DAMPED LYMAN ALPHA SYSTEMS AND GALAXY FORMATION

H. J. Mo\textsuperscript{1} and J. Miralda-Escudé\textsuperscript{1,2}

\textsuperscript{1} Institute of Astronomy
Madingley Road, Cambridge, CB3 0HA, UK

\textsuperscript{2} Institute for Advanced Study
Olden Lane, Princeton, NJ 08540

submitted to ApJL, \textit{Received:} 1994, ........

\textbf{ABSTRACT}

We examine the constraints on theories of galaxy formation that are obtained from observations of damped Ly\textalpha (DL) systems, assuming they are gaseous protodisks in dark matter halos. Using the Press-Schechter formalism, we find that the mixed dark matter model, with $\Omega_{\text{HDM}} = 0.3$, $\Omega_{\text{CDM}} = 0.65$, $\Omega_b = 0.05$, and $h = 0.5$, is ruled out because the number of galactic halos at $z \simeq 3$ is too small to account for the total gaseous mass in DL systems, even under the assumption that all the gas in collapsed halos has settled into disks of neutral gas. The standard CDM model can account for the gas in DL systems if the bias is $b \lesssim 2$; the same is true for the CDM model with a cosmological constant, if $b \lesssim 1.5$ for $\Lambda = 0.8$. However, one still needs to assume that a fraction $\gtrsim 0.4$ of the baryons in collapsed halos at $z \simeq 3$ is in the form of neutral gas in disks. We also calculate the column
density distribution \( f(N_{\text{HI}}) \) of the DL systems, in terms of the surface density profiles of disks and the distribution of their central column densities. It is shown that the form of \( f(N_{\text{HI}}) \) at the high end of column density is a diagnostic for the nature of DL systems.

*Subject headings:* galaxies: formation - QSO: absorption lines - cosmology
1. INTRODUCTION

Damped Ly\(\alpha\) absorption systems are, at present, the best observational probe we have to study galaxy formation and evolution at high redshift (see Wolfe 1993). The observed systems are selected only because they lie on the line-of-sight to an unrelated quasar, rather than from any special property such as a high optical or radio luminosity. Thus, damped systems are probably the progenitors of typical galaxies. In this paper, we show that the observations of DL systems can be used as a constraint for models of galaxy formation. In \S 2 we discuss how the column density distribution of DL systems can be used to infer the typical central column densities of the objects producing them. In \S 3 we investigate the number of DL systems and the total gaseous mass they contain, as predicted by currently favored models of galaxy formation. The results are discussed in \S 4.

2. THE COLUMN DENSITY DISTRIBUTION FOR DISKS

In this section, we calculate the column density distribution of DL systems that results from thin disks of HI gas. We write the surface HI density profile of a disk as

\[
\Sigma(r) = \Sigma_0 F(r/r_0),
\]

where \(r\) is the radius on the disk, \(\Sigma_0\) is the central surface density, and \(r_0\) is a typical scalelength; the function \(F(r/r_0)\) is a decreasing function of \(r\), and is normalized to \(F(0) = 1\). If the normal to a disk is inclined to an angle \(\theta\) with respect to the line of sight, the cross section for intersecting the disk at radius \(r\) is \(2\pi r \, dr \, \cos(\theta)\), and the column density observed is \(N_{\text{HI}} = N_0 \, F(r/r_0) / \cos(\theta)\). For randomly oriented disks, \(\cos(\theta)\) is uniformly distributed, and the total cross section for intersecting a
disk with column density larger than \( N_{\text{HI}} \) is

\[
\sigma(N_{\text{HI}}) = 2\pi \int_0^\infty r \, dr \int_0^a \cos \theta \, d\cos \theta,
\]

where \( a = \min[1, N_0 F(r/r_0)/N_{\text{HI}}] \). Differentiating with respect to \( N_{\text{HI}} \), we obtain:

\[
\frac{d\sigma}{dN_{\text{HI}}} = \frac{2\pi r_0^2 N_0^2}{N_{\text{HI}}^3} \int_{x_1}^{\infty} xdx[F(x)]^2,
\]

where \( x_1 \) is given by \( F(x_1) = \min[1, N_{\text{HI}}/N_0] \).

If the number density of systems of central column density between \( N_0 \) and \( N_0 + dN_0 \) is \( n(N_0, z) \, dN_0 \), then the number of absorption lines found per unit redshift and per unit column density is

\[
f(N_{\text{HI}}, z) = \frac{dl}{dz} \int \frac{d\sigma}{dN_{\text{HI}}} n(N_0, z) \, dN_0,
\]

where \( l(z) \) is the comoving distance at redshift \( z \) (see Sargent et al. 1980). If the systems have a distribution of scalelengths, then one simply needs to substitute \( r_0^2 \) in equations (3) by its average for all systems of a fixed central column density. When the column density \( N_{\text{HI}} \) is higher than \( N_0 \) for all the disks, then the HI column density distribution will be

\[
f(N_{\text{HI}}) \propto \left( \frac{N_0}{N_{\text{HI}}} \right)^3
\]

(see Barcons & Fabian 1987) independently of the forms of \( F \) and \( n \). For lower column densities, the \( N_{\text{HI}} \) distribution depends on the profiles \( F(r/r_0) \) and the distribution of \( N_0 \). For exponential disks with \( F(r/r_0) = \exp(-r/r_0) \), and \( N_0 = \text{const.} \), the HI column density distribution for \( N_{\text{HI}} < N_0 \) is

\[
f(N_{\text{HI}}) \propto \frac{N_0}{N_{\text{HI}}} \left[ 1 + \ln \left( \frac{N_0}{N_{\text{HI}}} \right)^2 \right].
\]
In Figure 1, we show the observed HI column density distribution, \( f(N_{\text{HI}}) \) taken from Lanzetta et al. (1991) and Tytler (1987). The curves are the distribution function derived for exponential disks from equations (3), assuming that \( N_0 \) is the same for all disks, for the cases \( N_0 = 10^{21}, 10^{21.5}, 10^{22}\text{cm}^{-2} \). The amplitudes of the curves are fitted to the observed points.

At present, the central surface brightness of normal galaxies are remarkably constant, with the value \( \sim 140L_{\odot}\text{pc}^{-2} \) (Freeman 1970), or a column density \( \sim 10^{23}\text{proton cm}^{-2} \) assuming a mass-to-light ratio \( \Upsilon \sim 5\Upsilon_{\odot} \) for disks. If the DL systems have similar surface densities in gas, no steepening of the distribution of \( N_{\text{HI}} \) should have been observed yet. But if most DL systems had much lower central column densities, a turnover of \( f(N_{\text{HI}}) \) could be present in the observed range. In fact, if the gaseous disks at high redshift had profiles similar to the present HI disks, a turnover should already have been observed (see Rao & Briggs 1993). The point in Figure 1 at the highest column density may be an indication of such a turnover, and therefore of a large number of disks with \( N_0 \simeq 10^{21.5} \) at high redshift. The statistics, however, are not yet conclusive.

3. CONSTRAINING MODELS BY THE OBSERVATION OF DL SYSTEMS

According to most current models, the formation of structure in the universe occurred through the growth of small inhomogeneities via gravitational instability. In this scenario, galaxies are assumed to form by cooling and condensation of gas in the potential wells of dark halos (e.g., White & Rees 1978). In this section we use the Press-Schechter formalism (Press & Schechter 1974) to estimate the abundance of dark halos in different models. We then combine this with some plausible assumptions on galaxy formation to predict the observed number of DL
systems and the gaseous mass they contain.

We consider three different models for the formation of structure. Model 1 is the standard CDM model, with \( \Omega_{\text{CDM}} = 0.95, \Omega_b = 0.05 \) and \( h = 0.5 \) (here and in the following we adopt a baryon density parameter \( \Omega_b = 0.0125 \) from primordial nucleosynthesis, where \( h \) is the Hubble constant \( H_0 \) divided by 100 km s\(^{-1}\)Mpc\(^{-1}\), see Walker et al. 1991). Model 2 has a cosmological constant \( \Omega_\Lambda = 0.78, \Omega_{\text{CDM}} = 0.2, \Omega_b = 0.02 \) and \( h = 0.8 \); we call this model CDM\( \Lambda \). In both of these models, we use the fit to the CDM power spectrum in equation (G3) of Bardeen et al. (1986). Model 3 (called MDM; mixed dark matter) has \( \Omega_{\text{CDM}} = 0.65, \Omega_{\text{HDM}} = 0.3, \Omega_b = 0.05 \) and \( h = 0.5 \). For this model we use the power spectrum in equation (1) of Klypin et al. (1993). The biasing parameters are varied for all models, and are chosen to bracket values currently favored by observations. These three models are of special interest in the “post-COBE” epoch of cosmogony (see Bond 1993 for a review).

In the Press-Schechter formalism, the comoving number density of halos as a function of halo mass \( M \) and redshift \( z \) can be written as

\[
n(M, z) \, dM = \frac{3}{(2\pi)^{3/2} r_0^3 \Delta^2(r_0, z)} \exp\left[-\frac{\delta_c^2}{2\Delta(r_0, z)}\right] \frac{d\Delta(r_0, z)}{dM} \, dM ,
\]

where \( M \) is the mass in a top-hat window with radius \( r_0 \) (comoving radius in present unit): \( M = 4\pi \rho_0 r_0^3/3 \), with \( \rho_0 \) being the present cosmic mass density in matter. The quantity \( \Delta(r_0, z) \) is the rms mass fluctuation in a top-hat window with comoving radius \( r_0 \), linearly evolved to redshift \( z \), and is determined by the initial power spectrum. The threshold \( \delta_c \) is chosen to be 1.68 irrespective of models (see White et al. 1993 for a discussion). Assuming the spherical collapse model, one can define a virialized radius, \( r_{\text{vir}} \), for each halo virialized at \( z \):

\[
r_{\text{vir}} = r_0(1 + z)^{-1}(1 + 178\Omega_0^{-0.6})^{-1/3} .
\]
where $\Omega_0$ is the present-day density parameter in matter. This radius is assumed to define the region within which the total virialized mass of an object should be calculated (White et al. 1993). The circular velocity $v_c$ for a virialized halo can then be written as:

$$v_c \equiv \left(\frac{GM}{r_{\text{vir}}}\right)^{1/2} = 2^{-1/2}H_0r_0\Omega_0^{1/2}(1 + z)^{1/2} \left[1 + 178\Omega_0^{-0.6}\right]^{1/6}. \quad (9)$$

We shall calculate the abundance of virialized halos as a function of circular velocity and redshift, using equations (7, 9).

Figure 2 shows the density of baryons (scaled to zero redshift, in unit of present critical density) in virialized halos as a function of redshift. This is calculated from equation (7) by assuming that the fraction of baryons in dark halos is the same as the global value in each model. The results are shown for three different intervals of halo circular velocities, as shown in the figures. If DL systems are due to neutral gas in systems which form normal spiral galaxies, then the relevant interval may be $v_c = 100 - 250 \text{ km s}^{-1}$. Gaseous disks might also form in systems of lower circular velocity, but probably not below $v_c = 50 \text{ km s}^{-1}$, since smaller objects would have a long cooling time due to the ionizing background (Efstathiou 1992). The upper limit corresponds to the maximum observed circular velocities in spiral galaxies, $\sim 250 \text{ km s}^{-1}$, but this is also uncertain since gaseous disks might survive for some time after their host halo merges with a more massive one. Clearly, the curves should be interpreted only as upper limits to the mass that may be present in DL systems, since some of the gas in halos may be ionized, or form stars rapidly, or be expelled from the halos in winds from supernova explosions. The data points shown by solid circles are the observed cosmic mass density of HI gas in DL systems, $\Omega_D$, adopted from Lanzetta et al. (1993) for the cosmological models in consideration. The figure shows that the baryonic mass in virialized halos at high redshifts depends
strongly on the bias parameter. The large excess of the predicted \( \Omega_D \) at low redshifts is not a problem for the models, since most of the gas has probably been used up to form stars at present. In fact, observations of present galaxies suggest that the mass of neutral gas in galaxies is only \( \sim 10\% \) of the total mass in stars.

At high redshifts, the baryonic mass in galactic halos may still be larger than that observed in DL systems in both the CDM and CDM\(\Lambda \) models, with the bias parameter given in the figures. For the MDM model, however, the baryonic mass in virialized halos is not enough to explain the DL systems. The deficit is very large for the model with \( b = 1.5 \), a case favored by a normalization according to COBE results (see e.g., Klypin et al. 1993; Jing et al. 1993). So if DL systems are indeed due to gas in galactic-sized virialized halos, then the MDM model based on the COBE normalization can be ruled out.

Similar conclusions have been reached recently by Subramanian \& Padmanabhan (1994), although their values for \( \Omega_D \) predicted by the models are lower than ours, because they assume a larger mass for the halos giving rise to damped systems.

Figure 3 shows the comparison of the predicted rate of incidence with that observed. The data points are adopted from Lanzetta et al. (1993). The number of absorption systems above a given column density depends not only on the mass of gas in each halo, but also on its spatial distribution, and is consequently much more uncertain and model dependent than the total mass in damped systems. Here, we will assume that the gaseous disks causing the DL systems have exponential profiles with scalelengths that are the same as those of stellar disks in spiral galaxies at the present time, for a fixed circular velocity. Assuming also the Tully-Fisher relationship, and a constant central surface brightness for spiral
disks, the scalelength is $R_0 = 3.5(v_c/220\text{ km s}^{-1})^2 h^{-1}\text{kpc}$; the normalization is chosen to give the right range of scalelengths observed (van der Kruit 1987), for $100 < v_c < 250\text{ km s}^{-1}$. We then use equation (4), integrated over $N_{\text{HI}}$, to find the total number of systems per unit redshift above a given column density. We take $N_{\text{HI}} = 10^{20.3}\text{ cm}^{-2}$ for the minimum column density required to identify an absorption line as a damped system (see Wolfe 1993).

From the results shown in Figure 3, we see that the predictions of the CDM model with $b = 1, 2$, and the CDMΛ model with $b = 1$ may be consistent with observations, if other effects do not reduce the cross section significantly. In the CDMΛ model, $n(z)$ at high $z$ depends strongly on the bias parameter $b$. If $b \approx 1.5$ (see Cen, Gnedin & Ostriker, 1993), the CDMΛ model may have difficulty in explaining the observed $n(z)$. But for the MDM model with $b \geq 1$, there is a much clearer disagreement with observations. The discrepancy at high redshift in this model is larger in $n(z)$ than in $\Omega_D(z)$ (see Fig. 2), because the average HI column density predicted by the model is larger than observed. This is primarily due to the fact that the central density of disks goes as $v_c^{-1}$ in our disc model and that most mass is in small haloes at high redshifts (see Fig. 2).

4. DISCUSSION

In this paper, we have seen that the large amount of mass in neutral gas observed in DL systems at high redshifts rules out the MDM model. The reason is that the fraction of gas in collapsed halos which can produce DL systems is too small. Even in the CDM and CDMΛ models, one needs to assume that a large fraction of the gaseous mass in galactic halos at $z \approx 3$ is in disks of neutral gas. Our calculated number of DL systems is more uncertain, since it depends on the
radial distribution of the gas in the disks. The number of DL systems could be larger if the radius where the column density is equal to \(10^{20.3} \text{cm}^{-2}\) (the threshold for DL systems) was increased. This could be done while keeping most of the gaseous mass close to the center, where it would produce higher column density systems, and would turn into the stellar disks in spiral galaxies at present. The lower column density regions of the disks at large radius might be destroyed before forming many stars, due to supernova explosions, or infalling material resulting in shock-heating of the gas. In fact, most HI disks in present galaxies are observed to flare at large radius (van Gorkom 1993 and references therein).

A second possibility is that there is a population of low column density disks, which extend to large radius. The star formation rate in such disks might be much lower than in regular spiral galaxies, and they might either be destroyed when the galactic halos where they reside merge, or might evolve into low surface brightness galaxies at present, which could be difficult to detect (McGaugh 1994).

Further constraints on the nature of DL systems may come through a better determination of the column density distribution (which depends on the surface density profiles and the maximum column density of the disks), and from measurements of their transverse size, either in gravitationally lensed quasars, or by direct imaging of the absorbing galaxies (Briggs et al. 1989; Wolfe et al. 1992).

We would like to acknowledge Stacy McGaugh, T. Padmanabhan, Martin Rees and Simon White for helpful discussions. HJM acknowledges support from a SERC Postdoctoral Fellowship. JM thanks SERC for support in Cambridge, and the W. M. Keck Foundation for support in Princeton.
REFERENCES

Barcons, X., & Fabian, A. C. 1987, MNRAS, 224, 675
Bardeen, J. M., Bond, J. R., Kaiser, N. & Szalay A. S. 1986, ApJ, 304, 15
Bond, J. R., 1993, in The Environment and Evolution of Galaxies, eds. J. M. Shull
& H. A. Thronson, Kluwer: Dordrecht, p3
Briggs, F. H., Wolfe, A. M., Liszt, H., Davis, M. M., & Turner, K. L. 1989, ApJ, 341, 650
Cen, R. Y., Gnedin, N. Y. & Ostriker, J. P. 1993, ApJ, 417, 387
Efstathiou, G., 1992, MNRAS, 256, 43P
Freeman, K. C. 1970, ApJ, 160, 811
Jing, Y. P., Mo, H. J., Börner, G., & Fang, L. Z. 1994, A&A, in press,
Klypin, A., Holtzman, J., Primack, J., & Regös, E. 1993, ApJ, 416, 1
Lanzetta, K. M., Turnshek, D. A., & Wolfe A. M., 1993, ApJ, in press,
Lanzetta, K. M., Wolfe, A. M., Turnshek, D. A., Lu, L., McMahon, R. G., & Hazard C., 1991, ApJS, 77, 1
McGaugh, S. S., 1994, Nature, in press,
Press, W. H., Schechter, P. 1974, ApJ, 187, 425
Rao, S., & Briggs, F. H. 1993, ApJ, 419, 515
Sargent, W. L. W., Young, P. J., Boksenberg, A., & Tytler, D. 1980, ApJS, 42, 41
Subramanian, K. & Padmanabhan, T. 1994, submitted to Nature
Tytler, D. 1987, ApJ, 321, 49
van der Kruit, P. C. 1987, A&A, 173, 59
van Gorkom J.H., 1993, in The Environment and Evolution of Galaxies, eds. J. M.
Shull, H. A. Thronson (Kluwer: Dordrecht), p345
Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H.-S. 1991,
White, S. D. M., Efstathiou, G., & Frenk, C. S. 1993, MNRAS, 262, 1023
White, S. D. M., & Rees M.J. 1978, MNRAS, 183, 341
Wolfe A., 1993, in Relativistic Astrophysics and Particle Cosmology, eds. C. W. Akerlof, M. A. Srednicki (New York Acad. of Sci.: New York), p 281
Wolfe, A. M., Turnshek, D. A., Lanzetta, K. M., & Oke, J. B. 1992, ApJ, 385, 151
FIGURE CAPTIONS

**Fig. 1:** The HI column density distribution function for damped Lyman alpha systems. The five observational data points at high $N_{\text{HI}}$ are adopted from Lanzetta et al. (1991); the other one is adopted from Tytler (1987). The curves (discussed in subsection 3.1) show the predictions of a model in which all damped Lyman alpha absorbers are exponential disks with central column densities $N_0$ shown in the figure. The amplitudes of the curves are adjusted to the observation.

**Fig. 2:** The density of baryons (scaled to zero redshift, in unit of present critical density) in virialized halos as a function of redshift, predicted by CDM (left panel), CDMΛ (middle) and MDM (right). For each model, results for two bias parameters are shown. For each bias parameter, results are shown for three different intervals of halo circular velocities: $v_c > 50, 50-250, 100-250 \, \text{km} \, \text{s}^{-1}$, with the higher curve corresponding to the case with a larger interval. The data points for the DL systems (solid circles) are adopted from Lanzetta et al. (1993), adjusted according to the cosmological model in consideration. The upper cross shows the density parameter of baryons in stars of present-day galaxies. The lower cross shows the HI mass in current spirals given by Rao & Briggs (1993).

**Fig. 3:** The rate of incidence, $n(z)$, of damped Lyman alpha absorptions predicted by CDM (left panel), CDMΛ (middle) and MDM (right). The gas mass in halos is assumed to settle in exponential disks with scalelengths given by the Tully-Fisher relation (see text).
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9402014v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9402014v1