Damped Lyman alpha systems and galaxy formation models - II. High ions and Lyman limit systems

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ABSTRACT

We investigate a model for the high-ionization state gas associated with observed damped Lyman-α systems, based on a semi-analytic model of galaxy formation set within the paradigm of hierarchical structure formation. In our model, the hot gas in halos and sub-halos is assumed to be in a multi-phase medium which gives rise to CIV absorption, while the low-ionization state gas is associated with the cold gas in galaxies. The model matches the distribution of CIV column densities if we assume that the hot gas has a mean metallicity log C/H = \(-1.5\), which is the observed mean metallicity of damped systems. The same model then leads naturally to kinematic properties that are in good agreement with the data, for both the low- and high-ionization state gas.

We examine the contribution of both hot and cold gas to sub-damped systems \((N_{HI} > 4 \times 10^{19} \text{cm}^{-2})\) and suggest that the properties of these systems can be used as an important test of the model. We expect that sub-DLA systems will generally be composed of a single gas disk and thus predict that they should have markedly different kinematics than the damped systems. We also find that the frequency of absorbers drops dramatically for column densities below \(4 \times 10^{19} \text{cm}^{-2}\). These results are a consequence of our model for damped Lyman-α systems and we believe they are a generic prediction of multi-component models.

Finally, we find that hot halo gas produces less than one third of Lyman limit systems at redshift three. We model the contribution of mini-halos (halos with virial velocities \(\leq 35 \text{km s}^{-1}\)) to Lyman limit systems and find that they may contain as much gas as is observed in these systems. However, if we adopt realistic models of the gas density distribution we find that these systems are not a significant source of Lyman limit absorption. Instead we suggest that uncollapsed gas outside of virialized halos is responsible for most of the Lyman limit systems at high redshift.

Key words: galaxies:formation—galaxies:spiral—absorption systems

1 INTRODUCTION

Semi-analytic models of galaxy formation, set within the hierarchical paradigm of structure formation generic to Cold Dark Matter (CDM) type models, have been very successful in accounting for many of the observed properties of galaxies. Previous investigations have focused on the emission properties of galaxies in optical, infrared, sub-mm and radio wavebands. Some of these successes include matching the Tully-Fisher relationship, the optical luminosity function, the HI mass function, the galaxy correlation function, and the distribution of sizes and Hubble types, both for local and distant galaxies (most recently Somerville & Primack [1999]; Cole et al. [2000], Devriendt & Guiderdoni [2000], Nagashima et al. [2001], Somerville et al. [2001], Springel et al. [2001]).

However, with the notable exception of Kauffmann [1998], these models have not been used to address observations of absorption systems in much detail, though several papers have performed the basic consistency check that the total amount of cold gas in these models is at least as much as that observed in damped Lyman-α (DLA) systems [Baugh et al. [1998], Somerville et al. [2001]]. The importance of utilizing absorption system data to confront galaxy formation models should not be underestimated. The optical properties of galaxies are determined by a sequence of poorly understood physics: star formation, the initial mass function, supernova feedback, metal enrichment, dust, etc. In contrast, absorption systems present an orthogonal means of observing the high redshift Universe, and are subject to
different theoretical uncertainties as well as different observational selection effects. Demanding that a single theory should be able to account simultaneously for the observed properties of both absorption and emission systems therefore presents a stringent test for any theory of galaxy formation.

In this paper, we use a model that has previously been shown to successfully account for the properties of nearby and $z \sim 3$ galaxies identified in emission (Somerville & Primack 1999; Somerville et al. 2001) to develop a parallel picture that can also account for the observed properties of absorption systems. This paper is the second in a series based on this approach. In the first paper (Maller et al. 2003, hereafter paper I), we demonstrated that the kinematic properties of DLA systems (absorption systems with HI column densities $\geq 2 \times 10^{20} \text{cm}^{-2}$) as traced by low-ionization state gas (Prochaska & Wolfe 1997, 1998) could be understood in this context if the gaseous disks of galaxies are very extended, so that a significant fraction of the absorption systems arise from lines of sight passing through multiple disks. We showed that the metallicity and number density of DLA absorbers in this model were also in general agreement with observations. In this paper, we turn our attention to the kinematics of the associated high-ionization state gas and its correlation with the cold neutral gas. The study of the relationship between high- and low-ionization state gas in DLA systems has been pioneered by Wolfe & Prochaska (2000a), who found that none of the models they explored could successfully match their observations.

The basic premise of our model is to associate the highly ionized gas that gives rise to CIV absorption with the hot gas in dark matter halos and sub-halos. Locally, high-ionization state gas like CIV is known to be associated with galactic halos (Chen et al. 2001). Unfortunately, modelling such systems is rather complicated because the gas is likely to be multi-phase (see for example Mo & Miralda-Escude 1996). We do not attempt to model the multi-phase medium in any detail, but rather to ascertain if the amount of hot gas in the galaxy formation model, distributed in a reasonable manner, can produce the observed high-ion kinematics. We find that such a model is fairly successful, suggesting that the general picture is compatible with the combined constraints from the high-ion and low-ion data.

We then explore the contribution of hot and cold gas in our model to lower column density HI systems. We find that cold neutral gas produces sub-DLA systems (column densities of $\sim 4 \times 10^{19} - 2 \times 10^{20} \text{cm}^{-2}$) and we demonstrate how the kinematics of these systems may differ from the higher column density DLAS. We also find in our model that CIV systems with associated low ion absorption have markedly different kinematic properties than those which do not, i.e., kinematic information discriminates between DLA and sub-DLA systems.

Lastly, we find that hot halo gas can produce no more than one third of observed Lyman limit (LL) systems, implying that the majority of these systems are produced by either uncollapsed gas or mini-halos (e.g. Abel & Mo 1998). We model the contribution of mini-halos and find that when we adopt a realistic gas distribution and include an ionizing background, we find that these halos are unlikely to be the source of a large fraction of LL absorbers.

The paper is organized as follows. Section 2 reviews the observations of DLA systems. Section 3 describes the basic ingredients of our model. In Section 4, we compare our model with the observations. In Section 5, we investigate the properties and origin of LL and sub-DLA systems in our model and identify future observational tests of the picture we have proposed. We close with our conclusions in Section 6.

### 2 BACKGROUND

Early on it was established that damped absorption systems are an important probe of galaxies at high redshift (Wolfe et al. 1984). The numerous subsequent studies of DLAS have focussed on their frequency, metallicity, and kinematics. A recent study of the frequency of DLAS is presented by Péroux et al. (2001), and Prochaska & Wolfe (2002) have presented the most recent study of their metallicity. Most of the kinematical data has been obtained by Wolfe and Prochaska in an ambitious program using the HIRES spectrograph (Vogt 1992) on the Keck Telescope. They acquired velocity profiles for a number of metal lines associated with each DLA system. They found that low ionization state lines (e.g. SiII, AlII, FeII) traced one another well and therefore presumably also the cold HI gas (Prochaska & Wolfe 1996). Higher ionization state lines (e.g. SiIV, CIV) showed different but correlated behavior, implying that they traced a different phase of the gas (see also Lu et al. 1996).

Wolfe & Prochaska (1997) introduced four statistics to characterize the gas kinematics: $\Delta v$, the width containing 90% of the optical depth; $f_{\text{rms}}$, the distance between the mean and the median of the optical depth profile; $f_{\text{sig}}$, the distance between the highest peak and the mean, and $f_{\text{dsk}}$, the distance of the second highest peak to the mean of the profile. The last three statistics are suitably normalized to have ranges between 0 and 1 or $-1$ and 1. They also introduced three statistics to quantify the correlations between the high- and low-ion kinematics (Wolfe & Prochaska 2000). These are:

- $\delta v$, the offset between the mean velocity of the high- and low-ionization state gas,
- $f_{\text{ratio}}$, the ratio of the velocity widths of the high- and low-ionization state gas, and
- $\zeta(v)$, the cross-correlation between the two gas states.

Previous semi-analytic modelling within the CDM cosmogony by Kauffmann et al. (1993) suggested that the majority of the cross section to DLAS systems should come from small mass halos with virial velocities between 35 and 50 km s$^{-1}$. Prochaska & Wolfe (1997) investigated a number of models to explain the kinematics of the low ionization state gas. They concluded that the distribution of velocities predicted by Kauffmann et al. (1993) was strongly ruled out by the data. The only model they investigated that was compatible with the data was one in which the absorption systems arose from a thickened, rapidly rotating disk ($V_{\text{rot}} \sim 200 \text{ km s}^{-1}$). Jedamzik & Prochaska (1998) demonstrated that most CDM-based models for galactic disks were incompatible with the observed velocity widths of the DLA systems — under the assumption that a single disk gave rise to each absorption system. Other workers, however, found that multiple component models, in which some of the DLAS were produced by lines of sight passing through
multiple disks or proto-galactic clumps, could explain the low-ion observations within the context of hierarchical structure formation (paper I; Haehnelt et al. 1998). McDonald & Miralda-Escudé (1996) used cosmological hydrodynamical simulations to determine the cross section of DLA and LL systems. They found their simulations could produce the observed number density of DLA and LL systems in a $\Lambda$CDM cosmology if sufficiently small mass halos were considered (60 km s$^{-1}$ for DLA systems and 30 km s$^{-1}$ for LL systems). They found the cross section as a function of halo virial velocity could be fit by a power law with a slope of $\approx 1.6$. However, Prochaska & Wolfe (2001) have pointed out that combining this distribution of cross-sections with the velocity width to virial velocity relationship found by Haehnelt et al. (1998) and in paper I is not compatible with the kinematic data. A slope of 2.5 is needed to produce the correct distribution of velocity widths (Haehnelt et al. 2000) which is consistent with what we found for our model in paper I. The different value found by Gardner et al. is probably due to the fact that there is effectively no feedback in their simulations leading to much higher baryon fractions in small mass halos. In models with efficient feedback we would expect the contribution from these low mass halos to be substantially decreased.

Wolfe & Prochaska (2001) found that none of their models including the thick disk model were consistent with the high-ionization state gas kinematics. They suggested that the multiple component model might be more successful, which we now explore.

Another long-standing question pertaining to QSO absorption systems is their connection with the galaxy population identified in emission. At $z \lesssim 1$, there is compelling observational evidence that metal line and LL absorbers are associated with galaxies (Steidel et al. 1995). Chen et al. 2001). A theoretical model has been proposed by Mo & Miralda-Escudé (1999) wherein these systems are produced by gas clouds in the halos of galaxies. At higher redshifts, it has been proposed that many of the absorbers may reside in mini-halos (Abel & Mc Kee 2000). We also investigate the origin of lower column density systems in the context of our model.

### 3 THE GALAXY FORMATION MODEL

For our analysis we use the semi-analytic model described in Somerville & Primack (1999) and Somerville et al. (2001). The backbone of the model is a Monte Carlo realization of a “merger tree”, which represents the build-up of halos over time through merging and mass accretion. Initially, the hot gas is assumed to be distributed like the dark matter (here, a singular isothermal sphere), to be uniformly at the virial temperature of the halo, and not to have any substructure. The cooling radius (the radius within which gas is dense enough to have cooled) is then calculated using the radiative cooling function for atomic gas in collisional equilibrium. When a halo contains more than one galaxy, gas is assumed to cool only onto the central object. Recent studies (Yoshida et al. 2002, Helly et al. 2003) suggest that this simple model is in good agreement with cosmological hydrodynamical simulations, at least in the absence of feedback. All gas in these simplified models is labelled as either “hot” (at the halo virial temperature) or “cold” ($T \lesssim 10^4$ K).

When halos merge, the central galaxy of the largest progenitor halo becomes the new central galaxy, and all other galaxies become satellites. Satellites lose angular momentum due to dynamical friction and gradually fall towards the center of the halo, where they may eventually merge with the central object.

Cold gas is converted to stars using a simple empirical recipe, at a rate proportional to the total mass of cold gas in the galaxy. Several different recipes were investigated in Somerville & Primack (1999) and Somerville et al. (2001), but here we adopt the “collisional starburst” recipe, which was shown to produce the best agreement with the observed galaxy population at $z \sim 3$, and with the total mass of neutral hydrogen implied by observations of DLAs (Somerville et al. 2001, Primack et al. 2001). In this model, cold gas in isolated disks is assumed to form stars with a low efficiency (similar to that in nearby observed spiral galaxies), while a more efficient starburst mode is triggered by galaxy mergers. Gas that has settled into a disk may be heated and removed by supernova (SN) feedback. The efficiency of the SN feedback is assumed to be inversely proportional to the potential well depth of the galaxy. Each generation of star formation produces a certain yield of heavy elements, which are mixed with the cold gas or ejected by SN into the hot gas halo.

After reionization, cooling only takes place in dark matter halos with virial velocities $v_{vir} > 40$ km s$^{-1}$ because of suppression of gas collapse and cooling by the UV background.

All of our analysis has been done assuming the currently favored $\Lambda$CDM cosmology (e.g., Primack 2002) with $\Omega_m = 0.7, \Omega_b = 0.3, \Omega_{\Lambda} = 0.72$, $h = 0.7$, and $\sigma_8 = 1.0$ and at a redshift of three. The values of the free parameters that control the efficiency of star formation and SN feedback, the chemical yield, etc., are as adopted in Somerville et al. (2001) based on low redshift galaxy observations.

Below we describe in some detail how we incorporate a model for both the low- and high-ionization state gas in absorption systems into this picture. A schematic illustration of the model is shown in Figure 1.

#### 3.1 Low-Ionization State Gas

We assume that the low-ionization state absorption is associated with the “cold” gas component of the galaxy formation model. In paper I, we explored a number of models for the distribution of cold gas in each galaxy and found that only by having very extensive gas disks was it possible to produce enough overlapping cross-section for a line of sight to a distant quasar to pass through multiple disks and thus produce low-ion kinematics in agreement with the observations. We found that a model where the cold gas in isolated disks is assumed to form stars with a low efficiency (similar to that in nearby observed spiral galaxies), while a more efficient starburst mode is triggered by galaxy mergers. Gas that has settled into a disk may be heated and removed by supernova (SN) feedback. The chemical yield, etc., are as adopted in Somerville et al. (2001) based on low redshift galaxy observations.

1 The virial velocity is just the circular velocity at the virial radius, which for isothermal spheres is the circular velocity everywhere.
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Figure 1. Gas in a typical halo at z = 3 seen in projection. The filled ellipses are cold neutral gas disks, while the solid circles mark the edge of the spherically distributed hot gas in subhalos. The entire halo is also filled with hot gas out to the virial radius (the dashed line). Three lines of sight through the halo illustrate how different components can give rise to DLA, sub-DLA and LL systems in our model (see section 5).

\[ N_t = 4 \times 10^{19} \text{ cm}^{-2}, \] produced absorption systems consistent with the low ion kinematics observed by Prochaska & Wolfe (1997, 1998), as well as with the observed \( f(N) \) distribution and metallicities of DLA systems (see paper I for more details).

We take the vertical \( (z) \) distribution of the cold gas to be exponential with a scale length \( z_s \) such that the disks are thin. Thus the gas distribution for each galaxy is given by

\[ \rho(R, z) = \frac{N_t}{2 z_s} \frac{R}{R_t} e^{-|z|/z_s} \quad (R < R_t). \]  

We distribute the cold gas in 10 clouds to properly sample the velocity field. Each cloud is given a small, 1D random velocity of \( \sigma_{\text{vel}} = 10 \text{ km s}^{-1} \).

We refer to the cold gas as being in “disks”, and we implicitly assume that the cold phase is concentrated and rotationally supported when implementing the star formation recipes. However, for the purposes of the kinematic modeling, the cold gas need not be rotationally supported — by disks we simply mean flattened systems. We emphasize that this description is a crude simplification of the distribution and dynamics of cold gas in real galaxies, especially in interacting galaxies, which show rather complex behavior.

\[ f(N) \] is the number of absorption systems with column densities between N and N+4dN found per comoving path length.

In the spirit of semi-analytic models, it is our hope that such a simplified description can still capture the general behavior of the cold gas when averaged over a large number of systems.

### 3.2 High-Ionization State Gas

The high-ionization state absorption is assumed to arise from the hot gas in halos. In the standard galaxy formation model, all the hot gas is assumed to be at a single temperature and only a single gas phase is considered. These simplifications may be reasonable for calculating the cooling rate of the gas, but for describing kinematics we will need to consider the substructure of the hot gas, and we will assume that the majority of it is in a phase suitable for CIV absorption, in general at temperatures less than the virial temperature of the halo. We will continue to refer to this as hot gas because it is dynamically hot even if parts of it have cooled.

To compare to the observations we must convert the hot gas mass to a CIV column density, \( N_{\text{CIV}} \). The column density of CIV along a line of sight is related to the column density of hydrogen by

\[ N_{\text{CIV}} = f_{\text{CIV}} Z_{\text{hg}} N_H, \]  

where \( Z_{\text{hg}} \) is the metallicity of the gas and \( f_{\text{CIV}} \) is the fraction of the gas in a state that produces CIV absorption. The column density in HI is related to the total amount of hydrogen by

\[ N_H = (1 - x) N_{\text{HI}}, \]  

where \( x \) is the ionization fraction of the gas. The quantities \( x, f_{\text{CIV}} \) and \( Z_{\text{hg}} \) can vary locally in the gas, but we will assume that suitably averaged quantities can be defined to give the global relationships we use here.

We emphasize that only the metal lines in the systems are measured, which creates an inherent degeneracy between the total amount of gas, its metallicity and its ionization state. For simplicity we will treat the ionization state and metallicity to be uniform within each halo and therefore \( N_{\text{CIV}} \) is directly proportional to \( N_H \). The reader should bear in mind however that an increase in \( N_H \) can equally well be thought of as an increase in \( f_{\text{CIV}} \) or \( Z_{\text{hg}} \). We well return to this issue in §.

For simplicity we take \( f_{\text{CIV}} = 1 \), noting that a smaller value of \( f_{\text{CIV}} \) can be directly offset by an increase in the hot gas metallicity. We fix \( Z_{\text{hg}} \) to be −1.5 dex for all hot gas in all halos, which produces a good match to the CIV column density distribution in DLA systems as measured by Wolke & Prochaska (2002). The mean metallicity of DLA systems at \( z > 2 \) is \( \approx -1.5 \text{ to } -1 \text{ dex} \) (Prochaska & Wolfe 2000), which is consistent with our assumed \( Z_{\text{hg}} \). However, because of the degeneracy mentioned above, this value is directly proportional to our choice of \( f_{\text{CIV}} \). Thus this can be thought of as a minimum metallicity since \( f_{\text{CIV}} \leq 1 \). A realistic estimate of \( f_{\text{CIV}} \) might be \( \approx 0.35 \) which would then require \( Z_{\text{hg}} \approx -1.0 \text{ dex} \). Alternatively, the hot gas metallicity could be lower if there is more hot gas in halos than calculated by our simple recipes.

The galaxy formation code calculates the metallicity of the hot gas as part of the chemical enrichment model described briefly above. We find that if we use the metallicities calculated in this way (which typically show a large scatter at fixed halo mass), we obtain too large a spread in the CIV absorption.
column density distribution. This is not too disturbing, as the modelling of the reheating and ejection of metals by supernova feedback is extremely uncertain. The galaxy formation model was calibrated to produce the correct mean observed stellar, cold gas, and hot gas metallicities in z = 0 galaxies and clusters, but this is no guarantee that it produces the correct results for these quantities at z = 3, or the correct dispersion in the mass-metallicity relation.

However, it is also possible that correlations between $f_{\text{CIV}}$, $Z_{\text{hg}}$ and the gas density conspire to reduce the spread in observed CIV column densities. An example of this kind of conspiracy would be a starburst which produces high metallicity in the hot gas but also reduces the hot gas mass density or changes the ionization state of the gas such that CIV is no longer the preferred ionization state of carbon. Unfortunately, the large number of uncertainties mean that few constraints can be placed on any aspect of the modelling that goes into determining CIV column densities. We discuss constraints that can be placed on these quantities in section 4.

We will assume that the hot gas is distributed like the dark matter, i.e. density proportional to $r^{-2}$. For our kinematic study we would like to consider hot gas associated with each galaxy in the halo, while in the galaxy formation model, all hot gas is assumed to be associated with the central galaxy. To do this we assume that the hot gas in each subhalo is related by a parameter $f_{\text{sub}}$ to the total amount of dark matter in the subhalo. Thus the mass of hot gas, $m_{\text{hg}}$, in a given subhalo is

$$m_{\text{hg}} = f_{\text{sub}} M_{\text{dm}} M_{\text{hg}} M_{\text{dm}}$$

where $m_{\text{dm}}$ is the dark matter mass of that subhalo and $M_{\text{hg}}$ and $M_{\text{dm}}$ are the total mass in hot gas and dark matter respectively, summing over all subhalos and the parent halo. The remaining hot gas is then associated with the parent halo. In our realizations we find that subhalos can contain up to 2/3 of the halo mass, requiring $f_{\text{sub}}$ to have values between 0 and 1.5. In the case that $f_{\text{sub}} = 0$, there is no hot gas associated with the subhalo and our high-ion model is similar to the one explored in Wolfe & Prochaska (2002).

We note that this is far from a model of the hydrodynamics of the hot gas in the halo, which is rather difficult to model especially including the poorly understood physics of supernova feedback. A successful model of gas in the halo of the Milky Way, where there is plentiful data, still eludes researchers (Collins et al. 2002), so we must accept that at the present moment we can only hope to sketch a rudimentary framework of the situation at high redshift.

For the purpose of simulating spectra we assume that a fraction $f_{\text{CIV}}$ of the hot gas is no longer at the virial temperature but has cooled into pressure confined clouds and is photoionized with a temperature $\approx 5 \times 10^4 \text{degK}$. We use 15 clouds to properly sample the velocity field and assume clouds have random velocities, $\sigma_{\text{CIV}}$, proportional to the halo’s circular velocity (see Table 1).

We compare our model only to the CIV data which best samples the hottest phase of the gas. The fact that there are some differences in the high-ion kinematics between ions (Prochaska & Wolfe 2002, e.g. SiIV vs. C IV) implies variations in the ionization state or metallicity of the gas. Future modelling of this may help us to understand metallicity, density and ionization gradients in the hot gas.

### 3.3 Mini-halo Model

Mini-halos ($v_{\text{vir}} \lesssim 35 \text{ km s}^{-1}$) are usually not considered in discussions of galaxy formation because their expected luminosities make them difficult to observe. However, Abel & Mo (1998) have shown that there may be sufficient cold gas in mini-halos at high redshift to comprise the LL systems at those redshifts.

Recently the issue of mini-halos has also been widely addressed because of what has been named the dwarf satellite problem; the fact that N-body simulations expect hundreds of mini-subhalos in a Milky Way sized halo (Klypin et al. 1999; Moore et al. 1999), but only a couple dozen or fewer are observed. While many exotic solutions to this problem have been proposed, the simplest is that the extragalactic UV background suppresses the accretion and cooling of gas in these mini-halos, and therefore stars form in only the small number that managed to collapse before the epic of reionization. Models of this scenario (Bullock et al. 2000; Benson et al. 2002; Somerville 2002) have been fairly successful in explaining why only a small fraction of mini-subhalos would have formed stars.

To explore the contribution of mini-halos to LL systems we use the squeezing model of Somerville (2002) to determine the amount of hot and cold gas in mini and low-mass (35 km s$^{-1}$ $> v_{\text{vir}} > 50 \text{ km s}^{-1}$) halos. This model uses a fitting function found by Medling (2003) in hydrodynamical simulations to determine the amount of gas that can accrete onto a dark matter halo in the presence of an ionizing field.

We assume that gas will only contract to density profiles steeper than the dissipationless dark matter. Therefore to explore the maximal contribution of these halos to LL systems, we take their projected density profiles to go as $R^{-1.1}$ like the cold gas disks and hot gas in galaxies described above (equation 1). We truncate the gas at the virial radius or we consider cases where the gas is truncated at a specified column density, $N_t$. In the latter case the truncation radius can then be evaluated by

$$R_t = \sqrt{\frac{M_{\text{gas}}}{2\pi N_t m_H}}$$

where $m_H$ is the mass of the hydrogen atom.

### 4 RESULTS

We pass multiple random lines of sight through each halo to produce Monte-Carlo realizations of spectra in the manner described in paper I. Enough realizations are performed to give us at least 10,000 sight lines with DLA systems in them.

Figure 2 shows the distribution of CIV column densities associated with DLA systems produced in our model. We see that the model distribution is in good agreement with the observations. We chose the hot gas metallicity ($\approx 1.5$ dex) so that the bottom range of log column densities is about 12.5 as seen in the data. The highest bin contains all systems with log column densities greater than 14.8 as this is where the CIV doublet becomes saturated and only lower limits on the column density can be determined. Of course we expect
that there is some spread in the hot gas metallicities. If we take $Z_{hg}$ to be distributed as a Gaussian in log metallicity then a mean of $-1.5$ dex and a standard deviation of 0.5 is in equally good agreement with the observations.

We can place a lower limit on the amount of hot gas in galactic halos needed to match the $N_{\text{CIV}}$ distribution by taking the highest reasonable values for $f_{\text{CIV}}$ and $Z_{hg}$. Since we have already started with the maximum value of $f_{\text{CIV}}$, the only way to lower the amount of hot gas is to increase the metallicity, $Z_{hg}$. If we believe that $Z_{hg}$ must be less than a third solar then we could get the same results with one tenth the mass of hot gas. Any model with less than this amount of hot gas would have difficulty producing enough CIV absorption.

Figure 2 shows the results for the most important kinematic characteristics of the high-ion gas: $\Delta v_{\text{low}}$, $\Delta v_{\text{CIV}}$, $\delta v$, and $f_{\text{ratio}}$ (see Section 2 for definitions of these quantities). We show the results for five variants of our model (a-d, and d+), summarized in Table 1. In the first four models we vary the parameters $\sigma_{\text{CIV}}$ and $f_{\text{sub}}$ as detailed in Table 1. All four models produce acceptable fits to the kinematic data and none of them can be rejected with high confidence. The statistical tests are sensitive to complimentary aspects of the DLA kinematics and place relatively tight constraints on the model parameters. For example, increasing $\sigma_{\text{CIV}}$ (model b) improves the $f_{\text{ratio}}$ but lowers the value of the $\Delta v_{\text{CIV}}$ statistic. Making the gas more clumped in subhalos (model d) improves the agreement with the observations but we cannot rule out a model with no clumping (model c).

Previous attempts by Wolfe & Prochaska (2000b) to model the high-ion gas of the DLA failed for scenarios involving a cold, rotating disk surrounded by a hot gas halo.

Figure 3 shows the results for the most important discriminatory tests are shown for high and low ions. These are the $\Delta v_{\text{low}}$, $\Delta v_{\text{CIV}}$, $\delta v$ and $f_{\text{ratio}}$ tests. Results are shown for four models where the parameters $\sigma_{\text{CIV}}$ and $f_{\text{sub}}$ have been varied (see Table 1). Also included is a model (d+) where we have added an additional source of CIV absorption associated with the cold gas disk. All the models are consistent with the observations. Increasing $f_{\text{sub}}$ and the addition of some CIV absorption in the gas disk improves the models’ agreement, but not drastically. Adjusting other parameters like $\sigma_{\text{CIV}}$ can improve one statistic ($\Delta v_{\text{CIV}}$ in model b) but at the expense of another statistic ($f_{\text{ratio}}$).

In short, the rapidly rotating disks favored by the low-ion kinematics lead to a bimodal distribution of $\delta v$ which is ruled out at a high confidence level by the DLA observations. The source of this inconsistency is the fact that the hot gas velocity field is centered at the rest-frame velocity of the halo while the rotating cold gas has a preferred velocity of $\sim \pm v_{\text{vir}}/2$. This offset between the cold disk gas and hot halo gas is not found in the observed $\delta v$ distribution. For the disks in our model, this offset also applies. The key differences between our model and the single disk models with respect to this issue are:

1) the rotation speeds of the SAM disks are considerably smaller than the $v_{\text{vir}} \sim 200$ km/s required by single disk scenarios (Prochaska & Wolfe 1998); and

2) the centroids of the hot and cold gas velocity fields converge as the number of disks intersected along a sight line increases.

While a large range of parameters (Table 1) lead to acceptable models, the agreement with the $\delta v$ statistic is
Table 1. Five models where the parameters $\sigma_{CIV}$ and $f_{sub}$ are varied. In the d+ model CIV absorption associated with the cold gas disk is included. The last four columns give the KS probability that the model is consistent with the data. All five models produce acceptable matches to the data. The d+ model produces significantly better agreement with the $\delta_v$ statistic than the other models.

![Table 1](http://example.com/table1.png)

Figure 4. The cross-correlation, $\zeta(v)$, between high- and low-ionization state gas. The solid line is for the data while the other line types are for the five models listed in Table 1. We see that the first four models show good agreement with the data down to velocities of 50 km s$^{-1}$ but then become less correlated than the data. By adding a high-ion component that rotates with the low-ion gas (model d+), we increase the correlation at small velocity differences, obtaining a better fit to the observed $\zeta(v)$ and leading to an improvement in the $\delta_v$ test.

![Figure 4](http://example.com/figure4.png)

5 SUB-DLA AND LL SYSTEMS

We have investigated the properties of DLA systems and the CIV absorption associated with them. Our model also makes predictions relating to gas that is below the DLA column density limit of $\log(N_{HI}) = 20.3$. It has been observed locally that gas disks are truncated at column densities of a few $\times 10^{19}$ cm$^{-2}$, which has been attributed to photoionization by extra-galactic UV radiation (Corbelli & Salpeter 1993; Maloney 1993). We have found that when we truncate our disks at $4 \times 10^{19}$ cm$^{-2}$, our model produces good agreement with the kinematic data at $z \approx 3$. One would expect the column density at which gaseous disks are truncated to decrease from $z = 3$ to the present as the intensity of the UV background drops.

Systems with log column densities less than 20.3 but greater than 19.0 have been referred to as sub-DLA systems (Péroux et al. 2001). We suggest that sub-DLAS should refer to cold neutral systems like DLA and therefore should have column densities greater than a few $\times 10^{19}$ cm$^{-2}$. The cutoff is probably a function of redshift as the strength of the UV background and/or density of the gas disks varies. Measurements of the ion abundances in these systems should be able to tell us where the systems make a transition from cold neutral gas to photo-ionized gas. For now we will adopt a value of $4 \times 10^{19}$ cm$^{-2}$ as the lower limit of sub-DLA systems to be consistent with the column density at which we truncate our gas disks in our model.

At lower column densities, LL systems must arise from something other than cold neutral gas. Lines of sight through galactic halos that fail to intersect cold neutral gas may give rise to LL systems (see Figure 3). It is also possible that LL systems are produced by uncollapsed gas not in virialized halos, or gas in mini-halos.

5.1 The contribution from mini-halos

Figure 3 shows the number per unit redshift $dN/dz$ of mini-halos as a function of $v_{vir}$. We see that the cross section for encountering a halo with a virial velocity in the range...
10 − 50 km s$^{-1}$ at $z = 3$ is 10 times as large as the observed dN/dz for LL systems.

As we have discussed, halos in this velocity range will have difficulty in accreting and cooling gas in the presence of a UV background. However, mini-halos which collapse before reionization may contain cold gas. If we assume that the cold gas in these systems extends out to the virial radius of the halo we obtain dN/dz = 3.7 (the dashed line in Figure 5). This is consistent with the results of Abel & Mc (1998).

It requires that the cold gas remain neutral at column densities far below $10^{19}$ cm$^{-2}$, which is probably unrealistic. If instead the cold gas is truncated at $10^{19}$ cm$^{-2}$ then we obtain dN/dz = 0.3, a negligible contribution to LL systems.

In this case, the mini-halos would account for more than half of the systems with $N_{HI} > 10^{19}$ cm$^{-2}$, but it is unclear why the truncation value for mini-halos should be less than that of galactic halos.

An examination of the hot gas in mini-halos leads to similar results. If the hot gas is taken to be neutral and to extend out to the virial radius then it has a rather high rate of incidence dN/dz = 4.7. However, once again it is difficult to understand why this gas would not be highly ionized.

In hydrodynamic simulations of mini-halos, Peroux et al. (2001) found that at maximum the HI column density only exceeds the Lyman limit threshold out to a radius less than one ninth the virial radius. If we assume that the hot gas is uniformly 99% ionized then dN/dz < 0.06.

Thus it seems that cold gas in mini-halos may contribute to sub-DLA systems but that in realistic scenar-

5.2 The contribution from hot gas in galactic halos and uncollapsed gas

The hot gas in halos which produces the high-ion gas in DLA and sub-DLA systems will also generate LL systems in lines of sight that do not intersect cold gas. The frequency of lines of sight that intersect hot gas in our model is only 0.78 per unit redshift, well below the observed number density of 2.0 ± 0.5 for LL systems. Furthermore the hot gas is highly ionized so that depending on the ionization fraction $x$ these systems may not have a high enough column density to be LL systems.

Prochaska (1999) has observed that $x = 0.97 ± 0.02$ in a LL System. If we assume that $x$ is within this range for the hot gas in halos then the resulting column density distribution is shown in Figure 5. The dashed line and the dot-dashed line show the distribution taking $x$ of 0.95 and
0.99 respectively. Column densities have only been measured for DLA systems, Péroux et al. (2001) has extrapolated the distribution to lower column densities assuming the distribution can be fit by a gamma function and constrained by the total number of LL systems. This is shown in Figure 6 by the dotted line. There is a tremendous drop (a factor of 100) in the number of absorbers after the cold gas truncation level. Of course a different source of absorbers may compensate for this drop, yet it seems unlikely that they would exactly cancel the drop caused by the truncation of cold gas disks. More data in this regime would be very helpful in clarifying the physical nature of the absorption systems.

Since there does not seem to be enough cross section to produce the observed number of LL systems in either galactic halos or mini-halos, we must infer that the majority of LL systems are likely to be associated with uncollapsed gas in the vicinity of galactic halos. This is consistent with the results of Davelo et al. (1999), who found that in a hydrodynamic CDM simulation, systems with column densities of \( \sim 10^{17} \text{ cm}^{-2} \), typical of LL systems, are produced in regions with overdensities of \( \sim 100 \) at \( z = 3 \). One can see from these simulations that these systems tend to reside in the weakly non-linear filaments surrounding halos. This gas may be enriched by material ejected by supernovae from the halos and will probably have velocity widths riched by material ejected by supernovae from the halos and non-linear filaments surrounding halos. This gas may be en-simulations that these systems tend to reside in the weakly non-linear regime in more detail.

More data are required to identify the origin of LL absorbers at high redshift and it is quite possible that hot gas in galactic halos, cold gas in mini-halos, and uncollapsed gas around halos all play a non-negligible role. Studies of the ionization state of the gas, its column density distribution and its kinematics will help identify the nature of these absorption systems.

5.3 The kinematics of sub-DLA systems

A kinematic investigation of sub-DLA systems provides a generic, direct test of the multiple component model. In any multiple component model, most lines of sight pass through only a single component. The only way for DLA systems to be dominated by multiple components is for the column density of a single component to be below the DLA cutoff. This means that at some lower column density (sub-DLA) the absorption systems must become dominated by single component encounters. In our model this happens at H I column densities less than \( 10^{20} \text{ cm}^{-2} \), as shown in Figure 7. This figure shows the fraction of absorption systems produced by more than one gas disk as a function of column density. The sub-DLA systems are very different below a log column density of 20. They are almost entirely composed of single disk systems. Thus we expect a significant change in the measured kinematics for these lower column density systems. The difference in the measured \( \Delta v \) for the low ions is shown in the upper two panels of Figure 8. One sees the transition to many more small \( \Delta v \) systems. Observing the low-ion \( \Delta v \) in these systems should be a direct test of the multiple component model.

O’Meara et al. (2001) have studied a system at \( z = 2.5 \) with a log column density of 19.4. This system is neutral and thus by our definition should be referred to as a sub-DLA system even though its column density is less than the truncation value we use in our model. The system has very simple kinematics clearly indicating it is a single component system; however, it was also selected for its simple kinematics to study deuterium so it is unclear if it is representative of the population. An unbiased investigation of systems like this one is needed to test the multiple-component scenario.

The strong trend with column density seen in our model may be an artifact of the fact that we have rather artificially truncated all gas disks at the same value. A spread in values would tend to weaken the effect; nevertheless, the trend should exist for any multiple component model for DLA systems because such a model must always have a larger cross-section to single encounters than multiple encounters. Thus we believe the kinematics of sub-DLA systems is a critical test of the multiple component model.

A similar effect would be predicted for CIV profiles if they are composed of multiple components. Again, lines of sight through single components are preferentially lower column density systems. The case of \( f_{\text{sub}} = 1 \) is shown the right side of Figure 7 for CIV associated with DLA and sub-DLA systems and for CIV with no associated low ions. The large difference in systems with column densities between 13.5 and 14.5 suggests that it may be possible to identify which systems contain cold neutral gas from the CIV kinematics.
6 CONCLUSIONS

We have presented a model for the high-ionization state gas seen in DLA systems, based on a galaxy formation model set within the hierarchical structure formation paradigm. The basis of this model is to associate hot halo or sub-halo gas with the highly ionized gas that gives rise to CIV absorption. Assuming a simple model for the hot gas distribution, we generate absorption systems with kinematic properties in reasonable agreement with observations of DLAs at $z = 3$. We thus conclude that a CDM-based galaxy formation model can also account for both the low- and high-ionization state gas in observed DLA absorption systems. Agreement with the data is not a strong function of any free parameter of the model and thus we conclude that the general concept of a spherical hotter component as the source of CIV absorption provides a viable explanation for the observed kinematic properties. Associating some hot gas with subhalos and including a CIV component in co-rotation with the low ionization state gas improves the agreement, but models without these features cannot be categorically ruled out.

While the galaxy formation model provides the information about the amount of hot and cold gas present in a given halo, our model requires a number of additional assumptions about the gas distribution. The most striking is our requirement that the cold gas be in a rather extended configuration (paper I). Also, in order for our model to work, we require that the gas termed “hot” in the semi-analytic model is in the form of clouds in a two-phase medium (as in Mo & Miralda-Escude [1996]). This is clearly beyond the level of detail that semi-analytic galaxy formation models or hydrodynamic simulations currently attempt to address.

Our model produces good agreement with the observed distribution of CIV column densities under the assumption that hot gas is distributed like the dark matter and that the fraction in a state suitable for CIV absorption $f_{CIV}$, and the metallicity, $Z_{hg}$, are uniform throughout the halo. While this description has the advantage of simplicity, it is unlikely to be correct. The fact that the different high-ionization species do not always trace one another implies that $f_{CIV}$ and $Z_{hg}$ vary throughout the gas. We found that a model in which a larger fraction of the gas was associated with sub-halos produced better agreement with the observations, but an alternative scenario in which the subhalo gas possesses higher values of $Z_{hg}$ or $f_{CIV}$ might provide a better explanation. The other high-ionization state metal lines may be used in future studies to help constrain the distributions of gas density, metallicity and ionization state in high redshift halos.

We also explored the predictions of our model for the lower column density sub-DLA and LL systems. We suggest that the kinematics of sub-DLA systems may be a decisive test of the multiple component model. Any multiple component model must have a large cross-section to single component intersections. Most sub-DLA systems should be produced by lines of sight passing through a single disk and therefore they should have significantly different kinematics than the DLA systems. This will also be true for CIV systems if the hot gas is clumped into subhalos. Finally, we expect a large drop in the number of absorption systems...
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with column densities below the level where our gas disks are truncated, an additional test of the model.

We find that in our model, only about a third of the observed population of LL systems are produced by hot gas in halos. We furthermore find in agreement with Abel & Mo (1998) that there is enough cold gas in mini-halos to produce all of the LL systems at $z = 3$ and that there is also a similar amount of hot gas in these halos. However if we adopt a realistic model of the gas in mini-halos, we find that they produce an almost negligible contribution to the cross-section of LL systems. This is because to cover a large area the gas must have a low column density and therefore will be photoionized by the UV background. Having high enough column densities to be self shielding implies the cross-section is small and therefore not a significant source of LL systems.

We therefore propose that gas surrounding halos but outside the virial radius (e.g. in filaments) may give rise to LL systems, a view supported by the hydrodynamical simulations of Davé et al. (1999). If this gas is pre-enriched or enriched by metals ejected from the halo it may also produce metal line systems. Further investigations using hydrodynamical simulations will be useful in studying uncollapsed gas outside of virialized halos and determining its contribution to absorption systems.

We have illustrated that absorption systems comprise a powerful probe of galaxy formation. Acquiring more data of this kind, and developing more detailed models of these systems, will help in forming a complete picture of the properties of the gas present in the early epochs of galaxy formation, which form the building blocks of the galaxies that we see today.

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