A joint model for the emission and absorption properties of damped Ly$\alpha$ absorption systems

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ABSTRACT

The recently discovered population of ultra-faint extended line emitters, with fluxes of a few times $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ at $z \sim 3$, can account for the majority of the incidence rate of damped Ly$\alpha$ systems (DLAs) at this redshift if the line emission is interpreted as Ly$\alpha$. We show here that a model similar to that proposed by Haehnelt, Steinmetz & Rauch (2000), which reproduces the incidence rate and kinematics of DLAs in the context of $\Lambda$ cold dark matter models for structure formation, also reproduces the size distribution of the new population of faint Ly$\alpha$ emitters for plausible parameters. This lends further support to the interpretation of the emission as Ly$\alpha$, as well as the identification of the emitters with the hitherto elusive population of DLA host galaxies. The observed incidence rate of DLAs together with the observed space density and size distribution of the emitters suggest a duty cycle of $\sim 0.2$–$0.4$ for the Ly$\alpha$ emission from DLA host galaxies. We further show that Ly$\alpha$ cooling is expected to contribute little to the Ly$\alpha$ emission for the majority of emitters. This leaves centrally concentrated star formation at a rate of a few tenths $M_\odot$ yr$^{-1}$, surrounded by extended Ly$\alpha$ haloes with radii up to 30–50 kpc, as the most plausible explanation for the origin of the emission. Both the luminosity function of Ly$\alpha$ emission and the velocity width distribution of low ionization absorption require that galaxies inside dark matter (DM) haloes with virial velocities $\lesssim 50$–$70$ km s$^{-1}$ contribute little to the incidence rate of DLAs at $z \sim 3$, suggesting that energy and momentum input due to star formation efficiently removes gas from these haloes. Galaxies with DM haloes with virial velocities of 100–150 km s$^{-1}$ appear to account for the majority of DLA host galaxies. DLA host galaxies at $z \sim 3$ should thus become the building blocks of typical present-day galaxies like our Milky Way.

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

1 INTRODUCTION

Quasar absorption spectra provide excellent probes of the distribution of baryons in the high-redshift Universe. Damped Ly$\alpha$ systems (DLAs, historically defined as having a neutral hydrogen column density $N_{\text{H}_1} > 2 \times 10^{20}$ cm$^{-2}$) are particularly useful as they are likely to play an important role as a reservoir of gas for the formation of stars and galaxies at high redshift. They dominate the neutral gas content of the Universe between $z \sim 0$ and 5, and at $z \sim 3.0$–$4.5$ their neutral gas content is comparable to visible stellar mass in present-day galaxies (Wolfe 1986; Storrie-Lombardi, McMahon & Irwin 1996; Storrie-Lombardi & Wolfe 2000). DLAs thus form an important link between primordial plasma and the stellar structures that form from it.

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In spite of observations of over 1000 DLAs, Wolfe, Gawiser & Prochaska (2005) still conclude that the question ‘what is a damped Ly$\alpha$ system?’ has not yet been answered conclusively. One of the reasons for this is that absorption spectra provide only indirect information in velocity space, and only probe the gas along one line-of-sight through the galaxy. The Ly$\alpha$ absorption feature itself provides no information about the velocity structure of the DLA because of the large optical depth even in the damping wings. This has led observers to look at the associated low ionization metal absorption features. Low ionization species like Si$\text{ii}$, C$\text{ii}$ and Fe$\text{i}$ are believed to be good tracers of the neutral gas in DLAs. Prochaska & Wolfe (1997) developed the velocity width distribution of metal absorption features into an important diagnostic tool for DLAs. The much lower absorption optical depth allows us to extract detailed kinematical information for the gas in DLAs. The absorption profiles are normally clumpy and asymmetric, with the strongest absorption feature often occurring at one edge of the profile. Velocity widths range from 30 km s$^{-1}$ to several hundred km s$^{-1}$. Note,
however, that there are few systems with narrow absorption profiles with velocity width <30 km s$^{-1}$.

Kinematical models aiming to reproduce the velocity width data fall into two categories. Wolfe (1986) suggested a close connection between DLAs and discs of present-day spiral galaxies. Prochaska & Wolfe (1997) modelled DLAs as thick rotating discs with a rotation speed (∼200 km s$^{-1}$) typical of present-day galaxies (see also Jedamzik & Prochaska 1998). Haehnelt, Steinmetz & Rauch (1998) challenged this interpretation and demonstrated that it is not unique. The merging of protogalactic clumps expected in cold dark matter (CDM)-like models for structure formation can explain the shape of the profiles equally well. Galactic winds have also been suggested to play an important role (e.g. Fabian 1999). They further showed that for the same virial velocity width, merging clumps produce significantly larger velocity width and argued that the latter interpretation is favoured by the observed velocity width distribution in the context of the CDM paradigm for structure formation (Haehnelt et al. 2000; Møller et al. 2001). Interestingly, Zwaan et al. (2008) use a study of the kinematics of the neutral hydrogen in the THINGS sample of nearby galaxies based on 21-cm emission spectra to argue that the expected velocity width of low ionization species from neutral gas in nearby disc galaxies with log $N_{\text{HI}} > 20.2$ is much smaller than that observed in DLAs at $z \sim 3$.

The level of enrichment with metals provides another important clue as to the nature of DLAs – see Pettini (2004, 2006); Wolfe et al. (2005) for reviews. Significant metal absorption is found in all DLAs, though as a population they are metal poor. DLAs are also relatively dust free (Ellison et al. 2001; Wild, Hewett & Pettini 2006). Initially, the low metallicity was used to argue that DLA host galaxies are the chemically unevolved but otherwise very similar counterparts of typical present-day spiral galaxies (Wolfe 1986). In the model of Haehnelt et al. (1998), DLAs instead preferentially probe the outer parts of much less massive galaxies, many of which end up as building blocks of typical present-day galaxies that form by hierarchical merging in CDM-like models for structure formation. Recently, Pontzen et al. (2008) demonstrated that such a model fits the observed metallicity of DLAs at $z \sim 3$ very well.

As already mentioned, absorption is measured along a single line of sight and thus is a one-dimensional probe of the properties of the DLA. To explore the spatial extent and structure of the DLA, we need to observe DLAs in emission. Attempts to do this have focused on both line and continuum emission. Lyman emission holds great potential in this respect. Star-formation, cooling radiation and fluorescence re-emission of the meta-galactic ultraviolet (UV) background are all expected to contribute at different levels. In addition, stellar continuum emission from the newly formed stars should also be bright enough to be detectable.

Many observers have attempted to find the galaxy counterparts of DLAs at high redshift in emission by searching adjacent to quasar sightlines with known absorption systems (Bunker et al. 1999; Fynbo, Møller & Warren 1999; Kulkarni et al. 2000, 2001; Warren et al. 2001; Christensen et al. 2007). This is a difficult task, as the light of the extremely bright quasar must be accurately subtracted to study the light of the galaxy, which is very faint in comparison. Kulkarni et al. (2000) and others caution of the possibility that a given emission feature is a Point Source Function artefact rather than a real source. Christensen et al. (2007) report that, for $z > 2$, six DLA galaxies have been confirmed through spectroscopic observation of Ly$\alpha$ emission, with other techniques producing a few additional candidates. Christensen et al. added another six Ly$\alpha$ emission candidates to this group. A quantitative statistical interpretation of the many (largely unsuccessful) searches is difficult if not impossible, but the rather low success rate appears to be consistent with their interpretation as galaxies of rather low mass and star formation rate.

Rauch et al. (2008) reported the results of a long-slit search for low surface brightness Ly$\alpha$ emitters at redshift $z \sim 3$, which reached flux levels that are about a 10 times lower than previous Ly$\alpha$ surveys at this redshift. They found 27 faint line emitters, many of which are extended in wavelength and real space. They argue that the majority of the emitters are likely to be Ly$\alpha$ (rather than low-$z$ interlopers). The angular size of the Ly$\alpha$ emission regions of the resolved sources is surprisingly large and corresponds to radii of 10–30 kpc. Wolfe & Chen (2006) searched for spatially extended low surface brightness continuum emission in the Hubble Ultra Deep Field and placed stringent upper limits on extended star formation in DLAS at $z \sim 3$. This result also argues against the possibility that we are seeing a distribution of several compact knots of stellar emission which are smeared out due to seeing effects. As discussed by Rauch et al. (2008), their observation can be reconciled with those of Wolfe & Chen (2006) if the emitters are powered by a central region of star formation and processed by radiative transfer through surrounding neutral hydrogen. This would, however, require scattering of Ly$\alpha$ photons to large radii. Dijkstra, Haiman & Spaans (2006) have performed Ly$\alpha$ radiative transfer for more massive haloes in a different context which suggest that this is – at least in principle – possible. Detailed radiative transfer modelling will be required to see whether this is indeed a realistic proposition for the observed sample of faint Ly$\alpha$ emitters. Rauch et al. (2008) note that the incidence rate inferred from the space density and the size distribution of the emitters is similar to that of DLAs, and suggest that they are the host population of DLAs and high column density Lyman Limit Systems (LLS). If the emitters are indeed the host galaxies of DLAs, then the observations of Rauch et al. (2008) give us the size distribution and space density of DLA host galaxies at $z \sim 3$ (fig. 19 of Rauch et al. 2008).

Models predicting the velocity width and size distribution of DLAs have been constructed based on the observed luminosity function of galaxies (Fynbo, Møller & Warren 1999; Fynbo et al. 2008) and on the Press–Schechter formalism (Press & Schechter 1974) in conjunction with numerical simulations (Gardner et al. 1997a,b, 2001; Haehnelt, Steinmetz & Rauch 1998, 2000; Nagamine, Springel & Hernquist 2004; Nagamine et al. 2007). More recently numerical simulations have attempted to model the entire DLA population self-consistently (Razoumov et al. 2006, 2008; Pontzen et al. 2008). Note that these models, like all models that reproduce the observed dN/dz of DLAs with host galaxies that have space densities similar to observed galaxies, require the H$\alpha$ distribution responsible for Ly$\alpha$ absorption to extend well beyond the stellar distribution of the host galaxies.

In this paper, we revisit models for the absorption properties of DLAs in the light of the size distribution data of Rauch et al. (2008), improved data on the velocity width distribution from metal absorption lines (which has presented a challenge to purely numerical simulations – see Razoumov et al. (2008) and numerical simulations with increased resolution, box size and sophistication incorporating the additional physics of radiative transfer, gas chemistry and star formation.

Throughout this paper, we use cosmological parameters of the 5-year Wilkinson Microwave Anisotropy Probe (WMAP) data (Hinshaw et al. 2008): ($\Omega_{M}, \Omega_{b}, \Omega_{\Lambda}, \sigma_{8}, n) = (0.701, 0.279, 0.046, 0.721, 0.817, 0.96)$.
2 A joint model for the kinematical properties of DLAs and the cumulative size distribution of the faint Lyα emitters

2.1 The Haehnelt et al. model

Rauch et al. (2008) argued that their population of faint Lyα emitters is the same as or has at least a large overlap with that of DLA/LLs host galaxies. They further pointed out that the space density and sizes should agree well with those predicted by the DLA model of Haehnelt et al. (1998), which models DLAs in the context of CDM models of structure formation.

We here revisit and update this model to investigate whether it can explain the properties of DLAs and the new population of faint emitters, assuming that these are the same objects. We start with summarizing the salient properties of the model. As discussed in the introduction, ab initio numerical simulation of the gas at the centre of galaxies, where complex non-linear gas physics including star formation and the associated feedback are important, is still very challenging. The Haehnelt et al. model therefore takes a hybrid approach, using a combination of Press–Schechter formalism and results from numerical simulations to model the kinematic properties of DLAs (see Johansson & Efstathiou (2006) for a semi-analytical model of DLAs that explicitly models feedback).

The model uses the space density of DM haloes as a proxy for the space density of DLA host galaxies. With the refinement to the Press–Schechter formalism introduced by Sheth & Tormen (2002), the number of DM haloes per unit comoving volume at redshift $z$ with mass (baryonic + CDM) in the interval $(M, M + dM)$ can be estimated as:

$$n_M(M,z) dM = A \left(1 + \frac{1}{V(z)}\right)^{\frac{3}{2}} \frac{\rho_0}{\pi M} \frac{d\nu}{dM} \exp\left(-\frac{\nu^2}{2}\right) dM,$$

where $\sigma_M$ is the rms fluctuation amplitude of the cosmic density field in spheres containing mass $M$, $\rho_0$ is the present cosmic matter (baryonic + CDM) density, $\nu = \sqrt{24 \nu}$, $\nu = \delta_i /[D(z) \sigma_M]$). $D(z)$ is the growth factor at redshift $z$ (Carroll, Press & Turner 1992). $\delta_c = 1.686, \alpha = 0.707, A \approx 0.322$ and $q = 0.3$. We have used the fitting formula in Eisenstein & Hu (1999) to calculate the matter power spectrum.

We will be interested in the kinematic properties of DLAs, for which the virial velocity is a more convenient quantity to characterize the DM halo than the mass. The two are related as follows (e.g. Maller & Bullock 2004):

$$\nu_c = 106 \text{ km s}^{-1} \left(\frac{\Delta_c}{174}\right)^{1/6} \left(\frac{\Omega_M h^2}{0.137}\right)^{1/6} \times \left(1 + \frac{z}{4}\right)^{1/2} \left(\frac{M}{10^{11} M_\odot}\right)^{1/3},$$

where $\Delta_c$ is the overdensity of the halo (see Bryan & Norman 1998).

We use a simple power-law relation between the virial velocity of the DM halo and the DLA cross-section,

$$\sigma(\nu_c) = \pi r_0^2 \left(\frac{\nu_c}{200 \text{ km s}^{-1}}\right) \beta,$$

where $\beta$ and $r_0$ are parameters. The value of $\beta$ has been the source of some controversy, due to numerical simulations still finding it challenging to reliably model the spatial distribution of the gas in the high-density region probed by DLAs and LLs. Gardner et al. (1997a) originally favoured a value of $\beta = 2.94$ (at $z = 3$, for a $\Lambda$CDM cosmology), but their later work revised this to $\beta = 1.569$. Prochaska & Wolfe (2001) pointed out that this low value of $\beta$ is incompatible with the observed DLA velocity widths. Haehnelt et al. (2000) found that the observed velocity width distribution of metal lines is reproduced well with a value of $\beta \sim 2.5$, which we also use here.

Haehnelt et al. further found that they needed to introduce a lower cut-off in virial velocity in order to fit the velocity width distribution of low-ionization absorption systems. Otherwise their model predicted too many very narrow metal absorption systems, which are not observed. They therefore assumed that DM haloes with virial velocities smaller than a minimum velocity $v_{\text{min}}$ do not host DLAs.

Here, we will slightly relax this assumption and model the suppression of the cross-section of DLAs in haloes with small circular velocities as a gentler exponential decline,

$$\sigma(\nu_c) = \pi r_0^2 \left(\frac{\nu_c}{200 \text{ km s}^{-1}}\right)^\beta \exp\left[-\left(\frac{\nu_c}{\nu_c}\right)^\alpha\right].$$

We consider a range of values for the parameters $\nu_c, \alpha$ and $\beta$. Note that a sharp cut-off corresponds to $\alpha = \infty$.

It remains to choose the parameter $r_0$. We will follow Haehnelt et al. (2000) by fixing $r_0$ so that the overall rate of incidence of absorbers per unit redshift $dN/vdz$ agrees with the observational value,

$$\frac{dN}{dz} = \frac{d\nu}{dz} (1 + z)^3 \int_0^\infty \sigma(M,z) n_M(M,z) dM.$$

We take the value of $dN/vdz = 0.24$ at $z = 3$, which is consistent with $dN/dz = 0.067$ (Prochaska, Herbert-Fort & Wolfe 2005; Péroux et al. 2005). The ratio of proper distance interval to redshift interval is given by

$$\frac{d\nu}{dz} = \frac{c}{H(z)(1 + z)},$$

and the so-called absorption distance, $X$, is defined by

$$dX = \frac{H_0}{H(z)} (1 + z)^2 \text{ dz}.$$
We will use here the conditional probability distribution as given in Haehnelt et al. (2000, fig. 1). The distribution peaks at $\frac{v_w}{v_c} \approx 0.6$, dropping to zero below $\frac{v_w}{v_c} \approx 0.1$ and above $\frac{v_w}{v_c} \approx 2$. The numerical simulations on which the distribution is based did not contain star formation feedback. Simulations have become more sophisticated since then. We have therefore compared the $p(v_w|v_c)$ distribution used here with that from the simulations of Pontzen et al. (2008, and private communication), which incorporate the effects of star formation and supernovae on the kinematics and spatial distribution of the gas in a simple manner. The differences in $p(v_w|v_c)$ are small. Unless there is a fortuitous cancellation of different effects, this suggests that star formation in the simulations has a small effect on $p(v_w|v_c)$. This is somewhat surprising, given the significant differences in resolution, cosmological volume and additional physics, albeit reassuring for our modelling. Note, however, that the simulations still fail to produce realistic galactic winds, probably due to the rather simplistic fashion in which stellar feedback is incorporated. The much larger differences in $I(\geq v_w, X)$ between our model and the numerical simulations must therefore be mainly due to the different respective dependence of the DLA cross-section on the virial velocity of the host halo.

Fig. 1 compares the predicted velocity width distribution with the observational data of Wolfe et al. (2005). The data of Prochaska & Wolfe (1997) are also shown in the bottom panels and are reasonably well fit with $v_{c,0} = 50\text{ km s}^{-1}$. This is very similar to what was found by Haehnelt et al. (2000). The new compilation of velocity width data by Wolfe et al. (2005) extends to significantly larger velocities and appears to require a somewhat larger value of $v_{c,0} = 70\text{ km s}^{-1}$. The apparent lack of neutral gas in small DM haloes can be plausibly attributed to the feedback effects of star formation and/or photoheating due to the metagalactic UV background and perhaps even active galactic nuclei. In most numerical simulations and models of galaxy formation, the feedback mainly affects haloes with somewhat smaller virial velocities than this. So either haloes with small virial velocities have larger velocity widths than we have assumed here (i.e. $p(v_w|v_c)$ is different) or else feedback in haloes with virial velocities of $v_{c,0} = 50\text{ km s}^{-1}$ is more efficient than generally assumed. Note also that many of these simulations overproduce the number of observed galaxies at the faint end of the luminosity function. The cumulative velocity width distribution is not very sensitive to the shape of the cut-off for $\alpha \geq 2$.

The high velocity tail of the velocity distribution as compiled by Wolfe et al. (2005) has proven difficult to reproduce with numerical simulations, which attempt to model the spatial distribution of the neutral gas in DLAs self-consistently rather than assume a scaling of the absorption cross-section with the virial velocity of DM haloes. Generally, the simulations fail to produce a sufficient number of absorption systems with velocity widths as wide as observed. This is normally attributed by the authors of these studies to the fact that momentum and energy input into the gas due to star formation may

![Figure 1](https://academic.oup.com/mnras/article-abstract/397/1/511/1007637/fig1.png)
2.3 The cumulative size distribution

We now ask whether our model, which successfully fits the velocity width distribution of the associated low-ionization metal absorption of DLAs, can also reproduce the cumulative size distribution of the emission regions of the new population of faint Lyα emitters, as shown by the black solid curve in Fig. 2 (Rauch et al. 2008, fig. 19, H1 corrected). It asymptotes to dN/dz = 0.23, which is very similar to the observed incidence rate of DLAs at the same redshift. To calculate the cumulative incidence rate for the DLA host galaxies in our model, we must relate the size of the emission region to the mass of the corresponding DM halo. The Lyα radiative transfer calculations of Dijkstra et al. (2006) show that Lyα photons can be scattered to radii comparable to the virial radius. However, in the absence of simulations directly aimed at the scenario we are considering, we have chosen a different approach.

We calculate the radius of the emission from the absorption cross-section, assuming that the absorber is a sphere. The dependence of the cross-section on vα then gives the radius as a function of mass. The cumulative incidence rate is given by

$$\frac{dN}{dz}(r, z) = \int_{M(r)}^{\infty} N(M', z) dM'.$$  \hspace{1cm} (11)

The result is shown\(^1\) in the left-hand panel of Fig. 2. The predicted sizes are consistently smaller than the observed sizes by a factor of between 1.5 and 3, suggesting that the emission regions of the Lyα emitters are even larger than the cross-section for damped absorption, which extend to the virial radius of the DM haloes in our model. Even though the integrated inferred incidence rate is similar to that of DLAs, in our model the emission regions of the Lyα emitters can thus not be identical to the regions responsible for damped Lyα absorption. Nevertheless, the two can be closely related.

To demonstrate this, we now explore a simple model where only a fraction f_d of the haloes are emitting Lyα radiation above the detection threshold at any one time. To keep the total inferred incidence rate fixed, we allow the cross-section of the individual Lyα emission regions to be larger than those for damped Lyα absorption by a corresponding factor f_d\(^1\). The Lyα emitters show typical signs of radiative transfer effects, like large velocity widths and asymmetric line profiles (Rauch et al. 2008, Section 6.3), and should thus be optically thick to Lyα radiation. However, we have no good handle here on the actual column density required to scatter emitted Lyα at large radii effectively. It may well be lower than that required for damped absorption, in which case it is certainly plausible that the region for Lyα emission extends beyond that for damped Lyα absorption. In the right panel of Fig. 2, the cumulative incidence rate is shown for three values of the duty cycle f_d = (1, 0.5, 0.2) with v_{c, 0} = 50 km s\(^{-1}\) and α = 3. Our simple assumption of a duty cycle for the Lyα emission reconciles the cumulative incidence rate predicted by our model with the observed distribution for sizes below 35 kpc for f_d = 0.2 (f_d = 0.4 for v_{c, 0} = 70 km s\(^{-1}\)). Our DLA host galaxies have large extended Lyα haloes which extend to the virial radius of their respective DM haloes and shine with a high duty cycle (f_d >= 0.2). The sudden drop in the observed distribution at r ~ 35 kpc is likely attributable to the following two effects. The first is the surface brightness limit of the instrument. Light from sources with large radii may be too diffuse to be detected. The second is the effect of searching a small survey volume. Large systems are rarer, so there is a limit to the size of sources that can be expected to be found within the rather small survey volume. Note that the size of the Lyα emitting region in our model is comparable to the virial radius of the corresponding DM halo hosting it.

3 MODELLING THE LUMINOSITY FUNCTION OF THE Lyα EMITTERS

3.1 The contribution of Lyα cooling radiation

Rauch et al. (2008) considered a number of astrophysical origins for the Lyα emission that they observe. They conclude that the most likely mechanism for producing Lyα photons is star formation. We here consider in more detail the argument that cooling radiation is unlikely to be the dominant source of Lyα for the observed emitters. Dijkstra et al. (2006) derive the following formula for the Lyα luminosity (L_{Lyα}) of a collapsing protogalaxy due to cooling radiation, assuming that the gravitational binding energy is radiated as

\[^1\] We do not show the impact of altering α here. The effect is small, especially beyond a radius of 10 kpc.
Lyα on a dynamical time-scale,
\[
L_{\text{Ly}\alpha} = 5.8 \times 10^{41} \left( \frac{M_{\text{tot}}}{10^{11}} \right)^{5/3} \left( \frac{v_{\text{amp}}}{v_c} \right)^2 \left( \frac{1 + z_{\text{vir}}}{4} \right)^{5/2} \text{erg s}^{-1}, \tag{12}
\]
where \(M_{\text{tot}}\) is the total (DM + baryons) mass of the halo, \(z_{\text{vir}}\) is the redshift at which the system virialises, and the bulk velocity of the infalling material, \(v_{\text{bulk}}(r)\), is parametrized by \(v_{\text{amp}}\) and \(\alpha_d\) as a power law, \(v_{\text{bulk}}(r) = v_{\text{amp}}(r/r_c)^{\alpha_d}\), where \(r_{\text{vir}}\) is the virial radius.\(^2\)

We will set \(z_{\text{vir}} = 3, v_{\text{amp}} = v_c\), and consider the lower limit of the range of \(\alpha_d\) discussed in Dijkstra et al. (2006), namely \(\alpha_d = -0.5\), so that we have an upper limit on \(L_{\text{Ly}\alpha}^c\).

Equation (12) gives a relation between the mass of a halo and the luminosity due to Lyα cooling, which we can combine with the Press–Schechter formalism of Section 2 to predict the number of DLAs per unit comoving volume with Lyα luminosity greater than some \(L_{\text{Ly}\alpha}^c\).

\[
n(>L_{\text{Ly}\alpha}^c, z) = \int_{M(>1.5 L_{\text{Ly}\alpha}^c)} n(M', z) dM'. \tag{13}
\]

There is, however, an inconsistency here. As already mentioned, equation (12) assumes that the cooling radiation will be emitted over the dynamical time \(t_{\text{dyn}}\) of the halo,

\[
t_{\text{dyn}} \approx \frac{r_c}{v_c} = \left( \frac{1}{4/(3\pi G \Delta \rho_{\text{crit}}(z))} \right)^{1/2} \approx 353 \text{ Myr}. \tag{14}
\]

The proper time corresponding to the redshift interval \([3.75, 2.67]\) of the Lyα survey is \(t_c = 789\) Myr. Thus, all the haloes cannot radiate at the luminosity \(L_{\text{Ly}\alpha}^c\) given by equation (12) for the entire redshift interval over which observations were taken. There are two ways to make the model consistent. The first is to impose a duty cycle, so that at any one time, only a fraction \(f_d = t_{\text{dyn}}/t_c \approx 0.45\) of the haloes will be radiating. The second is to reduce the luminosity of each emitter, so that the gravitational energy of the halo is radiated over 789 Myr.

The left-hand panel of Fig. 3 compares our prediction of \(n(>L_{\text{Ly}\alpha}^c, z)\) with the observed luminosity function as given in fig. 9 of Rauch et al. (2008), shown in black. The red dot–dashed curve shows the model assuming a duty cycle. The green dashed curve is for the reduced luminosity.

So far we have assumed (following Dijkstra et al. 2006) that all gravitational binding energy is converted into Lyα radiation. In reality, hot accretion flows could result in substantial amounts of bremsstrahlung and He\(^\text{II}\) line emission (Kereš et al. 2005), at the expense of \(L_{\text{Ly}\alpha}\). Furthermore, the observed luminosities have not been corrected for slit losses which can be as large as a factor of a few. We therefore conclude that cooling radiation is indeed unlikely to contribute significantly to the majority of the faint Lyα emitters. We therefore agree with the suggestion of Rauch et al. (2008) that the most plausible remaining alternative is that the emitters are predominantly powered by centrally concentrated star formation surrounded by extended Lyα haloes. As already briefly mentioned in the introduction, detailed radiative transfer simulation will be required to decide if this is indeed a viable explanation. Note that by stacking the spectra of a subset of the emitters, Rauch et al. (2008) showed that the emission from these haloes appears to extend to radii even larger than those for the individually detected emission plotted in Fig. 2 by a factor of at least 2.

### 3.2 A simple model for the Lyα luminosity function

We will demonstrate now that a simple model where the Lyα luminosity due to stars \(L_{\text{Ly}\alpha}^s\) is proportional to the total mass \((M \propto v_c^3)\) of the haloes with virial velocity above a threshold \(v_{\text{min}}\).

\[
L_{\text{Ly}\alpha}^s = \begin{cases} 
L_0^s (\frac{v_c}{v_{\text{min}}})^3 \text{erg s}^{-1} & \text{if } v_c > v_{\text{min}} \\
0 & \text{otherwise} 
\end{cases} \tag{15}
\]

fits the observed luminosity function remarkably well. Note that detailed numerical simulations of much brighter Lyman-break galaxies (LBGs) and Lyα emitters appear to be consistent with this simple scaling of the Lyα emission with the properties of the DM host halo (Nagamine et al. 2008). In the right-hand panel of Fig. 3, we compare the observed luminosity function of the faint Lyα emitters with a luminosity function modelled in this way for a range of values of \(f_d\). The observed luminosity function is fit well for the following parameter combinations \([f_d, L_0^s, v_{\text{min}}(\text{km s}^{-1})]\) = (1, \(4 \times 10^4\), 75), (0.5, 8 \times 10^4, 60), (0.2, 1.8 \times 10^2, 45). The upper and lower boundary of the grey shaded region can be fitted with

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\(^2\) See equation (10) of Dijkstra et al. (2006) for a correction to this formula when \(\alpha_d < 0\) and \(r\) is small.
values of \( L_\alpha^5 \) and \( v_{\text{max}} \) that differ from the quoted values by ~25 and ~5 per cent, respectively.

Our assumed scaling \( L_\alpha^5 \propto M \) is shallower than would be inferred from the star formation in most models of galaxy formation. The simulations of Pontzen et al. (2008) would for example predict \( L_\alpha^5 \propto M^{1.6} \). These models are, however, generally tuned to produce a rather shallow faint end of the luminosity function. As discussed by Rauch et al. (2008), their observations imply that the luminosity function of Ly\( \alpha \) emitters steepens considerably at very faint luminosities (cf. Le Delliou et al. 2006). Note that the faint end of the UV continuum luminosity function is also rather steep (Reddy & Steidel 2009).

Intriguingly, the values for the velocity cut-off and duty cycle in our model are very similar to those required to fit the velocity width distribution of the associated low-ionization metal absorption of DLAs and the size distribution inferred from the Ly\( \alpha \) emitters. We caution, however, that the significance of the apparent turnover at \( \sim 1.25 \times 10^{40} \) erg s\(^{-1} \) at the faint end of the observed luminosity function is uncertain. At faint flux levels, the luminosity function will be affected strongly by the sensitivity limit of the observations.

### 4 THE MASSES AND VIRIAL VELOCITIES OF DLA/LL HOST GALAXIES

If the population of faint Ly\( \alpha \) emitters detected by Rauch et al. (2008) can be identified with DLA/LL host galaxies, then this constitutes the first measurement of the space density and average size of DLA/LL host galaxies. The last section supported the suggestion by Rauch et al. that the Ly\( \alpha \) emission is powered by star formation. In this case, with standard assumptions for the conversion of Ly\( \alpha \) emission to star formation rate as used in Rauch et al. (2008) [based on Kennicutt (1998) and Case B assumptions for the conversion between H\( \alpha \) and Ly\( \alpha \) from Brocklehurst (1971)], the Ly\( \alpha \) luminosities correspond to star formation rates of 0.07–1.5 \( M_\odot \) yr\(^{-1} \), similar to that inferred by Wolfe, Prochaska & Gawiser (2003) from the CII* \( \lambda 1335.7 \) absorption in DLAs. No continuum is detected, so there is no information about stellar or total masses of the objects. Our modelling is thus currently the only handle we have on the masses (and virial velocities) of what should be a statistically representative sample of DLA host galaxies.

In Fig. 4, we show the contribution of DM haloes of different masses and virial velocities to the incidence rate of DLAs in our model, for the range of parameters used to model the suppression of the cross-section for damped Ly\( \alpha \) absorption in low-mass DM haloes. We also show the results from two recently published numerical simulations of DLAs (Razoumov et al. 2008; Pontzen et al. 2008). Note that our model and the numerical simulations have similar DM halo mass functions, so that Fig. 4 therefore allows a comparison of the respective DLA cross-sections as a function of halo mass. The differential line density for DLAs is calculated similarly to \( N \), except that we consider intervals of \( dX \) and \( \log_{10} M \),

\[
\frac{d^2N}{dXd\log_{10} M} = \frac{c}{H_0} \ln 10 M n_M(M, X) \sigma(M, X). \tag{16}
\]

Larger values of \( \alpha \) result in a sharper turnover at low masses, at the expense of increasing the abundance of DLAs with high masses (the area under the plot is normalized).

The majority of the DLAs in our model have virial velocities in the range 50–200 km s\(^{-1} \), corresponding to total masses of \( 10^{10}–10^{12} M_\odot \). Note that this range of virial velocities and masses is similar to that found by Nagamine et al. (2007) in their simulations. Bouché et al. (2005) suggested the use of the cross correlation of DLAs and LBGs to observationally constrain the masses of the DM haloes of DLA host galaxies. Cooke et al. (2006) applied this technique to a large observed sample of DLAs and LBGs at \( z \approx 3 \), and found that DM haloes in the mass range above reproduce the cross-correlation length of DLAs and LBGs.

As discussed in the previous sections, the turnover at small virial velocities is most constrained by the velocity width distribution of the associated low-ionization metal absorption and is most likely attributable to feedback effects due to star formation. The decline at large virial velocities and masses is due to the decline of the space density of DM haloes.

The incidence rate in the numerical simulations of Razoumov et al. (2008) shows a similar peak, albeit shifted to somewhat smaller masses/virial velocities than our model requires to fit the kinematical data of the DLAs. This is perhaps not surprising – Razoumov et al. (2008) find that the velocity widths in their simulations fall somewhat short of those observed. Their simulation also takes into account DLAs that are not contained within any halo, that is intergalactic DLAs.

The numerical simulations of Pontzen et al. (2008) show a sharper peak centred on virial velocities of 30–80 km s\(^{-1} \). Such a sharp peak at rather low virial velocities appears, however, at odds with
the observed velocity widths of the associated low-ionization metal absorption. In the simulations of Pontzen et al., the decline of the contribution to the incidence rate with increasing mass is much faster than the decline of the space density of massive haloes. This fast decline is due to a flattening of the absorption cross-section with increasing mass in massive haloes (Pontzen et al., fig. 4). This rather fast decline is the main reason that the numerical simulations are a worse fit to the velocity width distribution than our model. It will be important to investigate if such a fast decline is a robust prediction of the numerical simulations. Note, however, that if this were indeed the case then the distribution of velocity width for a given virial velocity of the DM halo would have to change in order to be able to fit the data.

An observational handle on the masses of the emitters will be important for testing the models further. For this, a detection of the rest frame UV continuum radiation of the objects will be a crucial first step. Knowledge of the continuum emission would allow us to confirm that the emitters are indeed high-redshift galaxies and would give a more reliable measure of the star-formation rate. Unfortunately, the expected continuum emission is very faint and detecting this emission will require imaging to the depth of the Hubble Ultra-Deep Field (Rauch et al. 2008).

5 SUMMARY AND CONCLUSIONS

We have considered an updated version of the Haehnelt et al. model for the kinematics of DLAs, in light of the discovery of a new population of extended low surface brightness Lyα emitters with a total inferred incidence rate similar to that of DLAs. The main differences with the modelling of Haehnelt et al. (2000) are the use of the Sheth–Tormen modification to the Press–Schechter formalism, an update of cosmological parameters, and the use of an exponential suppression of the cross-section for damped absorption for low virial velocities instead of a sharp cut-off.

Our main results are the following.

(i) The observed velocity width distribution of the associated metal absorption can be fitted with a model where the cross-section for damped absorption scales with the virial velocity of the halo as \( \sigma \propto v_c^{2.5} \), the absorption cross-section is suppressed in haloes with \( v_c \leq 50–70 \) km s\(^{-1} \), and the conditional velocity width is given by that in the simulations of Haehnelt et al. (or the very similar distribution of the simulations of Pontzen et al. 2008).

(ii) The same model can fit the cumulative incidence rate for absorption inferred from the size distribution of the Lyα emitters if the Lyα emission has a duty cycle of \( f_d = 0.2–0.4 \), and the emission extends over an area which is larger than the cross-section for damped Lyα absorption by a factor of \( f_d^{-1} = 2.5–5 \).

(iii) The maximum expected Lyα cooling luminosity due to collapsing gas in DM haloes falls short of the observed Lyα luminosities by a factor of 3–5, even for optimistic assumptions regarding the expected emission due to Lyα cooling. Furthermore, the expected dependence of the Lyα cooling luminosity on the virial velocity of DM haloes thereby maps into a luminosity function with a slope shallower than observed. Lyα cooling radiation should thus not contribute significantly to the Lyα emission for the majority of the objects, especially at the faint end of the Lyα luminosity function.

(iv) The Lyα luminosity function is well fit by a simple model where the Lyα luminosity scales linearly with the mass of the DM halo and the emission is suppressed for low mass DM haloes. The Lyα luminosity function can be fitted for a wide range of duty cycles including the duty cycle required to simultaneously explain the kinematic properties of DLAs and the cumulative incidence rate inferred from the observed size distribution of the Lyα emitters.

(v) Our model predicts that the bulk of the contribution to the incidence rate of DLAs comes from absorption systems hosted in DM haloes with virial velocities in the range from 50 to 200 km s\(^{-1} \) and masses in the range \( 10^{10}–10^{12} \) M\(_{\odot} \). The cut-off for damped absorption occurs at somewhat higher virial velocities than suggested by numerical simulations, which attempt to simulate the gas distribution and kinematics of DLAs self-consistently. These simulations, however, fall short of reproducing the observed velocity widths of the associated low-ionization metal absorption of DLAs. If the suppression of the cross-section for damped Lyα absorption in haloes with virial velocities up to 70 km s\(^{-1} \) is indeed real, then feedback due to star formation at high redshift has to be more efficient in removing gas – even from rather deep potential wells – than is assumed in most models of galaxies formation and numerical simulations. Alternatively, the simulation (and our model) may underestimate the effect of stellar feedback on the velocity width of absorbers hosted by DM haloes with small virial velocities. This may not be implausible given the fact that the simulations still fail to reproduce realistic galactic winds.

With the discovery of a faint population of Lyα emitters, most plausibly identified with the population of DL/LL host galaxies, we finally have a handle on their space density, sizes and (in conjunction with models like the one presented here) masses and virial velocities. As discussed extensively by Rauch et al. (2008), the large inferred space density of the population of faint Lyα emitters is similar to that of dwarfs in the local Universe. In the picture that emerges, DLAs are hosted by the galaxies that, in the context of the now well-established ΛCDM paradigm for structure formation, are expected to become the building blocks of typical galaxies like our Milky Way.

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