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Damped Lyα absorbers from dwarf galaxy ejecta

P. E. J. Nulsen,[1,2] X. Barcons[1,3] and A. C. Fabian[1]

[1] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2] *Department of Physics, University of Wollongong, Wollongong NSW 2522, Australia*
[3] *Instituto de Física de Cantabria (Consejo Superior de Investigaciones Científicas - Universidad de Cantabria), 39005 Santander, Spain*

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ABSTRACT

It is argued that the formation of a dwarf galaxy causes a massive burst of star formation, resulting in the ejection of most of the available gas from the galaxy as a weakly collimated wind. The ejected gas can give rise to a damped Lyα absorber (DLA). Weakly collimated outflows naturally explain the asymmetric profiles seen in low-ionization absorption lines caused by heavy elements associated with DLAs, where absorption is strongest at one edge of the absorption feature. The shape of the distribution of column densities in the model agrees reasonably well with observations. In particular, the break in slope is caused by external photoionization of the wind. A semi-analytical model for galaxy formation is used to show that, for currently acceptable cosmological parameters, dwarf galaxy outflows can account for the majority of DLA systems and their distribution with redshift. This model also predicts a correlation between velocity structure and metallicity of DLA systems, in qualitative agreement with observations. DLAs do not require many large, rapidly rotating disc galaxies to have formed early on, as in other models for their origin.

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

1 INTRODUCTION

High-redshift damped Lyα absorption systems (DLAs) in quasar spectra are generally thought to be associated with young galaxies or protogalaxies. One proposal is that they arise in young spiral galaxies (Wolfe 1988). In this model, disc rotation accounts for asymmetry of the observed heavy-element line profiles (Prochaska & Wolfe 1996, 1997), provided that the gas discs of the young, rapidly rotating spiral galaxies are substantially thicker than those of current-day spiral galaxies (requiring scaleheights ~0.3 times the radius of the disc). A problem of these models is that they require large spiral galaxies with rapidly rotating discs to form earlier than expected for a standard cold dark matter (CDM) fluctuation spectrum (e.g. Kauffmann 1996).

Haehnelt, Steinmetz & Rauch (1996) propose that gas structure resulting from growth of primordial density fluctuations accounts for DLAs and Rauch, Haehnelt & Steinmetz (1997) have shown that such a model can account for the velocity profiles and widths of the absorption lines. In this model, protogalactic clumps of gas in the process of merging to form large galaxies give rise to DLAs. Rotation, random motions, infall and, mainly, merging are responsible for the asymmetric line profiles.

In this paper we propose that the bulk of the absorbing gas in high-redshift DLAs arises in outflows from dwarf protogalaxies. We argue that a massive burst of star formation is likely to drive the bulk of the gas from newly formed dwarf galaxies in a weakly collimated wind, where it presents a substantial cross-section for lines of sight to quasars. We show that such a model can account for the numbers of absorption systems, asymmetric line profiles, the distributions of column density and velocity structure widths, and the observed correlation between velocity structure and metallicity, all in a standard open CDM model.

We outline our model for the process of dwarf galaxy formation in Section 2. Section 3 describes the simple model we use for dwarf outflows. Section 4 presents the details of the galaxy formation model used to compute the number density of DLAs in this scenario. Section 5 deals with the ionization state of the gas and the distribution of column densities, and Section 6 discusses the main features of the model and its possible observational tests.

2 DWARF GALAXY FORMATION

Semi-analytical models for galaxy formation (e.g. White & Frenk 1991; Kauffmann, White & Guiderdoni 1993; Cole et al. 1994; Baugh, Cole & Frenk 1996), which combine statistical simulations of the collapse hierarchy (merger trees) with heuristic models for the outcomes of individual collapses, have had some success in accounting for the general properties of galaxies, but still fail in several important respects (e.g. the spin of galaxy discs, Navarro, Frenk & White 1995). Considering our poor understanding of the physical mechanisms that govern the rate of star formation and the initial mass function, this is not surprising. It leaves the way open for substantial modifications to these models.

One constraint on models for galaxy formation is that they must account for the relatively high gas fractions in clusters of galaxies, where the mass of gas is substantially greater than the total mass of visible stars (e.g. White et al. 1993; White & Fabian 1995; White, Jones & Forman 1997). It seems unlikely that the gas fraction in clusters of galaxies exceeds the primordial baryon fraction, so that the earliest protogalaxies would have had a similar or larger gas fraction. This means that a 10^{10}-M$_\odot$ dwarf protogalaxy would have contained more than 10^9 M$_\odot$ of cold gas immediately after it collapsed. If most of this gas were to form quickly into stars, little gas would be left to make up the intergalactic medium. Heating by background ultraviolet radiation can prevent star formation in low-mass systems (Couchman & Rees 1986), but not in systems larger than about 10^8 M$_\odot$.

White & Frenk (1991) find that this is resolved by the effect of supernovae. They argue that, since the lifetime of a massive star is much shorter than the time-scale for star formation, feedback in the form of Type II supernovae regulates the rate of star formation locally. As a result, only a small fraction of the gas is consumed by star formation in small protogalaxies, with the bulk of it preserved until later stages of the hierarchical collapse. Most semi-analytical models follow their lead (e.g. Eke, Cole & Frenk 1996).

However, Nulsen & Fabian (1995, 1997) pointed out that the speed of propagation of the feedback also matters. With no feedback, the gas could be turned into stars in about one dynamical time. Thus, to regulate the rate of star formation the feedback must propagate throughout the cold gas in less than approximately one dynamical time. Unless the sites of star formation are homogeneously spread throughout the cold gas, this requires the energy in the feedback to be at least comparable to the binding energy of the gas. In that case, if supernova feedback is fast enough to regulate the global rate of star formation tightly, it will contain more than enough energy to unbind the gas. Nulsen & Fabian argue that in these circumstances supernovae resulting from the initial burst of star formation are likely to eject the bulk of the remaining gas from the protogalaxy, shutting off further star formation. This is essentially the model proposed by Dekel & Silk (1986) for dwarf galaxy formation. In this paper we argue that gas ejected in this manner accounts for the bulk of the DLAs at high redshifts.

Of course, it is only possible for supernovae to eject the remaining gas if they produce sufficient mechanical energy. In small protogalaxies the gravitational binding energy of the gas is relatively low, making it easier to eject. Low specific binding energy also means low virial temperatures, which leads to rapid radiative cooling of gas in small protogalaxies, so that shock-heating is, at best, transient, and the gas collapsing into a small protogalaxy ends up cold (Rees & Ostriker 1977; White & Rees 1978). Thus, all of the gas is available to form stars on roughly the dynamical time-scale. In larger protogalaxies the cooling time of some gas can exceed the dynamical time, so that after this gas is shock-heated in the collapse it forms a nearly hydrostatic hot atmosphere in the protogalaxy. Such gas is not available to form stars in the initial burst of star formation, but must be ejected if the bulk of the residual gas is to be ejected. This makes it much more difficult for supernovae resulting from an initial burst of star formation to eject the remaining gas. Thus there is no major ejection from protogalaxies large enough to be dominated by hot gas immediately after collapse. If the hot atmosphere of a massive galaxy cools by the present time, however, violent star formation can lead to ejection. Outflows from starbursts in such normal galaxies may account for some absorption-line systems at low redshift.

For the model parameters used here, a protogalaxy with a total mass (including its dark halo) of 10^{11} M$_\odot$, collapsing at a redshift of about 2, would produce no hot gas and a starburst of about 2×10^9 M$_\odot$. While this is several orders of magnitude larger than any starburst seen at low redshift, from the determinations by Sawicki & Yee (1998), it is quite comparable in size to the starbursts in a number of the galaxies with $z > 2$ from the *Hubble Deep Field*.

Larger protogalaxies tend to have higher virial temperatures and lower mean densities than smaller systems, both of which increase the cooling time, conspiring to favour the formation of hot gas. This makes the transition from protogalaxies dominated by cold gas to those dominated by hot gas abrupt, occurring at a total mass of about 10^{12} M$_\odot$ (depending on model details). We assume that those galaxies that were dominated by cold gas when they were protogalaxies form dwarf galaxies (Nulsen & Fabian 1997).

3 A SIMPLE MODEL FOR DWARF OUTFLOWS

In this section we describe the model used to determine the properties of absorption systems resulting from dwarf galaxy outflows. In constructing this model we are guided by the analogy of superwinds from starbursts (e.g. Marlowe et al. 1995), outflows from the most massive bursts of star formation seen at low redshift. Our basic assumption is that the gas is ejected as a weakly collimated wind of short duration.

If the number of dwarf galaxy collapses per unit volume per unit time is dn/dt, and the average lifetime of the H I clouds with given properties (e.g. column density) ejected by these galaxies is t_C, then the number of such clouds per unit volume is

$$N = t_\mathrm{C} \frac{\mathrm{d}n}{\mathrm{d}t}.$$

If the area of cross-section of these clouds is A, then the mean number encountered by the line element dl is NA dl. For photons the line element is $\mathrm{d}l = c\,\mathrm{d}t$, so that the mean number of such clouds encountered by a photon emitted at redshift z is

$$Q = \int_{t(z)}^{t_0} NA\,c\,\mathrm{d}t = \int_0^z ct_\mathrm{C}A\frac{\mathrm{d}n}{\mathrm{d}z}\mathrm{d}z.$$

The collapse history, dn/dz, is largely determined by the cosmological model and fluctuation spectrum, but we must make more detailed assumptions in order to determine At_C (really a weighted average of $\int A\,\mathrm{d}t$).

The mass density in a wind of speed v ejected into solid angle Ω is

$$\rho(r) = \frac{\dot{M}}{\Omega v r^2} \tag{1}$$

at a distance r from the source of the wind, where $\dot{M}$ is the mass flow rate in the wind. The column density along a line of sight through this wind is

$$N_\mathrm{H} = \int n_\mathrm{H}\,\mathrm{d}l = \frac{n_\mathrm{H}}{\rho}\frac{\dot{M}\theta}{\Omega v b}, \tag{2}$$

where b is the distance from the line of sight to the origin of the wind (the centre of the protogalaxy), $n_\mathrm{H}/\rho \simeq 0.75/m_\mathrm{H}$ is a constant for neutral gas and θ is the angle subtended at the centre of the galaxy by that part of the line of sight that intersects the wind (see Fig. 1). This column density exceeds N_H if the line of sight passes closer to the centre of the galaxy than

$$b_\mathrm{max} = \frac{n_\mathrm{H}}{\rho}\frac{\dot{M}\theta}{\Omega N_\mathrm{H} v}. \tag{3}$$

For a spherical wind, the area within b_max is $A = \pi b_\mathrm{max}^2$. If the wind burst lasts for a time $t_\mathrm{C} = \tau$, during which a fraction f of the total mass M is ejected from the protogalaxy, then the mass flow rate is $\dot{M} = fM/\tau$. As the burst of star formation is expected to last about

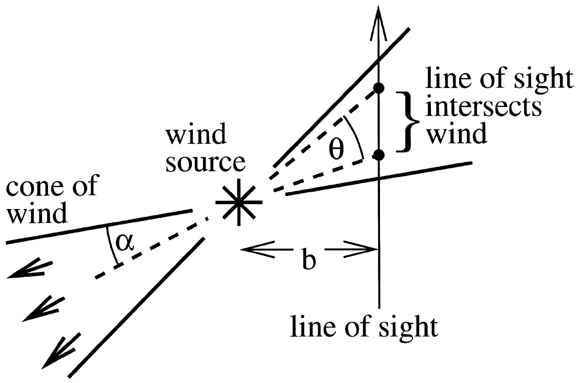

Figure 1. Geometry of the wind model. This shows the relative positions of the line of sight and the wind cone, seen in the plane of the line of sight and the wind source. In general, the axis of the wind cone does not lie in the plane of the figure, so that the half-angle of the cone is smaller than it appears to be in the diagram.

one dynamical time, so will the wind, and we assume

$$v\tau = \eta R_0, \qquad (4)$$

where R_0 is the size of the protogalaxy (i.e. R_{200}, the radius corresponding to an overdensity of 200) and η is of order unity. Putting this together gives

$$A t_{\mathrm{C}} \simeq \frac{\pi}{16}\left(\frac{n_{\mathrm{H}}}{\rho}\right)^2 \frac{f^2 M^2}{\eta v R_0 N_{\mathrm{H}}^2}. \qquad (5)$$

If the wind burst is collimated, the reduction in opening angle is more than offset by the increase in the maximum impact parameter ($\Omega \sim \theta^2$ in equation 3), so that At_{C} increases. The geometry of the intersection between a general line of sight and the wind is complicated. If the wind fills a double-sided cone with half angle α ($\alpha \leq \pi/2$, see Fig. 1), then we can use the approximation

$$A t_{\mathrm{C}} \simeq \frac{\alpha^3}{2\pi^2(1-\cos\alpha)^2}\left(\frac{n_{\mathrm{H}}}{\rho}\right)^2 \frac{f^2 M^2}{\eta v R_0 N_{\mathrm{H}}^2}.$$

This agrees with equation (5) for a spherical wind ($\alpha = \pi/2$). After averaging over possible directions for the wind, it is also within a few per cent of the asymptotically correct result in the limit of a tightly collimated wind ($\alpha \rightarrow 0$). As expected, it increases as the wind becomes more tightly collimated. For a weakly collimated wind, the increase is modest (about 50 per cent for $\alpha \simeq \pi/4$). We will use the result for a spherical wind, bearing in mind that this gives a lower limit for the actual result.

Note that we have assumed implicitly that the burst of wind may be treated as continuous, requiring it to continue for much longer than the time taken to cross to $b_{\max}$ (ignoring the effect of projection on to the plane of the sky). That is, we need $b_{\max} \ll \eta R_0$. In the protogalaxy model described below,

$$\frac{b_{\max}}{\eta R_0} \simeq 0.5\frac{f M_{12}^{1/3}}{\eta^2 N_{21} t_{10}^{4/3}},$$

where the collapse time is $10^{10} t_{10}$ yr, the total mass of the protogalaxy is $10^{12} M_{12}$ $\mathrm{M}_{\odot}$ and the column density of interest is $10^{21} N_{21}$ cm^{-2}. The approximation is well satisfied for recent collapses and high N_{H}, but fails at lower column densities. However, while the justification is modified, equation (5) is still valid to within factors of order unity. Other corrections, e.g. resulting from the decrease of v with distance in the wind, generally tend to increase this result slightly (but see the discussion of photoionization below).

4 THE GALAXY FORMATION MODEL

The model for dwarf outflows described in Section 3 has been incorporated into a semi-analytical model for galaxy formation. Most details of this model have been described elsewhere (Nulsen & Fabian 1997), although much of that detail is not relevant for the current problem. We outline the relevant details again here.

Our cosmological model is an open dust (CDM) model with density parameter $\Omega = 0.25$, a Hubble constant of 50 km s^{-1} Mpc^{-1} and a baryon density of $\Omega_{\mathrm{b}} = 0.075$, in reasonable agreement with current limits from cosmic nucleosynthesis (Burles & Tytler 1998). The block model (Cole & Kaiser 1988) is used to model the collapse hierarchy. The spectrum of initial density perturbations is taken as a scale-free CDM spectrum (Peacock & Dodds 1996), normalized to $\sigma_8 = 1$.

Collapsing protogalaxies are assumed to be dominated by dark matter. The mean density of a virialized dark halo is taken to be 200 times the critical density for a flat dust universe at the same time, i.e.

$$\bar{\rho} = \frac{200}{6\pi G t^2}$$

for collapse at time t. The dark matter is treated as a perfect isothermal sphere (density $\propto r^{-2}$), truncated abruptly at the cut-off radius, R_0. Since $\bar{\rho}$ is determined by collapse time, R_0 is readily expressed in terms of the collapse time and total mass by fixing the mean density of a collapsed halo at $\bar{\rho}$.

In each collapse, gas is divided according to whether its cooling time (as measured after a notional collapse with cooling ignored) is shorter or longer than its free-fall time. Gas that would cool in less than one free-fall time is assumed to end up cold immediately after the collapse. Any gas with a cooling time longer than its free-fall time is assumed to form an approximately hydrostatic atmosphere around the protogalaxy after the collapse. As discussed in Section 2, low-mass systems have no hot gas. Cooling times increase rapidly with halo mass, so that there is an abrupt transition, at a fairly well-defined mass, above which collapsed systems are dominated by hot gas and have no outflows (at least not the major outflows expected for dwarfs).

The gas is taken to be isothermal in the notional collapse and, like the halo, is truncated sharply at R_0. Because gas can be ejected from collapsed protogalaxies by supernovae, it may be less tightly bound to a collapsing halo than other matter, so we allow the energy per unit mass of the gas to differ from that of the dark matter. Thus, the ratio of the virial temperature to the gas temperature,

$$\beta = \frac{\mu m_{\mathrm{H}} \sigma^2}{kT},$$

where σ is the line-of-sight velocity dispersion, μm_{H} is the mean mass per gas particle and T is the gas temperature, may differ from unity. Hydrostatic equilibrium makes the distribution of the gas in the notional collapse $\rho \propto r^{-2\beta}$. In a collapse where the gas ends up cold, the energy dissipated by the gas is taken to be its notional thermal energy. For gas ejected by supernovae, the energy required for ejection is preserved as binding energy until a later collapse.

In this model we assume that the amount of star formation is just enough to expel the remaining gas from the dwarf protogalaxy to infinity. This is implemented by assuming that a fixed fraction of the mechanical energy of each Type II supernova goes to expel the gas (1.2×10^{50} erg supernova^{-1} in the model presented here). This must overcome the net binding energy of the gas (taken as $4\sigma^2$ per unit mass for cold gas) to expel it completely. For more detail see Nulsen & Fabian (1995).

Although their conclusion is disputed (e.g. Gibson, Loewenstein & Mushotzky 1997 and references therein), Loewenstein & Mushotzky (1996) have argued that the rate of Type II supernovae per unit mass of star formation must be boosted at early times in order to account for the pattern of heavy-element enrichment in intracluster gas. We allow for this by using a supernova rate in excess of the value of 1 per 80 $M_\odot$ of star formation estimated to apply locally (Thomas & Fabian 1990; the rate is boosted by a factor of 3 in the model presented below). The expected number of DLA systems depends on this boost and on the energy per supernova available to expel the gas, mainly through their product. In our simple model the only chemical evolution allowed for is enrichment by Type II supernovae. The resulting iron abundance is sensitive to the ratio of these parameters (although we present no quantitative results on this here).

5 IONIZATION AND COLUMN DENSITIES

We assume here that the temperature of the wind is determined principally by the effects of photoionizing radiation. In order to be accelerated to escape speed, it is generally necessary for the gas to attain temperatures comparable to the virial temperature of a protogalaxy. However, the gas feeding the wind can only remain at such high temperatures for a short time. Two factors affect this. First, a steady, spherical, adiabatic wind must be supersonic everywhere when the ratio of specific $\gamma = 5/3$ (the wind can only be subsonic in a region where it is being heated and/or time-dependent effects are significant). This means that the wind is supersonic immediately outside the region where it is generated. Since the density then decreases (approximately) as r^{-2} (equation 1), adiabatic cooling makes the gas temperature decrease as $T \propto r^{-4/3}$. Secondly, even at the virial temperature, the radiative cooling time of the gas is very short, so that the gas must be accelerated quickly or its thermal energy will be lost and the wind will fail. This requires the region where the wind is generated to be small ($\ll R_0$). The combined effects of the small size of the region where the wind is generated and adiabatic (and radiative) cooling in the wind mean that the region where the gas temperature is comparable to the virial temperature is small.

Gas ejected from the dwarf protogalaxy is photoionized by radiation from both the burst of star formation in the galaxy and the general ionizing background radiation. In what follows we treat the starburst that produces the outflow as instantaneous. The ionization state of the innermost part of the gas will be determined by the ionizing photons escaping from the galaxy, while the outer parts of the outflow will be ionized by the UV background.

Using the wind model of Section 3 and the collapse model of Section 4, the gas density is

$$n_{\mathrm{H}}(r) = 2.4 \times 10^{-4} \frac{f}{\eta t_{10}^{2}} \left(\frac{\Omega}{4\pi}\right)^{-1} \left(\frac{r}{R_0}\right)^{-2} \mathrm{cm}^{-3}.$$

At redshifts $z \sim 2$–3, the intensity of the background radiation at the Lyman limit, I, is about $I_{\mathrm{B}} = 5 \times 10^{-22}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} (Haardt & Madau 1996). This radiation keeps the outer part of the wind almost fully ionized. Measured radially inward, in a steady state the optical depth of the wind becomes unity at radius

$$r_{\mathrm{c}} = 72 \left(\frac{fM_{12}^{2/3}}{\eta t_{10}^{2/3}}\right)^{2/3} \left(\frac{\Omega}{4\pi}\right)^{-2/3} \left(\frac{I}{I_{\mathrm{B}}}\right)^{-1/3} \mathrm{kpc},$$

where we have assumed a temperature of ~5000 K for the ionized wind. Inside r_{c} the gas is largely neutral. Outside r_{c}, where the intensity of the ionizing radiation is close to the background level, the ratio of ionizations per neutral hydrogen to recombinations per free proton in the wind is

$$U_{\mathrm{B}}(r) = \frac{\Gamma_{\mathrm{B}}}{\alpha(T) n_{\mathrm{H}}(r)},$$

where Γ_{B} is the photoionization rate resulting from background radiation (taken from Haardt & Madau 1996) and $\alpha(T)$ is the recombination coefficient. This is large,

$$U_{\mathrm{B}}(r) = 10^{3} \left(\frac{fM_{12}^{2/3}}{\eta t_{10}^{2/3}}\right)^{1/3} \left(\frac{\Omega}{4\pi}\right)^{-1/3} \left(\frac{I}{I_{\mathrm{B}}}\right)^{1/3} \left(\frac{r}{r_{\mathrm{c}}}\right)^{2},$$

so that the gas is highly ionized outside r_{c}.

During the burst of star formation, all gas is efficiently ionized by UV photons escaping from the galaxy. The quantity corresponding to U_{B} for photons from the galaxy is

$$U_{\mathrm{G}} = 1.2 \times 10^{3} \frac{\eta t_{10}^{2/3}}{fM_{12}^{2/3}} \left(\frac{\Omega}{4\pi}\right) F_{\mathrm{G}} N_{53},$$

where F_{G} is a factor of order unity which depends on the spectrum of the ionizing photons emitted by the protogalaxy and N_{53} is the number of ionizing photons escaping from the galaxy per unit time in units of 10^{53} photon s^{-1}. From the computations of Leitherer & Heckman (1995), a 10^{6}-$M_\odot$ starburst produces $\sim 10^{53}$ photon s^{-1} during its first few times 10^{6} yr. Ionizing photons appear to be escaping from our own Galaxy at about this rate (Bennett et al. 1994). Indeed, in the model we are dealing with, the starburst is much more massive, involving of the order of 1 per cent of the total mass of the galaxy. The number of ionizing photons might therefore be as large as $N_{53} \sim 10^{3}$ during the first few million yr, producing a much more ionized outflow. The presence of dust (which has to be there if massive stars are produced) makes N_{53} highly uncertain, but it is likely to be large enough to keep the gas completely ionized at first. The *total* (i.e. neutral and ionized) H column density for a line of sight of impact parameter b is (see equation 2)

$$N_{\mathrm{H}} = 1.1 \times 10^{23} \frac{fM_{12}^{2/3}}{\eta t_{10}^{2/3}} \left(\frac{\theta}{\pi}\right) \left(\frac{\Omega}{4\pi}\right)^{-1} b^{-1}\ \mathrm{cm}^{-2}, \qquad (6)$$

for b in kpc, but because $U_{\mathrm{G}} \gtrsim 10^{3}$ the gas will not produce a damped absorption line.

However, the rate of emission of ionizing photons from the protogalaxy drops by a factor 10^{3}–10^{4} after 10^{7} yr. Even for a very massive starburst, producing $N_{53} \sim 10^{3}$ ionizing photons per second at first, N_{53} has dropped below 10^{-3} by 10^{8} yr, and the gas is no longer photoionized. The recombination time $[t_{\mathrm{rec}}(r)^{-1} = n_{\mathrm{H}}(r)\alpha(T)]$ is short,

$$t_{\mathrm{rec}} = 0.6 \times 10^{4} \frac{\eta t_{10}^{2/3}}{fM_{12}^{2/3}} \left(\frac{\Omega}{4\pi}\right) r^{2}\ \mathrm{yr},$$

for r in kpc, and all gas out to the radius r_{c} recombines in less than 10^{8} yr from the start of the starburst. A damped Lyα absorption system can then be produced, mainly by the H I gas within r_{c}. Note that this means we do not generally expect to see a massive starburst active at the same time that the resulting wind is a DLA.

Absorption lines from low-ionization species (e.g. Si II) are likely to appear in the neutral inner region, showing an asymmetric profile because of the velocity of the wind (see Section 6). High-ionization species (e.g. C IV, Si IV) are more likely to be associated with the more ionized outer shell, and so will display different structure and velocities from the H I and low-ionization metal lines. This appears to be a general property of DLAs (Lu et al. 1996).

Fig. 2 shows the cumulative distribution of H I column density for random lines of sight, with the values of the parameters fixed at

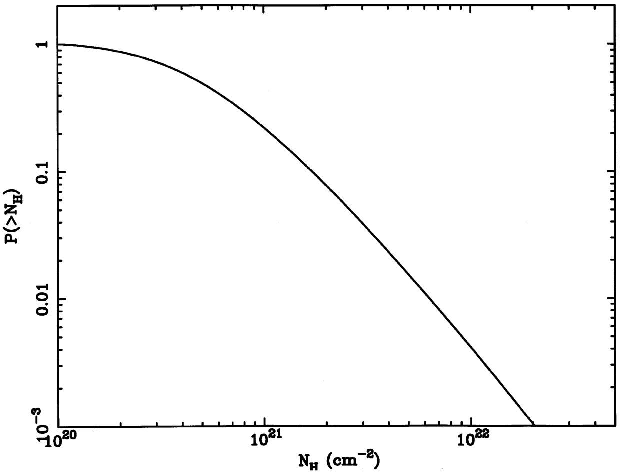

Figure 2. Cumulative distribution of the H I column density at $z = 2$ for a galaxy with $M_{12} = 0.1, f = 0.2$ and $\eta = 1$.

$z = 2$ ($M_{12} = 0.1, f = 0.2, \eta = 1$). The flattening of the distribution at $\sim 10^{21}$ cm^{-2} is caused by the ionization of the outer part of the wind. For lines of sight with impact parameters, b, well within the neutral region, (from equation 2) $N_{\mathrm{H}} \propto b^{-1}$, but N_{H} drops dramatically at r_{c}. The column density at the cut-off depends on the parameters, but it is not very sensitive to most of them,

$$N_{\mathrm{H,c}} \propto \left(\frac{fM_{12}^{2/3}}{\eta t_{10}^{2/3}}\right)^{1/3} \frac{\theta}{\pi} \left(\frac{\Omega}{4\pi}\right)^{-1/3} \left(\frac{I}{I_{\mathrm{B}}}\right)^{1/3}.$$

Although the dependence on mass and collapse time will smear the break seen in Fig. 2, the mass dependence is sufficiently weak that the break will be preserved when this model is applied to a distribution of collapses.

Wolfe et al. (1995) fitted a broken power law to the distribution of N_{H}, with $f(N_{\mathrm{H}}) \propto N_{\mathrm{H}}^{-3}$ at high column densities, flattening to $f(N_{\mathrm{H}}) \propto N_{\mathrm{H}}^{-1}$ at lower values. With no allowance for ionization from the starburst, our simple model gives a distribution with $f(N_{\mathrm{H}}) \propto N_{\mathrm{H}}^{-3}$ at high column densities (arising largely from the N_{H} dependence in equation 5), in agreement with the fitted slope. This is likely to be an overestimate at very high column densities for two main reasons. From equation (6), we see that a high column density requires the line of sight to pass very close to the centre of the outflow, with $b < 1$ kpc in many cases. For such a line of sight, our assumption that the outflow is effectively spherical, arising from a single point, is clearly questionable. Secondly, ionization from the starburst will have its greatest effect close to the source of the wind.

The model will clearly give a break in the distribution of column densities at roughly $N_{\mathrm{H\,I}} = 10^{21}$ cm^{-2}, which is in qualitative agreement with the observed distribution of column densities. However, if the background ionizing flux is uniform, our model would predict a distribution flatter than $N_{\mathrm{H\,I}}^{-1}$ below the break. Again, our assumptions might be too simplistic here, since weaker starbursts might follow the first one, producing lower column density DLAs. Optical/IR studies of Lyman-break galaxies in the *Hubble Deep Field* (Sawicki & Yee 1998) support the view of episodic starbursts, which can enhance the number density of lower column density systems in our model.

6 RESULTS AND DISCUSSION

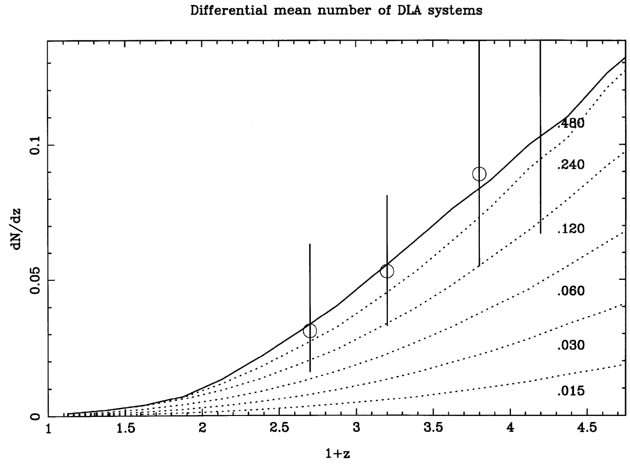

Figure 3. Expected number of DLA clouds with column densities $N_{\mathrm{H}} > 10^{21}$ cm^{-2} per unit redshift. The total is dissected by the total mass of the dwarf protogalaxy (on the right in units of 10^{12} M$_{\odot}$), which determines the outflow velocity. The data points are taken from Wolfe et al. (1995).

Fig. 3 shows the differential distribution of the number of DLAs with column densities in excess of 10^{21} cm^{-2} for the model outlined in the preceding sections, with $\eta = 0.4$ (equation 4). The value of η was chosen to give a reasonable match to the observed distribution (data from Wolfe et al. 1995 is shown in Fig. 3). While the choice of η is largely arbitrary, we note that such a value is reasonable. The expectation $\eta \simeq 1$ is based on the assumption that a starburst lasts about one dynamical time, making $v\tau$ about R_0. However, the cold gas cloud formed by the collapse of a protodwarf is likely to be considerably smaller than the size of the dark halo that contains it (R_0). In this case, supernova feedback may turn off star formation in less than one halo dynamical time and we would expect $\eta < 1$. Secondly, collimation increases the effective area of the wind over that given in equation (5) and this effect is mimicked by making $\eta < 1$. Given the uncertainties in the parameters of our model, the results are in good agreement with the observations.

The dependence of the results in Fig. 3 on the cosmological model is complex. For example, decreasing Ω_{b} reduces the halo mass that divides dwarfs from normal galaxies, so that, in addition to the direct reduction in the amount of gas ejected by dwarfs, the number of dwarf galaxies decreases, reducing the number of outflows. Combined with the quadratic dependence on gas fraction (equation 5), this makes the expected number of absorbers quite sensitive to Ω_{b}. Uncertainty in the value for η makes it difficult to be definitive, but, for example, it is implausible that dwarf outflows could account for most DLA systems for $\Omega_{\mathrm{b}} \lesssim 0.04$ (and no other changes to the model).

In the block model, halo masses are fixed as powers of 2, multiplied by a minimum mass. The total mean number of DLA systems per unit redshift has been dissected by total mass of the collapsing protogalaxy in Fig. 3. In our model, the velocity of gas ejected from a system with total mass M and cut-off radius R_0 would be about

$$v = 2\sqrt{\frac{GM}{R_0}}$$

(the value used in the calculations of Sections 3 and 5). As the cut-off radius, R_0, is determined by the collapse time and total mass, we obtain

$$v \simeq 280\, M_{12}^{1/3} t_{10}^{-1/3} \text{ km s}^{-1}.$$

For example, the time at $z = 2$ is about 4×10^9 yr, so that for the range of total masses 1.5×10^{10} to 4.8×10^{11} $\mathrm{M}_\odot$, the outflow velocity ranges from about 90 to 300 km s^{-1}. We see from the figure that, apart from the high-mass cut-off caused by the formation of hot gas, the distribution of outflow velocities will be quite uniform over this mass range (the low-mass limit has no physical significance, but is simply the lowest mass block in the simulation).

Translation from outflow velocity to line profile depends on the degree of collimation of the gas and the relative orientations of the line of sight and the wind cone. Relative to the centre of the protogalaxy, the velocity of the wind projected on to the line of sight is $v \sin \phi$, where ϕ is the angle that the line from the centre of the wind to a point on the line of sight makes with the plane of the sky. In a uniform spherical outflow, the differential absorption in the range of angle ϕ to $\phi + \mathrm{d}\phi$ is simply proportional to $\mathrm{d}\phi$ (equation 2), so that an absorption profile in the wavelength range $\lambda_0(1 \pm v/c)$ would be proportional to

$$\frac{1}{\cos \phi} = \left[1 - \left(\frac{\lambda - \lambda_0}{\lambda_0 v/c} \right)^2 \right]^{-1/2}$$

(the cusps at the extremes are limited by the finite extent of the wind). If the outflow is limited to a cone, then this line profile does not cover the full range of angle from $-\pi/2$ to $\pi/2$, and we will generally obtain an asymmetric profile, strongest near one edge. Non-uniformity in the wind is likely to add more complex structure to the line profile.

We see that a weakly collimated wind can account for the general features of the complex observed line profiles (e.g. Prochaska & Wolfe 1997). In particular, such a wind readily accounts for the range of observed absorption-line structure in an open CDM cosmology. Our model will generally give higher velocity structure than other models because the ejected gas moves faster than gas in the same sized halo in other models.

One clear prediction of this model is that, because the number of supernovae, and hence metallicity, is largely determined by the binding energy, there should be a correlation between metallicity and the velocity structure spanned by absorption lines (similar behaviour may be expected in any model where the velocity structure of the absorption lines is effectively determined by gravity). As projection can reduce the extent of the velocity structure, the sense of this correlation should be that DLAs with large velocity width should have high metallicity. This is certainly consistent with the plot of [Zn/H] versus velocity width in Wolfe & Prochaska (1998).

Our model for galaxy formation is highly simplified and, in particular, our assumption that all remaining gas is expelled exactly to infinity by a single starburst is overly simplistic. The model also lacks any treatment of disc formation. Many nearby galaxies show significant outflows, which are probably not the result of recent collapse. Such systems may be responsible for some DLA systems, especially at low redshifts where galaxy formation has slowed appreciably.

Lanzetta et al. (1997) have recently analysed the nearest DLA detected and the galaxy that is likely to produce the absorption. This galaxy lies 16.6 kpc away from the line of sight to the QSO, and morphologically it is bulge-dominated. Its spectrum, however, shows strong emission lines, which means that the galaxy is forming stars. An exponential disc is detected in addition to the bulge profile, but the exponential disc radius in only ~1 kpc. The emission lines, probably coming from ionized gas in the disc, show rotation with a velocity ~100 km s^{-1}. The gas producing the DLA (which is 75 km s^{-1} away from the systemic redshift of the galaxy) moves counter to the disc rotation. This system favours an outflow model, like that presented here, over a rotating galaxy disc as the absorber. Although the galaxy itself is not properly a dwarf in luminosity terms ($L = 0.4L_\star$), it might well be a bulge system in the process of forming a disc, where the burst of star formation has ejected the material that produces the DLA.

The model presented in Haehnelt et al. (1996) and Rauch et al. (1997) has much in common with the one presented here. The primary difference is that in their model the gas produces DLA systems during collapse, while in our model much the same gas produces DLA systems in the process of being expelled from protogalaxies. Depending on the significance of the photoionizing background radiation and details of the dwarf outflows, both processes may give rise to some DLAs. There are two ways in which the models may be distinguishable. First, our model predicts a tighter correlation between velocity structure and metallicity than theirs, because we would never expect to see a very extended velocity structure in an absorption system with low metallicity, whereas it is quite possible for gas with low metallicity to be accreted by a high-mass system. Secondly, our model predicts quite a sharp cut-off in velocity structure, which would not occur in the collapse models. This comes about in our model because of the formation of hot gas in high-mass systems, preventing expulsion of gas from these systems. Massive systems are quite rare and it would probably be difficult to identify absorption systems with very extended velocity structure, so the current lack of DLA systems with very extended velocity structure probably does not provide a useful test of the models at present. A further caveat on the infall model is that, although the gas needs to be substantially clumped during the collapse, star formation has to be suppressed in order to avoid excessive photoionization of the gas.

Our model assumes that most of the baryonic mass present in dwarf galaxies is effectively ejected to give rise to DLAs. Estimates of the gas mass associated with DLAs (see e.g. Wolfe et al. 1995) remain unchanged and approximately coincident with today's gas mass contained in galaxies. We note that, unless the high baryon fraction in clusters of galaxies is atypical, the total baryon content of the Universe is substantially larger than the visible baryon content of galaxies today, so that during the era of galaxy formation there was plenty of gas available to form DLAs. It is not then necessary that most of the baryons in the Universe were once part of a DLA system. While the baryon fraction that we have used is near the upper end of the range allowed by the observed deuterium abundance, it is in the range required to account for the gas fraction in clusters of galaxies.

Further observational work should be able to identify the galaxies responsible for DLA absorption at moderate redshifts. Detailed studies of these galaxies (including their kinematics) might be able to distinguish between the various models that have been proposed. In particular, they could be used as a way of measuring, or at least constraining, the frequency of outflows in star-forming galaxies.

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