Damped Lyman $\alpha$ systems in galaxy formation simulations

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ABSTRACT

We investigate the population of $z = 3$ damped Lyman $\alpha$ systems (DLAs) in a recent series of high-resolution galaxy formation simulations. The simulations are of interest because they form at $z = 0$ some of the most realistic disc galaxies to date. No free parameters are available in our study: the simulation parameters have been fixed by physical and $z = 0$ observational constraints, and thus our work provides a genuine consistency test. The precise role of DLAs in galaxy formation remains in debate, but they provide a number of strong constraints on the nature of our simulated bound systems at $z = 3$ because of their coupled information on neutral $\text{H}\text{I}$ densities, kinematics, metallicity and estimates of star formation activity.

Our results, without any parameter tuning, closely match the observed incidence rate and column density distributions of DLAs. Our simulations are the first to reproduce the distribution of metallicities (with a median of $Z_{\text{DLA}} \approx Z_{\odot}/20$) without invoking observationally unsupported mechanisms such as significant dust biasing. This is especially encouraging given that these simulations have previously been shown to have a realistic $0 < z < 2$ stellar mass–metallicity relation. Additionally, we see a strong positive correlation between sightline metallicity and low-ion velocity width, the normalization and slope of which come close to matching recent observational results. However, we somewhat underestimate the number of observed high-velocity width systems; the severity of this disagreement is comparable to other recent DLA-focused studies.

DLAs in our simulations are predominantly associated with dark-matter haloes with virial masses in the range $10^9 < M_{\text{vir}}/\text{M}_\odot < 10^{11}$. We are able to probe DLAs at high resolution, irrespective of their masses, by using a range of simulations of differing volumes. The fully constrained feedback prescription in use causes the majority of DLA haloes to form stars at a very low rate, accounting for the low metallicities. It is also responsible for the mass–metallicity relation which appears essential for reproducing the velocity–metallicity correlation. By $z = 0$, the majority of the $z = 3$ neutral gas forming the DLAs has been converted into stars, in agreement with rough physical expectations.

Key words: methods: numerical – galaxies: formation – quasars: absorption lines.

1 INTRODUCTION

One of the most difficult and important questions to ask of any cosmological simulation is whether, even if it matches some known properties of the observed Universe, the route via which it obtained those results is physically meaningful. It is tempting to argue that, with the degree of parameter tuning available to the modern simulator (stemming from our inability to maintain a sufficient dynamic range, uncertainty in gas physics and, in particular, star formation and feedback prescriptions), attempts to match a small number of observed properties can succeed without representing a physical route to that success. A sensible test of any suite of simulations, therefore, is to scrutinize its predictions for observed relations which were not considered in the process of planning those simulations. Success or failure of the simulation to match such relations

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cannot be equated to the success or failure of the simulation and its predictions as a whole, but it can lend weight in either direction.

In this paper, we will apply such an approach to the series of galaxy formation simulations most recently described in Governato et al. (2007), Brooks et al. (2007) and Governato, Mayer & Brook (2008) (hereafter G07, B07 and G08, respectively). The $z = 0$ outputs of these simulations contain more realistic disc galaxies than previously achieved. In particular, the simulated galaxies form rotationally supported discs falling on the $z = 0$ Tully–Fisher and baryonic Tully–Fisher relations, have a distribution of satellites compatible with local observations (G07) and have reasonable stellar mass–metallicity relations (B07).

It should be noted, however, that in common with other galaxy formation simulations, the mass in the bulge component of the G07 galaxies is overestimated (see also Eke, Navarro & Steinmetz 2001). The problem is essentially one of angular momentum loss; it seems that to prevent this, both high numerical resolution (Kauffmann et al. 2007) and better models of feedback from supernova explosions are important elements (G08). The exaggerated bulges cause rotation curves to decline unrealistically over a few disc scalelengths to $\sim 75$ per cent of their peak value. However, these problems appear to be shrinking in magnitude as resolution increases – and, regardless of this fact, the simulations under consideration form galaxies at $z = 0$ which are as realistic as current computational and modelling power will allow, so that a detailed study of their properties during formation is justified.

In this paper we will investigate, at $z = 3$, the predominantly neutral gas which gives rise to damped Lyman $\alpha$ systems (DLAs). These are systems with column densities of $\mathrm{H I}$ in excess of $2 \times 10^{19} \mathrm{cm}^{-2}$, seen in absorption against more distant luminous sources (generally quasars). For a recent review see Wolfe, Gawiser & Prochaska (2005). The particular limit is historical, corresponding to the column densities expected if the Milky Way were to be viewed face-on (Wolfe et al. 1986), but simple physical arguments suggest that it makes a convenient distinction between traces of $\mathrm{H I}$ in the ionized intergalactic medium (IGM; below the limit) and clouds which are predominantly composed of $\mathrm{H I}$ (above the limit; see Wolfe et al. 2005). The latter clouds must absorb, in an outer layer, the majority of incident photons capable of ionizing hydrogen ($h\nu > 3.6 \text{ eV}$) and are therefore termed ‘self-shielding’.

The existence of an intergalactic ultraviolet (UV) field arising from the cumulative effect of external galaxies and quasars (e.g. Haardt & Madau 1996) plays many roles in understanding the state of these clouds – not only does it affect the ionization levels in the optically thin transition regions, but it also contributes substantially to the heating budget via photoejection of electrons from atoms. Consequently, gas cannot cool to form neutral clouds without first collapsing in the presence of a gravitational mass with virial velocity of tens of $\mathrm{km s}^{-1}$ (Rees 1986; Quinn, Katz & Efstathiou 1996), suggesting that such clouds are associated with dark-matter haloes and hence protogalaxies. This rough physical argument is verified by previous simulations (many of which are listed in Table 1), although in the simulations of Razoumov et al. (2006) and Razoumov et al. (2008) (hereafter R06 and R08, respectively) DLAs often bridge multiple haloes, extending into the intervening IGM (We discuss this issue further in Section 5.5.).

Irrespective of their physical nature, it is simple to directly show that DLAs contain the majority of $\mathrm{H I}$ over all redshifts $z > 0$ (e.g. Tytler 1987), which suggests they have an important role to play in the global star formation history. Curiously, however, a wide range of diagnostics provide compelling evidence that the star formation rates (SFRs) in typical DLAs are small ($\leq 1 \mathrm{M}_\odot \text{ yr}^{-1}$).

### Table 1. Selected previous simulations of DLAs.

| Reference(s)          | Type          | SF          | Ionization/RT                      | Max Vol$^{(1)}$ | Gas res$^{(2)}$ |
|-----------------------|---------------|-------------|------------------------------------|----------------|----------------|
| Katz et al. (1996b)   | SPH           | None        | Plane correction$^{(3)}$            | (22 Mpc)$^3$   | $10^{8.2} \mathrm{M}_\odot$ |
| Gardner et al. (1997a)| SPH           | None        | Plane correction$^{(3)}$            | (22 Mpc)$^3$   | $10^{8.2} \mathrm{M}_\odot$ |
| Gardner et al. (1997b)|              |             |                                    |                |                |
| Haehnelt et al. (1998)| SPH           | None        | Plane correction$^{(4)}$            | N/A$^{(5)}$    | $10^{6.7} \mathrm{M}_\odot$ |
| Gardner et al. (2001) | SPH           | Yes, weak FB$^{(6)}$ | Plane correction$^{(3)}$          | (17 Mpc)$^3$   | $10^{8.2} \mathrm{M}_\odot$ |
| Cen et al. (2003)     | Eulerian      | Yes, with FB$^{(6)}$ | Hybrid$^{(2)}$                     | (36 Mpc)$^3$   | 11 kpc         |
| Nagamine et al. (2004a)| SPH          | Multiphase/GW$^{(8)}$ | Eq. thin/M$^{(6)}$                  | (34 Mpc)$^3$   | $10^{6.6} \mathrm{M}_\odot$ |
| Nagamine et al. (2004b)|              |             |                                    |                |                |
| R06                   | Adpt Eulerian$^{(9)}$ | None       | Non-eq. live RT/post-processor$^{(10)}$ | (8 Mpc)$^3$    | 0.1 kpc        |
| Nagamine et al. (2007)| SPH           | Multiphase/GW$^{(8)}$ | Eq. thin/M$^{(8)}$                 | (14 Mpc)$^3$   | $10^{5.0} \mathrm{M}_\odot$ |
| R08                   | Adpt Eulerian$^{(9)}$ | Basic       | Non-eq. thin/post-processor$^{(10)}$ | (45 Mpc)$^3$   | 0.09 kpc       |
| This work             | SPH           | Yes, with FB$^{(6,11)}$ | Eq. thin/RT post-processor$^{(11)}$| (25 Mpc)$^3$   | $10^{4.0} \mathrm{M}_\odot$ |

$^{(1)}$The largest volume simulated for the study, in comoving units.

$^{(2)}$The best gas resolution achieved in the study, which may not necessarily be the largest in volume. For SPH (Lagrangian) simulations, we give the smallest particle mass; for Eulerian simulations, we give the finest grid resolution (in physical units at $z = 3$).

$^{(3)}$UV background in optically thin limit; sightlines post-processed using plane-parallel radiative transfer and ionization equilibrium.

$^{(4)}$UVB optically thin, but in post-processing all gas particles assumed fully neutral for number densities $n > 10^{-2} \mathrm{ cm}^{-3}$.

$^{(5)}$This study used a re-sampling technique to study the high-resolution dynamics of a limited number of haloes and did not collect cosmological statistics.

$^{(6)}$FB = feedback, i.e. the deposition of energy into the ISM due to supernova explosions. By ‘weak’ FB is meant thermal injection only, which is generally recognized to be insufficient (see Section 5.1).

$^{(7)}$The optical depth for each cell was calculated and used to approximate a local attenuation to the UVB.

$^{(8)}$The multiphase method keeps track of the fraction of a gas particle in a cold cloud phase in pressure equilibrium with the warm medium; the cold clouds are assumed to be fully self-shielded while the ambient medium is regarded as optically thin. Phenomenological galactic winds are added, causing bulk outflows from all haloes.

$^{(9)}$Adaptive Eulerian: the grids which keep track of gas properties are automatically refined as regions collapse on small scales.

$^{(10)}$A comprehensive treatment of radiative transfer was used by this paper, using eight angular elements in the live simulation and 192 in a post-processing stage.

$^{(11)}$See Sections 2 and 3.1.
These include the low characteristic metallicities and dust depletions (for a review see Pettini 2006), the extreme rarity of detectable optical counterparts and the faintness of Lyα emission (a large number of studies are summarized in Wolfe et al. 2005). In DLAs with detectable molecular hydrogen (H2), the local UV can be estimated from pumping into high-energy rotational levels (e.g. Srianand et al. 2005), results suggesting SFRs comparable to the present-day Milky Way (∼ 1 M⊙ yr−1). However, since few DLAs are associated with detectable H2 absorption, these measurements are not necessarily representative of the wider population. The estimated cooling rates from the recently developed CII technique (Wolfe, Prochaska & Gawiser 2003) lead to the SFR density estimates of ∼10−2 M⊙ yr−1 kpc−2, although the exact interpretation of these results is complicated by various assumptions in the method and the unknown area of a typical DLA system.

A further constraint on the hosts of DLAs is given by kinematic information encoded in unsaturated metal absorption lines. Both the neutral gas (traced by low-ion transitions such as Si ii 1808) and any surrounding ionized gas (traced by high-ion transitions such as C iv 1548) may be probed. The exact relationship between the high and low-ion regions is not entirely certain (e.g. Fox et al. 2007, and references therein). Emphasis in our work, and most other studies, is placed on the low-ion profiles since these presumably reflect the kinematics of the gas giving rise to the DLA itself.

The earliest systematical survey of DLA low-ion velocity profiles was conducted by Prochaska & Wolfe (1997), who suggested that the observed kinematics could arise from a population of thick cold rotating discs with a distribution of rotational velocities similar to that observed in local disc galaxies. This is at odds with physical intuition and the prevailing cold dark matter (CDM) hierarchical cosmogony in the sense that it requires the halo mass function, and hence power spectrum of fluctuations, to remain almost unchanged over 10 Gyr between z = 3 and 0. A view more compatible with the standard model seems desirable. Haehnelt, Steinmetz & Rauch (1998) were quick to apply numerical simulations of structure formation to show that a fiducial population of z = 3 CDM haloes was not incapable of producing velocity profiles similar to those observed; however, some details have proved more problematic as we describe below.

One way of quantifying the simplest property of the kinematics is to assign to each DLA a ‘velocity width’ vlos, roughly measuring the Doppler broadening of any unsaturated low-ion transition (see Section 3.2 for a more precise definition). The velocity width may be presumed to give an indication of the underlying virial velocity of the system responsible, although there is no guarantee that a particular sightline will sample the entire range of the velocity dispersion within the system; the simulations of Haehnelt et al. (1998) suggest that vlos ∼ 0.6 vvir with a large scatter.

Simulations such as those by Katz et al. (1996b), Gardner et al. (1997a, 1998) and Nagamine, Springel & Hernquist (2004a) focused instead on the cross-sectional size of haloes as DLAs. Taken with a halo mass function (which, throughout this work, we will produce for a ΛCDM ‘concordance’ scenario), such trends can be used to predict the overall rate of occurrence of DLA systems – a prediction which, in most simulations, agrees roughly with observations. Including the results of Haehnelt et al. (1998), one can further attempt to predict the relative proportions of systems of differing velocity width. In general, simulations underestimate the incidence of high-velocity widths; this can be traced to the majority of the cross-section being assembled from low-mass (∼105 M⊙) haloes. Similar difficulties are also encountered in varying degrees by semi-analytic models of DLAs. These are, of course, not suited to produce the details of the linewidths, but they can help to pin down which physical considerations affect them (see e.g. Kauffmann 1996; Maller et al. 2001; Johansson & Efstathiou 2006).

Overall, the extent of the implications of the velocity mismatch is somewhat unclear. Some authors have argued that a fundamental difficulty with the ΛCDM scenario has been uncovered (Prochaska & Wolfe 2001). However, numerical modelling of the DLA population is intrinsically troublesome. The dynamic range of processes involved in making the final population is tremendous, with the relevant scales ranging from cosmological to stellar. Therefore, we suggest that failure to match – or, indeed, success in matching – specific observations should be interpreted conservatively. We now describe some specific uncertainties in understanding the simulated DLA population, and outline how these are dealt with in our work.

For comparison, Table 1 gives details of previous simulations and their approach to these problems.

(i) **Star formation.** Although Gardner et al. (1997a) argue that star formation at z > 2 has little impact on the column densities of individual systems, it is not a priori clear how the kinematics and cross-section are affected by the supernova feedback. Investigations in this direction have been made by Nagamine et al. (2004a) and Nagamine, Springel & Hernquist (2004b) using a phenomenological galactic wind (GW) prescription. In the present paper, our star formation is fully prescribed by physical models and z = 0 observations, leaving no parametric freedom (see Section 2).

(ii) **Self-shielding.** DLAs are known to contain gas which is largely self-shielding (see above); thus the fiducial ‘uniform UV background’, which is used in many cosmological simulations, proves inadequate. We use a simple radiative transfer post-processor to correct for this (Section 3.1). We assess both the algorithm’s reliability and the severity of neglecting radiative transfer in the live simulation in Section 5.4.

(iii) **Cosmological sampling.** The total DLA cross-section is thought to be evenly spread through many orders of magnitude of parent halo mass (Gardner et al. 1997a,b); observations of low-redshift DLAs appear to confirm such a view (Zwaan et al. 2005). Presumably, one must allow a sufficient volume in a simulation to study a number of protocluster regions as well as maintain sufficient resolution to resolve low-mass dwarf galaxies. Techniques involving extrapolation into unresolved regimes (such as fitting functional forms to the DLA cross-section as a function of halo mass; Gardner et al. 1997a,b) provide useful signposts but must naturally be regarded with caution. Our simulations, and those by R06 and Nagamine et al. (2004a), resolve all haloes of relevance only by separately simulating a number of boxes of varying size; thus a way of combining results from the various boxes must be found. In our case, this involves using the halo mass function to reweight sightlines in calculating cosmological properties (Section 3.3).

The remainder of this paper is structured as follows. In Sections 2 and 3, we describe, respectively, the series of simulations in use for our study and our methods for extracting DLA sightlines and producing quantities representative of a cosmological ensemble. We give results for these quantities and their underlying relations in Section 4. Section 5 describes a number of consistency checks and runs with altered parameters which shed further light on the origin of some of our relations. Finally, we summarize and discuss future work in Section 6. Two appendices contain technical detail for completeness.

We adopt the following conventions. Except where specified, all quoted measurements are given in physical units; where cosmological parameters enter calculations, these are based on the standard
cosmology used for the simulations: $\Omega_M = 0.30, \Omega_k = 0.044, \Omega_\Lambda = 0.70, \sigma_8 = 0.90, h = H_0/(100 \text{ km s}^{-1}) = 0.70, n_s = 1$. We briefly investigated the effect of incorporating the favoured parameters from the fifth year Wilkinson Microwave Anisotropy Probe (WMAP) results (Dunkley et al. 2008), but the overall differences are expected to be minor (Section 5.3).

## 2 SIMULATIONS

The simulations are successors to the galaxy formation simulations described in G07, with higher resolution and a more physical star formation feedback prescription as described by Stinson et al. (2006) (hereafter S06; see also below). They are computed using the smoothed particle hydrodynamics (SPH) code GASOLINE (Wadsley, Stadel & Quinn 2004), and include gas cooling and the effects of a uniform UV background (following Haardt & Madau 1996) in an optically thin approximation. We later perform post-processing to account for self-shielding effects (Section 3.1). We also ran test simulations which included an approximate treatment of self-shielding within the live simulation (Section 5.4).

The SPH smoothing lengths are defined adaptively to use the 32 nearest neighbours in all averaging calculations, except that a minimum smoothing length of 0.1 times the gravitational softening ($\epsilon$) is imposed. The star formation and feedback recipe (S06) are based on the algorithms originally described by Katz (1992). In short, gas particles can only form stars if $T < 30000 \text{ K}, n_{\text{gas}} > 0.1 \text{ cm}^{-3}$ and the local hydrodynamic flow is converging. The rate of star formation in such regions is assumed to follow the Schmidt (1959) law ($\dot{\rho}_{\text{gas}} \propto \rho_{\text{gas}}^{1.5}$) with index $n = 3/2$. This is a rather natural choice of $n$, since it implies the cold gas is turned into stars over some multiple $1/c_\star$ of the local dynamical time-scale:

$$\frac{1}{\rho_{\text{gas}}} \frac{d\rho_{\text{gas}}}{dt} = c_\star \sqrt{G \rho_{\text{gas}}}.$$  \hspace{0.5cm} (1)

Following the evolution of each star particle consistently with the Kroupa, Tout & Gilmore (1993) initial mass function (IMF), a fixed fraction $\epsilon_{\text{SN}}$ of the supernova energy created at each time-step is deposited thermally into the surrounding gas particles. To emulate the physics of the processes responsible for distributing this energy to the gas, radiative cooling is disabled in particles within a radius which must be determined. Traditionally, this can involve further parameters, but the S06 method obviates the need for these by modelling the physical processes according to a prescription based on blast wave models (e.g. Chevalier 1974; Ostriker & McKee 1988): this sets the radius of the local interstellar medium (ISM) affected as a function of the local density and temperature. The free parameters, consisting of the constant of proportionality in the Schmidt law ($c_\star$) and the efficiency of supernova energy deposition into the ISM ($\epsilon_{\text{SN}}$), are tuned such that isolated galaxy models match the Kennicutt (1998b) law and cold gas fractions observed in the present-day disc galaxies. This leaves no free parameters in the context of this study (setting $c_\star = 0.05$ and $\epsilon_{\text{SN}} = 4 \times 10^{-6}$ erg; see S06) but produces galaxies which satisfy a wide range of observational constraints (see Introduction). As part of the supernova algorithm, metals are also deposited into the ISM (see Section 4.2.3 for more details), but note that our simulations do not yet contain any contribution to radiative cooling from metals (which is expected to be physically dominant below temperatures $T \sim 10^4 \text{ K}$).

As in G07 and G08, the prescriptions are implemented in a fully cosmological context, based on a fiducial model with parameters given at the end of Section 1. The majority of our results are derived from four simulations (Table 2). Three of these take advantage of the

| Tag | $(M_{\text{p,gas}})$ | $(M_{\text{p,DM}})$ | $\epsilon$/kpc | Usable vol (comoving) |
|-----|-------------------|-------------------|----------------|----------------------|
| Dwf | $10^{4.0} M_\odot$ | $10^{5.0} M_\odot$ | 0.15 | 5 Mpc$^3$ |
| MW  | $10^{5.2}$        | $10^{6.2}$        | 0.31 | 50 Mpc$^3$ |
| Large | $10^{6.1}$ | $10^{7.0}$ | 0.53 | 600 Mpc$^3$ |
| Cosmo | $10^{6.7}$ | $10^{7.6}$ | 1.00 | 15625 Mpc$^3$ |

Table 2. The simulations used in this work. The first column is the tag which we use to refer to each simulation. For all except ‘Cosmo’, a subsample of the full box is simulated in high resolution; no results are taken from outside this region. The second and third columns refer, respectively, to the mean gas and dark-matter particles within the region, the fourth to the gravitational softening length (in physical units) and the final column gives the comoving volume of the region. The separate boxes are generated from entirely different sets of initial conditions; the ‘Dwf’ and ‘MW’ simulations are designed to form, respectively, a dwarf and Milky Way type galaxy at $z = 0$ while the ‘Large’ and ‘Cosmo’ boxes are more statistically representative.

3 PROCESSING PIPELINE

The processing pipeline is based on SIMAN, an object-oriented C++/PYTHON-based environment for analysing simulations of arbitrary file format with support for OPENGL real-time visualization. Such a framework allows us to understand our data rapidly, especially since it includes support for stereoscopic glasses – giving a true 3D rendering of the data. It is written in such a way as to allow the analysis of the data from an interactive python session, hiding a large number of details from the scientific user.

3.1 Self-shielding

We employ a basic radiative transfer post-processor to assess the effect of self-shielding. The simulation is divided into nested grids so that the lowest level cells contain close to 32 particles, to correspond with the SPH scheme of G07. We use a cosmic ultraviolet background (UVB) following a revised version of Haardt & Madau (1996) (Haardt, private communication); this is initially assumed to be present throughout the simulation volume.

In each cell, using the radiation field described above, the ionization state of the hydrogen and helium gas is determined using an equilibrium solver algorithm based on Katz, Weinberg & Hernquist (1996a). This requires the temperature and density of each SPH particle, derived directly from the simulation output. We keep the temperature, not the internal energy, fixed during this process. While not ideal, it is necessary to make some such assumptions to determine the thermal state in post-processing. As a test, we verified that keeping instead the internal energy fixed makes
little notable difference to our results. On the other hand, shielding can significantly drop the heating rate, so that an assessment of the dynamical effect is essential; we find it to be minor in terms of our final results, although uncertainties remain (see Sections 5.2 and 5.5).

With the ionization state determined, the attenuation of the UV field due to the H\textsubscript{i}, He\textsubscript{i} and He\textsubscript{II} ions is then calculated. This translates into an optical depth (as a function of frequency) for the cell. In subsequent iterations, the attenuation of the incoming UVB radiation is calculated by integrating the cell optical depths along the six directions defined by the orientation of the grid to the edge of the box. Because the grid is refined adaptively, this process is somewhat complicated by the need to ‘level-jump’, that is move to higher levels of the nested structure when the lower levels run out. Note that the grid walk stays at the lowest level in any directly connected region of the origin cell (including when crossing boundaries of higher levels). As it moves out of the high-resolution region, higher levels are selected as appropriate. The walk does not redescend, even if lower levels again become available, instead using the averaged properties of regions defined by the current level. This is primarily a matter of computational speed; however, it has the side effect of preventing long-distance shadowing which can arise in low angular-resolution radiative transfer mechanisms. Admittedly, we have not formulated this in terms of any limiting procedure yielding a well-defined physical calculation, but heuristically the averaging over larger solid angles as the integration proceeds away from the target cell is quite correct. We have illustrated this situation in Fig. 1.

This entire process is iterated over the full simulation, convergence being assessed by changes in the UVB field and ionization state between steps. We found that the system defined above had some oscillatory behaviour on its approach to convergence, which led us to introduce a damping term which in effect averages the optical depth between iterations. This results in faster convergence, but does not essentially alter the described scheme.

Our self-shielding process is crude when compared to recent radiative transfer codes (for a comparison see Iliev et al. 2006); however, we do not believe that this makes our results obsolete (see Section 5.4). A further complication must be considered, which is the failure of the scheme as described to account for any dynamic effects of the changing ionization fraction and heating rates. We have assessed the severity of this problem by using a local attenuation approximation (see Section 5.4).

Fig. 2 shows a $z = 3$ map of the neutral hydrogen in a 200 kpc (physical) cube centred on the major progenitor of a Milky Way type galaxy in our ‘MW’ box. It is coloured such that DLAs appear in red and Lyman limit systems appear in green/yellow. The locations and virial radii (see Section 3.2) of dark-matter haloes exceeding $5 \times 10^8 M_\odot$ in virial mass are overplotted.

### 3.2 Calculation of halo and sightline properties

We start by locating individual dark-matter haloes in the simulation using the grid-based code AMIGA (Knebe, Green & Binney 2001; Gill, Knebe & Gibson 2004). We then mark a spherical region of radius $r_{\text{vir}}$ (the radius within which the density exceeds the mean density of the simulation at the given redshift by a factor of 178 by analogy with spherical top-hat collapse models) as belonging to the halo of mass $M_{\text{halo}}$. We also record the masses in gas, stars and H\textsubscript{i} within the virial radius. The virial velocity is defined as usual, $v_{\text{vir}}^2 = GM_{\text{halo}}/r_{\text{vir}}$.

In the resampled simulations, we immediately discard any haloes which have been contaminated by low-resolution particles from the outer regions. We also discard any haloes with fewer than 200 gas particles or 1000 dark-matter particles. We determined this limit empirically by examining the point at which halo properties diverged in simulations at different resolutions (for more details, see Section 5.1).

Line-of-sight properties can be calculated from particle-based simulations by projecting quantities on to a grid. For instance, projecting all gas particles in a simulation on to the $z$–$y$ plane allows the column density along the $z$ direction to be estimated by summing the mass in a grid square and dividing by its area. This is the approach taken in previous SPH simulations of DLAs. However, in initial numerical experiments, we found that sightline properties in our simulations were not robust to changes in the somewhat arbitrary grid resolution.

We have instead calculated all quantities using a true SPH approximation (for details, see Appendix A). This results in a varying spatial resolution of sightlines which is automatically consistent with the simulation data. The minimum smoothing length allowed is 0.1 times the softening (given in Table 2), meaning we can resolve spatial gradients over as little as $\sim 20$ pc in our highest resolution simulation, although a more typical effective resolution is $\sim 200$ pc.

For our main results, sightlines are projected through the simulation in random orientations and at random sky-projected offsets from the centre of a halo up to its virial radius. We verified that extending this search area to twice the virial radius had no impact on our results (this can also be seen directly from Fig. 2). This confinement of our DLA cross-sections is discussed in Section 5.5.

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\[\text{Fig. 1. A 2D representation of our 3D radiative transfer scheme, which involves building a nested grid and integrating optical depths from a cell along that grid to the edges of the box. A combination of local fine spatial resolution and speed is achieved by traversing the grid at the lowest available level until this level is closed. At such a point, the algorithm jumps to a higher level in the grid. Subsequently, when lower levels become available, they are ignored since these high-density regions are not directly connected to the original high-density region. This is primarily a computational simplification, but also (in an admittedly ad hoc fashion) prevents long distance unphysical shadowing which would otherwise arise from our limited angular resolution (see text for details).}\]
Figure 2. The $z = 3$ neutral column density of H$^1$ in a 400 kpc cube centred on the major progenitor to a $z = 0$ Milky Way type galaxy (box MW). The colours are such that DLAs ($\log_{10} N_{\text{HI}}/\text{cm}^{-2} > 20.3$) appear in dark red and Lyman limit systems ($20.3 > \log_{10} N_{\text{HI}}/\text{cm}^{-2} > 17.2$) appear in green and yellow. The circles indicate the projected positions and virial radii of all dark-matter haloes with $M > 5 \times 10^8 \text{M}_\odot$. All units are physical. A stereoscopic and an animated version of this plot are available at www.ast.cam.ac.uk/~app26/.

For each sightline, we directly measure the column density in neutral hydrogen. If this column density exceeds the DLA threshold ($N_{\text{HI}} > 10^{20.3} \text{cm}^{-2}$), it is added to our catalogue. If not, it is immediately discarded, but we keep track of the numbers of all sightlines taken so that we may calculate

$$\sigma_{\text{DLA}} \equiv \sigma_{\text{search}} \left( \frac{n_{\text{DLA}}}{n_{\text{total}}} \right),$$

where $\sigma_{\text{search}} = \pi r_{\text{vir}}^2$ is the search area, $n_{\text{total}}$ is the total number of random sightlines calculated and $n_{\text{DLA}}$ is the number of such sightlines which exceed the DLA threshold. In this way, we obtain a representative DLA cross-section for each halo without assuming any particular projection.

We also produce an absorption line profile for a low-ion transition such as those of Si$^\text{II}$. We assumed that the relative abundances of heavy elements were solar and that Si$^\text{II}$ was perfectly coupled to H$^1$, so that for solar metallicity $M_X/M_\text{H} = 0.0133$ and $n(\text{Si}^\text{II})/n(\text{H}^1) = n(\text{Si})/n(\text{H}) = 3.47 \times 10^{-5}$ (Lodders 2003). In other words, given the metallicity $Z$ of each gas particle, we take $n(\text{Si}^\text{II}) = 3.47 \times 10^{-5} (Z/Z_\odot)n(\text{H}^1)$. Although an approximation, we found that the effect of relaxing the assumption of the Si$^\text{II}$–H$^1$ coupling was minor (see Section 5.2).

Example profiles are shown in Fig. 3, in which we have chosen four haloes and displayed five random sightlines from each. For the purposes of this plot, we choose one of Si$^\text{II}\lambda 1808, 1526, 1304$ or 1260 according to which transition has maximum optical depth closest to unity. The plots are centred such that $\Delta v = 0$ corresponds to the motion of the centre of mass of the parent dark-matter halo. We also added, for display purposes, Gaussian noise such that the signal-to-noise ratio (S/N) is 30/1. The range contributing to $v_{90\%}$ (see Section 4.2.2) is shown in Fig. 3 by vertical lines at either end. Absorption arising in haloes with virial velocities $v_{\text{vir}} \gtrsim 150 \text{ km s}^{-1}$ is often composed of multiple clumps whereas for smaller haloes, there tends to be one main, central H$^1$ clump, moving with the
Figure 3. Example low-ion (Si II) absorption profiles from random sightlines through selected $z = 3$ haloes: in reading order, these have virial velocities of 694, 207, 92, 59 km s$^{-1}$ (making the first halo extremely rare in cosmological sightline samples; see Section 4.1). The first is taken from our ‘Cosmo’ box, the second is the ‘MW’ major progenitor and the remaining two are smaller haloes from the ‘MW’ simulation. Note that the velocity axes are scaled differently in the respective plots. The zero velocity offset corresponds to the motion of the centre of mass of the halo (unobservable in practice), illustrating a qualitative shift in behaviour from multiple clumps (higher virial velocities) to single clumps (lower virial velocities). The vertical dotted lines indicate the velocity offsets where the cumulative optical depth reaches 5 and 95 per cent of its maximum value; $v_{90\%}$ is given by the difference in their position in velocity space. The pixel size is approximately 5 km s$^{-1}$, although internally we use a higher 1 km s$^{-1}$ resolution. For the purposes of this plot, the profiles are normalized to correspond to a definite transition, although this is not necessary for our computations. This chosen transition, along with the sightline H I column density and metallicity, is indicated in each panel. Noise is added to simulate S:N = 30:1; again this is only for illustrative purposes and is not part of our pipeline.

centre of mass of the halo. Visual inspection of the different systems suggests that the former systems are less dynamically relaxed, presumably because they have formed more recently and have longer dynamical time-scales; however, we did not verify this systematically.

3.3 Cosmological sampling

We aim to make statements about the agreement or otherwise of our simulations with cosmological observations of DLAs and therefore need to construct a representative global sample of absorbers. Our approach is related to that of Gardner et al. (1997a), in that we correct our limited sample by reweighting in accordance with the halo mass function. However, we emphasize that in our case, this is to make allowance for our limited statistics and combine results from separate boxes, whereas in Gardner et al. (1997a) this approach was used to extrapolate behaviour into an unresolved low-mass regime.

Consider any measurable property of DLA absorbers, $p$. The aim of the process discussed below is to construct the distribution function, $d^2N/dX dp$ (We will adopt the custom of using the absorption distance $X$, where $dX/dz = H_0(1 + z)^2/H(z)$: populations with constant physical cross-sections and comoving number densities maintain constant line densities $dN/dX$ as they passively evolve with redshift.). Given the monotonic invertible relations $\rho(M_{\text{vir}})$ and $\sigma_{\text{DLA}}(M_{\text{vir}})$, one has

$$
\frac{d^2N}{dX dp} = f[M_{\text{vir}}(p)]\sigma_{\text{DLA}}[M_{\text{vir}}(p)] \frac{d\rho}{dX} \frac{dM_{\text{vir}}}{dp},
$$

(3)
where $\sigma_{\text{DLA}}(M)$ is the cross-section of a DLA of mass $M$ and $f(M)$ is the halo mass function,\(^3\) so that the physical number density of haloes with mass in the range $M-\Delta M$ is $f(M)\Delta M$, and $dI/dX = c/H_{\Lambda}(1+z)^3$. However, for an ensemble of haloes of the same mass, $\sigma_{\text{DLA}}$ will be scattered – although it may be possible to define a mean value $\bar{\sigma}_{\text{DLA}}$. Similarly, $p$ will in fact be scattered around some suitably chosen average $\bar{p}(M)$ for a given halo mass; furthermore even for a single halo most properties $p$ will vary depending on the particular sightline taken through the halo to the distant quasar.\(^4\)

The easiest approach is to make the replacements $p \rightarrow \bar{p}(M_i)$, $\sigma \rightarrow \bar{\sigma}(M_i)$ in equation (3). However, even if significant deviation of $p$ from $\bar{p}$ is rare, one may be interested in variations of $d^2N/dXdp$ over several orders of magnitude – these rare fluctuations can therefore contribute significantly to the ‘tail’ of the observed values.

Accordingly, the method by which we perform the reweighting is non-parametric. Since at first this can seem a little obscure, we offer two descriptions. Below, we have described the method in a heuristic manner. In Appendix B, we have outlined how this method can be derived by discretizing a well-defined integral, which allows for an exact interpretation of our results should one be necessary.

First, we bin haloes (in logarithmic bins) by their virial mass. Within each bin $i$, ranging over virial mass $M_i \rightarrow M_{i+1}$, one may calculate a mean DLA cross-section $\bar{\sigma}_i$ and a total physical number density $F_i$:

$$F_i = \int_{M_i}^{M_{i+1}} f(M)dM.$$ (4)

The contribution of DLA systems per unit physical length from the bin $i$ is $F_i\bar{\sigma}_i$, and consequently one may calculate

$$\frac{dN}{dX} = \frac{dI}{dX} \sum_i F_i\bar{\sigma}_i.$$ (5)

To investigate the distribution of properties observed, we have two approaches. The simplest is to extract a representative set by discarding selected sightlines. This is ideal for comparing correlations between sightline parameters (e.g. velocity & metallicity, Section 4.2.3), where the observed data sets consist of only $O(100)$ separate sightlines. For each halo $h$, we need to select a number of sightlines proportional to $w(h) \equiv \sigma_s F_{\text{sh}}/n_{\text{sh}}$ [cf. equation B.10], where $\sigma_s$ is the cross-section of the specific halo, $i(h)$ represents the mass bin to which halo $h$ belongs and $n_i$ is the total number of simulated haloes in the mass bin $i$. The actual sightlines chosen from each halo are determined by a pseudo-random but deterministic approach, for stability of results.

This method is not ideal, however, because it throws away potentially useful information. In particular, when constructing distribution functions for a property $p$, we use an alternative method which uses the cosmological halo mass function to weight, rather than select, results. The set of all sightlines is binned by the property $p$, indexed by $j$. One then has

$$\frac{d^2N_{\text{DLA}}}{dXdP}(p_j) \propto \sum_h \frac{w_{\text{DLA}}(h)}{\Delta P} \times \frac{\text{Num. DLA obs. through }}{\text{Total DLA obs. through } h}.$$ (6)

\(^3\) We adopt the numerically calibrated version of the Sheth & Tormen (1999) halo mass function given by Reed et al. (2006).

\(^4\) We regard both of these effects as stochastic scatter, although presumably a complete theory would account for the exact value of $p$ in terms of a sufficient number of parameters pertaining to the halo and sightline.
Damped Lyman α systems

Figure 4. The DLA cross-section of haloes which meet our resolution criteria in the Dwf (plus symbols), MW (dots), Large (cross symbols) and Cosmo (tripod symbols) boxes plotted against their virial mass. There is a (resolution-independent) sharp cut-off at $M_{\text{vir}} \sim 10^9 M_\odot$ below which the cross-section for DLA absorption is negligible. Haloes with no DLA cross-section are shown artificially at $\log \sigma_{\text{DLA}}/\text{kpc}^2 = -1$. The fit to the equivalent results for two models in Nagamine et al. (2004a) is given by the dotted and dash–dotted lines (their models P3 and Q5, respectively). The major progenitors to the ‘MW’ (Milky Way like) and ‘Dwf’ (Dwarf type) $z = 0$ galaxies are indicated.

As expected from our previous discussion, our results have a peak at $\sim 10^{10} M_\odot$, which contrasts with the flatter results from fiducial power-law cross-sections. Consequently, at first glance, it appears that the area under our locus of points must be larger than that under the N04 curves, and hence a substantial disagreement in line density is inevitable; however, the cut-off for N04 is at rather lower masses ($M_{\text{vir}} \sim 10^8 M_\odot$), and this brings the total line density in N04 considerably closer to the observed value.

Plotting the total H I mass against the virial mass (Fig. 6) and DLA size against the total H I mass of a halo (Fig. 7) gives an alternative view of our cross-sections. A striking feature of the latter plot is a bifurcation, particularly notable in the ‘Cosmo’ box but also traced by the ‘Large’ box, in which haloes of a fixed H I mass $M_{\text{HI}} \sim 10^6 M_\odot$ can have different cross-sections. The primary physical distinction between the upper and lower branches is in halo mass: the former trace H I-rich haloes with $M_{\text{HI}} < 10^{10.5} M_\odot$ and the latter trace a population of H I-poor haloes with $M_{\text{HI}} > 10^{10.5} M_\odot$. This is reminiscent of recent claims of bimodality in observed DLAs (Wolfe et al. 2008).

Figure 5. The data of Fig. 4 multiplied by the halo mass function from Reed et al. (2006) to give a total line density for each representative system. Haloes with zero cross-section are shown artificially at $\log \sigma_{\text{DLA}}/\text{kpc}^2 = -4$. A guide $\sigma_{\text{DLA}} - M_{\text{HI}}$ relationship can be estimated by fixing a particular SFR. As explained in Section 2, in our simulations the instantaneous SFR is given by the Schmidt law. From this may be estimated a time-scale for conversion of neutral gas into...
Figure 7. As Fig. 4, except the cross-sections are now plotted against the total mass of neutral hydrogen in each halo. Haloes with no DLA cross-section are shown artificially at $\log_{10} \sigma_{\text{DLA}}/kpc^2 = -1$. The dotted lines are of time-scales for H\textsc{i} depletion through star formation; from top to bottom $\tau = 10^{10.0}, 10^{10.5}$ and $10^{10.9}$ yr. These illustrate constraints on our locus of points by considering both $\Omega_{\text{z}}(z = 0)$ and the lifetime of a typical DLA (see text for details).

In Section 3.3 to our sample yields an estimate for the cosmological column density distribution, shown by the solid line in Fig. 8. This can be compared directly to the observed distribution given by the points with error bars, which are derived from SDSS DR5 (see previous section for an explanation). The matching of the normalization and approximate slope of the observed column density distribution can be seen as a genuine success of the simulations: we emphasize that no fine-tuning has been applied to achieve this result. Furthermore, our results appear to have converged at the resolution of the simulations used (see Section 5.1).

From the column density distribution, one may express the total neutral gas mass in DLAs in terms of the fiducial definition:

$$\Omega_{\text{DLA}}(z) = \frac{m_p H_0}{c f_{\text{HI}} \rho_{\text{c,0}}} \int_{10^{10.3}}^{N_{\text{HI}}(z)} f(N_{\text{HI}}) N_{\text{HI}} dN_{\text{HI}},$$

where $m_p$ is the proton mass, $\rho_{\text{c,0}}$ is the critical density today, $(1 - f_{\text{HI}}) \approx 0.24$ gives the fraction of the gas in elements heavier than hydrogen and $N_{\text{max}}$ is an upper limit for the integration, which is discussed in the next paragraph. $\Omega_{\text{DLA}}(z)$ gives the fraction of the redshift zero critical density provided by the comoving density of DLA-associated gas measured at redshift $z$. (This is different from the more natural definition of time-dependent $\Omega_{\text{z}}$ which express a density at any given redshift in terms of the critical density at that redshift. Only in the Einstein–deSitter universe will these definitions coincide.)

Although the calculation should take $N_{\text{max}} = \infty$, this is not possible for the observational sample owing to the rapidly decreasing number of systems at the high-column density limit. Prochaska et al. (2005) discussed how different assumptions for the functional form of the column density distribution can lead to different values of $\Omega_{\text{DLA}}$. The discrepancies are small for the two best functional fits to the observational data (a double power law or a Schechter function with exponential roll-off at high-column densities). However, these extrapolations are actually only constrained by a few points at high-column densities; a more robust approach, albeit less physically transparent, is to calculate $\Omega_{\text{DLA}}$ directly from summing the total

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neutral hydrogen in the observed sample of DLAs, which for the SDSS DR5 sample is roughly equivalent to using the upper limit $N_{\text{max}} = 10^{21.75} \text{cm}^{-2}$.

Using this limit, we obtain $\Omega_{\text{DLA,sim}} = 1.0 \times 10^{-3}$, which can be compared with the result from SDSS DR5 in the combined bin $2.8 < z < 3.5$, $\Omega_{\text{DLA,obs}} = (0.84 \pm 0.06) \times 10^{-3}$. As expected from Fig. 8, the results are in fair agreement; the slight mismatch is driven by the overestimation of our high-column-density points ($10^{21.5} < N_{\text{HI}}/\text{cm}^{-2} < 10^{22.5}$).

Our weighting approach predicts the form of the distribution for much rarer, higher column-density systems than the sample-limited observations allow. Significant contributions to $\Omega_{\text{DLA}}$ are made by these rare systems unless $\gamma \equiv \ln f(N, X)/\ln N \ll -2$. In fact, directly measuring the slope $\gamma$ for our simulations shows that it slowly decreases from $\gamma \simeq -1.0$ for $N_{\text{HI}} = 10^{20.3} \text{cm}^{-2}$ to a constant value of $\gamma \simeq -2.5$ for $N_{\text{HI}} \geq 10^{21.5} \text{cm}^{-2}$. Thus, a correction to $\Omega_{\text{DLA,sim}}$ is expected if we allow $N_{\text{max}}$ to extend to arbitrarily high values. Performing the calculation with $N_{\text{max}} = \infty$ gives $\Omega_{\text{DLA,sim}} = 1.4 \times 10^{-3}$. This value is not directly comparable to observational estimates, but shows that an observer living in our simulations would underestimate $\Omega_{\text{DLA}}$ by about 30 per cent due to the missing contributions from the rare high-column-density systems. A further discussion of this issue is given in Section 6.4.

### 4.2.2 Velocity width distribution

We have already discussed some qualitative features of the low-ion velocity profiles generated in our simulations (Section 3.2, Fig. 3). These are important because they provide a direct observational measure of the kinematics of the DLAs, and therefore have the ability to substantially constrain the nature of the host haloes. We now turn to the comparison of our characteristic velocities with the observed quantitative distribution.

We assign a velocity width to each generated profile using the fiducial $v_{\text{LOS}}$ technique (Prochaska & Wolfe 1997). This inspects the ‘integrated optical depth’ $T(\lambda) = \int_0^\infty \text{d}x \tau(\lambda')$ and assigns the velocity width $v_{\text{LOS}} = \epsilon (\lambda_0 - \lambda_\alpha)/\lambda_0$ where $T(\lambda_\alpha) = 0.95 T(\infty)$ and $T(\lambda_0) = 0.05 T(\infty)$. The result is a representative velocity width for the sightline, produced without any of the difficulties associated with fitting multiple Voigt profiles.

To a good approximation, the only dependence on the particular low-ion transition chosen is in the overall normalization of the optical depths from the relative abundances and oscillator strengths. The $v_{\text{LOS}}$ measure of the velocity width is invariant under such rescalings, so that only for display purposes (i.e. Fig. 3) we need to choose a particular ion and transition. Observers require to choose unsaturated lines because, while our simulations calculate $\tau$ directly, spectra only determine $e^{-1}$ which cannot be inverted (in the presence of noise) for $\tau \gtrsim 1$.

Using our weighting technique, we calculate the cosmological distribution of velocity widths, $d^2N/dX dv$. This is plotted in Fig. 9 (solid line), along with observational constraints (points with error bars) calculated from data provided by Prochaska (private communication) based on the compilation of high-resolution ESI, HIRES and UVES spectra described in Prochaska et al. (2003). The data set consists of 113 observed DLAs with $4.5 > z_{\text{DLA}} > 1.6$ (we directly verified that the velocity width redshift evolution over this range is negligible, so that we use the full range of observed systems to bolster our statistics.). We normalize the line density of DLAs in the observational sample to match the observed $I_{\text{DLA}}(z = 3) = 0.065$ (Section 4.2.1).

Overall, the simulations reproduce the approximate pattern of observed velocity widths, with a peak in the distribution at $v \sim 50 \text{km s}^{-1}$; the agreement is fair for velocity widths $v < 100 \text{km s}^{-1}$. However, it is now a familiar feature of ΛCDM simulations that they produce too few high-velocity width systems (see Introduction) and our results are no exception. We provide a discussion of this discrepancy in Section 6.3.

Recent velocity width results by R08 and R06 have been presented by plotting a cumulative line density, $I_{\text{DLA}}(v)$. A direct comparison between our results and those from such work can be drawn from Fig. 10, in which we similarly replot our velocity width distribution cumulatively (thick solid line). As well as the observational data (thin solid line), we have overplotted results from two simulations described by R08. These two models, R08.N1 and R08.H1, differ in their size and hence resolution; the former covers a volume of approximately $(5.7 \text{ Mpc})^3$ (comoving), resolving grid elements of minimum side length 90 pc (physical) while the corresponding values for the latter are (46 Mpc)$^3$ and 0.7 kpc. Comparing our simulations with those of R08, the extent of the disagreement between simulated and observed results is similar (discounting the lack of low-velocity systems in R08.H1, which arises from the coarser resolution), although our own results are actually somewhat closer for low-velocity widths ($v < 100 \text{km s}^{-1}$). This is possibly linked to our somewhat higher-than-normal cross-sections for haloes of virial velocities $v_{\text{vir}} \sim 100 \text{km s}^{-1}$, but because much of R08’s DLA cross-section lies outside haloes it is hard to provide a concrete explanation for such disparities (see Section 5.5).

We caution that any cumulative measure has strongly correlated errors so that the plot can present a somewhat distorted picture of the discrepancy (one is really interested in its gradient in linear space). In our plot, we have shown the Poisson errors on the observed data as a shaded band, but these only represent the diagonal part of the covariance.
4.2.3 Metallicity

The metallicity, i.e. the ratio by mass of elements heavier than helium to hydrogen, is an important diagnostic of observed DLA sightlines. Since metals are deposited in the ISM through supernova explosions, the metallicity of a region is determined by the interplay between the integrated SFR and bulk motions of gas including galactic inflows and outflows. In general, one observes a positive correlation between the mass of a galaxy and its metallicity both at $z = 0$ (e.g. Tremonti et al. 2004; Lee et al. 2006) and at higher redshifts (e.g. Savaglio et al. 2005; Erb et al. 2006). This trend is also observed in our simulations (B07). Debate over a precise account of the origin of the relation continues, but the analysis of B07 shows that, for our simulations, the predominant effect is reduced star formation in low-mass haloes, with the dynamics of outflows providing an important correction to the simple closed box model.

There are many uncertainties in simulating metallicities, which reflect not only the mass formed in stars but also the dynamics of the gas, its accumulation from the IGM and mixing within the halo. B07 showed that, for our simulations, high resolution is required ($N_{\text{DM}} > 3500$) to attain convergence for the star formation history (and consequently the metallicities). We verified (using an independent analysis code) that our own results suffered similarly, but that our other results converge at lower resolutions (see Section 5.1). Whenever we deal with results concerning metallicities, we therefore have to discard a number of haloes (those with $N_{\text{DM}} < 3500$) which are included elsewhere. The effect of this is to reduce the number of haloes in each mass bin, and therefore exacerbate worries that we do not have a fully representative set of haloes for all mass scales. None the less, we do not find any evidence that this is causing systematic effects, as we verified that our other distributions are not significantly changed by this restriction.

Each of our sightlines is assigned a metallicity as follows. The metallicities are not significantly changed by this restriction.

A cosmological distribution of DLA metallicities is generated using our fiducial technique (Section 3.3). The result is shown by the thick solid line in Fig. 11 and closely matches the observational constraints, displayed as points with error bars. These are derived from the Prochaska et al. (2003) sample described in Section 4.2.2, restricted to $2 < z < 4$. We use metallicities based on $\alpha$-capture elements (primarily Si), updated using data from Prochaska et al. (2007).

Our simulated results are in good agreement with the observed distribution. They exhibit a roughly Gaussian distribution (as a function of log metallicity); the best-fitting parameters give a median metallicity of $[M/H]_{\text{med, sim}} = -1.3$ with a standard deviation $\sigma = 0.45$. A similar fit to the observed data gives $[M/H]_{\text{med, obs}} = -1.4$ and $\sigma = 0.54$. Given the uncertainties in abundances and yields, the differences are extremely minor. This success is unusual: previous simulations (e.g. Cen et al. 2003; Nagamine et al. 2004b) tend to substantially overproduce metals in DLA systems, and were only able to approach the observed result if metal-rich DLAs could be hidden using substantial dust biasing. However, such a scheme is unsupported by observational evidence, and our
simulations now suggest that it is unnecessary (for a further discussion see Section 6.4).

We also investigated the relationship between the mean metallicity of the gas within the virial radius of a halo and the spread of DLA metallicities derived from SPH sightlines through that halo. We found that the sightlines, on average, displayed slightly higher metallicities than the halo mean (by $\lesssim 0.5$ dex) with a spread of $\sim 1$ dex. We interpret the offset by noting that DLA sightlines sample the high-density gas in which star formation is occurring – even if the rate is low (Section 4.3), presumably the local star formation preferentially enriches these. Some haloes showed a detectable radius–metallicity gradient, but in general this was shallow compared with the overall scatter.

### 4.2.4 Correlation between metallicity and velocity widths

Observationally, there is known to be a correlation between the low-ion velocity width and the metallicity of a DLA sightline. Ledoux et al. (2006) presented a set of observations showing a positive correlation between these parameters at the 6 $\sigma$ level and suggested that the relation could reflect a mass–metallicity correlation analogous to that seen in galaxy surveys; the result was confirmed, using a separate sample, by Prochaska et al. (2008).

Our matching of the metallicity relation and near matching of the velocity width distribution give us confidence to attempt to probe this relationship in our simulations. We employ the Monte Carlo sample generator version of our halo mass function correction code (Section 3.3) to produce a sample of 64 coupled velocity and metallicity measurements, matching the size of the observational comparison sample described in Section 4.2.2 restricted to $2 < z < 4$ as in Section 4.2.3.

The simulation results are shown as crosses in Fig. 12, with the linear least-square bisector fit given by the solid line. The observational sample is shown by dots (the errors on each observation are small compared to the intrinsic scatter), with the linear least-square bisector fit shown as a dotted line. These fitted relationships are parametrized as log$_{10}$ $\Delta v_{\text{sim}} = 2.5 + 0.58$ [M/H] and log$_{10}$ $\Delta v_{\text{obs}} = 2.7 + 0.53$ [M/H], respectively.

Although the normalization of the relationship in our simulation is somewhat different from the observational sample, we emphasize that the slope and overall trend, as well as the mean metallicity of our sightlines, are correct and qualitatively the results are in agreement. Given that the metallicity distribution (Fig. 11) is in close agreement with that observed, we suggest that the quantitative disagreement arises from the previously noted underestimate of the velocity widths in our simulation (i.e. one should interpret the discrepancy in the relationships in Fig. 12 as a horizontal, not vertical, displacement). It is also apparent visually that the observational results show a larger scatter about the mean relationship than does our computed sample. We tentatively suggest that this points towards an ultimate resolution of the velocity width issue which involves ‘boosting’ the width of certain sightlines, perhaps by local effects such as outflows, while keeping the contribution by halo mass roughly as outlined in Section 4.1 (although this is not the only conceivable interpretation; see Section 6.3).

The origin of our relation between velocity widths and metallicity is the underlying mass–metallicity relation, as suggested by Ledoux et al. (2006). We verified this directly, but it can also be seen from Figs 9 and 11: the dashed, dash--dotted and dotted lines in each case show the contribution from haloes with $M_{\text{vir}} < 10^{9.5}$ $M_{\odot}$, $10^{9.5} M_{\odot} < M_{\text{vir}} < 10^{10.5} M_{\odot}$ and $10^{10.5} M_{\odot} < M_{\text{vir}}$, respectively. Both the sightline velocities and the metallicities can be seen to be a strong function of halo mass, and it is this fact that leads to the final relationship.

#### 4.2.5 Other correlations are weak

The correlation between column density and metallicity or velocity is weak in our simulations, in agreement with observations: contrast the strong dependencies of the velocity widths and metallicities on the underlying halo mass with the weak dependence of the column density (Fig. 8). Given the historical confusion over the evidence for correlation between the column density and metallicity, we have investigated this aspect of our observational and simulated samples in a separate note (Pontzen & Pettini, in preparation).

### 4.3 Star formation rates

In the Introduction, we noted that SFRs in DLAs are typically low ($\lesssim 1$ $M_{\odot}$ yr$^{-1}$) and yet these systems contain most of the neutral hydrogen, a necessary intermediary in the star formation process. We also see this behaviour in our simulations, and now describe how it comes about.

We associate a SFR with each halo by inspecting, at $z = 3$, the mass of star particles formed within the preceding 10$^8$ yr. For very low SFRs ($< M_{\text{gas}}/10^6$ yr$^{-1} < 10^{-5} M_{\odot}$ yr$^{-1}$), there may have been no star particles formed in such a period; in this case, we extend the averaging period by a variable amount up to $10^9$ yr so that we can resolve SFRs down to $\sim 10^{-4} M_{\odot}$ yr$^{-1}$.

The SFRs of our individual haloes are shown in Fig. 13; the horizontal dotted line shows the SFR of an $L^{*}$ LBG galaxy. This is
derived from Reddy et al. (2008), wherein is stated $M_{\text{DLA}}^* (1700 \, \text{Å}) = -20.8$. We adopt the conversion ratio of Kennicutt (1998a), but first correct the luminosity for dust attenuation by a factor of 4.5, which is the mean correction given (Reddy et al. 2008, section 8.5). We then divide the final result by 1.6 in order to consistently use the Kroupa IMF (Section 2), for which a larger number of massive, hot stars are formed relative to the Salpeter IMF assumed by Kennicutt (1998a). This gives a final characteristic LBG SFR of $39 \, M_\odot \, \text{yr}^{-1}$.

We also plot a shaded band indicating the approximate SFRs obtained for DLAs using the CII technique (Wolfe et al. 2003). This is intended to serve as a guide only – there are a number of uncertainties in the position of this band, including the intrinsic complexity of the observations and the conversion from a SFR per unit area: we have assumed a DLA cross-section of $1/2 \times 10^{-22} \, \text{cm}^{-2}$, which is our approximate range for the most common DLA haloes (see Figs 4 and 5).

By evaluating

$$\dot{m} = \int dM_{\text{vir}} f(M_{\text{vir}}) \sigma(M_{\text{vir}})$$

(10)

(using a binning technique to discretize the integral), we derive a global SFR, $\rho_*$, of $\sim 0.2 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3}$. The UV dust-corrected and IR estimates in Reddy et al. (2008) place this value between 0.05 and $0.2 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3}$, but these are again sensitive to the IMF, assuming a Salpeter form for their main results: for a Kroupa IMF, one should again reduce the rate by $\sim 1.6$. This caveat should be borne in mind, but overall our results are not unreasonable and a detailed understanding of remaining discrepancies is beyond the scope of the present work.

More importantly for our purposes, the SFR roughly scales as $M_* \propto M_{\text{vir}}^{-2}$ (see fit in Fig. 13). Given the low-mass end of the halo mass function is an approximate power law, $M_{\text{vir}}^{1.9}$, the overall dependence of the integrand of equation (10) is rather shallow and a wide range of halo masses contribute to the global SFR. Thus, there is no inconsistency in the view that a typical ($M_{\text{vir}} \sim 10^{10} \, M_\odot$) DLA has a low SFR but that the DLA cross-section as a whole contributes significantly to the star formation, and is largely converted into stars by $z = 0$.

We generate a cosmological DLA cross-section weighted sample of these SFRs (Section 3.3). Fig. 14 shows the resulting distribution, $d^3N / d\log M_{\text{vir}}$. As expected by the range of halo masses contributing to the DLA cross-section (Fig. 4), the SFR in most DLAs is much lower than that in visible LBGs. Qualitatively, the simulated rate of DLA star formation is consistent with or fractionally lower than the observed SFR estimates from the CII technique (see above). Since we have not included upper limits in our approximate observational band, this is an acceptable result.

Finally, we investigated the total stellar mass accrued in our DLAs (the integral of the SFR). This quantity can be estimated in surveys of LBG by fitting their spectral energy distribution deduced from multi-band photometry. In Fig. 15, we have plotted the distribution of our DLA stellar masses and compared it with the estimated range of observed LBG’s stellar masses, using the results of Shapley et al. (2001) adapted as described above for our Kroupa IMF. Most DLAs have formed a relatively small population of stars (the distribution ranges over $10^{6} < M_* / M_\odot < 10^{12}$ but peaks strongly at $M_* \sim 10^{10} \, M_\odot$), consistent with their low metallicities. There is a strong dependency on the underlying halo mass, which we have shown by plotting the contribution from different halo mass ranges. This arises not only because the baryonic mass rises roughly linearly with the virial mass, but also because the star formation in low-mass haloes is substantially suppressed by feedback (see also Sections 4.2.3 and 5.1).

The simulated $z = 3$ DLAs are clearly being consumed very slowly, and it will be a matter of considerable interest to understand the ultimate fate of the gas, especially given the apparent realism of the galaxies at $z = 0$. We intend to address this question fully in future work; for the present, we note that over 80 per cent of the neutral H I in the major progenitor at $z = 3$ has formed stars in our Milky Way type galaxy (box MW) by $z = 0$. However, this accounts for only 10 per cent of the total stars; 10 per cent of the stars were in fact already formed at $z = 3$, with the remainder coming from accreted gas and stars in satellites.
5 CONSISTENCY CHECKS AND EFFECTS OF PARAMETERS

In this section, we will discuss the effect of changing some details of our simulations and processing, including the resolution and star formation feedback prescription parameters. Since the effects are rather minor overall, some readers may prefer to skip directly to our conclusions (Section 6). The extra simulations used for the discussions below are summarized in Table 3.

5.1 Resolution and star formation feedback

In this section, we describe a further suite of simulations which probe the dependence of our overall conclusions on resolution and feedback strength. Previous studies of DLAs have been shown to be somewhat sensitive to the resolution (e.g. Nagamine et al. 2004a; R06) and the main difference between our simulations and previous work lies in the feedback implementation, so that both these considerations are worth exploring.

We described in Section 3.2 our resolution criteria, demanding a relatively small population of stars, consistent with their low metallicities. The distribution of stellar masses of our DLAs. The vertical band and vertical dotted line show, respectively, the range of and median value for observed LBG stellar mass from Shapley et al. (2001) (adapted for consistency with our IMF). As expected, most DLAs have formed a relatively small population of stars, consistent with their low metallicities.

Table 3. A summary of the comparison simulations used.

| Brief tag | \(\langle M_{\text{gas}} \rangle\) | \(\langle M_{\text{DM}} \rangle\) | \(\epsilon / \text{kpc}\) | Comment | Comment |
|-----------|-----------------|-----------------|-----------------|---------|---------|
| MW        | \(10^{5.2}\) M\(_{\odot}\) | \(10^{6.2}\) M\(_{\odot}\) | 0.31            | As Table 2 |         |
| LR        | \(10^{6.9}\)    | \(10^{6.7}\)    | 0.63            | Lower resolution |         |
| L.R.THF   | \(10^{6.9}\)    | \(10^{6.7}\)    | 0.63            | Thermal feedback |         |
| L.R.SS    | \(10^{6.9}\)    | \(10^{6.7}\)    | 0.63            | Self-shielding |         |
| Large     | \(10^{6.1}\)    | \(10^{7.0}\)    | 0.53            | As Table 2 |         |
| LR        | \(10^{7.0}\)    | \(10^{7.0}\)    | 1.33            | Lower resolution |         |
| L.R.THF   | \(10^{7.0}\)    | \(10^{7.0}\)    | 1.33            | Thermal feedback |         |
| SS        | \(10^{6.1}\)    | \(10^{7.0}\)    | 0.53            | Self-shielding |         |
| Cosmo     | \(10^{6.7}\)    | \(10^{7.6}\)    | 1.00            | As Table 2 |         |
| SS        | \(10^{6.7}\)    | \(10^{7.6}\)    | 1.00            | Self-shielding |         |

At lower resolution (for details see Table 3). For haloes with coarser resolution than this stated limit, we found that the DLAs started to exhibit scatter about the locus defined by their higher resolution counterpart, and a slight tendency to underestimate the DLA cross-section (while overestimating individual column densities). These resolution effects are relatively mild compared to some previously reported effects (e.g. Gardner et al. 1997a; Nagamine et al. 2004a; R06). We suggest that this is because our treatment of feedback (see Section 2), which leads to efficient energy deposition from supernovae in dense areas, helps to impose an effective scalelength below which the particles composing the ISM do not collapse further. Ultimately, given the impossible task of maintaining sufficient dynamic resolution to track the actual gas components making up the ISM, this is not an unreasonable behaviour. Fig. 16 shows the ‘MW’ and ‘Large’ simulations along with their low-resolution counterparts (‘MW.LR’, ‘Large.LR’) and demonstrates that the simulations are in good agreement when restricted according to our resolution criteria. The velocity widths from these low-resolution simulations were also overall in agreement with their high-resolution counterparts; however, as previously noted, the star formation histories and metallicities only converge for a more stringent resolution cut (Section 4.2.3).

We took the low-resolution initial conditions and reran the simulations, replacing our normal feedback implementation with a purely thermal approach (i.e. the same energy per supernova was produced, but the cooling switch-off was not implemented). This has the well-known effect of causing the supernovae energy to be radiated away over much less than the dynamical time-scale (Katz 1992; Thacker & Couchman 2000) and is thus the weakest conceivable mechanism. It is almost certain to be unphysical, since the fast cooling times arise from the combination of high temperature and density. This is caused by averaging properties of unresolved regions; in fact, the high-temperature (blast interior) and high-density (undisturbed exterior) regions are presumably separated in the true parsec-scale ISM.

Our cross-sections arising from this approach lie considerably closer to those of Nagamine et al. (2004a) (Fig. 16). We also find...
more usual results for quantities such as the metallicity; because our metallicities converge only at high resolutions (see Section 4.2.3) quantitative comparisons between our low-resolution runs are a little dangerous, but we see a much weaker mass–metallicity relation (see also B07), with metallicities all approximately $Z_{\odot}/5$. This is, as expected, in poor agreement with observations but in better agreement with older simulations. Recall that our fiducial feedback formulation causes a reduction in metallicities primarily by suppressing star formation efficiently, rather than causing any bulk outflows (B07).

We also note that the velocity widths arising from particular haloes in our thermal feedback simulations are comparable to, or somewhat (~5 per cent) higher than, the velocity widths in our fiducial simulations. (The velocity widths agree between low-resolution and standard runs.) This does not result in a closer matching of the cosmological velocity width distribution because the proportion of intermediate and high-mass haloes is reduced. We interpret this as suggesting that the origin of our velocity widths is chiefly gravitational, and that the thermal feedback runs form denser, compact $H_\text{i}$ regions. This is no surprise: there is no physics in our simulations that can plausibly give rise to large-scale bulk GWs. Future improvement in DLA velocity width modelling may therefore arise from an understanding of what drives such flows, and whether cold gas can indeed exist within them. However, this understanding will augment, not replace, a sufficient feedback model for the local suppression of star formation (see Section 6.3).

5.2 Si II and low-ion regions

One possible explanation for the underestimated incidence of high-velocity width absorbers in our simulations (Section 4.2.2) is a misidentification of the precise regions responsible for producing the low-ion profiles. Therefore, we briefly investigated the effect of relaxing our assumptions (Section 3.1) that $n(Si\,\text{II})/n(H\,\text{I}) = n(Si)/n(H)$. This assumption is based on comparing the energetics of the ion transitions; however, there is no actual physical mechanism coupling the $Si\,\text{II}$ stage to $H\,\text{I}$. This is to be contrasted with $O\,\text{I}$, which is strongly coupled to $H\,\text{I}$ via a charge transfer mechanism (e.g. Osterbrock & Ferland 2006). There are clear examples of DLAs in which the $O\,\text{I}$ width is significantly smaller than the $Si\,\text{II}$ width (see e.g. the lowest two panels in Fig. 6 of Ledoux et al. 1998) and thus there must be contributions to the $Si\,\text{II}$ velocity structure from outside the cold $H\,\text{I}$ gas.

Because DLAs are low-metallicity environments (both observationally and in our simulations), a first approximation to the silicon ionization problem can be achieved by taking the radiation intensity from our hydrogen/helium radiative transfer code (Section 3.1) and calculating the equilibrium state of silicon. To address this in a simple way, we calculated a grid of CLOUDY$^{10}$ models which varied in the local density, temperature and incident radiation strength indexed by the single photoionization parameter $\Gamma_{\text{He}^+_{\text{He}^+}}$. For each particle in our simulation, we calculated the value of Si $\text{II}/Si(T, T, \rho)$ by interpolating these models. Then, we recalculated our DLA sightlines (Section 3.2) using the new Si $\text{II}$ values, rather than the old assumed values. We used exactly the same set of offsets and angles, so that the final reprocessed catalogue can be compared on a per-sightline basis. Our sightlines extend through the entire box so that any trace gas outside our haloes could theoretically contribute to the velocity width. However, the combination of the decreasing neutral gas density and decreasing metallicities makes the intergalactic contribution to the unsaturated linewidths extremely minor.

We have plotted, for all sightlines, the probability distribution of the ratio $r$ of the updated velocity widths to the original velocity widths which assume $n(Si\,\text{II})/n(H\,\text{I}) = n(Si)/n(H)$. Although higher velocity widths do arise by considering these effects, the mean differences are not large enough to have a significant impact on, for example, the overall distribution of observed DLA linewidths (Fig. 9).

Figure 17. The probability distribution of the ratio $r$ of the velocity width from the CLOUDY-based Si $\text{II}$ ionization runs to the original velocity widths which assume $n(Si\,\text{II})/n(H\,\text{I}) = n(Si)/n(H)$. Although higher velocity widths do arise by considering these effects, the mean differences are not large enough to have a significant impact on, for example, the overall distribution of observed DLA linewidths (Fig. 9).

5.3 Cosmological model

The parameters used throughout this work were fixed when running the first of the simulations described. Since then, our knowledge of cosmological parameters has improved, thanks to the expanding wealth of constraints from galaxy surveys measuring the baryon acoustic oscillations (BAO), supernovae surveys and most significantly 3- and 5-yr WMAP results (Spiegel et al. 2007; Dunkley et al. 2008). Our chosen parameters are $(\Omega_M, \Omega_b, \Omega_{\Lambda}, \sigma_8, h, n_s) = (0.30, 0.044, 0.70, 0.90, 1.0)$, whereas the latest WMAP, BAO and SN results combined suggest $(\Omega_M, \Omega_b, \Omega_{\Lambda}, \sigma_8, h, n_s) = (0.269, 0.046, 0.721, 0.82, 0.70, 0.96)$. It is natural to question whether such differences can have a significant effect on our results.

Given our confined cross-section (Section 4.1), any effect can be split into two components: the change in the halo mass function and the change in the individual objects. Considering the halo mass function first, since at $z = 3$ the relative density of $\Lambda$ to CDM is suppressed by a factor of $4^3 = 64$, the difference in $\Omega_{\Lambda}$ has a negligible effect. Further, the value of $\Omega_b/\Omega_M$ has only minor consequences for the transfer function (amounting to the form of the

10 Version 07.02.01, available at www.nublado.org and last described by Ferland et al. (1998).
the acoustic oscillations). The most important difference, therefore, should arise from the reduction of $r_S$; this will decrease the scale on which fluctuations have become non-linear, and hence reduce the number of high-mass objects. However, we also need to consider the lower value of $n_e$. The high-mass end of the halo mass function is less affected (since it is closer to the normalization scale), but at the low-mass end (corresponding to high $k$) there are a lower than expected number of haloes. Overall then, the effect of updating our halo mass function is to slightly reduce the line density of DLAs (to $I_{\text{DLA}} = 0.049$, which is marginally lower than the observed line density, but acceptable given the uncertainties in our simulations) and shift the cross-section to somewhat lower masses. However, we verified that this had negligible effect on, for example, our velocity width distribution. This is because, fortuitously, the two effects produce an almost flat value of $f_{\text{WMAP}}(M)/f_{\text{fiducial}}(M) \simeq 0.7$ over $10^8 < M/M_\odot < 10^{11}$.

On halo scales, the $\sim 5$ per cent shift in the value of $\Omega_b$ must be the dominant effect. We do not believe this will have a large effect on our simulations, being a small correction, especially since equilibrium considerations determine the physics on these scales. A complete resolution of this question, however, awaits new simulations with the updated values.

### 5.4 Radiative transfer

We have incorporated a correction for self-shielding (Section 3.1) which is coarse compared to some recent simulations (R06; R08). On the other hand, the complexity of the fine structure of the ISM today (and presumably also at $z = 3$) means that even the most advanced simulations cannot capture its ‘microscopic’ (i.e. parsec scale) behaviour. Nagamine et al. (2004a) employed a sub-resolution two-phase pressure equilibrium model for the ISM (McKee & Ostriker 1977; Springel & Hernquist 2003), apparently obviating the need for radiative transfer since the cold clouds are assumed to be fully self-shielded and the warm ambient medium to be optically thin. This is a promising approach, but it is not entirely clear how it links to the messy observational picture in which atomic gas exists in distinct warm and cold phases, ionized gas in warm and hot phases, and photoionized regions occur within the cold phase around star formation (H II regions) as well as in the diffuse disc ISM.

For this work, our essential aim was to identify large-scale regions in which the cosmological UV background should be significantly suppressed. We verified our code using a variety of tests comprising comparisons of equilibrium ionization front positions with simple constant temperature CLOUDY models. While our radiative transfer code performs well in simple plane-parallel setups, it resolves only six angular elements and its true 3D performance is therefore significantly degraded. However, we believe that for the purposes of the present study it is adequate: in both optically thin and optically thick limits, the angular resolution is of little importance; only in the transition regions will significant differences arise. We ran a final test in which we post-processed our ‘Large’ box after rotating it through 45°, thus providing a different set of angular elements to the code. None of our DLA results was significantly affected by this change.

We do not include the UV emission of star forming regions in our calculation. This would introduce a significant extra complexity to our algorithm without any real benefits for the following reason. The SFR of most DLAs is known observationally – and in our simulations – to be $\lesssim 1\ M_\odot\ yr^{-1}$ (see Section 4.3, Fig. 14). For such low SFRs, the local contribution to the UVB is comparable to, or usually significantly smaller than, the $z = 3$ field. This can be estimated, for example, using the data of Black (1987), or more usually is obtained directly from observational data (see Introduction). Although the theoretical picture of the importance of local sources is not straightforward (e.g. Miralda-Escudé 2005; Schaye 2006), we are confident that these direct observational upper limits justify our approximation.

There is another slight inconsistency in our approach, in that the radiative transfer post-processor identifies certain regions of gas as neutral which in the live simulations is treated as ionized; further, UV heating occurs for the uniform background even in regions which are later identified as self-shielding. To assess the magnitude of this effect, we re-simulated ‘MW.LR’, ‘Large’, and ‘Cosmo’ using a local UVB attenuation approximation (‘SS’ simulations in Table 3). In these simulations, for each gas particle the strength of the UVB used for ionization equilibrium and heating calculations was reduced by the mean attenuation for particles of that density in the post-processed simulation. We continue to apply our radiative transfer post-processor, but the corrections involved are smaller in the new outputs.

In general, the differences between the ‘live’ self-shielding and original runs were rather minor. They consisted of a slight increase in the DLA cross-section ($\sim 0.2$ dex) and a reduction in the SFRs. Consequently, the cold gas metallicity of these low-mass haloes was seen to drop by up to 0.5 dex (Fig. 18); this was apparently the biggest change caused. In fact, this could help to resolve the slight paucity of low-metallicity ([M/H] $< -2.0$) DLAs in our simulations (Fig. 11), although without a fuller set of statistics we were not able to verify this directly. Importantly, however, we reproduced all our measured distributions replacing ‘Cosmo’ with ‘Cosmo,SS’ and ‘Large’ with ‘Large,SS’. The effects of this were dominated by an increase in overall line density to $I_{\text{DLA}} = 0.080$ (see Section 4.2.1). This takes us further away from the observed result $I_{\text{DLA}} = 0.065 \pm 0.005$. However, excepting normalization, the
distribution of properties was left almost unchanged. We believe these effects warrant further investigation in the future, but their direct effects seem to be fortuitously small. One should be aware that, as well as the self-shielding effect which reduces the UV heating and hence equilibrium temperature and pressure in the ISM, other inaccuracies in the detail of the ISM (such as magnetic pressure) could easily contribute opposite effects of similar magnitudes; however their study is well beyond the scope of this work.

5.5 Intergalactic DLAs?

It is clear from Fig. 2 that our DLA cross-section is confined to within the virial radii of our host haloes. This is in qualitative agreement with the majority of previous DLA simulations listed in Table 1, and is an assumption of all DLA semi-analytic models that we are aware of. However, it contrasts with the recent results of R06 and R08 in which as much as 50 per cent of the DLA cross-section resides outside the virial radii of haloes (see table 2 in R08 and the top right panel of fig. 3 in R06).

Although rough estimates suggest that DLAs should form in dark-matter haloes, it is not unreasonable for DLAs to form in overdense surrounding regions. Given the requirement for self-shielding, \[n_{\text{HI}} \gtrsim 10^{-2} \text{ cm}^{-3}\] (Haehnelt et al. 1998), one may compare the gravitational mass required to confine such gas, \[M_{\text{grav}} \approx \frac{N_{\text{HI}} kT}{G n_{\text{HI}}}\] to the total gas mass enclosed in the DLA (\[\sim m_p n_{\text{HI}}^3 N_{\text{HI}}\]), giving the ratio

\[
\frac{M_{\text{grav}}}{M_{\text{gas}}} \approx 2 \left( \frac{T}{10^6 \text{ K}} \right) \left( \frac{N_{\text{HI}}}{10^{20.3} \text{ cm}^{-2}} \right) \left( \frac{n_{\text{HI}}}{10^{-2} \text{ cm}^{-3}} \right).
\]

Thus, for DLAs with column densities close to the lower limit, it may be possible for the self-gravity of gas, or slight dark-matter overdensities, to obviate the need for a fully collapsed dark-matter halo. This is especially true if (unlike in our simulations) gas is allowed to cool efficiently to temperatures \(<10^5 \text{ K}\).

The bigger problem is in understanding how the gas cools to become neutral in the first place. One key difference between our simulations and those of R06 and R08 is that the latter include an approximate algorithm to correct the temperature for shielding effects, whereas we keep our temperatures constant during the radiative transfer processing (Section 3.1). While our approach is clearly an approximation, the latter may overcool gas since dynamical and feedback heating effects could easily become significant as the UV field drops. The only way to correctly resolve this problem is (as in R06, but not in R08) to include radiative transfer in the live simulations.

It will be interesting to see how this issue and a physical understanding of it develop with future generations of simulations and radiative transfer codes. But while it remains to be adequately resolved, we should note that (i) the effect in R06/R07 is resolution dependent, and therefore the physical status is not transparent; (ii) our self-shielding runs suggested the effect was rather small (Section 5.4), at least with the local approximation and (iii) we have produced a DLA cross-section which matches nearly all observational constraints, which lends some indirect reinforcement to the validity of our approximation.

6 DISCUSSION AND CONCLUSIONS

6.1 Overview

We have investigated the occurrence of DLAs in a series of simulations (see B07; G07; G08) which produce galaxies at \(z = 0\) with as near as currently possible to realistic physical properties (see Introduction). These high-resolution simulations include a physically motivated star formation feedback prescription with only one free parameter (the efficiency of energy deposition) which is set by observations of low-redshift star formation. Thus, as well as providing information on DLAs themselves, this work is an independent cross-check of the formation process of the G07/B07/G08 galaxies.

To produce cosmological statistics from a smorgasbord of boxes, we used a non-parametric weighting process, in effect correcting the halo mass function of the combined sample. This does not involve any fitting or parametrization, and hence no extrapolation: all the results presented in this paper are derived directly from resolved regions of simulations.

The picture that emerges from our simulations is of a cosmological DLA cross-section predominantly provided by intermediate-mass haloes, \(10^8 < M_{\text{vir}}/M_\odot < 10^{11}\). These ranges are somewhat higher than many early simulations suggested (e.g. Gardner et al. 1997b, 2001), and are close to the range of \(10^{9.7} < M_{\text{vir}}/M_\odot < 10^{10}\) suggested by observations of DLA/LBG correlations (Cooke et al. 2006). Our DLAs form stars at low rates (predominantly \(<0.1 M_\odot \text{ yr}^{-1}\) and have metallicities in the range \(-2.5 < [M/H] < 0\) with a median of approximately \(Z_\odot/20\), both in agreement with observations. We also investigated the distribution of total stellar masses of DLAs, finding them to be predominantly spread over \(10^6 < M_* / M_\odot < 10^{10}\), with a peak at \(\sim 10^7 M_\odot\). By \(z = 0\), the majority of the neutral gas forming the DLAs has been converted into stars, but during this time substantial merging complicates the direct identification of low-redshift galaxies with high-redshift absorbers. In plots showing overall halo properties, we have marked the location of the major progenitors to our \(z = 0\) Milky Way like and dwarf-type galaxies (from boxes ‘MW’ and ‘Dw’, respectively); they appear to have been fairly typical DLAs.

6.2 Mass–metallicity relationships

A tight relationship between dark-matter halo mass and SFR (Fig. 13) underlies a strong mass–metallicity relation; in Fig. 12 we have shown that this is manifested by a correlation between DLA velocity widths and metallicities (for equivalent observational results, see Ledoux et al. 2006; Prochaska et al. 2008). Further, the same simulations produce a realistic mass–metallicity relation for \(0 < z < 2\) galaxies (B07), suggesting that these simulations capture the metal enrichment of collapsed systems in a meaningful way. The DLA result is not significantly affected by gradients within the discs of our forming galaxies, but the DLA sightlines do preferentially sample regions of gas with higher metallicities (by factors of \(\sim 2\) than the mass-weighted halo mean. Further work on metallicities in these simulations is ongoing, in particular regarding the importance of metal diffusion – the metals are simply advected with the SPH particles, which can lead to inaccuracies where spatial gradients are important. In connection with this work, it will be interesting to see whether the metal enrichment of the simulations’ less overdense regions also appears realistic, providing a connection to the importance (or otherwise) of outflows (Section 6.3).

Recent work has suggested that the origin of the observed relationship between kinematics as measured by Mg \(\text{II}\) rest-frame equivalent widths (\(W_{5175}\)) and metallicity of DLAs should not be relied upon as an indicator of an underlying variation with mass (Bouché 2008). However, this claim is not directly relevant to fiducial velocity width determinations which are measured from unsaturated or mildly saturated transitions; Mg \(\text{II}\) is a strongly saturated
absorption line, and as such $W^\lambda_{2796}$ can easily be affected by trace gas in the outer regions of galaxies (or perhaps even the ambient IGM).

### 6.3 Velocity profiles

Overall, we reproduce the spread of velocity widths seen in DLA systems (Fig. 9) and approximately match the distribution of low-velocity width systems ($v < 100 \, \text{km} \, \text{s}^{-1}$). However, the long-standing difficulty of underestimating the observed incidence rate of high-velocity widths ($v > 100 \, \text{km} \, \text{s}^{-1}$) persists in our simulations, although the discrepancy is rather small compared with older simulations and comparable to that seen in the recent work by R08. It is not entirely clear why simulations in general have encountered such persistent difficulty in this respect. There are essentially three possibilities.

First, it is possible that our assumption $n(\text{Si}/n(\text{H}) = n(\text{Si})/n(\text{H})$ oversimplifies the identification of regions responsible for the low-ion profiles and leads to systematic underestimates of the velocity dispersion. We investigated this avenue briefly (Section 5.2), but the correction did not appear sufficient to resolve the discrepancy, although this could be sensitive to the description of the ISM on sub-resolution scales (see also below). We ran a brief test in which all gas was assumed to contribute to the velocity width; in this (completely artificial) scenario, the cosmological rate of high-velocity widths is over-estimated, showing that the required motions are, at least, ‘available’ in this sense.

Secondly, perhaps the internal gas kinematics still require some correction. Although we did not, for this work, attempt a rigorous decomposition, qualitative inspection suggested that a mixture of disc kinematics (Prochaska & Wolfe 1998) and merging clumps (Haehnelt et al. 1998) is responsible for the final spread of velocities.

We did not find that our feedback made any significant contribution via turbulent motions to the velocity widths (Section 5.1) – hardly a surprise, given that the coupling to the ISM is achieved entirely thermally. A better understanding of feedback is likely to help the kinematical situation by inducing bulk outflows. It would be interesting to see how the simulations of Nagamine et al. (2004a) perform in reproducing DLA line profiles, since they include a phenomenological model of GWs. Promising progress in placing such winds on a more physical footing was recently described by Ceverino & Klypin (2007), whose simulations reproduce such bulk motions starting from an explicit model for the ISM.

Thirdly, it is possible that our cross-section is associated with, on average, haloes of insufficient mass; in other words, DLAs at the high-mass end could be overly compact. This in turn could be connected to the more well-known angular momentum problem in which simulated disc galaxies have underestimated scalelengths (Navarro & Steinmetz 2000; Eke et al. 2001). Our simulations, as was noted in the Introduction, go some significant way towards a resolution of the issue for $z = 0$ disc galaxies by combining sufficient feedback (S06) with high resolution (Kauffmann et al. 2007); our elevated DLA cross-sections for intermediate-mass haloes are connected to this same feedback (Section 5.1). As the mechanisms preventing angular momentum loss are further understood, these same mechanisms may continue to increase the DLA cross-section for high-mass haloes. On the other hand, our matching of the metallicity distribution (Fig. 11) provides an alternative joint constraint on the star formation history and mass of responsible haloes, and is in good agreement with observations. Any change in the mass of haloes comprising our DLA cross-section would therefore need to be compensated by a change in our virial mass–star formation relation (Fig. 13).

### 6.4 Column density distribution and dust biasing

As we discussed in Section 4.2.1, we match the overall column density distribution well, but somewhat overestimate the number of observed systems with $N_{\text{HI}} > 10^{21.5} \, \text{cm}^{-2}$. This causes us to slightly overpredict the value of $\Omega_{\text{DLA}}$ (we obtain $\Omega_{\text{DLA,sim}} = 1.0 \times 10^{-3}$, whereas the SDSS data yield $\Omega_{\text{DLA,obs}} = 0.8 \times 10^{-3}$). The simulated value of $\Omega_{\text{DLA,sim}}$ is obtained by imposing an upper cut-off on the column density of systems contributing to the measured $\Omega_{\text{DLA}}$ because stronger systems are too rare to be observed with current observational data sets. But in our simulations, these same systems actually contribute significantly to the cosmic density of DLAs; when included in the census, they boost the total to $\Omega_{\text{DLA,sim}} = 1.4 \times 10^{-3}$. Thus in our picture, ‘invisible’ systems contribute about 30 per cent to the H i budget; but functional fitting of the observed data from SDSS suggests a much steeper cut-off at high-column densities than our simulations, and hence that the observed value $\Omega_{\text{DLA,obs}}$ given above should be essentially correct (Prochaska et al. 2005).

While the precise observational extrapolation is subjective and the fit is driven by a couple of bins with $N_{\text{HI}} > 10^{21.5} \, \text{cm}^{-2}$, there is a strong constraint in the lack of systems at high-column density. For instance, only three systems with $N_{\text{HI}} > 10^{21.8} \, \text{cm}^{-2}$ are observed in the SDSS DR5 survey, whereas our simulation predicts 10 over the same path length (a glance at the Poisson distribution function shows that this is a significant discrepancy).

It is notable that host galaxies of gamma-ray bursts (GRBs), which trace a sample weighted towards higher column densities, routinely display column densities of $N_{\text{HI}} \sim 10^{22} \, \text{cm}^{-2}$ (Jacobsen et al. 2006), so that such systems certainly exist but have a smaller cross-section than our simulations suggest. It is possible that we overpredict the number of high-column density systems because our simulations are inadequate in the responsible regions, which are cold and dense: one should form $H_2$ but the complex physics responsible are not implemented in our code. Schaye (2001) suggested that this molecular cloud formation could determine a characteristic cut-off for the column density distribution. On the other hand, observations suggest that DLAs harbour very little molecular gas, with fractions at the very most $f_{H_2} \sim 10^{-2}$ (Leduc, Petitjean & Srianand 2003). Of course, the typical DLA sightline could miss high-density clumps within giant molecular cloud formations, which would mean the global fraction of $H_2$ could be somewhat higher. It is therefore currently unclear how feasible this explanation could be.

It has been claimed in the past (e.g. Cen et al. 2003) that DLA dust obscuration effects should substantially reduce the number of observed high-$N_{\text{HI}}$ systems relative to their true abundance. However, this is hard to reconcile with the most recent observations; in particular, radio-selected samples (which are unlikely to be biased by dust considerations) show little if any evidence for increased high-$N_{\text{HI}}$ absorbers (Ellison et al. 2001; Jorgenson et al. 2006; Ellison et al. 2008). Further, in a companion paper (Pontzen & Pettini 2008), we show that there is only marginal statistical evidence for dust-induced obscuration in the joint distribution of observed DLA column densities and metallicities, which are in fact nearly uncorrelated. This also arises quite naturally in our simulations, because the dependence of $N_{\text{HI}}$ on the underlying halo mass is weak (Fig. 8), whereas metallicities and kinematics are strongly correlated with the halo mass. Combining all the above considerations with our successful reproduction of the observed distribution...
of metallicities (Section 4.2.3), we believe dust biasing is unlikely to have a major part to play in a future understanding of DLAs.

The very slight trend which is observed linking the column density to the halo mass in our simulations biases low-column density observations in favour of finding low-mass haloes (Fig. 8). We have not explicitly studied the sub-DLA population, so that these results are not directly comparable with the work of Khare et al. (2007), in which it is suggested that sub-DLAs preferentially probe more massive haloes than DLAs. However, there is certainly a tension between these results which deserves some attention in the future.

6.5 Bimodality

Although we did not specifically set out to investigate the possibility of bimodality within the DLA population (Wolfe et al. 2008), we saw a bifurcation in our cross-sections as a function of HI mass (Fig. 7). The bifurcating lower branch in Fig. 7 has higher virial masses for a given HI mass, wider velocity profiles, higher SFRs and higher mean temperatures. It is important to emphasize that these systems, which are perhaps undergoing a starbursting phase, account for only ~2 per cent of the DLA cross-section; our results are therefore not directly comparable to the observational claim of two populations of roughly equal importance.

We ran some careful tests to try to understand the origin of this effect, but it essentially remains work in progress: further simulations and detailed studies of the evolution of these objects will be key to a full account. The critical halo mass, $M_{\text{vir}} \sim 10^{10.5} M_\odot$, is probably too small to be directly related to the shock-stability model of Dekel & Birnboim (2006). There are no spatial correlations which would suggest the abnormal haloes are associated with protocluster regions. We verified that the results from the ‘Large’ box were consistent with being drawn from a subvolume of the ‘Cosmo’ box. Since the low cross-section branch objects account for such a small fraction of our DLAs, we felt justified in postponing their full study to later work.

6.6 Future work

In general, we have commented throughout that the lack of resolution on fine ISM scales (a common feature of all current cosmological simulations, likely to persist into the foreseeable future) is a fundamental limitation. The ISM is a complex mixture of gas in different phases with variations on truly tiny scales. It is also interesting to note that observations suggest that the pressure contributed by magnetic effects in the disc of our galaxy and other local galaxies is comparable in magnitude to turbulent kinetic pressure (e.g. Heiles & Crutcher 2005); hence magnetic effects could contribute at least as much as stellar feedback to an understanding of the formation of disc galaxies, at least at $z = 0$. It is not impossible to fathom that magnetic fields could have an important role to play in a better understanding of DLAs. But regardless of any particular physical processes, our feeling is that long-term future focus should remain on improving our understanding of the coarse-grained behaviour of such a mixture, i.e. in developing sub-grid physics models. This conclusion was reached independently by R08.

Even with our current set of simulations, it will be interesting to investigate in more detail the predictions of these simulations with regard to the LBG population; in Section 4.3, we showed that the total SFR at $z = 3$ may be very slightly overpredicted compared to observation. But, in work not presented here, we have also investigated the shape of the luminosity function (at $z = 3$ and higher redshifts) and found both $L_*$ and the faint end slope to be consistent with observations. Remaining shortcomings could easily be accounted for by details of the IMF, suggesting that the underlying populations are quite reasonable (Governato et al., in preparation).

In terms of the properties of DLAs, this work opens the door to an array of further studies. In particular, we intend to address in more detail the time evolution of our DLA population and the transfer of gas through hot, warm and stellar phases in the near future. Given the realistic nature of metals in our $z = 3$ DLAs and in our galaxies at $z = 0$ (B07), the details of the intervening time could, amongst other things, shed light on the ‘missing metals’ problem (Pettini 2006). Further, it is known observationally that the metallicities, velocity widths and column density distributions evolve only slightly with decreasing redshift; will our simulations reproduce such slow evolution, which depends on finely balancing the cooling of gas, forming HI, with the formation of stars, destroying it? If so, the manner in which this is accomplished will be of considerable interest. (For instance, do individual objects maintain the same DLA cross-section, or is the slow evolution only seen over cosmological averages?) Although flawed in many respects, simulations offer a guide to our understanding of these issues which should not be ignored – as long as it is taken with a healthy pinch of salt.

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APPENDIX A: SPH CALCULATIONS

For convenience, we will denote the SPH averaging procedure by square brackets, i.e. for any quantity Q

\[ [Q](r) \equiv \int d^3r' W(r, r'; h(r)) Q(r') \]

\[ \approx \sum_i Q_i \rho_i W(r, r_i; h_i), \]

where W is the smoothing kernel, and the smoothing length for each particle is given by h_i, which notionally corresponds to a smoothing field h(r). For each sightline, the ω-axis is aligned such that the line of sight is parametrized by \( r = (0, 0, z) \). The column density is calculated as

\[ N_{HI} = \int_{-\infty}^{\infty} dz [n_{HI}(r)] \]

\[ = \sum_i n_{HI,i} m_{HI,i} W_{\perp}(r_i, h_i), \]

\[ W_{\perp}(r_i, h_i) \equiv \frac{1}{h_i} \int_{-\infty}^{\infty} dz W[(x^2 + y^2) + z^2]^{1/2}, \]

where \( n_{HI,i} \) is the number density of HI ions, and \( n_{HI,i}, m_{HI,i}, \rho_i, \) refer to each SPH particle’s HI number density, mass and density.
respectively, and we have assumed a fiducial form for the kernel $W(r_1, r_2; h) = \mathcal{V}(|r_1 - r_2|/h)^3$. The projected kernel (A5) is calculated numerically; however, since conventionally $\mathcal{V}$ has compact support, so too does $W_\bot$, which need only be tabulated once for a finite range of values. The upper limit depends on the choice of kernel, but is conventionally max ($\delta$) = 2h. The sum (A4) is taken over all particles, although in practice many particles are culled by considering their distance from the line of sight.

In general, by projecting the kernel in this way, one obtains an efficient and justifiable method for calculating any projected quantity. Integrated quantities follow directly by replacing $n H_j$ in equation (A4) with the appropriate particle property, subject to the following caveat: there is an ambiguity in calculations of this type involving more than one particle property or functions of particle properties. In particular, we will consider the generation of an absorption profile:

$$\tau_{\text{tot}}(\lambda) = \int_{-\infty}^{\infty} dz \, n(r) \tau(\lambda, 1 - v_z(r)/c; T(r)),$$  \hspace{1cm} (A6)

where $\tau_{\text{tot}}(\lambda)$ gives the total line-of-sight optical depth for wavelength $\lambda$ and $\tau$ gives the absorption (Voigt) cross-section with parameters assumed for the ion under consideration and temperature broadening $T(r)$. There are (at least) two different methods for approximating this.

The first method is easiest to evaluate, and lumps the integrand into a single quantity which is to be SPH interpolated:

$$\tau_{\text{tot}}(\lambda) = \int_{-\infty}^{\infty} dz \, \sum_i n_i m_i \tau_i \frac{\lambda(1 - v_z^i(r)/c; T_i)}{P_i} W_\bot(|r_i|/h_i).$$  \hspace{1cm} (A7)

The second is considerably more computationally intensive and interpolates each fluid quantity within the integrand before performing the integration:

$$\tau_{\text{tot}}(\lambda) = \int_{-\infty}^{\infty} dz \, \sum_i [n_i \tau_i \lambda(1 - v_z^i(r)/c; T_i)](r) \, W_\bot(|r_i|/h_i).$$  \hspace{1cm} (A8)

In the continuum limit $W \to \delta$, both these expressions reduce to (A6); further, it is simple to write a number of different expressions midway between which have this same property. For quantities varying on scales $\gg h$, the two methods will give identical results; however, it is not clear a priori which, if any, method is optimal for the DLA problem where as much information from near the resolution limit needs to be extracted.

This problem is not confined to line-of-sight integrals, and so we may turn for guidance to standard approaches to SPH. Although we have not seen the ambiguity discussed explicitly, in general expressions are used where the interpolation is performed as a final step as in (A8). We therefore adopt this approach; however we note that it has some odd properties, and in particular one may define a dispersion in any quantity $r$,

$$\sigma^2(r) = \langle v^2 \rangle(r) - \langle v \rangle^2(r) \geq 0$$  \hspace{1cm} (A10)

with equality holding if and only if $v(r)$ is constant within the smoothing region. In other words, the standard method forces us to accept a subsolution resolution velocity dispersion in the fluid. The exact interpretation of this is somewhat elusive. Given a strictly Lagrangian interpretation, at any point there is a well-defined velocity and it should only vary over resolved spatial scales. But, owing to the method of interpolation, if we find nearby two SPH particles on top of each other with equal and opposite velocities, this would not lead to any significant spatial variation in $v(r) \simeq 0$ but would create a non-zero $|v|^2$. The evolution of this `turbulence’ would make for an interesting study, not least to determine its physical meaning, but is beyond the scope of this paper.

Our final expression for the line profile is therefore

$$\tau_{\text{tot}}(\lambda) = \int_{-\infty}^{\infty} dz \, n_i \tau_i \lambda(1 - v_z^i(r)/c; T_i, \langle |v|^2 \rangle^r(r)),$$  \hspace{1cm} (A11)

where the indicated thermal and turbulent broadening components are added in quadrature. Because $\sigma^2$ is not a projected quantity, the $\tau$ integration cannot be performed by simple integration of the kernel, and therefore this quantity is performed as an explicit numerical integration over the sightline.

Note that this intrinsic velocity dispersion should be distinguished sharply from the line-of-sight velocity dispersion, for example, $\langle v \rangle^2$ (A10).

It is clear, given the fiducial positioning of the SPH averaging brackets [], that this quantity will include contributions from the intrinsic velocity dispersion, as well as genuine line-of-sight dispersion effects.

**APPENDIX B: WEIGHTING METHOD AS DISCRETIZATION OF AN INTEGRAL**

Let us consider a calculation of the line density of DLAs for the situation described in Section 3.2, in which $\sigma$ has some range of values with probability densities $P(\sigma | M)$ for a given halo mass $M$. Our starting point is the integral

$$\frac{dN_{\text{DLA}}}{dl} = \int dM \int d\sigma f(M) P(\sigma|M),$$  \hspace{1cm} (B1)

where we have temporarily adopted the physical distance measure $l$ to obviate the need for $d l/d X$ on the right-hand side. We discretize this equation by assigning all haloes to bins in virial mass. Indexing these mass bins by $i$, and denoting the set of all haloes within each mass bin by $\mathcal{H}_i$, one makes the replacement $\int dM f(M) \to \sum F_i \cdots$ where $F_i$ is defined by equation (4). Our probability distribution for $\sigma$, $P(\sigma | M)$, is represented by individual haloes. The simplest way to represent $P$ is therefore by a sum of $\delta$ functions

$$P(\sigma | M_i) \to \frac{1}{n(\mathcal{H}_i)} \sum_{\mathcal{H}_i} \delta(\sigma_i - \sigma),$$  \hspace{1cm} (B2)

where $n(\cdots)$ counts the elements of its parameter set, and $\sigma_i$ denotes the cross-section of the particular halo $i$. This expression reduces, as expected intuitively, to

$$\frac{dN_{\text{DLA}}}{dl} = \sum_i F_i \frac{n(\mathcal{H}_i)}{n(\mathcal{H}_i)} \sigma_i,$$  \hspace{1cm} (B3)

where $\sigma_i$ is the mean DLA cross-section of a halo in bin $i$.

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11 One could produce a more sophisticated method in which the $\delta$ functions are replaced by smooth functions with unit area to create a smoother final $P(\sigma|M)$. However, it is not clear to what extent this is helpful and both methods reduce to the correct integral in the infinite-halo limit.
We are next interested in computing, for some property \( p \),
\[
\frac{d^2 N_{\text{DLA}}}{dl dp} = \int d\sigma \int dM \sigma n(M) P(\sigma & p | M).
\] (B5)

This will involve exactly the same replacements as before, with the only difference being
\[
P(\sigma & p | M) \rightarrow \sum_{h \in H} \frac{\delta(\sigma_h - \sigma)}{n(H_i)} \sum_{j \in S_h} \frac{\delta(p_j - p)}{n(S_h)}.
\] (B6)

Here, \( S_h \) is the set of all DLA sightlines taken through halo \( h \). The expression (B6) will leave us with a floating \( \delta \) function in the chosen property \( p \), so the final stage is to bin by this property. In other words, one integrates both sides of the equation with respect to \( p \) over a bin centred on \( p_j \) with width \( \Delta p \):
\[
\frac{d^2 N_{\text{DLA}}}{dl dp} \bigg|_{p_j} \Delta p = \sum_i \frac{F_i}{n(H_i)} \sum_{h \in H_i} \frac{n(P_{j,h})}{n(S_h)}
\] (B7)
in which we have introduced \( P_{j,h} \), the set of all sightlines in halo \( h \) such that \( p \) falls within property bin \( j \) \((p_j - \Delta p/2 < p < p_j + \Delta p/2)\). Note there is no sum over sightlines in the above (only a counting of sightlines in particular sets); the two sums are, respectively, over the mass bins and the haloes within them. Since every halo falls into exactly one mass bin, this is really just a sum over all haloes:
\[
\frac{d^2 N_{\text{DLA}}}{dl dp} \bigg|_{p_j} \Delta p = \sum_{h \in H} \frac{n_i(h) \sigma_h}{n(H_i)} \frac{n(P_{j,h})}{n(S_h)} \Delta p
\] (B8)
where \( i(h) \) denotes the mass bin \( i \) to which halo \( h \) belongs.

For completeness, with all constants (including the conversion to absorption distance \( X \)), our final calculation reads
\[
\frac{d^2 N_{\text{DLA}}}{dX dp} \bigg|_{p_j} = \frac{c}{H_0(1+z)^3} \sum_{h \in H} \frac{w_h \ n(P_{j,h})}{\Delta p \ n(S_h)}.
\] (B9)

\[ w_h = \frac{F_{i(h)} \sigma_h}{n(H_i)}. \] (B10)

There is no essential barrier to investigating correlations between properties by extending this method to produce \( d^3 N_{\text{DLA}}/dX dp dq \) for some extra property \( q \). However, the growing sparsity of the data in the increasing dimensional binning is such that an easier method suggests itself. Correlations between parameters in DLA studies are generally known only for \( O(100) \) observed systems. One can generate from our simulations, using a Monte Carlo technique, just such a limited sample; this can be compared directly to observational data. The probability for accepting a particular input sightline through this technique must be proportional to the output line density ‘generated’ by that individual sightline. From equation (B3), it is clear that the contribution of halo \( h \) to the line-of-sight density of systems is given by a probability \( w_h \) (one may verify that this remains true for correlations between any number of sightline properties) and thus the probability of accepting that sightline should be proportional to this quantity.

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