are consistent with respect to the projected grid resolution.

Table 1 lists the \(N_{\text{H}_1}\) bins, absorption lines per bin, and total absorption distance used for the low and high \(N_{\text{H}_1}\) analyses of our fiducial model. The \(25 h^{-1} \text{ Mpc}\) volume searched for absorbers contains \(\approx 39,000\) friends-of-friends dark matter halos with masses above \(7.32 \times 10^8 h^{-1} M_\odot\) and yields \(\approx 2 \times 10^4\) lines of sight containing DLAs. The size of this data set obviates the need to re-weight a limited sample of absorbers using an analytic mass function as in Gardner et al. (1997) or Pontzen et al. (2008).
with self-shielding predicts fewer lines, because systems are moved to higher column densities in the self-shielded model. Above \( N_{\text{HI}} = 10^{18} \text{ cm}^{-2} \), the model that neglects self-shielding stays on the Ly\( \alpha \) forest power law until it steepens around \( N_{\text{HI}} = 10^{21.5} \text{ cm}^{-2} \) due to the formation of molecules. The other models flatten due to self-shielding and then steepen due to both the formation of molecules and the saturation of the neutral fraction. The flattening of \( f(N_{\text{HI}}, z) \) is a hallmark of self-shielding and was also found in the original numerical work of Katz et al. (1996) and in the analytic work of Zheng & Miralda-Escudé (2002). Changes in the UV background normalization by factors of three result in constant shifts of \( f(N_{\text{HI}}, z) \) until the gas is completely shielded around \( N_{\text{HI}} = 10^{21.5} \text{ cm}^{-2} \). This normalization adjustment is larger than any of the uncertainties claimed in recent work (e.g., Faucher-Giguère et al. 2008).

### 3.3. DLAs

In the right panel of Figure 2, we isolate the effects of \( \text{H}_2 \) and the photo-heating of self-shielded gas. The models with \( \text{H}_2 \) approach a vertical asymptote just above \( N_{\text{HI}} = 10^{22.0} \text{ cm}^{-2} \) while the model without \( \text{H}_2 \) predicts the existence of systems out to \( N_{\text{HI}} = 10^{24.5} \text{ cm}^{-2} \) although at such low abundance that less than one would have been discovered in the SDSS.

The introduction of \( \text{H}_2 \) produces a steepening of \( f(N_{\text{HI}}, z) \) around \( N_{\text{HI}} = 10^{21.5} \text{ cm}^{-2} \). Such a transition, suggested theoretically in Schaye (2001b), has been observed at \( z = 0 \) using CO maps as a tracer for \( \text{H}_2 \) (e.g., Zwaan & Prochaska 2006). This feature coincides with the break in the double power law.

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**Table 1**

| VPFIT | Projection |
|-------|------------|
| \( \Delta \log N_{\text{HI}} \) | \( \Delta \log N_{\text{HI}} \) |
| No. of Lines | No. of Lines |
| \( 1000 \times \Delta X_1 = 133.1 \) | \( 16, 384 \times \Delta X_1 = 3.574 \times 10^7 \) |

| \( 12.50-12.75 \) | 3598 | 17.00–17.10 | 858,492 | 20.00–20.10 | 314,774 |
| \( 12.75-13.00 \) | 4062 | 17.10–17.20 | 747,955 | 20.10–20.20 | 309,333 |
| \( 13.00-13.25 \) | 4135 | 17.20–17.30 | 658,685 | 20.20–20.30 | 302,340 |
| \( 13.25-13.50 \) | 3651 | 17.30–17.40 | 582,018 | 20.30–20.40 | 291,816 |
| \( 13.50-13.75 \) | 2918 | 17.40–17.50 | 518,006 | 20.40–20.50 | 275,818 |
| \( 13.75-14.00 \) | 2144 | 17.50–17.60 | 468,662 | 20.50–20.60 | 254,368 |
| \( 14.00-14.25 \) | 1362 | 17.60–17.70 | 431,614 | 20.60–20.70 | 228,520 |
| \( 14.25-14.50 \) | 842 | 17.70–17.80 | 406,575 | 20.70–20.80 | 198,641 |
| \( 14.50-14.75 \) | 466 | 17.80–17.90 | 387,631 | 20.80–20.90 | 167,671 |
| \( 14.75-15.00 \) | 254 | 17.90–18.00 | 374,532 | 20.90–20.00 | 135,412 |
| \( 15.00-15.25 \) | 145 | 18.00–18.10 | 359,789 | 21.00–21.10 | 103,583 |
| \( 15.25-15.50 \) | 73 | 18.10–18.20 | 350,348 | 21.10–21.20 | 76,751 |
| \( 15.50-15.75 \) | 49 | 18.20–18.30 | 342,146 | 21.20–21.30 | 54,326 |
| \( 15.75-16.00 \) | 40 | 18.30–18.40 | 334,534 | 21.30–21.40 | 37,745 |
| \( 16.00-16.25 \) | 25 | 18.40–18.50 | 329,178 | 21.40–21.50 | 25,140 |
| \( 16.25-16.50 \) | 19 | 18.50–18.60 | 324,411 | 21.50–21.60 | 16,784 |
| \( 16.50-16.75 \) | 11 | 18.60–18.70 | 320,648 | 21.60–21.70 | 10,938 |

| \( \Delta \log N_{\text{HI}} \) | \( \Delta \log N_{\text{HI}} \) |
| No. of Lines | No. of Lines |
| \( 1017 \) | \( 1017 \) |
| \( 2 \) | \( 2 \) |
| \( 1018 \) | \( 1018 \) |
| \( 5 \) | \( 5 \) |
| \( 2 \) | \( 2 \) |
| \( 1020 \) | \( 1020 \) |
| \( 1 \) | \( 1 \) |
| \( 2 \) | \( 2 \) |
| \( 1021 \) | \( 1021 \) |
| \( 1 \) | \( 1 \) |
| \( 2 \) | \( 2 \) |

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Figure 1. $\text{H}_i$ column density distribution function, $f(N_{\text{H}_i},z)$, at $z \sim 3$; simulation results are shown as curves and observational data as symbols. The low $N_{\text{H}_i}$ curve is obtained using mock spectra fitted with VPFFIT. Self-shielding and $\text{H}_2$ are unimportant in this range. The high $N_{\text{H}_i}$ curve is obtained by projecting the simulation box onto a plane and includes self-shielding and $\text{H}_2$. The gap around $N_{\text{H}_i} \sim 10^{17}$ cm$^{-2}$ separates low and high $N_{\text{H}_i}$. Poisson errors on the simulation curves are always smaller than their thickness. We also show high-resolution observations of the Ly$\alpha$ forest (Kim et al. 2002, “Kim02”), LLSs (Péroux et al. 2005, “Per05”; O’Meara et al. 2007, “Ome07”), analysis of SDSS DLA data (Noterdaeme et al. 2009, “NPLS09”), and power-law constraints (Prochaska et al. 2010, “POW10”; open circles are spaced arbitrarily along power-law segments and do not represent $N_{\text{H}_i}$ bins or errors). (A color version of this figure is available in the online journal.)

commonly used to fit $f(N_{\text{H}_i},z)$ in the DLA column density range (Prochaska & Wolfe 2009; Noterdaeme et al. 2009), suggesting a relationship between the two. At DLA column densities, ionizing radiation from local sources may play a role (Schaye 2006). We have not included these sources in our self-shielding model, but Nagamine et al. (2010) have recently shown that $f(N_{\text{H}_i},z)$ changes by less than 0.1 dex when local sources are included.

Because the UV background suppresses cooling, the temperature recorded in the OWLS snapshots for particles that are identified as self-shielded in post-processing is an overestimate. To compensate for this, we enforce a temperature ceiling of $T_{\text{shld}} = 10^4$ K in self-shielded particles in our fiducial model. The curve labeled “w/o $T_{\text{shld}}$” shows a model in which we have not performed this temperature adjustment. Because the temperature dependence of the collisional equilibrium neutral fraction is very small below $10^4$ K, the two temperature models should bracket the neutral fractions one would expect from a more accurate treatment of the temperature. The difference between these two models is about a factor of 10 smaller than the difference between the optically thin and self-shielded models but can be on the order of the observational 1$\sigma$ error bars around the DLA threshold where the data are most abundant. We plan to explore hydrodynamic simulations that include self-shielding in future work.

3.4. Physical Properties of High $N_{\text{H}_i}$ Absorbers

Neutral hydrogen mass weighted values for the neutral fraction, $x_{\text{H}_i} \equiv n_{\text{H}_i}/n_\text{H}$, and total hydrogen number density, $n_\text{H} = n_{\text{H}_i} + n_{\text{H}_II} + 2n_{\text{H}_2}$, are plotted as a function of $N_{\text{H}_i}$ in Figure 3. The effects of self-shielding produce a steep deviation from the optically thin power law in $x_{\text{H}_i}$ above $N_{\text{H}_i} = 10^{17}$ cm$^{-2}$. As the UV Background normalization is reduced, and as higher temperatures are used, the deviation becomes smaller. The median $x_{\text{H}_i}$ at $N_{\text{H}_i} = 10^{18}$ cm$^{-2}$ in our fiducial model is 0.3, however there is a large spread in the data in this column density range. It begins to drop around

Figure 2. $f(N_{\text{H}_i},z)$—LLS and DLA range. In the left panel, we vary the amplitude of the UV background and show the impact of neglecting self-shielding. In the right panel, we isolate the effects of $\text{H}_2$ and show a model in which we have not lowered the temperature in self-shielded particles (w/o $T_{\text{shld}}$). On top of each panel, we show the ratio of each model to our fiducial model (solid red curve), which includes self-shielding and $\text{H}_2$. The observational data are a subset of those in Figure 1 plus SDSS analysis from Prochaska & Wolfe (2009, “PW09”). Self-shielding becomes important for $N_{\text{H}_i} \gtrsim 10^{18}$ cm$^{-2}$ leading to a flattening of $f(N_{\text{H}_i},z)$. Cooling the self-shielded gas yields a constant offset while $\text{H}_2$ becomes important above column densities of $N_{\text{H}_i} > 10^{21.5}$. (A color version of this figure is available in the online journal.)
$N_{\text{HI}} = 10^{21} \text{ cm}^{-2}$ due to the formation of H$_2$. Systems above $N_{\text{HI}} = 10^{22} \text{ cm}^{-2}$ have lost much of their atomic hydrogen to molecules, however the H$_2$ likely has a small covering fraction.

The median $n_{\text{H}}$ flattens around the beginning of the LLS range, $N_{\text{HI}} = 10^{19.2} \text{ cm}^{-2}$, to approximately $2 \times 10^{-2} \text{ cm}^{-3}$ where it remains roughly constant until the start of the DLA range, $N_{\text{HI}} = 10^{20.3} \text{ cm}^{-2}$. Above this column density, the gas is fully neutral (see left panel) causing $n_{\text{H}}$ to rise steeply with $N_{\text{HI}}$ and $f(N_{\text{HI}}, z)$ to steepen (see Figure 2). Above $N_{\text{HI}} = 10^{21} \text{ cm}^{-2}$, the medians for models which include H$_2$ are steeper than linear due to the formation of molecules. The normalization of the UV Background and the treatment of temperature can change the LLS characteristic density by half a decade. For the optically thin case we find excellent agreement with the corresponding prediction in Schaye (2001a).

4. CONCLUSIONS

We have used a hydrodynamic simulation of galaxy formation together with an accurate ray-tracing treatment of self-shielding from the UV background and an empirical prescription for H$_2$ formation, to compute the $z \approx 3$ H$_1$ column density distribution function. We find agreement between the reference OWLS model and the entire column density range probed by observations ($10^{12} \text{ cm}^{-2} < N_{\text{HI}} < 10^{22} \text{ cm}^{-2}$). We have shown that $f(N_{\text{HI}}, z)$ flattens above $N_{\text{HI}} = 10^{19} \text{ cm}^{-2}$ due to self-shielding, and steepens around $N_{\text{HI}} = 10^{20.3} \text{ cm}^{-2}$ and $N_{\text{HI}} = 10^{21.5} \text{ cm}^{-2}$ due to the absorbing gas becoming fully neutral, and the transition from atomic to molecular hydrogen, respectively. In future work, we will examine the systems causing this absorption in greater detail and repeat these analyses on a large sample of OWLS models.

We thank Joseph Hennawi, Matt McQuinn, Pasquier Noterdaeme, Xavier Prochaska, and the OWLS team. These simulations were run on Stella, the LOFAR Blue-Gene/L system in Groningen, and on the ICC Cosmology Machine which is part of the DiRAC Facility jointly funded by STFC, the Large Facilities Capital Fund of BIS, and Durham University as part of the Virgo Consortium research program and would not function without the extraordinary efforts of Lydia Heck. This work was sponsored by the National Computing Facilities Foundation (NCF) for the use of supercomputer facilities, with financial support from the Netherlands Organization for Scientific Research (NWO).

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Bahcall, J. N., & Peebles, P. J. E. 1969, ApJ, 156, L7
Bi, H., & Davidsen, A. F. 1997, ApJ, 479, 523
Blitz, L., & Rosolowsky, E. 2006, ApJ, 650, 933
Carswell, R. F., Webb, J. K., Baldwin, J. A., & Atwood, B. 1987, ApJ, 319, 709
Cen, R., Ostriker, J. P., Prochaska, J. X., & Wolfe, A. M. 2003, ApJ, 598, 741
Cen, R. 2010, arXiv:1010.5014
Dalla Vecchia, C., & Schaye, J. 2008, MNRAS, 387, 1431
Faucher-Giguère, C., Lidz, A., Hernquist, L., & Zaldarriaga, M. 2008, ApJ, 688, 85
Gardner, J. P., Katz, N., Hernquist, L., & Weinberg, D. H. 1997, ApJ, 484, 31
Görski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759
Haardt, F., & Madau, P. 2001, in Clusters of Galaxies and the High Redshift Universe Observed in X-rays, ed. D. M. Neumann & J. T. T. Van, 64 (arXiv:astro-ph/0106018)
Haardt, F., & Madau, P. 2011, arXiv:1105.2039
Haehnelt, M. G., Steinmetz, M., & Rauch, M. 1998, ApJ, 495, 647
Hong, S., Katz, N., Davé, R., et al. 2010, arXiv:1008.4242
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escude, J. 1996, ApJ, 457, L57
Kim, T., Carswell, R. F., Cristiani, S., D’Odorico, S., & Giallongo, E. 2002, MNRAS, 335, 555
Kohler, K., & Gnedin, N. Y. 2007, ApJ, 655, 685
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Krumholz, M. R., Ellison, S. L., Prochaska, J. X., & Tumlinson, J. 2009, ApJ, 701, L12
McQuinn, M., Oh, S. P., & Faucher-Giguere, C.-A. 2011, arXiv:1101.1964
Nagamine, K., Choi, J.-H., & Yajima, H. 2010, ApJ, 725, L219
Nagamine, K., Springel, V., & Hernquist, L. 2004, MNRAS, 348, 421
Noterdaeme, P., Petitjean, P., Ledoux, C., & Srianand, R. 2009, A&A, 505, 1087
O'Meara, J. M., Prochaska, J. X., Burles, S., et al. 2007, ApJ, 656, 666
Péroux, C., Dessauges-Zavadsky, M., D’Odorico, S., Sun Kim, T., & McMahon, R. G. 2005, MNRAS, 363, 479
Petitjean, P., Webb, J. K., Rauch, M., Carswell, R. F., & Lanzetta, K. 1993, MNRAS, 262, 499
Pontzen, A., Governato, F., Pettini, M., et al. 2008, MNRAS, 390, 1349
Prochaska, J. X., O’Meara, J. M., & Worseck, G. 2010, ApJ, 718, 392
Prochaska, J. X., & Wolfe, A. M. 2006, ApJ, 645, 55
Razoumov, A. O., Norman, M. L., Prochaska, J. X., & Wolfe, A. M. 2006, ApJ, 659, 507
Schaye, J. 2001a, ApJ, 559, 507
Schaye, J. 2001b, ApJ, 562, L95
Schaye, J. 2006, ApJ, 643, 59
Schaye, J., & Dalla Vecchia, C. 2008, MNRAS, 383, 1210
Schaye, J., Dalla Vecchia, C., Booth, C. M., et al. 2010, MNRAS, 402, 1536
Springel, V. 2005, MNRAS, 364, 1105
Tescari, E., Viel, M., Tornatore, L., & Borgani, S. 2009, MNRAS, 397, 411
Theuns, T., Leonard, A., & Efstathiou, G. 1998a, MNRAS, 297, 49
Theuns, T., Leonard, A., Efstathiou, G., Pearce, F. R., & Thomas, P. A. 1998b, MNRAS, 301, 478
Tytler, D. 1987, ApJ, 321, 49
Wiersma, R. P. C., Schaye, J., Theuns, T., Dalla Vecchia, C., & Tornatore, L. 2009a, MNRAS, 399, 574
Wiersma, R. P. C., Schaye, J., & Smith, B. D. 2009b, MNRAS, 393, 99
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861
Zheng, Z., & Miralda-Escudé, J. 2002, ApJ, 568, L71
Zwaan, M. A., & Prochaska, J. X. 2006, ApJ, 643, 675