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EFFECTS OF UV BACKGROUND AND LOCAL STELLAR RADIATION ON THE H I COLUMN DENSITY DISTRIBUTION

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ABSTRACT

We study the impact of ultra-violet background radiation field (UVB) and the local stellar radiation on the H I column density distribution $f(N_{\rm HI})$ of damped Lyman-α systems (DLAs) and sub-DLAs at $z = 3$ using cosmological smoothed particle hydrodynamics simulations. We find that, in the previous simulations with an optically thin approximation, the UVB was sinking into the H I cloud too deeply, and therefore we underestimated the $f(N_{\rm HI})$ at $19 < \log N_{\rm HI} < 21.2$ compared to the observations. When the UVB is shut off in the high-density regions with $n_{\rm gas} > 6\times10^{-3}\,{\rm cm}^{-3}$, then we reproduce the observed $f(N_{\rm HI})$ at $z = 3$ very well. We also investigate the effect of local stellar radiation by post-processing our simulation with a radiative transfer code, and find that the local stellar radiation reduces the $f(N_{\rm HI})$ by a factor of ~ 0.7, which further improves the agreement with the observation. Our results show that the shape of $f(N_{\rm HI})$ is determined primarily by the treatment of UVB, with a weaker effect by the local stellar radiation, and that the optically thin approximation often used in cosmological simulation is inadequate to properly treat the ionization structure of neutral gas in and out of DLAs.

Subject headings: cosmology: theory — stars: formation — galaxies: evolution – galaxies: formation – methods: numerical

1. INTRODUCTION

The H I column density distribution function $f(N_{\rm HI})$ is one of the most basic statistics of quasar absorption systems, similarly to the luminosity function of galaxies. The accuracy of observational data on $f(N_{\rm HI})$ has dramatically improved over the past several years, thanks to the large samples of DLAs discovered in large data sets of quasar spectra (e.g., Péroux et al. 2003; Prochaska & Herbert-Fort 2004; Péroux et al. 2005; Prochaska et al. 2005, 2008). Their results indicate that the observed $f(N_{\rm HI})$ can be fitted well with either a double power-law or a Schechter-type function.

It would be desirable to understand the physical origin of the shape of $f(N_{\rm HI})$ in a cosmological context of the standard Λ cold dark matter model. The first such attempt was by Katz et al. (1996b), who used a cosmological smoothed particle hydrodynamics (SPH) simulation with a comoving box-size of $22.22h^{-1}$ Mpc, 2×64^3 particles, and cosmological parameters $(\Omega_m,\Omega_\Lambda,\Omega_b) = (1.0, 0.0, 0.05)$. They found that their simulation underpredicted $f(N_{\rm HI})$ compared to the observational data by a factor of few or more, using a uniform UVB $J(\nu) = J_0(\nu_0/\nu)$ at $z = 3$, where ν_0 is the Lyman-limit frequency and $J_0 = 10^{-22}\,{\rm erg\,s^{-1}\,cm^{-2}\,sr^{-1}\,Hz^{-1}}$. The UVB is usually treated with an optically thin limit regardless of gas density in cosmological hydrodynamic simulations owing to the computational limit. This simplified approximation may artificially increase the ionization fraction of gas, and gives rise to the discrepancy in $f(N_{\rm HI})$.

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Nagamine et al. (2004, 2007) updated the work of Katz et al. (1996b) using cosmological SPH simulations with a comoving box-size of $10h^{-1}$ Mpc, 2×324^3 particles, and $(\Omega_m,\Omega_\Lambda,\Omega_b) = (0.3, 0.7, 0.044)$. Interestingly, they also found a similar underprediction of $f(N_{\rm HI})$ compared to the observations, despite of significantly higher resolution than that of Katz et al. (1996b). Their simulations included a uniform UVB of Haardt & Madau (1996) spectrum, modified by Davé et al. (1999) to match the Lyα forest observations.

We have attempted to resolve this discrepancy by modifying the models of star formation (SF) and supernova feedback; e.g., changing the SF threshold density, SF time-scale, feedback strengths, or adding metal-line cooling (Choi & Nagamine 2009a,b). However, none of these changes in the physical models resolved the discrepancy in $f(N_{\rm HI})$ fundamentally.

In this *Letter*, we show that the effect of UVB is the key in determining the shape of $f(N_{\rm HI})$ at $\log N_{\rm HI} \lesssim 21.6$. In addition, we consider the effect of local stellar radiation on $f(N_{\rm HI})$ by performing a radiative transfer (RT) calculation, and find that it improves the agreement between simulations and observations. Our paper is organized as follows. In § 2, we briefly describe the setup of our simulations, and present the results in § 3. We then discuss the comparison with other recent works, and conclude in § 4.

2. SIMULATIONS

We use the updated version of the tree-particle-mesh SPH code GADGET-3 (originally described in Springel 2005). Our conventional code includes radiative cooling by H, He, and metals (Choi & Nagamine 2009b), heating by a uniform UVB of a modified Haardt & Madau (1996) spectrum (Katz et al. 1996a; Davé et al. 1999), star formation, supernova feedback, a phenomenological model for galactic winds, and a sub-resolution model of multiphase ISM (Springel & Hernquist 2003). In this multiphase ISM model, high-density ISM is pictured to be a two-phase fluid consisting of cold clouds in pressure equilibrium with a hot ambient phase. Cold clouds grow by radiative cooling out of the hot medium, and this material forms the reservoir of baryons available for star formation. We use the 'Pressure SF' model described by Choi & Nagamine (2009a) (which is based on the work by Schaye & Dalla Vecchia (2008)), but we have checked that the details of the SF model does not change the main conclusions of this paper.

For all the simulations used in this paper, we employ a box size of comoving $10\,h^{-1}$ Mpc and a total particle number of 2×144^3 for gas and dark matter. The initial gas particle mass is $m_{\rm gas} = 4.1 \times 10^6\ h^{-1} M_\odot$, and the dark matter particle mass is $m_{\rm dm} = 2.0 \times 10^7\ h^{-1} M_\odot$. The comoving gravitational softening length is $2.78\,h^{-1}$ kpc, so the physical resolution of our simulation is $\sim 0.7\,h^{-1}$ kpc at $z = 3$. Nagamine et al. (2004) showed that increasing the particle number from 2×144^3 to 2×324^3 did not change the shape of $f(N_{\rm HI})$ very much, therefore our results would not be strongly affected by the resolution effect. The adopted cosmological parameters of all simulations are consistent with the latest WMAP result (Komatsu et al. 2009, 2010): $(\Omega_{\rm m}, \Omega_\Lambda, \Omega_{\rm b}, \sigma_8, h, n_s) = (0.26, 0.74, 0.044, 0.80, 0.72, 0.96)$, where $h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}})$.

With this setup, we run four simulations with different models of UVB: 'Fiducial', 'No-UV', 'Half-UV', and 'OTUV' (Optically-Thick UV) runs. In the Fiducial run, the gas is heated and ionized by the uniform UVB under the optically thin approximation. In the No-UV run, the UVB strength is set to zero. In the Half-UV run, the normalization of UVB is reduced by half. In the OTUV run, we assume that the uniform UVB cannot penetrate into the high-density gas with $n_{\rm gas} > n_{\rm th}^{\rm UV}$, but otherwise it is the same as the Fiducial run at $n_{\rm gas} \le n_{\rm th}^{\rm UV}$.

We adopt the threshold density $n_{\rm th}^{\rm UV} = 0.01\, n_{\rm th}^{\rm SF} = 6 \times 10^{-3}\,{\rm cm^{-3}}$, where $n_{\rm th}^{\rm SF}$ is the SF threshold density above which the stars are allowed to form. In our simulations, the gas with $n_{\rm gas} > n_{\rm th}^{\rm SF}$ is mostly neutral owing to the multiphase ISM model. We originally arrived at the above value of $n_{\rm th}^{\rm UV}$ by successively lowering its value from $n_{\rm th}^{\rm SF}$ and checking the agreement with the observed $f(N_{\rm HI})$, but will provide further justifications below.

There is evidence that the above value of $n_{\rm th}^{\rm UV}$ is physically appropriate. Kollmeier et al. (2010) performed a 3-D UVB RT calculation with an isothermal sphere, and showed that the above value of $n_{\rm th}^{\rm UV}$ approximately corresponds to the transition density from H II to H I. Tajiri & Umemura (1998) also found that the hydrogen cloud becomes fully self-shielded above a critical density of $1.4 \times 10^{-2}\,{\rm cm^{-3}}$ through RT calculations for a spherical top-hat sphere, and that the critical density has a mild dependence on the cloud mass and the UVB intensity. Furthermore, we also confirmed that the above $n_{\rm th}^{\rm UV}$ is appropriate by postprocessing our simulations with a RT code, which we will report in detail in a separate paper (Yajima et al., 2010, in prep.). For these reasons, we consider that the correct value of $n_{\rm th}^{\rm UV}$ is in the range of $10^{-2} - 10^{-3}\,{\rm cm^{-3}}$, depending on the cloud mass and UVB intensity.

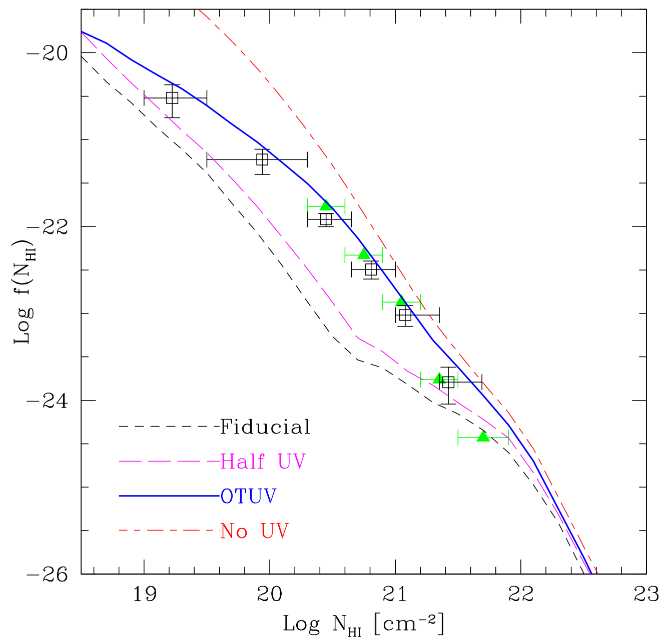


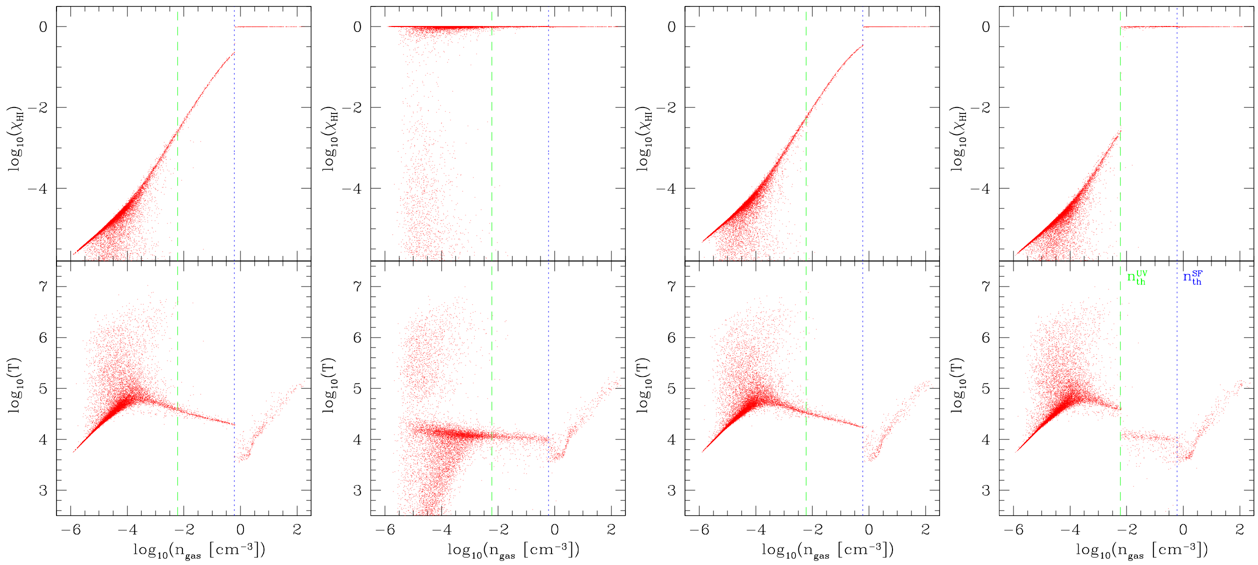
Fig. 1.— H I column density distribution functions at $z = 3$ for the four runs with different treatment of UVB. The observational data points are from Prochaska & Wolfe (2009, green triangles) and (Péroux et al. 2005, black open squares).

3. RESULTS

3.1. *Effect of UVB on $f(N_{\rm HI})$*

Figure 1 shows the $f(N_{\rm HI})$ in the four runs with different UVB treatment, which was calculated by the same method described in Nagamine et al. (2004). In short, we set up a uniform grid around each dark matter halo, and project the gas density field onto a face of the grid to compute $N_{\rm HI}$. Fig. 1 clearly shows that the Fiducial run underpredicts the $f(N_{\rm HI})$, particularly at $\log N_{\rm HI} < 21.2$. The Half-UV run is somewhat higher than the Fiducial run, but still not enough to account for the observed number of columns at $19.5 < \log N_{\rm HI} < 21$. On the other hand, the No-UV run completely overpredicts the observed $f(N_{\rm HI})$ at all column densities. The sudden decrease in $f(N_{\rm HI})$ from the No-UV run to the Half-UV run shows that even a weak UVB can ionize the gas and the simulation cannot account for the observed number of columns. The OTUV run agrees very well with the observed data at $19.2 < \log N_{\rm HI} < 21.2$. The comparison of these four runs suggests that the UVB affects the shape of $f(N_{\rm HI})$ significantly, and that applying the optically thin approximation at all densities is too simplistic to reproduce the $f(N_{\rm HI})$ properly.

To obtain a better physical intuition on the effect of UVB, we plot the hydrogen neutral fraction ($\chi_{\rm HI}$) and temperature against gas density for the four runs in Figure 2. The difference of $f(N_{\rm HI})$ between the Fiducial and the OTUV run must be due to the different neutral fraction of gas at $n_{\rm th}^{\rm UV} < n_{\rm gas} < n_{\rm th}^{\rm SF}$ in the two runs. The Fiducial run predicts a high degree of ionization at $n_{\rm gas} < n_{\rm th}^{\rm SF}$ ($\approx 0.6\,{\rm cm^{-3}}$). For example, the gas with $n_{\rm gas} \sim 0.1\,{\rm cm^{-3}}$ at $z = 3$ has $\chi_{\rm HI} \sim 0.05$ for the Fiducial run. By referencing to the $f(N_{\rm HI})$, the gas with this density should correspond to the DLA with



(a) Fiducial (b) No-UV (c) Half-UV (d) Optically-Thick

FIG. 2.— Neutral hydrogen fraction ($n_{\rm gas}$ vs. T; top panels) and phase space distribution ($n_{\rm gas}$ vs. $\chi_{\rm HI}$; bottom panels) of the cosmic gas at $z = 3$ for the four runs. The neutral fraction is defined as $\chi_{\rm HI} = n_{\rm HI}/(n_{\rm HI} + n_{HII})$. For plotting purpose, we plot only randomly selected 1% of the total gas particles in the simulation. The two densities, $n_{\rm th}^{\rm UV}$ and $n_{\rm th}^{\rm SF}$, are indicated by the green dashed line and blue dotted lines, respectively.

$\log N_{\rm HI} \sim 20$, and $\chi_{\rm HI} \sim 0.05$ is too low to match the observed data on $f(N_{\rm HI})$. The Half-UV run has a higher neutral fraction for the gases with $n_{\rm gas} < n_{\rm th}^{\rm SF}$, but still $\chi_{\rm HI} < 0.3$. In contrast, most hydrogen in the No-UV run has $\chi_{\rm HI} \sim 1.0$, except for the small fraction of hot gas which is ionized by collisional ionization in shocked regions. Eliminating the UVB completely is not a realistic assumption, and the No-UV run clearly overpredicts $f(N_{\rm HI})$ as expected. Lastly, in the OTUV run, the gas with $n_{\rm gas} > n_{\rm th}^{\rm UV}$ has $\chi_{\rm HI} \sim 1.0$, which allows it to match the observed $f(N_{\rm HI})$. Figures 1 & 2 clearly show that the optically thin approximation ionizes the gas with $n_{\rm th}^{\rm UV} < n_{\rm gas} < n_{\rm th}^{\rm SF}$ too much. In order to properly reproduce the observed $f(N_{\rm HI})$ with our simulations, the gas should be mostly neutral at $n_{\rm gas} > n_{\rm th}^{\rm UV}$.

The effects of UVB can also be seen in the $\rho - T$ phase diagrams in the bottom panels of Figure 2. The comparison of the Fiducial and No-UV runs shows the well-known dramatic photoionization effect on the diffuse IGM at low densities of $n_{\rm gas} < 10^{-2}\,{\rm cm}^{-3}$. Compared to the Fiducial run, the gas with $n_{\rm th}^{\rm UV} < n_{\rm gas} < n_{\rm th}^{\rm SF}$ in the OTUV run is neutral with a lower temperature of $T \sim 10^4$ K. We will show in a separate paper (Yajima et al., 2010, in prep.) that a full RT calculation supports the results shown in Fig. 2d.

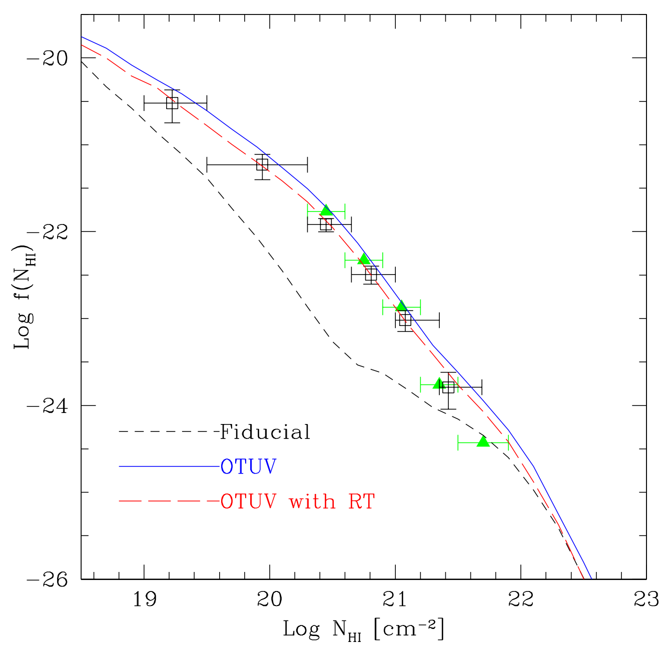


FIG. 3.— Effect of local stellar radiation on $f(N_{\rm HI})$ at $z = 3$. The observational data points are the same as in Figure 1.

3.2. *Effects of Radiative Transfer on* $f(N_{\rm HI})$

The OTUV run is remarkably successful in reproducing the observed $f(N_{\rm HI})$ at $19 < \log N_{\rm HI} < 21.5$, but so far we have neglected the radiative effects of the stellar radiation from local stellar sources, which could heat and ionize the high-density gas in the star-forming regions.

In order to consider the effects of local stellar radiation, we postprocess our simulation with the Authentic Radiation Transfer (ART) code (Nakamoto et al. 2001; Yajima et al. 2009, 2010), which uses the ray-tracing technique. Figure 3 compares the results from the Fiducial run, the OTUV run, and the OTUV run postprocessed with the ART code. The transferred stellar spectra are computed by using the PÉGASE v2.0 (Fioc & Rocca-Volmerange 1997) based on the mass, formation time, and age of the star particles generated in the simulation. We find that the local stellar radiation ionizes the H I and reduces $f(N_{\rm HI})$ by a factor of $\sim$0.7, as shown by the red long-dashed line in Fig. 3. The amount of this change is not significant compared to the difference between the Fiducial and the OTUV run, but it improves the agreement between the simulation and the observations. We will report more details of the RT calculation results in a separate publication (Yajima et al., 2010, in preparation).

4. DISCUSSIONS & CONCLUSIONS

Using cosmological SPH simulations, we examined the effects of UVB on $f(N_{\rm HI})$, and clarified the reason why earlier simulations have underestimated this quantity compared to the observations. We find that the radiation to sinks into the dense gas too deeply under the optically thin approximation of UVB, and the gas with $19 < \log N_{\rm HI} < 21.5$ is overly ionized. When we turn off the UVB above a physical density of $n_{\rm th}^{\rm UV} = 6 \times 10^{-3}\,{\rm cm}^{-3}$, then we reproduce the observed $f(N_{\rm HI})$ at $z = 3$ very well. The exact value of $n_{\rm th}^{\rm UV}$ would depend on the details of the spectral shape and the intensity of UVB, and the size of gas cloud (Tajiri & Umemura 1998). Based on the comparison to other works, we consider that a value of $n_{\rm th}^{\rm UV} \sim 10^{-2} - 10^{-3}\,{\rm cm}^{-3}$ would be appropriate for current cosmological simulations. Our results clearly show that the optically thin approximation was responsible for the failure in matching the observed $f(N_{\rm HI})$ in earlier simulations.

Recently, problems in the optically thin approximation have been pointed out in the context of the He II reionization effect on the thermal history of IGM (McQuinn et al. 2009; Faucher-Giguère et al. 2009). Our present work is another example of the inadequacy of the optically thin approximation of UVB for modeling the ionization of gas near DLAs. The radiative transfer effects, as well as the exact shape of UVB, have significant impact on the details of galaxy formation history including DLAs (e.g. Tajiri & Umemura 1998; Zheng & Miralda-Escudé 2002; Hambrick et al. 2009; Kollmeier et al. 2010).

Although cosmological radiative transfer simulations are beginning to be performed, it is still difficult to do a self-consistent ray-tracing RT calculation concurrently with the hydrodynamics due to limitated computational speed. Under this circumstance, it would still help to have a physically plausible working model of self-shielding for cosmological simulations. Our result provides a useful proxy for the threshold density ($n_{\rm th}^{\rm UV}$) above which the self-shielding effect kicks in.

We also examined the effects of local stellar radiation by postprocessing the simulation with a ray-tracing code. The effect is not as strong as the UVB, but it slightly decreases $f(N_{\rm HI})$ (by ~ 0.15 dex) and brings the agreement with observation even better. We will report the further details of this ray-tracing work and its effect on DLA cross sections in a separate publication (Yajima et al., 2010, in preparation).

To put it in another way, our results suggest that $f(N_{\rm HI})$ and the ionization structure of sub-DLAs and DLAs would be great probes of UVB at high redshift, and that the DLA gas is closely related to the transition region from optically-thin ionized gas to optically-thick neutral gas within dark matter halos. Further comparisons on the physical properties of sub-DLAs and DLAs between simulations and observations would give us useful insight on the nature of UVB.

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REFERENCES

Choi, J.-H. & Nagamine, K. 2009a, arXiv:0909.5425
—. 2009b, MNRAS, 393, 1595
Davé, R., Hernquist, L., Katz, N., et al. 1999, ApJ, 511, 521
Faucher-Giguère, C., Lidz, A., Zaldarriaga, M., et al. 2009, ApJ, 703, 1416
Fioc, M. & Rocca-Volmerange, B. 1997, A&A, 326, 950
Haardt, F. & Madau, P. 1996, ApJ, 461, 20
Hambrick, D. C., Ostriker, J. P., Naab, T., et al. 2009, ApJ, 705, 1566
Katz, N., Weinberg, D. H., & Hernquist, L. 1996a, ApJS, 105, 19
Katz, N., Weinberg, D. H., Hernquist, L., et al. 1996b, ApJ, 457, L57
Kollmeier, J. A., Zheng, Z., Davé, R., et al. 2010, ApJ, 708, 1048
Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2010, ArXiv e-prints
McQuinn, M., Lidz, A., Zaldarriaga, M., et al. 2009, ApJ, 694, 842
Nagamine, K., Springel, V., & Hernquist, L. 2004, MNRAS, 348, 421
Nagamine, K., Wolfe, A. M., Hernquist, L., & Springel, V. 2007, ApJ, 660, 945
Nakamoto, T., Umemura, M., & Susa, H. 2001, MNRAS, 321, 593
Péroux, C., Dessauges-Zavadsky, M., D'Odorico, S., et al. 2005, MNRAS, 363, 479
Péroux, C., McMahon, R. G., Storrie-Lombardi, L. J., et al. 2003, MNRAS, 346, 1103
Prochaska, J. X., Hennawi, J. F., & Herbert-Fort, S. 2008, ApJ, 675, 1002
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. & Wolfe, A. M. 2009, ApJ, 696, 1543
Schaye, J. & Dalla Vecchia, C. 2008, MNRAS, 383, 1210
Springel, V. 2005, MNRAS, 364, 1105
Springel, V. & Hernquist, L. 2003, MNRAS, 339, 289
Tajiri, Y. & Umemura, M. 1998, ApJ, 502, 59
Yajima, H., Choi, J.-H., & Nagamine, K. 2010, ArXiv e-prints (arXiv:1002.3346)
Yajima, H., Umemura, M., Mori, M., et al. 2009, MNRAS, 398, 715
Zheng, Z. & Miralda-Escudé, J. 2002, ApJL, 568, L71