ADAPTIVE MESH REFINEMENT SIMULATIONS OF THE IONIZATION STRUCTURE AND KINEMATICS OF DAMPED Lyα SYSTEMS WITH SELF-CONSISTENT RADIATIVE TRANSFER

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ABSTRACT

We use high-resolution Eulerian hydrodynamics simulations to study kinematic properties of the low-ionization species in damped Lyα systems at redshift $z = 3$. Our adaptive mesh refinement simulations include most key ingredients relevant for modeling neutral gas in high column density absorbers: hydrodynamics, gravitational collapse, continuum radiative transfer above the hydrogen Lyman limit, and gas chemistry, but no star formation. We model high-resolution Keck spectra with unsaturated low ion transitions in two Si $\upiota$ lines (1526 and 1808 Å) and compare simulated line profiles to the data from the SDSS DLA survey. We find that with increasing grid resolution the models show a trend in convergence toward the observed distribution of H I column densities. While in our highest resolution model we recover the cumulative number of DLAs per unit absorption distance, none of our models predicts DLA velocity widths as high as indicated by the data, suggesting that feedback from star formation might be important. At $z = 3$ a nonnegligible fraction of DLAs with column densities below $10^{21}$ cm$^{-2}$ is caused by filamentary structures in more massive halo environments. Lower column density absorbers with $N_{HI} < 10^{21.4}$ cm$^{-2}$ are sensitive to changes in the UV background, resulting in a 10% reduction of the cumulative number of DLAs for twice the quasar background relative to the fiducial value and nearly a 40% reduction for 4 times the quasar background. We find that the mass cutoff below which a large fraction of dwarf galaxies cannot retain gas after reionization is $\sim 7 \times 10^7 M_{\odot}$, lower than the previous estimates. Finally, we show that models with self-shielding commonly used in the literature produce significantly lower DLA velocity widths than the full radiative transfer runs, which essentially renders these self-shielded models obsolete.

Subject headings: galaxies: formation — methods: numerical — quasars: absorption lines — radiative transfer

1. INTRODUCTION

Damped Lyα absorbers (DLAs) are an excellent tool for probing structure formation in the early universe. By definition, DLAs are systems with neutral hydrogen column densities above $2 \times 10^{20}$ cm$^{-2}$, and for many years they have been linked to forming protogalaxies at high redshifts. With high-resolution spectroscopy, DLAs can shed light on physical processes and substructure within individual young galaxies. However, the exact nature of the host absorbers has been debated for many years. From metal line kinematic analysis of absorption line widths and profile asymmetries Prochaska & Wolfe (1997) concluded that the observed DLA population can be best explained with a model in which absorption is caused by rapidly rotating ($v_{circ} \sim 225$ km s$^{-1}$) cold thick $(h \sim 0.3 R_e)$ disks that have already assembled at high redshifts, and they ruled out the competing models in which DLAs are small ($v_{circ} \leq 100$ km s$^{-1}$) protogalaxies in the process of hierarchical merger. However, in most models of hierarchical structure formation it is extremely difficult to have an abundant population of such massive disks at $z \sim 3-4$.

On the other hand, in high-resolution (1 kpc spatial and $5 \times 10^9 M_{\odot}$ mass resolution) smoothed particle hydrodynamics (SPH) simulations of a small number of high-redshift galaxies Haehnelt et al. (1998) showed that irregular protogalactic clumps with $v_{circ} \sim 100$ km s$^{-1}$ can reproduce the observed velocity width distribution and absorption profile asymmetries very well, without the need to invoke rapidly rotating massive disks. In their models large velocity widths are caused by a mixture of rotation, random motions, infall, and merging, and the resulting picture is fully consistent with most standard hierarchical structure formation scenarios. Despite having achieved very high numerical resolution, this simulation features a small volume size ($2$ Mpc$^3$) and may not be representative of a typical DLA absorber in the cosmological context. Another shortcoming of the Haehnelt et al. (1998) paper is that their models do not include radiative transfer of the ultraviolet background (UVB), instead assuming simple self-shielding above a critical density, an assumption that directly affects the cross section of DLAs. In our paper we address this issue in detail.

Simulations with larger volume sizes inherently suffer from an inability to resolve the lower mass part of the DLA distribution. Katz et al. (1996) studied the formation of DLAs in a 22.22 Mpc (comoving) volume with SPH simulations with dark matter mass resolution $2.8 \times 10^9 M_{\odot}$, effectively meaning that only halos with masses above $\sim 10^{11} M_{\odot}$ could be resolved. Gardner et al. (1997) developed a method to account for absorption in halos below the numerical resolution of simulations. They used the Press & Schechter (1974) formalism to calculate the number density of unresolved halos and then convolved this distribution with the relation between the neutral hydrogen cross section and halo circular velocity observed in their SPH simulation to obtain the total abundance of DLAs in a large simulation volume. We return to the important question of DLA cross-sectional dependence on the dark matter (DM) halo velocity dispersion further in this introduction. Gardner et al. (1997) find
that accounting for unresolved halos with this resolution correction increases the DLA incident rate per unit redshift by about a factor of 2, bringing it closer to the observed value but still underpredicting the amount of Lyman limit absorption by approximately a factor of 3.

Gardner et al. (2001) used newer SPH simulations and an improved technique to compute the contribution from unresolved halos and found that their DLA incidence matches observations as long as they adopt a \( v_{\text{esc}} \sim 60 \text{ km s}^{-1} \) circular velocity cutoff (corresponding to virial mass \( \sim 2 \times 10^{10} M_\odot \) at \( z = 3 \)) below which halos cannot host DLA absorption systems, a value that is somewhat higher than the more traditional threshold \( v_{\text{esc}} \sim 40 \text{ km s}^{-1} \) for suppressing the formation of dwarf galaxies by a UV photoionization background (Quinn et al. 1996; Thoul & Weinberg 1996). The highest dark matter mass resolution in these simulations is \( 8.3 \times 10^9 M_\odot \), immediately suggesting that halos with masses below a few times \( 10^{10} M_\odot \) are not resolved, which is very similar to the suggested cutoff.

On the other hand, Maller et al. (2001) used semianalytic models of galaxy formation to further investigate the hypothesis that multiple galactic clumps give rise to the observed kinematics and column density distributions. They studied several variants of the exponential disk model in which the sizes of individual galaxies are based on angular momentum conservation, noting that the resulting gaseous disks by themselves are too small to produce the observed kinematics and the overall number density of DLAs. However, with a simple toy model they showed that a larger covering factor of the cold gas in these clumps can successfully reproduce the observed properties, suggesting that lines of sight most likely go through tidal tails caused by mergers.

Furthermore, Prochaska & Wolfe (2001) showed that the DLA cross sections obtained from the SPH simulations (Gardner et al. 2001) are not consistent with the observed velocity width \( \Delta v \) distribution, in fact leading to too many low-\( \Delta v \) systems. On the one hand, one would need a sufficient number of these low-mass systems to match the total observed number density of DLAs; on the other hand, low-mass systems result in very small \( \Delta v \). Prochaska & Wolfe (2001) suggested two possible solutions. One possibility is that the cross-sectional dependence on the halo mass does not hold below the resolution limit of Gardner et al. (2001) where processes on subkpc scales range from various feedback mechanisms to tidal stripping would disrupt this cross-sectional dependence. The second solution is that the same feedback mechanisms in lower mass systems could easily double the typical velocity widths and are therefore central to understanding the overall kinematics of DLAs.

These concerns were the focus of the recent simulations by Nagamine et al. (2004). Arguing that the relation between the absorption cross section and the DM halo mass might not follow the same trend below \( 10^{10} M_\odot \), they performed a series of simulations covering a wide spectrum of box sizes and mass resolutions, employing a new conservative entropy formulation of SPH and a two-phase subresolution model for the interstellar medium (ISM), and varying the amount of feedback from star formation (SF) with a new phenomenological model for galactic winds. Their highest resolution run features 216\(^3\) dark matter particles (and the same number of gas particles) in a 3.375 Mpc box, giving \( 2.75 \times 10^5 M_\odot \), mass resolution, whereas their lowest simulation volume is 100 Mpc on a side with 324\(^3\) dark matter particles and \( \sim 10^4 \) times lower mass resolution. With high-resolution runs in small boxes, they see DLAs in halos with masses down to \( M_{\text{DM}} \sim 10^{8.3} M_\odot \). Below this mass at \( z = 4.5-3 \) they notice a sharp drop-off in the DLA cross section, which they associate with photoevaporation of gas in these halos by the ionizing UVB and/or supernova feedback. They use the same approach as Gardner et al. (2001) to find the cumulative abundance of DLAs at each redshift. They fit a functional form to the relation between the DLA cross section and the total halo mass observed in their simulations and then convolve it with the Sheth & Tormen (1999) parameterization of the dark matter halo mass function to obtain the total number of DLAs per unit redshift as a function of halo mass. They find a steeper slope for the DLA cross section dependence on halo mass than Gardner et al. (2001), resulting in fewer DLAs from low-mass halos, and they report a good agreement between the simulated and observed number of DLAs at \( z \geq 3 \).

However, none of the simulations mentioned above addressed both the kinematics and the gas cross section properties of DLAs in the same numerical output. We consider these issues in this paper. We also compute self-shielding of protogalaxies from the UVB with a new radiative transfer algorithm.

Before we proceed to describe our models, it is useful to review how the numerical simulations mentioned above accounted for shielding from the UVB beyond the hydrogen Lyman edge. Haehnelt et al. (1998) have adopted a simple scheme to mimic the effect of self-shielding based on the correlation between the column density and the physical density predicted by earlier numerical simulations in the optically thick regime. Arguing that self-shielding becomes important above an \( \text{H i} \) column density of \( 10^{17} \text{ cm}^{-2} \), which corresponds to the absorption-weighted density \( 10^{-3}-10^{-2} \text{ cm}^{-3} \) along the line of sight, they assume that all gas above a density threshold of \( 10^{-2} \text{ cm}^{-3} \) is self-shielded and fully neutral and that lower density gas is ionized.

Katz et al. (1996) developed a more complex self-shielding correction. During actual simulation they compute the species abundances from ionization equilibrium in gas that is optically thin at the Lyman limit everywhere in the volume. Then, at the postprocessing stage they correct projected \( \text{H i} \) maps pixel by pixel, recomputing ionizational equilibrium with proper attenuation of the UVB in a plane-parallel slab with the same total hydrogen column density and the same physical size, and therefore accounting for shielding in optically thick systems. According to Katz et al. (1996), at column densities \( 10^{16}-10^{17} \text{ cm}^{-2} \) the correction is small and varies between 1% and 10%, whereas at higher column densities, \( N_{\text{H i}} \gg 10^{17} \text{ cm}^{-2} \), this correction can be as large as a factor of 100. Gardner et al. (1997, 2001) use this self-shielding correction, analyzing models initially computed with ionizational equilibrium in an optically thin gas.

On the other hand, Nagamine et al. (2004) do not apply any self-shielding correction at all, arguing that DLAs with column densities above \( \sim 10^{20} \text{ cm}^{-2} \) are fully neutral even without the correction—an assumption that, in our view, may not hold in all situations, e.g., for dense shocks in tidal tails, which can nevertheless be subjected to a photoionizing background. Instead, they use a more complicated two-phase model in which they compute the neutral hydrogen fraction with the standard optically thin approximation and a uniform UVB if the local density is below a density threshold \( \rho_{\text{th}} \), which marks the onset of cold cloud formation. Above \( \rho_{\text{th}} \) they use a two-phase model in which the \( \text{H i} \) fraction is a function of the local cooling and SF rates and a few parameters including feedback from supernovae.

In this paper we present new high-resolution simulations of damped \( \text{Ly} \alpha \) systems at \( z = 3 \). To resolve individual galaxies, we use a customized version of the adaptive mesh refinement (AMR) Eulerian hydrodynamics cosmology code Enzo (Bryan & Norman 1999; O’Shea et al. 2005), which includes simultaneous...
radiative transfer of the UVB beyond the hydrogen Lyman edge on all levels of grid refinement. Our goal is to see whether very high spatial resolution models with sophisticated physics can reproduce the observed kinematic and statistical properties of the low-ionization DLA metal lines.

We do not include SF feedback in the present study, instead focusing on the physical complications associated with radiative transfer in galaxy formation models with limited numerical resolution. We are planning to include feedback in our future models.

Unlike earlier DLA simulations (Nagamine et al. 2004; Gardner et al. 2001; Haehnelt et al. 1998) that considered only absorption by neutral gas in isolated (and mostly virialized) galaxies, we do not rule out the hypothesis that at high redshifts \( z \geq 3 \) a significant fraction of DLA absorption is caused by \( \text{H}^\text{I} \) outside the virial radii of the galaxies. There is evidence of active galaxy assembly at those redshifts, and while DLAs are most likely associated with the neutral gas from which galaxies form, there is a certain possibility that DLA absorption is caused by \( \text{H}^\text{I} \) in tidal tails in mergers (Maller et al. 2001), or even in filaments along which the gas is still falling into dark matter potential wells. Haehnelt et al. (1998) addressed the possibility that DLAs are not necessarily caused by virialized systems, but they assumed a one-to-one correspondence between the local baryon density and the ionizational state of hydrogen, which automatically placed all neutral gas into small self-shielded protogalactic clumps. Similarly, Gardner et al. (2001) and Nagamine et al. (2004) identified all DM halos in their simulations and used a relation between the DLA cross section and the total mass of associated halos to compute the number of DLAs per unit redshift.

Since our models include full angular-dependent radiative transfer, we expect the association between the distribution of neutral hydrogen and dark matter halos to emerge as we move to lower redshifts and higher levels of grid refinement, and consequently as more intergalactic \( \text{H}^\text{I} \) either settles down in halos or gets destroyed by the UVB, but we do not put this association into our models in any way. In fact, the existence of high-velocity clouds in the halo of our own Milky Way at present day (e.g., Blitz et al. 1999 and references therein) implies that we can expect to see extended neutral gas configurations at high redshifts.

This paper is organized as follows. In § 2 we describe our numerical simulations, along with the two-stage radiative transfer algorithm, the choice of the UVB, and our spectrum generation routine. Sections 3 and 4 present our results and conclusions.

### 2. Simulations

All simulations were run for a flat \( \Lambda \text{CDM} \) (cold dark matter) cosmology with \( \Omega_m = 0.3 \), \( \Omega_\Lambda = 0.7 \), \( \Omega_b = 0.045 \), and \( h = 0.67 \), for a primordial power spectrum \( \sigma_8 = 0.9 \) and \( n_s = 1 \). All models are summarized in Table 1, which lists the simulation volume size, the base grid size, the maximum number of levels of refinement, the total number of grids at the end of each run at \( z = 3 \), grid resolution, and mass resolution of each model, which is simply the mass of a DM particle. Most of the models include full radiative transfer, except for runs C2s and C2t, which were computed with self-shielding above \( 10^{-2} \text{ cm}^{-3} \) (C2s) and one with the optically thin approximation throughout the entire simulation volume (C2t).

| Model | \( L \) (h\(^{-1}\) Mpc comoving) | Base Grid\(^a\) | \( N_{\text{levels}} \) | \( N_{\text{grid at } z = 3} \) | \( \Delta x \) (h\(^{-1}\) kpc comoving) | \( \Delta m \) (M\(_\odot\)) |
|-------|-------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| A1    | 2                             | 128\(^3\)       | 6               | 13,160          | 0.25            | 4.0 \times 10^5 |
| B1    | 4                             | 128\(^3\)       | 6               | 14,150          | 0.5             | 3.2 \times 10^6 |
| C1    | 8                             | 128\(^3\)       | 4               | 13,228          | 4               | 2.6 \times 10^7 |
| C0    | 8                             | 128\(^3\)       | 5               | 14,151          | 2               | 2.6 \times 10^7 |
| C2    | 8                             | 128\(^3\)       | 6               | 14,865          | 1               | 2.6 \times 10^7 |

\(^a\) Number of base grid cells is always the same as the total number of dark matter particles.

\(^b\) Three different UVBs were used with this model: one with the full stellar (\( \beta_s = 1 \)) and full quasar (\( \beta_q = 1 \)) components from Fig. 2 (C1), one with \( \beta_s = 1 \) and \( \beta_q = 2 \) (C1b), and finally one with \( \beta_s = 1 \) and \( \beta_q = 4 \) (C1c).

In addition to the run with full UVB transfer (C2), two other models were computed: one with complete self-shielding above \( 10^{-2} \text{ cm}^{-3} \) (C2s) and one with the optically thin approximation throughout the entire simulation volume (C2t).

\[ \Delta M \approx 3.2 \times 10^5 \left( \frac{L_{\text{box}}}{\text{Mpc}} \right)^3 \left( \frac{N_{\text{base}}}{32} \right)^{-3} M_\odot. \] (1)

Therefore, for a fixed base grid, mass resolution is determined by the current box size.

#### 2.1. Two-Stage Radiative Transfer

We use a two-step algorithm for radiative transfer. First, we evolve all simulation volumes by solving the radiative transfer equation in a low angular resolution mode simultaneously with the equations of hydrodynamics. To correct for low resolution, we apply a high angular resolution transfer filter iteratively to our solutions at \( z = 3 \) to improve on the equilibrium position of the \( \text{H}^\text{I} \), He \( \text{i} \), and He \( \text{ii} \) ionization fronts.

We developed a UVB radiative transfer module for the parallel AMR cosmology N-body Eulerian hydrodynamics code Enzo. The fluid flow equations are solved with the piecewise parabolic
method scheme (Colella & Woodward 1984) on a comoving grid (see O’Shea et al. 2005 for details), and chemical abundances for various ionization and molecular states of hydrogen and helium are solved with a chemical reaction network with nine species and 28 reactions (Anninos et al. 1997; Abel et al. 1997). Each level of grid refinement has twice the spatial resolution of the previous level. We solve the radiative transfer equation with a photon-conserving scheme self-consistently at each level of resolution, carrying fluxes explicitly from a parent grid to all of its subgrids. On each grid, radiative transfer is computed with a time step that is usually significantly smaller than the hydro time step and is adjusted adaptively to obtain the best balance between accuracy and the speed of calculations. Due to the complexity of the setup, we have not included point-source radiation in our models yet, and also we limit the transport of background radiation to simple sweeps along the xyz-coordinate axis. We then postprocess Enzo output with much higher angular resolution transfer. Below we describe these two steps in detail.

2.2. Stage One: Time Stepping and Parallelization of the Base Grid

By definition, radiation propagates at the speed of light. In an explicit advection numerical scheme the Courant condition would necessarily require prohibitively small time steps to guarantee stability. However, our photon conservation technique is inherently stable, and from this standpoint there is no need to take very small time steps, but accuracy of the solution is an entirely different issue. In many cases where the supply of ionizing photons greatly exceeds the recombination rate, I-fronts can propagate at or close to the speed of light, and even in this regime our photon conservation will give an accurate solution as long as the radiation chemistry time step is small enough. How do we ensure that we provide time steps small enough to balance accuracy and speed of calculations?

Let us first describe our numerical setup. Since in general radiation-driven fronts can propagate much faster than the fluid flow, radiative transfer and chemistry normally have to be iterated multiple times per hydro time step. On each subgrid, independently of the resolution level, first we perform a hydrodynamic update at a fixed time step $\Delta t_f$ determined from the hydrodynamic Courant condition on that subgrid. We then proceed to compute photon conservation in all directions on a much smaller time step $\Delta t_r = \Delta t_f / (2^n - 1)$, where $n$ is some positive integer. We then update temperature and solve the chemical rate equations on the same small $\Delta t_r$. Next we compare distributions of some state variable, e.g., a fraction $x_{\text{IIa}}$ of ionized hydrogen on our subgrid. If the maximum change in $x_{\text{IIa}}$ during $\Delta t_r$ on the subgrid does not exceed 10%, then we increase $\Delta t_r$ by a factor of 2; otherwise, we keep the same small $\Delta t_r$ and do another radiation chemistry update, and we repeat the whole procedure of these updates until we reach the end of the hydro step $\Delta t_f$. Ideally, if there are no I-fronts on the subgrid, we can do the entire radiation chemistry calculation with $n$ subcycles for each hydro step. On the other hand, in the worst-case scenario with fast I-fronts we need $2^n - 1$ subcycles. The exact number of subcycles between $n$ and $2^n - 1$ is determined automatically by the code based on maximum relative changes in $x_{\text{IIa}}$ in our subvolume.

To determine a suitable value of $n$, we ran a number of tests with $\Delta t_r = \Delta t_f / (2^n - 1)$ fixed throughout the entire run from high to moderate redshifts. We observe fast convergence as the number of subcycles reaches a few tens, but the solution is accurate enough even for $(2^n - 1) \sim 10$. In all our calculations we use $n = 4$, varying the number of subcycles between $n$ and $(2^n - 1)$ as described above.

Ionizing photons in our model all originate at the edge of the base grid and propagate inward. Parallelization in Enzo is done through volume decomposition in which the lowest resolution base grid is subdivided equally between all processors. Since we treat radiation explicitly, solutions to the radiation field in all directions on all processors have to be connected to each other at every radiation chemistry subcycle, and at the same time we need to minimize the amount of idle time each processor spends waiting for flux updates from neighboring volumes. To achieve this goal of optimal parallelization and best load balancing while simultaneously transporting photons in all directions, we constructed the following algorithm. At the beginning of every radiation chemistry subcycle each processor scans all angular directions in some preset order, checking whether input fluxes (from the boundary or from another processor) are available in that direction and whether radiative update has not been done yet. When it finds such an angle, it performs radiative transfer in that direction, while all other processors are doing their own updates. If no input flux in any direction is available, then the processor sits idle for the duration of this directional subcycle. When the subcycle is done, fluxes are passed to neighboring volumes, and a new subcycle begins. To further illustrate this idea, we drew a sequence of directional updates for the $3 \times 2 \times 1$ volume decomposition in Figure 1. In this particular example we have a 100% parallelization efficiency, which is clearly not always achievable for larger decompositions.

To summarize, in the hierarchy of events on a base grid every single hydrodynamic step is followed by a series of radiation chemistry updates, each of which in turn contains directional subcycling with flux exchanges among individual processors. When a spatial region is refined, radiation fluxes for both stellar and quasar components in all six directions are passed from parent grids to subgrids, along with all hydrodynamic variables.

2.3. Stage Two: High Angular Resolution Transfer

Our radiation hydrodynamics (RHD) calculation is parallelized via domain decomposition, in which we pass radiative intensities from one processor to another on the base grid, and in turn, on each processor we advect these intensities along the AMR grid hierarchy. This approach results in a fairly complex algorithm, forcing us to limit RHD transport only to the six directions along the major axes. The total number of photons entering the volume in plane-parallel fluxes is kept the same as if we had an isotropic incident distribution; therefore, those photons that burn their way into a denser environment at small solid angles tend to overheat and overionize the medium. At the same time this approximation naturally leads to the formation of shadows behind self-shielded regions that in reality could be exposed to ionizing radiation. To compensate for this shortcoming, we postprocess our three-dimensional ionization and temperature distributions with a much higher angular resolution radiative transfer code based on a new fully threaded transport engine algorithm (FTTE) by Razoumov & Cardall (2005).

At each output redshift we convert the block-structured AMR output of our coupled RHD runs to a fully threaded format and use it as a first guess to compute radiative transfer with FTTE along 192 directions chosen to subdivide the entire sphere into equal solid angle elements. We then use this updated radiation field to compute the ionizational structure and temperature, and then iterate in radiative transfer and chemistry until we find the equilibrium positions of $\text{H} \, \alpha$, $\text{He} \, \alpha$, and $\text{He} \, \text{II}$ ionization fronts at a given redshift. We find that ~20 iterations are needed for convergence.
2.4. Adopted UVB and Frequency Dependence

Constraints on the UVB at high redshifts come from the Ly\(\alpha\) forest studies. Scott et al. (2000) used the proximity effect in quasar absorption spectra to derive the UVB amplitude assuming that it has the same spectrum as individual quasars. Using Ly\(\alpha\) emission line redshifts, they got the value \(J_\nu = 1.4 \times 10^{-21} \text{ergs s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}\) for \(1.7 < z < 3.8\). On the other hand, with O iii and Mg ii redshifts they got a lower value, \(J_\nu = 7.0 \times 10^{-22} \text{ergs s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}\) for \(1.7 < z < 3.8\), corresponding to the H\(\alpha\) photoionization rate \(1.9 \times 10^{-12} \text{ergs s}^{-1}\).

More recently, Tytler et al. (2004) and Jena et al. (2005) built a concordance model of the Ly\(\alpha\) forest at \(z = 1.95\) using a series of hydrodynamic simulations with grid sizes up to 1024\(^3\) and box sizes up to 76.8 Mpc to reproduce the observed flux decrement from the low-density intergalactic medium (IGM) alone. Their UVB corresponds to an ionization rate per H i atom of \(\Gamma_{\text{HI}} = (1.44 \pm 0.11) \times 10^{-12} \text{ s}^{-1}\), which is slightly higher than the earlier estimates, e.g., the prediction by Madau et al. (1999) with 61% from QSOs and 39% from stars. The redshift evolution of this concordance model can be found in Paschos & Norman (2003). A more recent study by Kirkman et al. (2005) extends this higher estimate of \(\Gamma_{\text{HI}} \sim 1.4 \times 10^{-12} \text{ s}^{-1}\) to the redshift range \(2.2 < z < 3.2\), translating into \(J_\nu \sim 5 \times 10^{-22} \text{ergs s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}\).

The background in the vicinity of DLAs in a cluster that does not host a quasar is most likely going to be smaller than these average values, due to the geometrical dilution factor and local attenuation in the cluster. In our other models not listed in Table 1 we experimented with a variety of UVB spectra and amplitudes, and as a reference we decided to use a smaller background based on Abel & Haehnelt (1999). We included both stellar and quasar ionizing photons, adopting a two-component power-law UVB

\[
I_\nu = \beta_s J_{21,s} \left( \frac{\nu}{\nu_L} \right)^{-\alpha_s} + \beta_q J_{21,q} \left( \frac{\nu}{\nu_L} \right)^{-\alpha_q},
\]

where \(\alpha_s = 5\), \(\alpha_q = 1.8\), and \(\beta_s\) and \(\beta_q\) are the model parameters. We extend the stellar and quasar components of Abel & Haehnelt (1999) to higher redshifts with the expressions

\[
I_{21,q} = Q + a(S - Q),
\]

\[
I_{21,s} = \left[ S + a(Q - S) \right] \left[ 1 - \tanh \left( 0.5z - 7 \right) \right],
\]

where

\[
Q = \frac{10 \exp\left( -\left( z/2.5 \right)^3 \right)}{1 + \left[ 7/(1 + z) \right]^{1/4}},
\]

\[
S = \frac{1 - b \exp\left( -\left( z/4 \right)^3 \right)}{2 + \left[ 7/(1 + z) \right]^{1/2}} + \frac{b(1 + z)^{3.35}}{106.4 \times \exp\left[ \frac{-(z - 0.5)^2}{1 + (z + 2.09)^2} \right]},
\]

\[
a = 0.3 \exp\left[ -\left( z - 4.5 \right)^2 \right],
\]

\[
b = 1 + \tanh \left( 1.5z - 6.3 \right).
\]

We plotted \(I_{21,s}, I_{21,q}\) and the background from Abel & Haehnelt (1999) in Figure 2. We allow for a substantial stellar component at \(z > 8\), which is consistent with the current theoretical views of the global history of SF in a \(\Lambda\)CDM universe (Springel & Hernquist 2003) in light of the discovery of a large optical depth to electron scattering by the Wilkinson Microwave Anisotropy Probe (WMAP; Kogut et al. 2003), suggesting the presence of bright ionizing sources at \(z \sim 15-17\) (Wyithe & Loeb 2003; Haiman & Holder 2003; Hui & Haiman 2003; Ciardi et al. 2003). As the main focus of this paper is to study the resolution effects of radiative transfer in galaxy formation models, we do not explore other possible star formation histories, but
undoubtedly the cumulative history of star formation at \( z > 6 \) might have an important effect on the observable properties of galaxies even at lower redshifts.

We use three frequency bands, 13.6–24.6, 24.6–54.4, and >54.4 eV, to compute \( H \text{ i}, \text{He i}, \) and \( \text{He ii} \) ionization. Inside each frequency band \( \{ \nu_g, \nu_{g+1} \} \) the transport variable is the intensity at frequency \( \nu_g \) weighted by a corresponding power-index-dependent factor

\[
    f_g = \frac{1 - (\nu_{g+1}/\nu_g)^{1-\alpha_g}}{\alpha_g - 1},
\]

where \( g = 1, 2, 3 \). All radiation-related rates (photoionization, photoheating, and absorption) also depend on \( \alpha_g \). Finally, inside each frequency band we use a single transport variable describing both stellar and quasar components with an effective index \( \alpha_g \) constructed to ensure that the total energy inside the band is equal to the sum of the two individual components.

### 2.5. Spectrum Generation

To analyze the statistical properties of DLAs, we drew 100,000 random (through a random point in a random direction) lines of sight through the entire grid hierarchy of each model using the highest resolution cells available at each point along the line and studied all absorption systems with \( H \text{ i} \) column densities \( N_{H\text{i}} \geq 2 \times 10^{20} \) cm\(^{-2}\). For analysis we use two "low ion" lines of Si \( \text{ii} \) at 1526 and 1808 Å. Since the latter line has a significantly lower oscillator strength, we use it only in absorbers with log \( (N_{\text{Si ii}}/\text{cm}^{-2}) > 20.6 \), and for the lower column densities we use the former transition. We assume a uniform abundance throughout the volume with metallicity \( \text{[Si/H]} = -1.3 \) (Wolfe et al. 2005). Noise is added to our artificial spectra such that the resulting signal-to-noise ratio of each \( 1 \text{ km s}^{-1} \) pixel is \( 20:1 \). We define the Si \( \text{ii} \) line width as the width of the central part of the profile responsible for 90\% of the integrated optical depth as described in Prochaska & Wolfe (1997). In the unlikely case that a line of sight crosses multiple absorbers, we consider two components to be caused by a single DLA if the separation between the centers of the two corresponding line profiles is less than \( 400 \) km \( \text{s}^{-1} \); otherwise, we just analyze the strongest component.

\[ dX = \frac{H_0}{Hz} (1 + z)^2 dz. \] (6)

In principle, any combination of the following four factors can affect our results: finite grid resolution, finite mass resolution, the amplitude and spectrum of the assumed UVB background, and radiative and mechanical feedback from SF. As the goal of this work is to demonstrate a method to compute the ionization structure of the outskirts of high-redshift galaxies with self-consistent radiative transfer of the UVB, we do not include the uncertainties of feedback from SF here. In this paper we concentrate on resolution issues in the new models and the dependency on the UVB, at a fixed redshift (\( z = 3 \)). In our next paper we will study the redshift evolution and stellar feedback.

### 3.1. Numerical Resolution

In Figure 4 we have plotted \( f(N, X) \) for all of our runs at \( z = 3 \). For comparison, we have also plotted the data from the Sloan Digital Sky Survey (SDSS) DLA survey from Prochaska et al. (2005) for redshift intervals \( z = 2.5–3.0 \) and \( 3.0–3.5 \). The top panel shows our \( 8 \text{h}^{-1} \) Mpc models, for which the grid resolution ranges from \( 4 \text{h}^{-1} \) kpc (comoving) for run C1 to \( 0.5 \text{h}^{-1} \) kpc for run C2. At this redshift these numbers translate into \( 1.5 \) kpc and \( 190 \) pc physical resolution, respectively. Although the results have not converged yet at our highest resolution, the trend is clear: as we increase grid resolution, the baryons in halos can collapse further, yielding smaller DLA cross sections. For any curve, the disagreement between models and observations is the largest for high column density systems, which have the sharpest baryon concentrations and are particularly sensitive to grid resolution.

The challenging aspect of the DLA modeling is clearly illustrated in Figure 4 (bottom), in which we apply the same \( 128^3 \) base grid with six levels of refinement to a smaller (\( 4 \text{h}^{-1} \) Mpc) volume, resulting in 2 times better grid resolution and 8 times higher mass resolution (run B1; dashed line). Unlike model C1 (solid line), this run has a population of self-shielded halos in the \( 10^8–10^9 M_\odot \) mass range. While naively one would expect to see higher \( f(N, X) \), especially at low column densities, this effect is almost precisely offset by the reduced size of individual halos through higher grid resolution. This is further seen in run A1 (dotted line), which extends the population of self-shielded halos down to \( \approx 7 \times 10^7 M_\odot \), but features almost identical \( f(N, X) \).

The same effects can be observed in Figure 5, which shows the line density \( I_{DLA}(X) \) of DLAs per unit absorption distance with the Si \( \text{ii} \) velocity width higher than \( v_{\text{Si ii}} \). This figure is similar to the cumulative abundance plots versus halo circular velocity (or mass) in Gardner et al. (2001) and Nagamine et al. (2004), but...
we chose the neutral gas line width as a more generic measure of the strength of the absorber, since our simulated absorbers can also be caused by tidal tails and filaments. The horizontal lines in Figure 5 show the mean observed DLA line density from Prochaska et al. (2005).

In the top panel we see a monotonic decrease in the line density of DLAs as we increase the grid resolution. The higher velocity tail is not affected until we compute our highest resolution model, C2, which starts to resolve individual minihalos in the highest density regions. With a certain probability that is related to the physical size of their neutral cores, these small galaxies (with a few tidal streams mixed in) can be seen as multiple absorption components in a single line of sight to a remote quasar. This effect can be further illustrated in Figure 6, in which we plotted Si\text{ii} 1526 or 1808 line profiles for a typical DLA (top profile) and for nine DLAs with the largest velocity widths (profiles 2–10, from top to bottom) in model C2. With the line detection criteria defined in § 2.5, we found the following velocity widths for these spectra: 31, 468, 191, 149, 281, 168, 170, 306, 193, and 205 km s\(^{-1}\) (Fig. 6, from top to bottom). Spectra 2 and 8 (counting from the top) are particularly clear examples of several components falling onto the same line of sight. These multiple-component DLAs give rise to distinct tails at higher velocities that stand out in our high (190 pc physical) resolution models C2 (Fig. 5, top) and B1 (Fig. 5, bottom). While the highest resolution run A1 (Fig. 5, bottom) shows a similar tail, it is shifted toward lower (65–100 km s\(^{-1}\)) velocity widths, in part due to the smaller velocity dispersion in the cluster and in part due to the lower cross sections of individual absorbers.

To summarize, none of our models at this stage are able to reproduce the observed velocity width distribution for systems with \(v_{\text{Si,II}} \gtrsim 30\) km s\(^{-1}\). Although the resolution effects are complex and none of our models have fully converged to the observed column density distribution yet, it seems plausible that some of the effects described in this section can drive the line profile distribution to even lower velocities. For example, as we increase grid resolution, fewer and fewer systems will be crossed by the same line of sight, moving many DLAs in Figure 5 from 100–400 into the 30–100 km s\(^{-1}\) range. We therefore conclude that feedback from star formation seems to be the most likely mechanism to get DLA velocity widths as high as indicated by observations. In our future simulations, in addition to exploring feedback, we will also strive to increase mass resolution in progressively larger simulation volumes, which should produce many more self-shielded halos with masses of a few times \(10^8 M_\odot\) in galaxy clusters with larger velocity dispersions.

3.2. Halo and Intergalactic DLAs

We find that the nature of DLA absorption is a function of the halo environment. The cumulative halo mass function in our 8, 4, and 2 \(h^{-1}\) Mpc volumes at \(z = 3\) is plotted in Figure 7. Most of these halos give rise to DLAs; however, not all DLAs can be associated with individual halos.

Gardner et al. (1997) assumed a relation between the neutral hydrogen cross section and the host halo mass to predict the total abundance of DLAs in a large simulation volume. On the other hand, Nagamine et al. (2004) computed this relation for individual halos in a series of SPH models with the assumption that
all DLAs are fully neutral and therefore a self-shielding correction is not necessary.

Since we include the effects of the UVB on gas at the surface of DLAs, it is interesting to make an independent estimate of neutral hydrogen cross sections for individual absorbers in our models. We draw a large number ($N_{\text{LOS}} = 10^8$) of random lines of sight parallel to all three major axes and find all absorption systems with the neutral hydrogen column density above $2 \times 10^{20}$ cm$^{-2}$. We then look for all halos inside the same base grid cell as the geometrical center of a DLA, find the one that is closest to this DLA, and associate it with this absorption system. Some extended DLAs caused by intergalactic H$\text{I}$ will have no host halos. Halos were identified with the HOP algorithm (Eisenstein & Hut 1998) using the routine enzohop, which is part of the Enzo package. Following this procedure, we count the number of damped systems $N_{\text{DLA}}$ associated with each halo. Then the effective radius of the absorber can be estimated approximately as

$$r_{\text{eff}} = \sigma^{1/2} = L_{\text{box}} \left( \frac{N_{\text{DLA}}}{N_{\text{LOS}}} \right)^{1/2},$$

where $L_{\text{box}}$ is the physical box size. In Figure 8 we plotted the relation between the halo mass $M_{\text{halo}}$ and its absorption radius $r_{\text{eff}}$ in runs A1 (diamonds), B1 (triangles), and C2 (crosses). A least-squares fit to these data with equation

$$\log \left( \frac{r_{\text{eff}}}{\text{kpc}} \right) = \alpha \log \left( \frac{M_{\text{halo}}}{M_\odot} \right) + \beta$$

(8)

gives $\alpha = 0.38$ and $\beta = -3.07$ (thick solid line). At $z = 3$ our absorption cross sections are approximately a factor of 2 lower than the ones in Nagamine et al. (2004). To avoid any confusion, we want to stress that this finding does not contradict our DLA counts in Figures 4 and 5, since the halos in Figure 8 do not represent all DLAs in the volume, as this plot does not include intergalactic H$\text{I}$ clouds. In addition, our data in Figure 8 should be viewed as lower limits to DLA cross sections rather than their actual values, since in a massive cluster environment very often we cannot identify a single halo responsible for a particular DLA. For example, in Figure 3 we can see larger H$\text{I}$ clouds engulfing multiple halos. For this reason, in our estimate of $r_{\text{eff}}$ we only searched for halos inside the same base grid cell.
as the geometrical center of a DLA, which undoubtedly underestimates the true absorption cross section.

In addition, interactions between galaxies in more massive environments create tidal streams, which can produce DLA lines. The cluster in our \(8 \, h^{-1} \text{Mpc} \) volume at \(z = 3\) has extended H\(\text{I}\) tails formed by galaxy-galaxy interactions, which—at certain line-of-sight orientations—produce column densities in the range \(2 \times 10^{20}\) to \(5 \times 10^{21} \text{cm}^{-2}\). The typical physical density in the self-shielded filaments in these streams is of the order of \(\sim 10^{-2} \text{cm}^{-3}\), the hydrogen neutral fraction often (but not always) exceeds 0.9, and physical widths are of the order of 5–10 kpc. Gas that is not self-shielded from the UVB will never reach these column densities unless perhaps it is highly compressed into shocks by feedback, which we do not include here.

To estimate the fraction of the line density \(l_{\text{DLA}}(X)\) due to gas outside of halos, we removed all neutral hydrogen from inside the virial radii of all halos in the highest resolution \(8 \, h^{-1} \text{Mpc} \) run C2 and reran the analysis. We defined the virial radius as the radius of the sphere that encloses 180 times the mean mass density of the universe at that redshift. We found that at our highest numerical resolution approximately 29% of all DLAs are due to gas outside of galaxies at \(z = 3\). While in the original run C2 the highest DLA column density is \(10^{23.8} \text{cm}^{-2}\), it changes to \(10^{21.5} \text{cm}^{-2}\) if we consider only intergalactic gas.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{\(\text{Si} \ II 1526 \AA\) (or 1808 \AA) line profiles for 10 selected DLAs in run C2 at \(z = 3\).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Cumulative halo mass function at \(z = 3\) for dark matter only, for runs C1 (thick solid line), B1 (thick dashed line), and A1 (thick dotted line). The thin solid line is the analytical mass function from Mo & White (2002).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{Effective radius vs. halo mass, for all DLAs with identified host halos in runs A1 (diamonds), B1 (triangles), and C2 (crosses) at \(z = 3\), for the fiducial background in Fig. 2. This figure does not account for DLAs caused by intergalactic H\(\text{I}\) clouds for which no host halo in the same base grid cell was found. The dotted horizontal line shows the size of the base grid cell in the \(8 \, h^{-1} \text{Mpc} \) volume. The solid lines are our least-squares fits with eq. (8) for all halos from runs A1, B1, and C2 (thick line) and all halos from runs A1, B1, and C1 (thin line). For comparison, we have also plotted the fits to DLA radii from Nagamine et al. (2004), for models O3 (no wind, 10 Mpc volume; dashed line), Q3 (strong wind, 10 Mpc volume, low resolution; dashed-dotted line), and Q5 (strong wind, 10 Mpc volume, high resolution; dotted line).}
\end{figure}
On the other hand, in less massive halo environments, especially in the smaller 4 and 2 $h^{-1}$ Mpc simulation volumes, the main reason behind our fairly large DLA counts despite the small effective cross sections is a much larger contribution to $f(N, X)$ from lower mass halos in the range $\sim 7 \times 10^7$ to $10^8 M_\odot$, which we demonstrate below.

### 3.3. Photoionization of Low-Mass Galaxies

It is well known that low-mass galaxies cannot retain gas after reionization. The exact value of the cutoff is not very well established and without doubt depends on the local environment. Nagamine et al. (2004) notice a sharp drop-off in the DLA cross section below mass $\sim 10^8 M_\odot$, which they associate with photo-evaporation of gas in these halos by the ionizing UVB and/or with supernova feedback.

Among all of our models, the least massive halo that is associated with a DLA has a dark matter mass $3.6 \times 10^7 M_\odot$ (Fig. 8). It was found in run A1 in which the halo mass function extends down to $1.4 \times 10^7 M_\odot$ (Fig. 7), which is $\sim 35$ times the mass resolution of this run. The two other least massive halos associated with DLAs were also found in this highest resolution run. However, it is only above the mass $\sim 7 \times 10^7 M_\odot$ that we start seeing a significant population of halos with H I in absorption.

The fact that we see neutral gas in halos with masses slightly below the cutoff of Nagamine et al. (2004) can be attributed to both the spatial variations in the UVB inside the galaxy cluster and the lack of supernova feedback in our models. As Nagamine et al. (2004) pointed out, a sharp cutoff should be expected due to the strong dependence of baryon cooling and photoheating on the virial temperatures of halos around $\sim 10^4 K$. In fact, we see such a cutoff at $\sim 7 \times 10^7 M_\odot$ in Figure 8. As all photoionizing radiation in our models comes from the box boundary, a few low-mass halos might be shadowed by other more massive systems and be able to retain their neutral gas, as we see in two or three galaxies with masses below $7 \times 10^7 M_\odot$. Furthermore, a number of galaxies in the mass range $7 \times 10^7$ to $10^8 M_\odot$ are not exposed to the full UVB, as part of their “sky” is blocked by nearby absorption systems (see, e.g., Fig. 3, insets), and the mass cutoff above which galaxies can retain neutral gas is shifted toward slightly lower masses. Of course, this effect depends on the environment and will be more pronounced at higher redshifts where the spatial variations in the UVB are larger. Star formation and supernova feedback will partially reverse this effect by removing neutral material from lower mass galaxies, assuming that these galaxies have accumulated enough cold gas to host star formation in the first place. However, this effect is very complex and, in addition to the mechanical feedback from winds and supernovae, will have to include transfer of locally generated UV photons.

### 3.4. Dependence on the UVB

Our distributions are somewhat sensitive to a change in the UVB. In model C1 we varied the quasar parameter from the fiducial value in Figure 2 to twice (C1b) and 4 times (C1c) that amplitude and plotted the results in Figure 9. As we increase the UVB amplitude and simultaneously steepen its spectrum, more H I is ionized everywhere on the outskirts of galaxies, but in terms of DLA statistics—not surprisingly—primarily low column density systems are affected. While the underresolved model C1 features the cumulative number of DLAs $\sim 25\%$ above the observed value at $z = 3$, the higher UVB model C1c has the number of DLAs $\sim 25\%$ below the observed value. Noticeable differences between the two models extend to the column density $10^{21.4} \text{cm}^{-2}$, but the higher column density systems are not affected.

### 3.5. Effects of Radiative Transfer

In addition to the full radiative transfer run C2 in the $8 h^{-1}$ Mpc volume, we also computed a model C2s with complete self-shielding above the physical density $10^{-2} \text{cm}^{-3}$, assuming that the local UVB is just the uniform cosmic background from Figure 2 in every cell below this threshold and zero above it. This assumption has been previously used in DLA modeling, e.g., in Haehnelt et al. (1998). We also computed a model C2t with the optically thin approximation imposing the same uniform cosmic UVB in every cell in the volume. In Figure 10 we plotted distributions for these three models. All three models were iterated until H/He ionization equilibrium.

It is evident that self-shielding of neutral gas is the dominant mechanism determining all properties of DLAs. The model with the uniform background in the optically thin regime produces very few DLAs as expected. Surprisingly, the full transfer model and the one with self-shielding give roughly the same cumulative number of DLAs. However, since the transfer model includes high-energy photons, the ionizational structure of H I...
regions is more complex than in the fully shielded case. These differences result in vastly different line width distributions: in the self-shielded model most line widths are clustered around 15 km s$^{-1}$, whereas in the model with transfer they are concentrated at higher velocities in the range 15–30 km s$^{-1}$. It is reassuring that the model with full transfer in Figure 10 (bottom) is about halfway from the self-shielded model to observational data.

It is important to point out that our self-shielded model produces results very different from those of Haehnelt et al. (1998), namely, substantially smaller velocity widths on average. A number of factors could contribute to this difference, such as the use of Eulerian hydrodynamics with AMR instead of SPH, but perhaps the most important factors are our much larger sample of galaxies (we used 710 distinct halos to generate 406 DLAs in run C2s vs. their sample of 40 protogalactic clumps used repeatedly to produce 640 DLAs) and our much higher grid resolution (190 pc physical vs. their 1 kpc). But as we point out, our full radiative transfer runs produce further improvement in kinematics modeling, rendering any self-shielded models obsolete.

In Figure 11 we have plotted the mean specific intensity at 13.6, 24.6, and 54.4 eV versus the local gas number density at $z = 3$. One can easily see hardening of the spectrum in self-shielded regions above the physical density $10^{-2}$ cm$^{-3}$, as more energetic photons travel farther in the neutral medium.

4. SUMMARY

The standard hierarchical model is very successful in explaining the emergence of structures in the early universe. DLAs are viewed as neutral gas clouds confined to individual galaxies, whether in virialized systems or systems still in the process of merging. This paradigm is clearly seen in most previous DLA simulation literature where analysis is based on a fit to the relation between DLA cross section and halo mass. The results of high-resolution simulations by Haehnelt et al. (1998) suggest that small protogalactic clumps in the process of merger could explain the observed line profiles, and the statistical analysis of absorption-line kinematics within semianalytical models by Maller et al. (2001) suggests that tidal tails can be responsible for absorption.

To test both these hypotheses and the broader idea that DLAs can be caused by absorption in neutral intergalactic clouds either stripped of galaxies during interactions or even still accreting onto galaxies from the IGM, we propose to include radiative transfer of the UVB into galaxy formation models, and we argue that this new piece of physics is essential in order to reproduce DLA observables such as the column density and velocity width distributions. An accurate treatment of background photons allows us to address the ionization structure of the outskirts of high-redshift galaxies in a much more precise way.

We simulate galaxy formation in a series of cosmological volumes ranging in size from 2 to 8 Mpc, solving simultaneously for the first time coupled equations of hydrodynamics, self-gravity, multispecies chemistry, and radiative transfer to account for shielding against the UVB. Radiative transfer is computed on all levels of grid refinement with a two-stage calculation, first just along the three major axes simultaneously with hydrodynamics and then in 192 directions in the postprocessing mode. We use AMR to resolve individual galaxies with the same refinement criteria everywhere in the volume. Similar to Nagamine et al. (2004), we use a series of computational volumes of different sizes while varying numerical resolution to try to achieve optimal balance between resolution and fair volume sampling. However, because we do not restrict damped Ly$\alpha$ absorption to halos, we do not assume any single relation between DLA cross section and halo mass for analysis. There is a relation between
DLA cross section and associated line width that in some cases is indeed caused by the velocity dispersion within individual galaxies. Our findings are as follows.

Resolution.—As we increase grid resolution, our column densities demonstrate a trend in convergence toward the observed distributions. However, we cannot reproduce the high-end tail of the velocity width distribution. Although it is possible that the resolution effects and limitation in box sizes are responsible for this shortcoming, feedback from star formation, which we have not included in the current models, is likely to produce expanding shells and therefore higher velocity widths on average. The column density distributions alone indicate that the minimum required grid resolution has to be better than ~500 pc in comoving coordinates, or ~100 pc in physical space. The minimum mass resolution is $10^7 M_\odot$, corresponding to at least 100 DM particles per halo, which is still capable of being self-shielded from the UVB.

Filamentary DLAs.—The nature of DLA absorption is a function of halo environment, at any given redshift. Although all self-shielded halos can give rise to DLAs, not all DLAs can be associated with individual halos. We find that in massive cluster environments at $z = 3$ tidal tails and quasi-filamentary structures often appear to be self-shielded against the UVB. The typical column densities of filamentary DLAs are below $10^{21} \text{ cm}^{-2}$, and physical widths are of the order of $5\text{–}10 \text{ kpc}$. Since we have not achieved numerical convergence, we have not attempted a comprehensive, redshift-dependent statistical study to distinguish halo DLAs from the ones caused by tidal tails, and both of these from DLAs caused by primordial gas still accreting onto galaxies.

Provided that filamentary structures are still self-shielded at higher grid resolution, it seems plausible that going to higher resolution would only increase the filamentary contribution to DLA absorption, as the three-dimensional density peaks (halos) would contribute progressively less to the total $H\,\text{I}$ column density than the two-dimensional density peaks (filaments) as baryons cool and collapse on finer grids.

Photoionization of low-mass galaxies.—The least massive single galaxy associated with DLAs in our models has the mass $3.6 \times 10^7 M_\odot$. However, we see a significant population of halos with $H\,\text{I}$ in absorption only above the mass $\sim 7 \times 10^7 M_\odot$, below which just a few dwarf galaxies retained any sufficient amount of neutral gas by $z = 3$. This threshold is slightly lower than the previously reported values of $10^8$ to a few times $10^9 M_\odot$ (Nagamine et al. 2004), contributing to larger DLA counts in less massive halo environments. Part of this discrepancy can be explained by spatial variations in the UVB inside the galaxy cluster, and it is possible that supernova feedback, which is not included in our models, could also have a role in removing neutral gas from low-mass galaxies.

Self-shielding model.—Calculations with self-shielding above density $10^{-2} \text{ cm}^{-3}$ produce roughly the same total number of DLAs per unit absorption distance as the run with full radiative transfer. However, the absorption-line width distributions in the two models are markedly different due to variations in ionization profiles.

We intend to work on the first in a series of papers exploring DLA properties with our new cosmological simulations with high angular resolution radiative transfer on adaptively refined meshes. A number of topics are open to further exploration.

1. At the moment it is not clear to what extent DLAs produced with full coupled RHD simulations of galaxy formation would be different from the ones we get with our radiative chemical postprocessing approach. The inclusion of radiative terms into hydrodynamic equations might be important for both accessing the effect of the external UV irradiation of primordial galaxies (Iliev et al. 2005) and studying feedback from SF (Whalen et al. 2004; O'Shea et al. 2005).

2. We have not included SF in our current models. Its mechanical and radiative feedback could change the ionization structure and kinematics of gas in high-redshift galaxies. For example, winds from SF regions and/or SNe could create denser shells around low-density bubbles. If dense enough, these shells might contribute to an overall increase in DLA effective cross sections (Schaye 2001). Of course, there is a competing effect if feedback destroys neutral gas in halos as observed in Nagamine et al. (2004).

3. Besides the obvious merit of providing more statistics, going to larger simulation volumes of a few tens of megaparsecs would allow us to test the effect of large-scale fluctuations in the UVB on the absorption properties of high-redshift galaxies. The average separation between quasars at $z = 3\text{–}4$ is more than an order of magnitude greater than our current largest simulation volume. Similar to the proximity effect observed in quasar spectra, very few halos would produce a DLA in a cluster that hosts a quasar. As we move farther away from the quasar, the mean background drops. It is also attenuated in large clusters of galaxies due to the overall higher IGM column densities. If the typical UVB in the vicinity of DLAs is 50%–75% lower than the cosmic average, it could yield dramatically different DLA counts. In addition, larger simulation volumes would produce more massive clusters of galaxies, with more violent interactions and more prominent tidal tails, which would also have a direct impact on DLA observables.

4. To restrict our parameter space, we omitted the interesting topic of fine tuning the initial power spectrum (particularly on galactic scales) to match the observed line density of DLAs, which we are planning to do in the future.

In order to derive a single realistic population of hydrogen absorbers from Ly$\alpha$ forest clouds to DLAs, ideally one would like to build a subkiloparsec resolution model with both stellar feedback and UVB radiative transfer in a large (50–80 Mpc) volume. To achieve the required mass and grid resolution, one would need to use a $2048^3$ grid with six levels of refinement and $2048^3$ DM particles. An $N$-body model of this size (but in a much larger volume) has been recently computed by the Virgo Consortium—the “Millenium Simulation” (Springel et al. 2005)—and can be potentially postprocessed with our fully threaded transport engine following the routine used in this paper.

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REFERENCES

Abel, T., Anninos, P., Zhang, Y., & Norman, M. L. 1997, NewA, 2, 181
Abel, T., & Haehnelt, M. G. 1999, ApJ, 520, L13
Anninos, P., Zhang, Y., Abel, T., & Norman, M. L. 1997, NewA, 2, 209
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
Bryan, G. L., & Norman, M. L. 1999, in Adaptive Mesh Refinement (SAMR) Grid Methods, ed. S. B. Baden et al. (New York: Springer), 165
Ciardi, B., Ferrara, A., & White, S. D. M. 2003, MNRAS, 344, L7
Colella, P., & Woodward, P. R. 1984, J. Comput. Phys., 54, 174
Eisenstein, D. J., & Hut, P. 1998, ApJ, 498, 137
Gardner, J. P., Katz, N., Hernquist, L., & Weinberg, D. H. 1997, ApJ, 484, 31
Haehnelt, M. G., Steinmetz, M., & Rauch, M. 1998, ApJ, 495, 647
Haiman, Z., & Holder, G. P. 2003, ApJ, 595, 1
Hui, L., & Haiman, Z. 2003, ApJ, 596, 9
Iliev, I. T., Shapiro, P. R., & Raga, A. C. 2005, MNRAS, 361, 405
Jena, T., et al. 2005, MNRAS, 361, 70
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escudé, J. 1996, ApJ, 457, L57
Kirkman, D., et al. 2005, MNRAS, 360, 1373
Kogut, A., et al. 2003, ApJS, 148, 161
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Maller, A. H., Prochaska, J. X., Somerville, R. S., & Primack, J. R. 2001, MNRAS, 326, 1475
Mo, H. J., & White, S. D. M. 2002, MNRAS, 336, 112
Nagamine, K., Springel, V., & Hernquist, L. 2004, MNRAS, 348, 421
O’Shea, B. W., Abel, T., Whalen, D., & Norman, M. L. 2005, ApJ, 628, L5
O’Shea, B. W., Bryan, G., Bordner, J., Norman, M. L., Abel, T., Harkness, R., & Kritsuk, A. 2005, in Adaptive Mesh Refinement—Theory and Applications, ed. T. Plewa, T. Linde, & V. G. Weirs (Berlin: Springer), 341
Paschos, P., & Norman, M. L. 2005, ApJ, 631, 59
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
Prochaska, J. X., Herbert-Fort, S., & Wolfe, A. M. 2005, ApJ, 635, 123
Prochaska, J. X., & Wolfe, A. M. 1997, ApJ, 487, 73
———. 2001, ApJ, 560, L33
Quinn, T., Katz, N., & Efstathiou, G. 1996, MNRAS, 278, L49
Razoumov, A. O., & Cardall, C. Y. 2005, MNRAS, 362, 1413
Schaye, J. 2001, ApJ, 559, L1
Scott, J., Bechtold, J., Dobrzycki, A., & Kulkarni, V. P. 2000, ApJS, 130, 67
Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119
Springel, V., & Hernquist, L. 2003, MNRAS, 339, 312
Springel, V., et al. 2005, Nature, 435, 629
Thoul, A. A., & Weinberg, D. H. 1996, ApJ, 465, 608
Tytler, D., et al. 2004, ApJ, 617, 1
Whalen, D., Abel, T., & Norman, M. L. 2004, ApJ, 610, 14
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861
Wyithe, J. S. B., & Loeb, A. 2003, ApJ, 588, L69