A model for the metallicity evolution of damped Lyman-α systems

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ABSTRACT
We apply a physically motivated stellar feedback model to analyse the statistical properties of damped Lyman-α systems (DLAs) expected in the concordance cold dark matter (CDM) model. Our feedback model produces extended low-metallicity cold gaseous discs around small galaxies. Since the space density of galaxies with low circular speeds is high, these discs dominate the cross-section for the identification of DLAs at all redshifts. The combined effects of star formation, outflows and infall in our models result in mild evolution of the N_H-weighted metallicity content in DLAs with redshift, consistent with observations. According to our model, DLAs contribute only a small fraction of the volume averaged star formation rate at redshifts z < 5. Our model predicts weak evolution in Ω_{HI} over the redshift range z = 0 − 5. Furthermore, we show that the cosmological evolution of Ω_{HI} and the cosmic star formation rate are largely disconnected and conclude that the evolution of Ω_{HI} as a function of redshift is more likely to tell us about feedback processes and the evolution of the outer gaseous components of small galaxies than about the cosmic history of star formation.

Key words: methods: analytical - intergalactic medium - quasars: absorption lines, - galaxies: formation - galaxies: ISM - cosmology: theory

1 INTRODUCTION
Damped Lyman-α systems (DLAs) are defined as quasar absorption systems with a column density of N_{HI} ≥ 2 × 10^{20} cm^{-2}, i.e. with neutral hydrogen column densities similar to present day galactic discs (see e.g. Zwaan et al. 2005b). DLAs probe the high column density end of the distribution of absorption line systems and are particularly interesting because their high concentrations of neutral hydrogen suggests that there may be a close connection with disc galaxies that we see today (Wolfe et al. 1986). In addition observations of DLAs measure, in a model independent way, the total neutral hydrogen mass density of the Universe as a function of redshift.

There are two main competing scenarios for the origin of the DLAs. In the first model, the DLAs are interpreted as large-redshift progenitors of present day massive spiral discs (Wolfe et al. 1986; Lanzetta et al. 1991). These discs are assumed to have formed at high (z > 5) redshift and to have evolved little apart from converting their gas into stars. In support of this theory Prochaska & Wolfe (1995) argue that the kinematics of metal absorption lines in DLAs are best explained by models of rapidly rotating (v_c ≥ 200 kms^{-1}) galactic discs. The alternative picture, which is more in line with current views of hierarchical structure formation, posits that the DLA systems are ‘dwarf’ galaxies rather than fully formed ∼ L^∗ discs (Kauffmann & Charlot 1994; Mo & Miralda-Escudé 1994). In particular, Haehnelt et al. (1998) used hydrodynamic simulations to show that the statistical properties of the velocity structure seen in the metal lines could be reproduced by infalling sub-galactic clumps within dark matter haloes with low virial velocities of (v_{vir} ≤ 100 kms^{-1}).

On the observational side, the nature of the DLA host galaxies at high redshift is largely unknown, with only a handful of optical detections. Møller et al. (2002) identified three DLA host galaxies at z ∼ 2−3 and found them to have luminosities much fainter than L^∗. At lower redshifts, z ∼ < 1, approximately 30% of the DLA host galaxies have luminosities larger than L^∗ (see Zwaan et al. 2005b). However, it is dangerous to extrapolate from low redshift to high redshift since it is plausible (perhaps likely) that the cross-section based selection criteria select different objects at different redshifts.

The first comprehensive metallicity surveys of DLAs Pettini et al. (1994) derived a global mean N_{HI}-weighted metallicity of log(Z/Z_⊙) ≈ −1 at z ≈ 2. Further observations Pettini et al. (1999) Prochaska & Wolfe (2000) found similar metallicities and no evidence for evolution of the
metallicity in the redshift range \( z \sim 1 - 3.5 \). At lower redshift \( (z \lesssim 1) \) the situation is more uncertain because of the small sample of DLAs. Recent measurements at \( z \lesssim 1 \) by Kulkarni et al. (2003) indicate that the evolution of metallicity for DLAs remains weak at lower redshifts and does not rise up to solar, or near-solar, values by \( z = 0 \). In addition, the cosmological density of neutral hydrogen (\( \Omega_H \)) as traced by the DLA population shows little evolution between \( z \approx 0.5 - 5 \) (Rao et al. 2004).

Attempts to model DLAs in cosmological simulations have proved difficult because of the high numerical resolution required and the difficulties in modelling stellar feedback and galactic winds (see e.g. Katz et al. 1996; Gardner et al. 1997, 2003). In addition to limited numerical resolution, early simulations did not follow the chemical evolution of the DLAs in any detail. Some of these shortcomings have been overcome with recent simulations by Cen et al. (2003) and Nagamine et al. (2004b). Both studies are able to reproduce the flat metallicity evolution of the DLAs, but their metallicity values tend to lie at around \( \log(Z/Z_\odot) \approx -0.5 \), considerably lower than observed. To reconcile this higher value with the observations, both groups invoke a large dust obscuration correction. A dust bias has also been invoked to explain the lack of DLA absorbers with \( [\text{Zn}/H] + \log[N(\text{HI})] > 21 \) noted by Boissier et al. (1998). However, a recent study by Murphy & Liske (2004) using a large sample of quasar spectra from the SDSS Data Release 2 did not find any evidence for dust-reddening caused by intervening DLAs at \( z \sim 3 \). In addition DLAs extracted from samples of radio selected QSOs, which should be largely free from any dust bias, show only marginally higher metallicities compared to absorbers from optically selected control samples (Ellison et al. 2002; Akerman et al. 2002; Horencson et al. 2003).

Semi-analytic modelling of DLAs provides a complementary approach to numerical simulations (Kauffmann et al. 1999; Prantzos & Boissier 2000; Maller et al. 2001; Somerville et al. 2001; Okoshi et al. 2004). The semi-analytic approach is, of course, much faster than numerical simulations and so can be used to explore parametric representations of physically complex processes such as stellar feedback. Semi-analytic modelling can also provide physical insight, which is sometimes difficult to acquire from numerical simulations. The disadvantage of semi-analytic modelling is that some aspects of the models may be sensitive to processes that are extremely difficult to model analytically. Even if this is the case (as it is in the models described in this paper) it is useful to identify aspects of a theoretical model that are robust, and can be understood analytically, and those that are likely to require further investigation using numerical simulations.

In this paper we develop a semi-analytic model of DLAs using the feedback model described by Efstathiou (2000) (hereafter E00). Some aspects of the application of this feedback model to DLAs were sketched in E00. The purpose of this paper is to develop a more detailed model that can be compared with a wide range of new observations. The E00 feedback model produces extended cold gaseous discs around ‘dwarf’ galaxies (defined crudely in this paper as any system in a halo with a circular speed \( v_c \gtrsim 100 \text{ km s}^{-1} \)). In CDM-like models such gaseous discs would dominate the cross-section for the identification of DLAs at high redshift because the space density of haloes with low circular velocity is high (Kauffmann & Charlot 1994; Mo & Miralda-Escudé 1994). In our model, most of the cross-section is dominated by largely unprocessed gas in the outer parts of the galaxies that does not participate in the bulk of the star formation process. As a result, the evolution of \( \Omega_H \) in this model is linked only indirectly to the star formation history. There are some similarities between our models and recent semi-analytic modelling of DLAs by Okoshi et al. (2004). The main differences, which are particularly significant for modelling the metallicities of DLAs, are: (i) our stellar feedback and outflow models are physically motivated, i.e. they are related to a well defined, though simplified, model of the interstellar medium in galaxies; (ii) rather than applying ad-hoc rules of star formation and chemical enrichment, our star formation prescription is based on the self-regulated\(^1\) model described in E00.

The structure of the paper is as follows. Section 2 summarizes the feedback model and its application to DLAs. In Section 3 the feedback model is applied to calculate the metallicity evolution of the DLA population. Theoretical predictions of various global properties of the DLA population are described in Section 4. In Section 5 we summarize our results and present our conclusions.

2 THE MODEL

The E00 feedback model is used to evolve a grid of galaxy models as described below. In this Section we will summarize briefly some aspects of the model and describe the relevant parameters involved. We refer the reader to E00 for a more detailed description of the model. All calculations in this paper assume a concordance CDM cosmology with parameters\(^2\) \( \Omega_m = 0.27, \Omega_{\Lambda} = 0.73, \Omega_b = 0.044, h = 0.71, \text{e.g. Spergel et al. (2003)} \). We assume a scale-invariant adiabatic fluctuation spectrum, normalized so that \( \sigma_8 = 0.84 \).

2.1 Feedback model

E00 developed a self-regulated feedback model in which the instantaneous star formation rate is regulated by disk instabilities and in which supernovae blastwaves convert some fraction of the cold disc gas into a hot component which can flow out of the system. The model is based, in part, on the McKee & Ostriker (1977) theory of the interstellar medium, but also includes the infall of gas within a dark halo and the formation of a stellar disc through self-regulated star formation.

The dark matter halo of the model galaxies is described by a static NFW profile (Navarro et al. 1996). A galaxy forms through infall of gas from the surrounding halo under the assumption that the angular momentum of the disc material is approximately conserved during the collapse of the disc (Fall & Efstathiou 1984). The angular momentum distribution within a dark matter halo is based on a fit to

\(^1\) There is considerable empirical support in favour of self-regulated star formation in disc systems (Kennicutt 1998).

\(^2\) where \( \Omega_m, \Omega_{\Lambda} \) and \( \Omega_b \) are the cosmological densities of matter, dark energy and baryons respectively and \( h \) is defined such that \( H_0 = 100h \text{ km s}^{-1} \text{Mpc}^{-1} \).
the results of N-body simulations and is normalised to reproduce a target value of the dimensionless spin parameter
\[ \lambda = J |E|^{1/2} G^{-1} M^{-5/2}, \]
where \( J, E \) and \( M \) are the angular momentum, binding energy, and mass within the virial radius \( r_V \).

The stability of the resulting gaseous disc is determined by a Goldreich & Lynden-Bell (1965) like criterion,
\[ \sigma_0 = \frac{\pi G \mu g}{\kappa} g(\alpha, \beta), \]  
(1)
where \( \mu g \) is the gas surface density, \( \kappa \) is the epicyclic frequency, \( \alpha \) and \( \beta \) are defined as \( \sigma_\epsilon = \alpha \sigma_0, \mu_\epsilon = \beta \mu g \) and \( g(\alpha, \beta) \) is a correction factor of order unity that applies to a two-component gaseous-stellar disc (see E00 for details and Fig 1, in E00 for a plot of \( g(\alpha, \beta) \) as a function of \( \alpha \) and \( \beta \)).

Following McKee & Ostriker (1977) the interstellar medium of the galaxy is modelled as a multiphase medium. Most of the gas is assumed to be in cold clouds. The system of cold clouds is assumed to be marginally unstable and so their velocity dispersion is fixed in terms of the surface mass densities of gas and stars by equation 4. Supernova blast-waves propagating through the interstellar medium convert some of the cold clouds into a low-density hot component. The instantaneous star formation rate is fixed by balancing the energy dissipated in collisions between cold clouds with that supplied by supernovae shells.

Assuming a standard Salpeter (1955) stellar initial mass function (IMF) with mass cutoffs of \( m_l = 0.1 M_\odot \) and \( m_u = 50 M_\odot \) and that each star of mass greater than \( 8 M_\odot \) releases \( 10^{51} E_{51} \) erg in kinetic energy in a supernova explosion, the energy injection rate is related to the star formation rate by
\[ \dot{E}_{\text{SN}} = 2.5 \times 10^{41} E_{51} M_\odot \text{ erg s}^{-1}, \]
(2)
where \( M_\odot \) is the star formation rate in \( M_\odot \) per year. A fraction of this energy rate, \( \epsilon_c \dot{E}_{\text{SN}} \) is assumed to balance the rate of energy loss per unit surface area due to cloud collisions
\[ \dot{E}_{\text{coll}} = 5.0 \times 10^{29} \left( 1 + \frac{\beta}{\alpha} \right) \mu g^3 \sigma_g \text{ erg s}^{-1} \text{pc}^{-2}, \]
(3)
where \( \mu g \) is the surface mass density of the gas component in units of \( 5 M_\odot \text{pc}^{-2} \) and \( \sigma_g \) is the cloud velocity dispersion in units of \( 5 \text{ km s}^{-1} \).

The uncertain parameter \( \epsilon_c \) is fixed by normalizing the typical star formation rate for a Milky Way type galaxy. Assuming a flat surface mass density profile for the gas to \( R_{\max} = 14 \text{kpc} \) and \( \beta \approx 10, \alpha \approx 5 \) results in
\[ \epsilon_c M_\star = 0.004. \]
(4)

The choice \( \epsilon_c = 0.01 \) results in a reasonable net star formation rate of \( 0.4 M_\odot \text{yr}^{-1} \) for a Milky Way-type galaxy. We therefore adopt \( \epsilon_c = 0.01 \) throughout this paper. We also assume a cooling function for gas of a primordial composition with a sharp lower cutoff at \( T = 10^{4} \text{K} \).

Following McKee & Ostriker (1977) an expanding supernova remnant will evaporate a mass of
\[ M_{\text{ev}} \approx 311 E_{51}^{5/4} / (4 \pi a_1 N_{11} \phi_1 )^{3/5} n_{10}^{-4/5} M_\odot \]
(5)
where \( n_0 \) is the density interior to the supernova remnant (in units of \( \text{cm}^{-3} \)), \( a_1 = 0.5 \text{pc} \) is the lower limit of the distribution of cloud radii and \( N_{11} \) is the number density of the clouds (in units of \( \text{pc}^{-3} \)). (Note that for the typical sizes and densities of the cold clouds, the filling factor for HI absorption will always be greater than unity for HI column densities above the DLA threshold). The second free parameter of the model, \( \phi_1 \), quantifies the effectiveness of classical thermal evaporation (via conductivity) of the clouds \( \kappa_{\text{eff}} = \kappa \phi_1 \) and is expected to be less than unity if conductivity is reduced by tangled magnetic fields, turbulence, etc. The parameter \( \phi_1 \) controls the strength of stellar feedback.

In our normal model we adopt \( \phi_1 = 0.1 \), but we have also run models with weaker feedback \( \phi_1 = 0.01 \) and stronger feedback \( \phi_1 = 1.0 \), (WFB and SFB models, respectively) so...
that the reader can gauge the sensitivity of our results to uncertainties in the strength of stellar feedback.

The cold gas component is assumed to be in the form of HI, which is clearly an oversimplification since some of this gas could be converted to molecular hydrogen. However, this is likely to occur in the central high-density regions of galaxies rather than the outer parts that dominate the DLA cross-section. Together with the low molecular gas fractions observed for DLA systems (see Wolfe et al. 2005 and references therein) suggests that ignoring the molecular component will not affect our results. We also ignore the metagalactic UV flux since at the column densities of the DLA systems they are of course self-shielded to photoionization.

The hot phase of the interstellar medium can escape the galaxy if the wind speed $v_w$ exceeds the escape velocity $v_{esc}$ from the centre of the galaxy (see E00 for details on how $v_w$ is calculated). A wind with $v_w < v_{esc}$ is assumed to participate in a galactic fountain and is therefore returned to the disc on a dynamical timescale, as described in E00. The model thus incorporates simultaneous inflow and outflow of gas ignoring any interactions between these flows. As discussed in E00 this may not be a bad approximation since the feedback may produce a mildly collimated outflow with infall occurring primarily in the equatorial plane, this type of behaviour has been seen in numerical simulations with stellar feedback (see e.g. Tassis et al. 2003, Springel & Hernquist 2003).

Chemical evolution is included using the instantaneous recycling approximation. Separating between primordial infalling gas accreting at a rate $d\mu/S$ with metallicity $Z_I$ and processed gas from the galactic fountain of metallicity $Z_F$ accreted at a rate $d\mu/F$ results in

$$\mu_y dZ = p d\mu_S + (Z_I - Z) d\mu_I + (Z_F - Z) d\mu_F.$$  

Here $p = 0.02$ (Hirschi et al. 2005) is the yield and, unless otherwise stated, we assume that primordial gas has zero metallicity. The metallicities are normalized to the solar value for which we adopt the new value of $Z_\odot = 0.0133$ by Lodders (2003).

### 2.2 Modelling the DLA population

Using the model described above we computed the gas and stellar surface densities, and their respective metallicity profiles, for a grid of models parameterized by the virial velocity of the parent dark halo (defined as the circular speed at the virial radius) and the spin parameter $\lambda$. We computed a grid of 17 models with virial velocities in the range $v_{vir} = 35 - 350$ km/s and 7 spin parameters in the range $\lambda = 0.021 - 0.15$ resulting in a total of 119 models. The lower cutoff of the virial velocity was chosen because gas in haloes with low circular speeds will be heated by the external UV background at high redshifts and so is unable to cool (Rees 1983, Efstathiou 1992). (The precise value of this lower cutoff is unimportant for most of the results presented in this paper. Over the redshift range $0 \lesssim z \lesssim 5$, the smaller cross-section of such low circular speed systems more than compensates for their larger space density. As discussed in Section 4, the peak contribution to the DLA population occurs at higher circular speeds.) Radial profiles for each model were stored for thirteen output times in the range $0.17 - 13.5$ Gyr.

Following Lacey & Cole (1993) we define the formation time of a halo as the time when it has assembled half of its final mass. The distribution of formation redshifts for a halo with final mass $M_1$ at redshift $z_1$ can therefore be approximated by

$$p(z_1)dz_1 = p(\omega)dw = 2\omega \text{erfc} \left( \frac{\omega}{\sqrt{2}} \right) dw,$$

where $\omega = (\delta_{cl} - \delta_{cl})^{2}/(S_1 - S_1)$, $\delta_{cl} = \delta_{cl}(z_1)$, and $S_1 = \sigma^2(M_1/2)$. Here $\delta_{cl}(z)$ is the overdensity required for spherical collapse at redshift $z$ extrapolated using linear theory to the present time and $\sigma^2(M)$ is the variance of the initial density fluctuation field. Using this description we can estimate (approximately) the age distribution of haloes as a function of $v_{vir}$ at each output redshift. At high redshifts the halo age distribution is of course narrow and broadens significantly at lower redshifts where a large number of output ages are needed to model the halo population.

At each output redshift we calculated the number density of haloes as a function of virial velocity using the Sheth & Tormen (1999) mass function

$$n_{ST}(M)dm = \frac{\left( \frac{2}{\pi} \right)^{1/2} A \left[ 1 + \left( \frac{a\delta^2}{\sigma^2} \right)^{-p} \right] a^{1/2} \rho_0 M}{\pi \sigma^2 dM} \exp \left( -\frac{a\delta^2}{2\sigma^2} \right) dM,$$

where $A = 0.322$, $p = 0.3$, $a = 0.707$, $\rho_0$ is the background density, $\sigma$ is the rms density fluctuations on scale $R$ corresponding to mass $M = 4\pi\rho_0 R^3/3$ and $\delta_{cl} \approx 1.68$.

The distribution of halo spin parameters is assumed to follow a lognormal distribution and is assumed to be independent of both time and $v_{vir}$

$$p(\lambda) d\lambda = \frac{1}{\sqrt{2\pi} \sigma_{\lambda}} \exp \left[ -\frac{\log^2(\lambda/\lambda)}{2\sigma_{\lambda}^2} \right] d\lambda,$$

with $\lambda = 0.045$ and $\sigma_{\lambda} = 0.56$ (Vitvitska et al. 2003).

All haloes are assumed to evolve in isolation. We have not included an elaborate merger tree to describe the merger history of an individual dark matter halo and its baryonic content. Our model is thus not designed to give a description of the history of an individual galaxy. Instead our model has been constructed to provide an approximate ‘snapshot’ of the galaxy distribution at each output redshift characterized by the parameters $(t_1, v_{vir}, \lambda)$. By using the simplified model of equations (4) and (3) we are, in effect, assuming that the baryonic parts of galaxies follow a similar merger history to that of the dark matter within the virial radius. This is, of course, a simplification and one would expect the high density baryonic components to survive as distinct systems for a longer time than their parent haloes. Our main results on the metallicity distributions of DLAs (Section 3) are insensitive to the merger history. However, some properties, in particular the numbers of DLAs at high redshift, are extremely sensitive to the merger history (see Section 4).

Our model can give only a very approximate description of properties that are sensitive to merger history and further progress will probably require high resolution gas dynamical numerical simulations.

At each output redshift we calculate properties of the galaxy distribution along sight-lines assuming galaxies are
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Figure 2. The ejection fractions defined as \( f_{\text{ej}} = \frac{M_{\text{ej}}}{M_{\text{tot}}} \), where \( M_{\text{tot}} = M_{\text{ej}} + M_{\text{gas}} + M_{\text{star}} \) is the total baryonic mass. The results are plotted at \( z = 0 \) (left panel) and \( z = 3 \) (right panel) as a function of the spin parameter \( \lambda \) and the virial velocity of the halo \( v_{\text{vir}} \) for the 119 models. The ejection fraction shows a strong increase with decreasing \( \lambda \) and \( v_{\text{vir}} \).

Figure 3. The metallicity of the ejected gas relative to the galaxy gas metallicity \( (Z_{\text{ej}}/Z_g) \) at \( z = 0 \) (left panel) and \( z = 3 \) (right panel) as a function of the spin parameter \( \lambda \) and the virial velocity of the halo \( v_{\text{vir}} \) for the 119 models. The ejected gas is predominantly enriched relative to the gas in the parent galaxy.

2.3 Model properties

In our model, galaxies form in an intense starburst followed by a rapid buildup of metallicity, as can be seen in Fig. 1 which shows the formation of a disc in halo with a relative high \( \lambda \) and a virial velocity \( v_{\text{vir}} = 100 \text{ km s}^{-1} \) (see also E00 for a more extensive discussion). The initial burst is followed by quiescent star formation that builds up the galactic disc from inside-out. The model develops an extended gaseous disc with surface density well above the DLA definition of \( N_{\text{HI}} \gtrsim 2 \times 10^{20} \text{cm}^{-2} \approx 1.6 \text{M}_\odot \text{pc}^{-2} \). The sharp outer edge of the gas disc seen in Fig. 1 is a consequence of the infall model in which the final time of the model sets the maximum cooling radius within the halo. The oscillatory behaviour of the radial gas profile near the centre is a consequence of the galactic fountain and similar behaviour can be also seen in the star formation profile.

In addition to gaseous infall and star formation, the
evolution of galaxies according to this model is strongly influenced by outflows produced by stellar feedback. The ejected mass fraction, $f_{\text{ej}}$, at time $t$, is defined as the ratio of the ejected baryonic mass $M_{\text{ej}}$ divided by the total baryonic mass $M_{\text{tot}} = M_{\text{ej}} + M_{\text{gas}} + M_{\text{star}}$, where $M_{\text{gas}}$ and $M_{\text{star}}$ are the mass in the cold gaseous disc and the stellar disc at time $t$. The parameter $f_{\text{ej}}$ is a strong function of both $v_{\text{vir}}$ and $\lambda$ as can be seen in Fig. 4. According to our model, galaxies with small $v_{\text{vir}}$ and $\lambda$ can have 75% or more of their gas mass ejected by $z = 0$. This is expected to have a large effect on various properties (particularly metallicities) of DLAs as the low mass haloes dominate the cross-section especially at high redshift (see Fig. 9).

In addition to their large ejection fraction, galaxies with small $v_{\text{vir}}$ and $\lambda$ predominantly eject gas that is enriched relative to the host galaxy. This is especially true at high redshifts as can be seen in the right-hand plot of Fig. 5. By $z = 0$ the metallicity enhancement of the ejected material is lower because most of the ejection occurs at high redshift and the galactic disc, by $z = 0$, has had time to evolve to higher metallicity.

The effectiveness of supernova feedback in ejecting gas from spiral and irregular galaxies has also been studied observationally by Garnett (2002). They found an increasing correlation for both the metallicity $Z$ and the effective yield $y_{\text{eff}}$ as a function of rotational velocity $v_{\text{rot}}$. However, at $v_{\text{rot}} \sim 150$ km/s both correlations turn over and both the $Z$ and $y_{\text{eff}}$ become approximately constant for $v_{\text{rot}} \gtrsim 150$ km/s. Garnett (2002) conclude that this observed trend suggests that galaxies with $v_{\text{rot}} \gtrsim 100 - 150$ km/s may lose a large fraction of their metal-enriched gas through supernova feedback, whereas more massive galaxies tend to retain their metals.

To test this observational picture we calculated the average stellar metallicities of our model galaxies as a function of $v_{\text{vir}}$ and $\lambda$ at different redshifts. Our models produce an increasing correlation of the stellar metallicity with $v_{\text{vir}}$ until a critical $v_{\text{vir}}$ is reached, after which the metallicity becomes approximately constant. At $z = 0$ this critical velocity is $v_{\text{vir}} \sim 70 - 85$ km/s, which corresponds to $v_{\text{rot}} \gtrsim 170 - 200$ km/s for a typical model. Thus the chemical evolution of the stellar component in our model seems to be in very good agreement with observations.

### 3 METALLICITY EVOLUTION OF DLAS

#### 3.1 Normal feedback (NFB) model

The metallicity evolution of the DLAs as a function of redshift is shown in Fig. 4 for the normal feedback model with $\phi_0 = 0.1$. The square (green) points show the mean DLA metallicity and the (blue) shaded contours illustrate the metallicity distributions at each output redshift. The diamond (yellow) points show the predicted $N_{\text{HI}}$-weighted mean metallicities. The metallicity evolution binned in unit redshift bins for the observational data set and our feedback model predictions is summarized in Table 3.

Figure 4 shows observational measurements of $[\text{Zn}/\text{H}]$ for DLA systems. The observational sample consists of 87 abundance measurements compiled by Kulka et al. (2003) (see references therein) and 16 measurements by Akerman et al. (2003) totalling 103 abundance measurements. These data consist of both observations with error bars and upper limits indicated by triangles. We used the $[\text{Zn}/\text{H}]$ abundance as an indicator of total metallicity to compare with our models. The assumption that zinc is undepleted on grains and traces the iron abundance over three orders of magnitude in $[\text{Fe}/\text{H}]$ (see e.g. Sneden et al. 1991) is strongly supported by the recent work of Nissen et al. (2004). Zinc should therefore provide an accurate overall indicator of the total metallicity in the gas. In addition, by using $[\text{Zn}/\text{H}]$ abundances we can compare our results to a large observational sample.

The most important result from Fig. 4 is that our model predicts a typical DLA metallicity of $[\text{M}/\text{H}] \approx -1.0$ with very little evolution over the entire redshift range $z = 5$ to $z = 0$. In more detail, the model predicts a mean $N_{\text{HI}}$-weighted metallicity of $[\text{M}/\text{H}] = -0.86$ at $z = 5$ and shows a slight decrease from $z = 5$ to $z \approx 2$. This decrease can be seen in the model shown in Fig. 4 and is accentuated by the stronger outflows of enriched gas from galaxies with small $v_{\text{vir}} \sim 70$ km/s which dominate the DLA cross-section at high redshift. From $z = 2$ to $z = 0$ the model shows a small but steady increase in the average metallicity. This is caused by two effects: a) galaxies at lower redshifts have had time to build up higher metallicities via quiescent star formation; b) the DLA cross-section becomes dominated by galaxies with larger virial velocities ($v_{\text{vir}} = 70 - 100$ km/s) for which the effects of metal enriched outflows are not as pronounced as for galaxies with lower $v_{\text{vir}}$. The combined effect of a shift in the typical $v_{\text{vir}}$ of the DLA population with redshift and the dependence of the metallicity of the outflows as a function of $v_{\text{vir}}$ and time results in almost no evolution in the DLA metallicity. It is worth emphasising that this follows with no adjustment of the feedback parameters compared to those used by E00. The parameters of the model have not been tuned specifically to match the observations plotted in Fig. 4 instead we adopted a model that roughly matches the gross properties of the ISM of the Milky Way and reproduces its net star formation rate.

Performing a least-squares linear fit to the mean $N_{\text{HI}}$-weighted model predictions over the entire redshift range we derive a slope of $m = -0.04$ dex/\Delta z with a zero point of $[\text{M}/\text{H}]_0 = -0.76$ dex confirming the visual impression of no evolution within the error bars. The fit to the unweighted mean metallicities yields $m = -0.02$ dex/\Delta z with $[\text{M}/\text{H}]_0 = -1.26$ dex. The unweighted metallicity tracks the $N_{\text{HI}}$-weighted metallicity accurately with an offset of 0.5 dex.

However the model predicts some evolution in the metallicity distributions of the DLAs with a tail extending to low metallicities at redshifts $z \gtrsim 1.5$. In fact our model predicts that about 5%-10% of the DLAs should have metallicities of $[\text{M}/\text{H}] < -3$ in the redshift range $z = 2-4$. In contrast there is an apparent observed 'floor' in DLA metallicities. In particular, in the sample analysed by Prochaska et al. 3 The observational data points were kindly provided by Chris Akerman.

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Figure 4. The redshift evolution of DLA metallicity for our normal feedback model ($\phi_\kappa = 0.1$) overplotted with observations from (Akerman et al. 2005; Kulkarni et al. 2005) and references therein. The (blue) shaded contours give the range of metallicity for DLAs at each output redshift. The square (green) points show the mean DLA metallicity and diamond (yellow) points show the $N_{\text{HI}}$-weighted mean metallicity.

Figure 5. The redshift evolution of DLA metallicity for our weak (left-hand panel) feedback model ($\phi_\kappa = 0.01$) and strong (right-hand panel) feedback model ($\phi_\kappa = 1.0$) overplotted with the same observational data and symbols as Fig. 4.

(2003) no single DLA system was observed with a metallicity $[M/H] \gtrsim -3$. These authors use $\alpha$-elements and Fe measurements, in addition to Zn measurements, and so are able to detect lower metallicities than would be possible with Zn alone. At face value this suggests a discrepancy, however our metallicity model assumes that the primordial infalling gas has zero metallicity. By allowing for a mild pre-enrichment of the intergalactic medium to the level of $[M/H] = -4.5$ the 99%-contour would move to $[M/H] \sim -4$ with the 95%-contour also at higher metallicity resulting in better agreement with the apparent observed metallicity floor. We will return to this issue in Section 3.3, where we discuss possible effects of selection biases and dust obscuration.

Comparing to the observations, we see that the majority of the data points lie within the 75%-contour with some outliers at high metallicities. Especially at around $z = 2$ a few
Table 1. The metallicities as a function of redshift for the observations and for our three feedback model predictions. ‘All obs’ includes all observations, with upper limits as if they were detections, whereas ‘Errbars’ excludes the upper limit data points. The observations have been included with 95% uncertainties given by a bootstrap analysis. For the lowest redshift bin we only have one observation with errorbars.

| Data set | $0 < z < 0.5$ | $0.5 < z < 1.5$ | $1.5 < z < 2.5$ | $2.5 < z < 3.5$ |
|----------|----------------|-----------------|-----------------|-----------------|
| All obs  | $-0.87 \pm 0.25$ | $-1.02 \pm 0.27$ | $-1.00 \pm 0.15$ | $-1.20 \pm 0.18$ |
| Errbars  | $-0.76 \pm 0.26$ | $-0.98 \pm 0.27$ | $-0.90 \pm 0.18$ | $-0.90 \pm 0.18$ |
| NFB      | $-0.70 \pm 0.28$ | $-0.70 \pm 0.28$ | $-0.66 \pm 0.20$ | $-0.60 \pm 0.20$ |
| WFB      | $-0.66 \pm 0.28$ | $-0.70 \pm 0.28$ | $-0.66 \pm 0.20$ | $-0.60 \pm 0.20$ |
| SFB      | $-0.77 \pm 0.28$ | $-0.99 \pm 0.28$ | $-1.13 \pm 0.20$ | $-1.19 \pm 0.20$ |

Figure 6. The HI column density versus gas metallicity at redshifts $z=0-5$ for the NFB model (left-hand panel) marked with N and for the NFB coeval evolution model (right-hand panel) marked with C. The model (open circles) is overplotted with observations with error bars (red squares) and upperlimits (red triangles) from [Akerman et al. 2005; Kulkarni et al. 2005] and references therein. In addition we include the recent gamma-ray burst DLA (red star) observed by [Fynbo et al. 2006]. The observational data has been binned in unit redshift bins at each redshift.

Figure 5. The HI column density versus gas metallicity at redshifts $z=0-5$. The model (open circles) is overplotted with observations with error bars (red squares) and upperlimits (red triangles) from [Ledoux et al. 2002] and references therein. In addition we include the recent gamma-ray burst DLA (red star) observed by [Fynbo et al. 2006]. The observational data has been binned in unit redshift bins at each redshift.

DLAs have been observed with ‘anomalously’ high metallicities of almost solar value. In fact, the highest metallicity system observed by Ledoux et al. (2002) has $[\text{M/H}] = -0.11$. These authors argue that this DLA is probably connected to a star formation region because they find evidence of dust and a relatively high molecular hydrogen fraction. Our model does not include spatial inhomogeneities within galaxies which could affect the predicted metallicity distributions. Furthermore our model does not include any variance in the strength of stellar feedback, which as we will show in the next subsection could also influence the predicted distributions.

In summary the results of this Section show that our model reproduces the lack of evolution in the metallicity of the DLA systems seen in the observations over the wide redshift range $z \approx 4$ to $z = 0$. In addition, the mean metallicity and dispersion predicted by the model also provides a good match to the observations. There may be some discrepancies between the predicted metallicity distributions and the observations at both extremely high and low metallicities. However as we will argue later in this Section the tails of these distributions are sensitive to model parameters and selection biases.

3.2 Dependence on the strength of stellar feedback

We also calculated the metallicity evolution adopting strong ($\phi_\kappa = 1.0$) and weak ($\phi_\kappa = 0.01$) feedback prescriptions. The predicted metallicity distributions as a function of redshift are plotted in Fig. 5. As expected, the SFB model produces strong outflows that eject a high fraction of the metal enriched gas from the galaxies, especially in their early phases of evolution. The overall effect is to produce a net metallicity that is 0.1-0.3 dex lower than for the NFB model.
A model for the metallicity evolution of damped Lyman-α systems

Figure 7. The redshift evolution of DLA metallicity for the bias-corrected normal feedback model \( \phi_k = 0.1 \) overplotted with the same observational data and symbols as Fig. 4.

| Data set               | \( m \)   | \([M/H]_0\) |
|------------------------|----------|-------------|
| NFB                    | -0.04    | -0.76       |
| NFB unweighted         | -0.02    | -1.26       |
| WFB                    | +0.03    | -0.69       |
| SFB                    | -0.07    | -0.88       |
| NFB bias-corrected     | -0.03    | -0.79       |
| NFB dust-corrected     | -0.03    | -0.84       |

Table 2. The best fit linear fits to the metallicity evolution with redshift for the various data sets, \( m \) is the slope in units of dex/\(\Delta z\) and \([M/H]_0\) the zero point in units of dex. All metallicities weighted with \(N_{\text{HI}}\), unless otherwise stated.

model, with the difference being larger at high redshifts. Fitting the linear evolution of the \(N_{\text{HI}}\)-weighted metallicity we get \( m = -0.07 \) dex/\(\Delta z\) with \([M/H]_0 = -0.88 \) dex. This model produces slightly stronger evolution in the metallicity because stronger outflows lower the metallicities at high redshift in comparison to the NFB model. However, the main effect of the strong feedback is to lower the overall mean metallicity, making it more difficult to explain the observed high metallicity DLAs.

The WFB model produces mean metallicities that are 0.1-0.3 dex higher than for the NFB model. The main differences with the NFB model are at high redshift where the reduced effects of outflows allow the buildup of high mean weighted metallicities of \([M/H] \sim -0.5\). This high early enrichment results in a small positive evolution in metallicity with increasing redshift \( m = +0.03 \) dex/\(\Delta z\) with \([M/H]_0 = -0.69 \) dex.

Both the strong and weak feedback models produce essentially no evolution in the metallicity. The main effect of altering the feedback efficiency is to raise or lower the overall metallicity by a relatively small amount. Interestingly our default NFB model comes closest to providing a match to the observations. Evidently the assumption of a uniform feedback efficiency is a gross oversimplification. More realistically, we would expect a range of feedback efficiencies caused by both differences in the properties of the interstellar medium in galaxies (cold cloud temperatures, sizes, heating mechanisms etc.) and from transient departures from our self-regulated model of star formation (e.g. stronger stellar feedback in interacting systems and weaker feedback in more isolated systems). Variations in feedback efficiencies might well affect the overall metallicity distributions of DLA systems particularly in the tails at high and low metallicities. However, although it would be possible to construct an ad-hoc model with variable feedback efficiencies, developing a physically motivated model is beyond the scope of this paper.

3.3 Selection biases and dust

The model predictions of the previous sub-section were computed assuming that the effects of dust and other observational biases are negligible. Boissé et al. (1998) report an anti-correlation between the observed Zn abundance and \(N_{\text{HI}}\), independent of redshift. This result has been confirmed...
by Prantzos & Boissier (2000) who note that all observed DLAs are found between $18.8 < \frac{\text{Zn}}{\text{HI}} + \log(N_{\text{HI}}) < 21$ in the $\frac{\text{Zn}}{\text{HI}} - N_{\text{HI}}$ plane. The lower limit in this relation may arise because low column density and low-metallicity systems are not detectable through their absorption lines in current surveys. There are several possible explanations for the lack of DLAs with high column density and high-metallicity: a) The light of the background quasars may be severely extinguished by dust; b) the cross-section for high $N_{\text{HI}}$ absorption may decrease with increasing metallicity as gas is consumed by star formation; c) systems with $\log(N_{\text{HI}}) > 21$ may be intrinsically rare (Schaye 2001).

The left-hand panel of Fig. 4 shows our default $\rho_s = 0.1$ model predictions in the $\frac{\text{Zn}}{\text{HI}} - N_{\text{HI}}$ plane. The straight lines show the Prantzos & Boissier (2000) bias thresholds. The fraction of the models that lie above the upper cutoff (and therefore may be biased by dust obscuration) is always low except for the higher redshifts where its contribution is of order $7\% - 8\%$ at $z = 4 - 5$. However we find that a significant fraction of our models lie below the lower threshold (typically 10-20%). It is therefore clear that removing points below the lower line will have a significant effect on metallicity distributions, whereas removing points above the upper line will have little effect. We have also overlapped the observational data on this diagram. At redshifts $z < 1$ the observations match our models reasonably well but at $z > 2$ the models fail to match the observational points with $\log N_{\text{HI}} < 20.5$ and metallicities $\left[\frac{\text{Zn}}{\text{HI}}\right] > -1$. In the bin centered on $z = 4$ there is almost no overlap between the observations and our NFB model, though at high redshift all but one of the quasar selected metallicity observations are upper limits. We have also plotted the recent metallicity determination for a DLA system at $z = 4.048$ detected against the optical after-glow of the gamma-ray burst GRB060206 (Fynbo et al. 2006). This lies much closer to the model predictions.

Recently there has been considerable interest in sub-damped Lyman-α systems (see e.g. Ledoux et al. 2003; Dessauges-Zavadsky et al. 2004) with column densities of $10^{13} \text{cm}^{-2} < N_{\text{HI}} < 2 \times 10^{18} \text{cm}^{-2}$, i.e. below the classical definition of DLAs. The analysis by Péroux et al. 2003 found that the sub-DLAs contribute about 20% to the total neutral gas mass density at redshifts $2 < z < 5$. Furthermore, Péroux et al. 2006 recently discovered a sub-DLA with super-solar metallicity at $z = 0.716$ indicating that sub-DLAs might be more metal-rich than classical DLAs. We do not consider sub-DLAs in the present analysis. However, we note that a large number of sub-DLAs with low-column densities and high metallicities cannot be explained within the framework of our model as discussed below.

Our model cannot produce large numbers of low column density systems at high redshift with high metallicity. As can be seen from Fig. 4 the model tends to produce flat $N_{\text{HI}}$ distributions of high column density with a sharp cutoff. Clearly, the sharpness of the cut-offs are an idealization and a consequence of applying a simplistic model of self-regulated star formation based on the stability criterion of equation 14. In reality, there are many physical process that will tend to ‘smear’ the cut-offs. These include tidal disruption and realistic deviations from axial symmetry both during collapse, and from disc instabilities. In this context, it is worth noting that the highest column densities within the Magellanic Stream are only just below the DLA column density threshold (Putman et al. 2003, suggesting that tidal debris may contribute to the DLA cross section). Additional effects, not incorporated in our model, that might increase the spread in column densities at high metallicities include bursts of star formation (triggered by, say, an interaction) that can consume much of the gaseous disc, or ram pressure stripping of disc gas. We note that the numerical simulations of Nagamine et al. (2004b) produce a wide spread of column densities extending down to the DLA threshold. However, they find a strong correlation between metallicity and column density and (as in our models) cannot account for the low metallicity, high column density, systems observed at high redshift. Understanding the column density distributions plotted in Fig. 4 in greater detail poses an interesting challenge for both theory and observations.

Our simplified model for the age distribution of disc galaxies can affect some aspects of our model at high redshift. This is discussed in greater detail in Section 4, but to illustrate the effects on the column density distributions we plot in Fig. 5 the evolution of a model with coeval evolution and a formation redshift set to infinity (model NFBc) in addition to our standard models using the Lacey & Cole (1993) (hereafter LC93) age distributions. In the coeval model, discs have more time to evolve, especially at high redshifts as discussed in Section 4. The additional evolution time shifts the $N_{\text{HI}}$ distributions towards lower column densities, (and the gas metallicities to slightly lower values) but not by enough to match the observations at $z \sim 3$.

In Fig. 6 we plot the metallicity evolution with redshift for the DLAs in our models that lie within the diagonal lines plotted in Fig. 4, i.e. the relations that according to Prantzos & Boissier (2000) roughly delineate regions in the diagram that might be affected by observational selection biases. Including the lower limit, $18.8 < \frac{\text{Zn}}{\text{HI}} + \log(N_{\text{HI}})$, makes quite a large difference because it eliminates most of the systems with metallicities less than $[\text{M/H}] = -2$. After this bias-correction almost all of the observations at low metallicity lie within the 99% contour predicted by our model. It may therefore be necessary to understand a bias of this type in more detail to interpret the Zn abundances at very low metallicities. This type of bias will be less important in direct observations of Fe, which is more abundant than Zn. Indeed as we have mentioned previously Prochaska et al. 2003 find abundances as low as $[\text{M/H}] \sim -3$ using Fe and o elements.

The bias-correction at high column densities removes some DLA systems in our models with high metallicity, which makes it even more difficult to explain the observed high metallicity systems at $z \sim 2$. Fitting a linear evolution model to the ‘bias-corrected’ model predictions of Fig. 6 results in $m = -0.03 \text{dex}/\Delta z$ with $[\text{M/H}]_0 = -0.79 \text{dex}$, i.e. virtually identical to fitting the uncorrected results shown in Fig. 4.

If we only impose the upper cut, $\frac{\text{Zn}}{\text{HI}} + \log(N_{\text{HI}}) > 21$, the fit to the metallicity evolution gives $m = -0.03 \text{dex}/\Delta z$ with $[\text{M/H}]_0 = -0.84 \text{dex}$. In this case our model predicts a slightly lower metallicity of $\sim 0.1 \text{dex}$ compared to the uncorrected results of Fig. 4. According to our model only a small number of systems are expected to lie above the line defined by the line $\frac{\text{Zn}}{\text{HI}} + \log(N_{\text{HI}}) > 21$, and re-
moving the ones that do lie above this line has very little effect on the overall metallicity distribution. Dust obscuration in high metallicity, high column density systems, is therefore unlikely to lead to significant biases in the DLA metallicity distributions according to our model, since such systems are rare. This is consistent with the results of Akerman et al. (2003), who find only a marginally higher metallicity of 0.2 dex for their unobscured (radio-selected quasar) CORALS DLA sample compared to a control sample from Kulkarni et al. (2003).

4 GLOBAL PROPERTIES OF DLAS

In this Section we compute various global properties of the DLA population. Many of the properties discussed in this Section are sensitive to the merger history of the absorbers, and hence to the age of the model galaxy that determines its cross-section and mass. As explained in Section 2.2, we have employed a simplified description based on the LC93 model for the age distributions of dark matter haloes as a function of their virial velocity. The high density baryonic systems within these haloes will be longer lived than the haloes themselves and will follow a more complex merger history. The metallicity distributions described in the previous Section are insensitive to models of the merger history because the metallicity of the gas is not a strong function of age. Likewise, the gas metallicity gradients in our models are shallow and so the metallicity distributions are insensitive to any process, such as tidal stripping, that might truncate the gaseous discs. The metallicity distributions discussed in the previous Section are therefore robust and are largely a consequence of the model for feedback and self-regulated star formation.

The cross-sections, on the other hand, are extremely sensitive to the age distribution and hence to the merger history. Although it is possible, in principle, to construct a more elaborate analytic merger model for the baryonic components (see e.g. Penarrubia and Benson 2005) the physics involved is complex and difficult to model accurately. To illustrate the sensitivity of various results to the merger history, in addition to our standard models using the LC93 age distributions, we have therefore calculated the evolution of a model with coeval evolution and a formation redshift set to infinity (model NFBc). The NFB and NFBc models provide two extreme representations of the merger history of early disc systems that should bracket the predictions of a more realistic model. The differences between the two representations is particularly important at high redshift. At $z = 5$ the age of the coeval population is 1.2 Gyr compared to the LC93 model which predicts ages for the models of only 0.3 Gyr. This difference of a factor of four leads to large differences in the calculation of cross-sections, redshift number densities and $\Omega_H$.

To summarize, our model provides robust predictions for the metallicity evolution of DLAs. Properties that are sensitive to the disc age distributions and cross-sections, particularly the rates-of-incidence (see equation 10) and (to a lesser extent) $\Omega_H$ are less reliably predicted by our model, especially at high redshifts. Many of the results presented in this Section are therefore meant to be indicative at the ‘order-of-magnitude’ level, rather than detailed fits to the observations. To make accurate predictions of such properties, it is likely that high resolution numerical simulations that properly model the formation, evolution and merger history of dwarf galaxies will be required (cf. Nagamine et al. 2004a).

4.1 Abundance of DLAs as a function of column density and redshift

Following Nagamine et al. (2004a) (see also Wolfe et al. 2003 and references therein) we can compute the total DLA rate-of-incidence from

$$\frac{dN_{DLA}}{dz} = \frac{dr}{dz} \int_{M_{min}}^{\infty} n_{dim}(M', z) \sigma_{DLA}(M', z) dM', \quad (10)$$

where $n_{dim}(M', z)$ is the Sheth & Tormen (1999) (comoving) dark matter halo mass function, $\sigma_{DLA}(M', z)$ is the comoving DLA cross-section and $dr/dz = c/H(z)$, with $H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_k}$.

The results for our models are plotted in the left panel of Fig. 8 together with observations from Prochaska & Herbert-Fort (2004) and Zwaan et al. (2005a, 2005b).

We discuss first the results for our standard models based on the LC93 age distributions. The strength of feedback has almost no effect on the rate-of-incidence, but the overall shape is very different from the observations. At redshifts below two the models match the observations reasonably well (within a factor of two) but at higher redshifts, the models significantly underproduce $dN_{DLA}/dz$ by a factor of five. The main reason for the underproduction of $dN_{DLA}/dz$ at high redshifts is that the prescription of LC93 leads to galaxies of very young ages (and therefore small cross-sections) at high redshifts. Assuming coeval evolution as described above (model NFBc) produces $dN_{DLA}/dz$ which is higher by a factor of five at high redshifts, roughly matching the observational data at $z \gtrsim 4$. However, the coevalution model significantly overpredicts $dN_{DLA}/dz$ at lower redshifts.

As we have argued above, the true age range of the galaxy distribution is likely to lie somewhere between the LC93 and coeval distributions and so Fig. 8 suggests that it may be possible to account for the observed rate-of-incidence with a model of the type described here incorporating a more realistic merger history. The numerical simulations of Nagamine et al. (2004a) actually reproduce the observed $dN_{DLA}/dz$ quite well and in fact their comoving tabulated cross-sections as a function of $v_{vir}$ lie in between the cross-sections of our NFB and NFBc models. It would be interesting to make a more detailed comparison of our models with age distributions and cross-sections from numerical simulations to determine the key physics required to reproduce the observed rate-of-incidence.

The right-hand panel of Fig. 8 shows the differential distribution of $f(N_{HI}, X(z)) = d^2N/dN_{HI}dX$ predicted by our models. This quantity gives the number of DLAs per unit column density $N_{HI}$ and per unit absorption distance (Bahcall & Peebles 1969). The data points plotted on the right-hand panel of Fig. 8 are from Storrie-Lombardi & Wolfe (2001), adjusted for our $\Lambda$CDM cosmology. The model results are calculated by averaging $f(N_{HI})$ over the redshifts $0 \lesssim z \lesssim 5$ and all three models...
fit the observational data reasonably well at high column densities but underproduce systems at the low column density end by a factor of two. The three models differ only at the highest column densities, where the weak feedback model produces slightly more high column density systems compared to the normal and strong feedback models. On the other hand, the coeval evolution model fits the observational data nicely with the exception of the highest column density point. Again, as with the rate-of-incidence analysis, the two extreme merger models roughly bracket the observational data.

4.2 DLA halo properties

In the two next sub-sections we discuss the properties of typical DLA haloes and of the galaxies that lie at their centres. Unless otherwise stated, we show results for NFB model using the LC93 halo age distributions.

The evolution of the average virial velocity of the DLA haloes, together with the 50% (quartile, black lines) and 95% (red lines) ranges, are shown in Fig. 9a. We find a gradual but mild increase of the average velocity from $\bar{v}_{\text{vir}} \approx 60 \text{ km s}^{-1}$ to $\bar{v}_{\text{vir}} \approx 75 \text{ km s}^{-1}$ with a large scatter. The contribution of systems with $v_{\text{vir}} \gtrsim 100 \text{ km s}^{-1}$ to the DLA cross-section increases from 14% at $z = 5$ to 22% by $z = 0$. The contribution of even higher virial velocities of $v_{\text{vir}} \gtrsim 200 \text{ km s}^{-1}$ (i.e. haloes hosting large Milky-Way type galaxies) remains low at less than 2% at all redshifts. Our results agree well with those from the semi-analytic models of Okoshi et al. (2004), especially at high redshift. At lower redshift, the typical virial velocities are somewhat lower than theirs. However our results for $z \approx 0$ are in better agreement with Zwaan et al. (2005b) who infer a mean virial velocity for the local DLA population of $\bar{v}_{\text{vir}} \approx 70 \text{ km s}^{-1}$.

In Fig. 8 we show the corresponding evolution in the median mass (within the virial radius) of the dark matter haloes containing DLAs. We find that the median mass increases from $M_{\text{DM}} \sim 5 \times 10^8 M_\odot$ at $z = 4 - 5$ to a few times $10^{10} M_\odot$ at $z = 0.5 - 3.5$ with an upturn to $M_{\text{DM}} \sim 10^{11} M_\odot$ at $z = 0$. Our halo masses are somewhat lower than those inferred by Bouché et al. (2001) in an observational study of MgII absorbers in the redshift range $0.4 \lesssim z \lesssim 0.8$. Their results imply that the hosts of MgII absorbers (typically 40% of MgII absorbers are DLAs) have halo masses of $\sim 2 - 8 \times 10^{11} M_\odot$, perhaps suggesting that MgII selection biases samples towards higher virial velocities than the average. The abrupt increase at $z \lesssim 0.25$ is caused by the exhaustion of gas in low mass haloes which placing them below the DLA selection criterion of $N_{\text{HI}} \gtrsim 2 \times 10^{20} \text{ cm}^{-2}$.

We conclude that the DLA cross-section is dominated at all redshifts by systems residing in small mass (low virial velocity) haloes with a mild evolution towards systems with higher mass at low redshift. This is in agreement with recent semianalytic (Okoshi et al. 2004) and numerical investigations (Cen et al. 2003) but in strong disagreement with the classical picture in which the majority of DLAs at all redshifts are massive disc galaxies like our own (Wolfe et al. 1986).

The spin parameter $\lambda$ of the DLA haloes as a function of redshift is shown in Fig. 9b. As DLAs are selected by cross-section, one would expect DLAs to be biased towards bigger discs with larger $\lambda$ in comparison to the general galaxy population. This is seen in our models. The DLA cross-section is dominated by systems in haloes with large $\lambda$, especially at high redshift where high $\lambda$ systems rapidly build up large gaseous discs. Systems with small $\lambda$ also experience more extensive mass loss caused by the feedback from supernovae (see Fig. 2). At lower redshifts the mean cross-section weighted $\lambda$ decreases. This is explained by the slower buildup of gaseous discs in lower $\lambda$ systems. In sum-

Figure 8. The DLA rate-of-incidence $dN_{\text{DLA}}(z)/dz$ (left-hand panel) for the three feedback models and the coeval evolution model is plotted with data from Prochaska & Herbert-Ford (2004) (solid circles at $z > 2$), Rao et al. (2006) (solid squares at $z \approx 1$) and the open square at $z = 0$ from Zwaan et al. (2005b). In the right panel the DLA column density distribution $f(N_{\text{HI}})$ is shown for the four models overplotted with observational data (solid symbols) from Storrie-Lombardi & Wolfe (2006). The model results are averaged over $0 \lesssim z \lesssim 5$. 

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Figure 9. The evolution of the mean $v_{\text{vir}}$ and $\lambda$ with 50% (quartile, black lines) and 95% (red lines) ranges (top-panel). Evolution of the median DLA halo mass and comoving halo density with 50% (quartile, black lines) and 95% (red lines) ranges (bottom-panel). For points where only one low/high error bar is shown the 50% and 95% ranges are the same, which is a result of the limited number of bins in our model (17 in $v_{\text{vir}}$, $M_{\text{DM}}$ and $n_{\text{DLA}}$; 7 in $\lambda$, see Section 2.2 for details). All plots are for the normal feedback model ($\phi_\kappa = 0$).

4.3 DLA galaxy properties

Fig. 10 shows the evolution of various properties of the DLA galaxy population. The DLA median hydrogen gas mass evolves by a factor of ten from $M_{\text{HI}} = 10^8 M_\odot$ at $z = 5$ to $M_{\text{HI}} = 2 \times 10^9 M_\odot$ at $z = 0$. Our model prediction at $z = 0$ is in excellent agreement with Zwaan et al. (2005b). The evolution of $M_{\text{HI}}$ is associated with an increase in the median stellar mass from $M_* \sim 6 \times 10^7 M_\odot$ at $z = 5$ to $M_* \sim 10^9 M_\odot$ by $z = 0$. According to our model, the DLA cross-section is dominated by 'dwarf' (low-mass) galaxies with large HI discs at all redshifts and especially at higher redshifts. However, the width of the distribution (indicated in the figure) increases at lower redshifts because higher mass systems make a growing contribution to the DLA cross-section. The contribution of Milky Way-type systems, with total disc masses of $M \geq 5 \times 10^{10} M_\odot$, to the cross-section is completely negligible at high redshifts, growing to only 0.5% at $z = 2$. At
lower redshifts this fraction grows to 2% at $z = 1$ with an increase to 6% by the present epoch. These results agree well with the semi-analytic models of Okoshi et al. (2004), who found a $\sim 5\% - 10\%$ contribution of Milky Way type systems at low redshift with negligible contribution to the cross-section at $z \gtrsim 3$. According to our model, the majority of the DLA population must consist of ‘dwarf’ galaxies with typical masses of $\lesssim 0.1 M_\odot$. This result is also consistent with the lack of direct detections (see e.g. Wolfe et al. 2005).

Figure 10c shows the evolution of the median impact parameter (in physical units) as a function of redshift. We find a very strong, almost linear evolution in this parameter, from very small values of $\sim 1$ kpc at $z = 5$ to values of $\sim 7$ kpc at the present epoch. The local value again agrees well with the observational results of Zwaan et al. (2005) who find a median value for the local impact parameter of 7.8 kpc. The small impact parameters in combination with the relatively low number densities of the DLA haloes at high redshifts results in the low rate-of-incidence at high $z$ discussed in Section 4.1 (Fig. 10b).

4.4 Star formation of DLAs

The typical star formation rates of DLAs according to our model are shown in Fig. 10d. We find that the DLAs have a very broad distribution of star formation rates, ranging from $\sim 5 \times 10^{-3}$ up to $\sim 50 M_\odot yr^{-1}$ at all redshifts. The evolution of the median star formation rate is virtually constant with a median star formation rate of $\dot{M}_* \sim 0.1 - 0.2 M_\odot yr^{-1}$ over the entire redshift range $z = 0 - 5$. The mean star formation rate is considerably higher at $\dot{M}_* \sim 1 - 2 M_\odot yr^{-1}$. The distribution of star formation rates has a long tail extending to high values for sightlines probing the central regions of massive galaxies (see the 95\% ranges in Fig. 10d).

However, we find strong evolution in the star formation rates per unit area, with the median evolving from $\Sigma_* \sim 1.5 - 3.0 \times 10^{-2} M_\odot yr^{-1} kpc^{-2}$ at $z = 4 - 5$ to...
Figure 11. The top left panel (a) shows the evolution of global volume weighted cosmic star density. Panel (b) shows the evolution of the global volume weighted star formation density. The lower panels (c) and (d) show the same quantities but weighted by cross-section (above the DLA threshold). In each case we plot results for the three feedback models using the LC93 age distributions and for the coeval evolution model with the normal feedback model. The shaded regions in the figures show the volume averaged stellar densities and star formation rates from Hopkins (2004) and Hopkins, Rao & Turnshek (2005) that encompass the majority of the observational points on the ‘Madau’-diagram after correction for dust obscuration. The points plotted in panel (d) show the star formation rates inferred by Hopkins, Rao & Turnshek (2005) for DLA systems (see text for details).

$\dot{\Sigma}_* \sim 10^{-3} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ at $z < 2$. In our model, galaxies at high redshift are experiencing bursty star formation (with high star formation rates per unit area) followed by more quiescent star formation evolution at late times, when the gas infall rate is regulated by the Hubble time rather than the free-fall time (see E00 for details). The median values of $\dot{\Sigma}_* \sim 10^{-3} - 10^{-2} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ are in good agreement with the semi-analytic model of Okoshi et al. (2005) and with the numerical simulations of Nagamine et al. (2004).

The evolution of the cosmological stellar density and star formation rates are shown in Fig. 11. We show results for the three feedback models for the LC93 merger history, and for a model with coeval evolution. It is important to note that the volume averaged stellar density and star formation rates shown in this figure are weighted strongly towards the inner regions of massive disc systems, which make little contribution to the DLA cross-sections. As we will show below, these global volume averaged properties are largely disconnected from the properties of the DLA population. It is also worth noting that, unlike more elaborate semi-analytic models (Croton et al. 2006; Bower et al. 2006), our model has not been fine-tuned to match these global properties. Nevertheless, it performs surprisingly well given its simplicity.

All models show high star formation rates at high redshift arising from the initial ‘bursty’ phase of star formation model, followed by a gentle decline in the comoving star formation density. The differences between the feedback models are larger at higher redshifts, where the weaker feedback in the WFB model results in high star formation rates. At lower redshifts ($z \lesssim 2$) all three feedback models produce
star formation rates which are within a factor of two of each other. The global volume averaged star formation rates are quite sensitive to the assumed age distributions, especially at high redshift.

Fig. 11b show the evolution of the volume averaged star formation rates in our models. The shaded regions in Figs 11a and 11b shows the range of observational estimates from the papers of Hopkins (2004) and Hopkins, Rao & Turnshek (2005), including corrections for dust obscuration. Figs 11a and 11b give an impression of the uncertainties in both the model predictions and the observations. The models broadly match the extinction corrected star formation rates, though it is clear that a more accurate treatment of the merger history is required to produce reliable predictions.

The main point of this comparison is illustrated in Figs. 11a and 11b. These show the evolution of the cosmic stellar density and star formation rate but now weighted by cross-section above the DLA threshold, rather than volume averaged over all systems. According to our model, DLA systems account for a small fraction of the total star formation at all redshifts. This is broadly consistent with the results of Hopkins, Rao & Turnshek (2005), who infer the contribution of DLAs to Ω∗ and dρ∗/dt by integrating over the observed DLA column-density distribution assuming a Kennicutt (1998) relation between the star formation rate and the gas surface density. (The Hopkins, Rao & Turnshek (2005) results are shown by the points in Fig. 11d). Most of the star formation occurs in the inner parts of galaxies, whereas the DLA are sampling the outer gaseous discs where there is relatively little star formation. This, of course, is why the metallicity distributions are skewed to low metallicities at all redshifts. One should therefore be extremely cautious in interpreting models of cosmic chemical evolution that link the volume averaged star formation rates to the metallicity evolution of DLA selected systems (Wolfe and Prochaska 1998; Pei et al. 1999; Wolfe et al. 2005). As our models show, these quantities are linked only indirectly and are very likely probing star formation in very different environments.

4.5 Cosmological evolution of ΩHI

From our models we can calculate the cosmological evolution of neutral hydrogen. This is an important consistency check of the models, since unlike the stellar density, most of the volume averaged density in neutral hydrogen in our models is contained in DLA systems. Fig. 12 shows observational results from Zwaan et al. (2005a), Rao et al. (2006), Prochaska & Herbert-Ford (2004) spanning the entire redshift range 0 ≤ z ≤ 5. The observations show little evidence for any evolution in ΩHI over the redshift range 1 ≤ z ≤ 5.

Our model predictions are also shown after correcting for a hydrogen fraction of XH = 0.7. No correction has been made for the fraction of hydrogen in molecular form. The results are relatively insensitive to the strength of feedback, but are quite sensitive to the assumed age distributions. The models with the LC93 age distributions underpredict ΩHI at z ≥ 2, whereas the coeval model agrees quite well with the observations over the redshift range 1 ≤ z ≤ 5. As with
several other properties discussed in this Section, the coeval
models with those with the LC93 age distribution roughly
brace the observations. All of the models are high (by a
factor of $\sim 3$) compared to the observed HI density at $z = 0$
(determined from 21 cm observations of Zwaan et al. 2005a).
We do not regard this discrepancy as particularly serious,
since it can be explained if some of the gas in the extended
outer parts of small disc systems is stripped and returned to
the intracluster or intra-group medium as structure grows.

Most of the neutral hydrogen density in our models is in
the outer parts of dwarf galaxies and plays little role in the
volume averaged star formation history of the Universe. The
evolution of $\Omega_{\text{HI}}$ at high redshift is therefore more closely
linked to feedback processes and the spatial distribution of
gas in the outer parts of dwarf galaxies than it is to the cos-
omic star formation history. Our models show that the low
metallicities, characteristic of DLAs, and the lack of evo-
lution of $\Omega_{\text{HI}}$ are consistent with a picture in which the
DLA sight-lines are preferentially sampling the outer parts
of dwarf galaxies.

5 CONCLUSIONS

In this paper we have used a model of self-regulated
star formation and a physically motivated model of stellar
feedback to construct a simple model of damped Lyman-$\alpha$
systems.

Our models reproduce the low mean metallicities seen
in DLAs, the lack of evolution of the mean metallicity and
can account, at least qualitatively, for the observed spread
in metallicities at each redshift. In our model, most DLA
sight-lines probe the outer gaseous parts of `dwarf' galaxies ($v_{\text{esc}} \lesssim 70 \text{ km s}^{-1}$), where the star formation rates and metal
enrichment are always low. Occasionally, sight-lines intersect
the inner regions of disc systems where the gas metallici-
ties are high. Thus geometry is primarily responsible for the
large spread in metallicities seen in the observations. The
metallicity distributions in our models are relatively insen-
itive to the strength of the stellar feedback assumed and
to the assumed merger histories of the galaxies (parameter-
ised by their age distributions). We therefore believe that
the DLA metallicities are a robust feature of our model.
The metallicities predicted by our model are lower, and in
much better agreement with observations, than those found
in numerical simulations (Cen et al. 2003; Nagamine et al.
2004). Differences in the models for stellar feedback and
star formation are the most plausible reasons for this.

In many respects, our conclusions are similar to those
of previous semi-analytic models (Oishi et al. 2004) and
numerical simulations (Cen et al. 2003; Nagamine et al.
2004). However, our model differs from previous semi-
analytic calculations in that the infall model, star formation
prescription and feedback model, all key factors in deter-
mining the metallicities and spatial distributions of gas and
stars, are all physically motivated. The model has, therefore,
few adjustable parameters. Indeed, the model was developed
specifically to investigate the role of stellar feedback during
galaxy formation (E09), yet with no further modification
provides a reasonable description of the properties of DLA
systems.

Nevertheless, it is clear that the physics behind the DLA
population is complex, and it is important to understand
both the strengths and weaknesses of a simple semi-analytic
model of the type described here. Although the metallicity
predictions are robust, the sizes of the gas discs in our model,
particularly at high redshifts, are sensitive to the assumed
age distributions. These distributions, in turn, depend on
the merger history of the gaseous discs. To illustrate the
sensitivity of our results to the age distributions, we have
used two simple models, one based on the age distributions
of the dark haloes (using the prescription of LC93) and the
other based on the assumption that all systems formed at
$t = 0$ (the coeval model). The actual age distribution for
the baryonic components is likely to lie between these two
extremes.

The rates-of-incidence (Figure 8) are particularly sensi-
tive to the total gas cross-section, and hence to the model of
the age distribution. Our model cannot predict this quanti-
ity reliably. Nevertheless, the two models for the age distri-
butions roughly bracket the observations over the redshift
range $1.5 \lesssim z \lesssim 5$, suggesting that a more realistic merger
model may be able to account for the data over this redshift
range. In fact, the numerical simulations of Nagamine et al.
(2004) reproduce the observed rates-of-incidence quite well,
and (not surprisingly) their cross-sections are intermedi-
ate between those of our two age-distribution models. (The
physical mechanisms governing the cross-sections in the nu-
merical simulations are not clear, however.) At lower red-
shift, both age-distribution models overpredict the rates-
of-incidence, suggesting that we are missing some physical
mechanism that can limit the growth of extended gaseous
discs at low redshift. The cosmic density in neutral hydro-
gen is also dependent, but to a much lesser degree, on the
assumed age distributions. As with the rates-of-incidence,
the two models for the age distribution roughly bracket the
observations, except at $z = 0$, where our models overpredict
the local HI density by a factor of $\sim 1.5$–2.5.

The relation between the metallicities and column den-
sities is not well reproduced by our models, particularly at
redshifts $z \gtrsim 2$. In our models, the gaseous discs at any time
have roughly constant surface density and truncate abruptly
(with an outer radius fixed by the angular momentum of in-
falling gas). As a result, our models fail to reproduce the
spread to low column densities seen in the observations
(though only by a factor of two or so) . The abrupt trunca-
tion is clearly an artificial feature of our models and it is easy
to think of a number of physical mechanisms (discussed in
Section 3.2) that would lead to lower column densities in the
outer parts of galaxies, without altering the metallicity of the
gas. The numerical simulations of Nagamine et al. (2004)
do show a large range of column densities, extending below
the DLA threshold. The observed high proportion of low
metallicity, high column density density ($N_{\text{HI}} > 10^{21}$ cm$^{-2}$)
systems at $z \gtrsim 2$ is more problematic, both for our model
and the numerical simulations. The resolution of this dis-
crepancy is not at all clear.

Our models can roughly reproduce the observed volume
averaged stellar density, HI density and star formation rate
as a function of redshift (though the models were not finely
tuned to do so). The cosmic density in HI is dominated
by gas in DLA systems. However, the stellar density and
star formation rates weighted by cross-section are consider-
ably lower than their cosmic values over the entire redshift

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range $0 \lesssim z \lesssim 5$. In our models, the galaxies responsible for DLAs make only a small contribution to the total stellar density produced in the Universe. This conclusion is broadly in line with the results of Hopkins, Rao & Turnshek (2005), who used a Kennicutt (1998) relation to infer the contribution of DLA systems to the volume averaged star formation rate. According to our model, there is only a indirect relation between the volume averaged star formation rate, $\Omega_M$ and DLA metallicities. Thus one should be skeptical of models of ‘cosmic’ chemical evolution that attempt to relate these quantities (e.g. Wolfe and Prochaska (1998); Pei et al. (1993); Wolfe et al. (2003)).

As we have mentioned in the Introduction, one of the main purposes of a semi-analytic model is to gain physical insight into complex problems. Ultimately, given high enough spatial resolution, it should be possible to develop realistic numerical hydrodynamical models of DLAs. In the meantime, we pose the following problems for numerical simulators:

(i) In our model, the sizes (and hence cross-sections) of the DLA systems are set by the high angular momentum gas within the dark haloes, assuming angular momentum is strictly conserved. (The low angular momentum gas is preferentially expelled in a wind). Is this really true?

(ii) We have found that some properties of the DLA population are sensitive to the age distribution and hence the merger history of the baryonic systems within dark haloes. What is the actual merger history of these baryonic systems? To what extent does this merger history affect the properties of DLAs?

(iii) How sensitive are the metallicities of DLAs to star formation and stellar feedback? Is it possible to incorporate more realistic models of these processes in numerical simulations? Is it possible to resolve the discrepancies between observations and simulations performed so far (Cen et al. 2003; Nagamine et al. 2004)?

(iv) Is it possible to reproduce the observed proportion of low metallicity systems with high column density, that neither our model or the numerical simulations seem able to explain?

(v) Clearly a theoretical model in which dark haloes are populated by single circular, homogeneous, gaseous discs is a gross over-simplification. To what extent are tidal features and other irregularities important in understanding the DLA population? How important are inhomogeneities, such as individual star forming regions, in explaining the high end of the metallicity distribution?

(vi) Our model is too simplified to model the velocity structure seen in metal-line-systems associated with DLAs. Can this structure be reproduced by detailed hydrodynamical simulations, as suggested by the work by Haehnelt et al. (1998)?

(vii) In our model, the DLAs make a sub-dominant contribution to the cosmic star formation rate at all redshifts. Is this really true?

No doubt the reader can think of many other problems. Despite the compelling case for further work, we do believe that the simple model presented here gives a plausible explanation for the observed metallicities of DLAs, and that these metallicities can only be understood if the DLAs are predominantly ‘dwarf’-like systems that contribute little to the net cosmic stellar density. The ‘classical’ picture of DLAs as giant spiral discs slowly converting their gas into stars seems to us to be irreconcilable with the observations. Furthermore, we now know enough about the primordial cosmological fluctuations, from Mpc scales to the scale of the Hubble radius (Spergel et al. 2003) that it is difficult to imagine a cosmogenic context for the classical picture.

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