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A SIMPLE ANALYTICAL MODEL FOR THE ABUNDANCE OF DAMPED Lyα ABSORBERS

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ABSTRACT

A simple analytical model for estimating the fraction ($\Omega_{\rm gas}$) of matter in gaseous form within the collapsed dark matter (DM) halos is presented. The model is developed using (1) the Press-Schechter formalism to estimate the fraction of baryons in DM halos and (2) the observational estimates of the star formation rate at different redshifts. The prediction for $\Omega_{\rm gas}$ from the model is in broad agreement with the observed abundance of the damped Lyα systems. Furthermore, it can be used for estimating the circular velocities of the collapsed halos at different redshifts, which could be compared with future observations.

Subject headings: intergalactic medium — large-scale structure of universe — quasars: absorption lines

1. INTRODUCTION

The damped Lyα systems (DLAs) are identified with the lines having the highest column densities in a typical observed absorption spectrum of a distant quasar. The generally adopted threshold value of the column density ($N_{\rm H\,I}$) for identifying DLAs is $N_{\rm H\,I} \geq 2 \times 10^{20}$ cm^{-2}. These high column density systems are important in understanding the baryonic structure formation, because they contain a fair amount of the neutral hydrogen in the universe at high redshifts (Wolfe et al. 1986; Storrie-Lombardi, McMahon, & Irwin 1996). In contrast, the ionized hydrogen is mostly contained in the low column density systems, which manifest themselves as the Lyα forest in the quasar absorption spectrum (see, for example, Miralda-Escude et al. 1996; Bi & Davidsen 1997; Choudhury, Padmanabhan, & Srianand 2001a; Choudhury, Srianand, & Padmanabhan 2001b and references therein). By probing the DLAs at high redshifts, one is able to extract information about formation and evolution of galaxies. In recent years, the DLAs have been studied extensively using high-quality quasar absorption spectra (Pettini et al. 1994, 1997a, 1997b, 1999; Lanzetta, Wolfe, & Turnshek 1995; Storrie-Lombardi et al. 1996; Prochaska & Wolfe 1997, 1998), which has helped in constraining galaxy formation models.

Currently, the theoretical understanding of the DLAs is based on the hierarchical models for galaxy formation (White & Rees 1978; White & Frenk 1991). These models start with the fact that, initially, the DM density inhomogeneities collapse via gravitational instability and form potential wells. In the next stage, the baryonic matter, mostly in gaseous form, follow these DM potential wells. The baryonic gas can cool and form galaxies, provided its cooling timescale is short compared to the Hubble expansion timescale. Once this condition is met, the gas is able to dissipate its energy and "virialize" in the centers of the DM halos. This cooled gas, contained within the DM halos, is believed to be responsible for the damped Lyα absorption lines in the quasar spectra. Various analytical and semianalytical models (Mo & Miralda-Escude 1994; Kauffmann & Charlot 1994; Subramanian & Padmanabhan 1994; Jedamzik & Prochaska 1998; Kauffmann 1996; Maller et al. 2001), as well as simulations (Ma & Bertschinger 1994; Katz et al. 1996; Ma et al. 1997; Gardner et al. 1997a, 1997b; Haehnelt, Steinmetz, & Rauch 1998), have shown that the observed mass in the DLAs is similar to the baryonic mass, which can collapse and efficiently cool in the DM halos. However, not all the collapsed baryonic matter in the halos remains in gaseous form—a fraction will turn into luminous stars. It is, therefore, clear that estimation of the total baryonic mass in the collapsed halos and the mass turned into stars can be used to calculate the mass of the cooled gas in the halos.

In this paper, we use the simple idea that the mass contained in DLAs (i.e., the mass that remains in gaseous form in the collapsed halos) should be equal to the total baryonic mass in the collapsed halos minus the mass that is turned into stars. In doing this, we have neglected the mass of the ionized gas within the halos (which is small because the gas is dense enough to be shielded from the background radiation) and also the small amount of mass that might have turned into molecular gas. The total baryonic mass contained within the collapsed halos can be estimated through Press-Schechter formalism (Mo & Miralda-Escude 1994; Kauffmann 1996), while the matter that has turned into stars is calculated from the observed estimates of the star formation rate (SFR) at various epochs (Steidel et al. 1999). It turns out that this simple model is able to produce the mass of the cooled gas in the collapsed halos, as seen in observations. Furthermore, it is able to predict the circular velocities of the collapsed halos associated with DLAs.

This simple model should not be thought of as in competition with the previous detailed models, which use many more inputs for their modeling. Rather, we have tried to show that it is possible to reproduce many of the physical effects through a simple argument of "baryon conservation." Our paper should be judged in this backdrop of simplicity.

Section 2 discusses the basic analytical formalism used for the model. It describes the usage of the Press-Schechter formalism to calculate the total baryonic mass in collapsed halos. It also discusses how to obtain the stellar mass density from the observed SFR. In § 3, we discuss the parameters of our model, followed by the results. In § 4, we summarize our main conclusions and discuss the limitations of our model.

2. ANALYTICAL FORMALISM

This section contains the basic formalism for the model. Although most of it is available in existing literature, we briefly summarize here in order to set up the notation and to state the assumptions used in our model. To calculate the mass contained within the collapsed objects of a given mass range, we use the Press-Schechter formalism (Press & Schechter 1974). The total mass (dark matter) contained per unit of comoving volume within collapsed objects of (logarithmic) mass range $[\ln M, \ln(M + dM)]$ is given by

$$\rho_M^{\rm halo}(z) d\ln M = -\left(\sqrt{\frac{\pi}{2}} e^{-\nu^2/2}\right) \rho_0 \frac{d\ln \sigma(M)}{d\ln M} \nu(z, M) d\ln M \ , \tag{1}$$

where ρ_0 is the mean comoving density of the universe. The other quantities are defined as

$$\sigma^2(R) = \int_0^\infty \frac{dk}{k} \left[\frac{3(\sin kR - kR\cos kR)}{k^3 R^3}\right]^2 \left[\frac{k^3 P_{\rm DM}(k)}{2\pi^2}\right] ; \quad M = \frac{4\pi}{3} R^3 \rho_0 \ . \tag{2}$$

The quantity ν is defined as

$$\nu(z, R) = \frac{\delta_c}{D(z)\sigma(R)} \ , \tag{3}$$

where $P_{\rm DM}(k)$ is the normalized dark matter power spectrum, $D(z)$ is the growth factor for density perturbations, and δ_c is the critical density, usually 1.69 for $\Omega_m = 1$ flat universe. The corresponding Ω is given by

$$\Omega_M^{\rm halo}(z) \equiv \frac{\rho_M^{\rm halo}(z)}{\rho_c} = \frac{\rho_M^{\rm halo}(z)\Omega_m}{\rho_0} \ , \tag{4}$$

where $\rho_c = 2.8 \times 10^{11}\ h^2\ M_\odot\ {\rm Mpc}^{-3}$ is the present critical density of the universe, and $\Omega_m = \rho_0/\rho_c$.

We now calculate the total mass contributed by *baryons* in the collapsed halos within the logarithmic mass range. In order to do this, we assume that the baryonic fraction of matter in each halo is the same as the global value. Then, the Ω contributed by baryons in collapsed halos within a logarithmic mass range $[\ln M, \ln(M + {\rm d}M)]$ is given by

$$\Omega_{M,b}^{\rm halo}(z) = \Omega_M^{\rm halo}(z)\frac{\Omega_b}{\Omega_m} = -\left(\sqrt{\frac{\pi}{2}} e^{-\nu^2/2}\right) \times \nu(z, M) \frac{d\ln \sigma(M)}{d\ln M} \Omega_b \ . \tag{5}$$

We now have the total baryonic $\Omega_{M,b}^{\rm halo}$ contained within collapsed dark matter halos of mass M at a given epoch. We will assume that all the baryons either are converted into luminous stars or form gaseous clouds. Mathematically, this can be expressed as

$$\Omega_{M,b}^{\rm halo}(z) = \Omega_{M,{\rm gas}}(z) + \Omega_*(z) \ . \tag{6}$$

It is believed that the damped Lyα systems are mainly contributed by the gaseous clouds *within the collapsed and virialized* dark matter halos. Hence, one should *not* include the low column density systems in this analysis, which are believed to be density perturbations within a diffuse intergalactic medium (IGM; Choudhury et al. 2001a, 2001b).

It is clear that once we obtain the quantity Ω_* contained in stars, we can estimate $\Omega_{M,\ {\rm gas}}$ from the above relation. To calculate Ω_* from observational data, we proceed as follows. The star formation rate (SFR) $(d\rho_*/dt) \equiv \dot{\rho_*}(t)$ is defined as the rate at which baryonic mass is converted into stars per unit (comoving) volume. Given this quantity, we can obtain the total density of matter contained within stars at a particular t,

$$\rho_*(t) = \int_0^t dt\, \dot{\rho_*}(t) \ , \tag{7}$$

or, in terms of redshift

$$\rho_*(z) = \int_\infty^z dz\, \dot{\rho_*}(z) \frac{dt}{dz} = \int_z^\infty dz\, \frac{\dot{\rho_*}(z)}{H(z)(1+z)} \ . \tag{8}$$

The corresponding Ω is

$$\Omega_*(z) = \frac{\rho_*(z)}{\rho_c} \ . \tag{9}$$

One can determine $\dot{\rho_*}(t)$ from observations, which can then be integrated to give $\Omega_*(z)$. It is well known that not all the gas that is turned into stars is removed from the gaseous phase forever. Actually, some of the stellar material is returned by stellar winds and supernovae. However, we ignore this contribution for the following reasons: (1) It is difficult to implement this feedback effect in our model without introducing more free parameters (Efstathiou 2000). This spoils the simplicity as well as the predictive capacity of our model. (2) The SFR has large uncertainties at high redshifts because of extinction (see below). The correction due to the feedback through stellar winds and supernovae is less than this uncertainty in the SFR and can be ignored as a first approximation.

To compare our results with observations, or to discuss any observational consequences of our model, it is better to work in terms of the circular velocities (v_c) of the collapsed halos, rather than in terms of their masses. The mass M and v_c can be related to each other using the spherical collapse model. The relevant equations for a universe with cosmological constant are (Somerville & Primack 1999)

$$v_c^2 = \frac{GM}{r_{\rm vir}} - \frac{\Omega_\Lambda H_0^2 r_{\rm vir}^2}{3} \tag{10}$$

and

$$\Delta_{\rm vir}(z) = \frac{2GM}{r_{\rm vir}^3 H^2(z)} \ , \tag{11}$$

where $\Delta_{\rm vir}(z)$ is the virial density of the collapsed halo at redshift z, and $r_{\rm vir}$ is the corresponding virial radius. The circular velocity is calculated assuming that the virialized halo has a singular isothermal density profile $\rho(r) \propto r^{-2}$. The above relations can be used to eliminate $r_{\rm vir}$ and obtain

$$\frac{M}{10^{11}\ h^{-1}\ M_\odot} = \left(\frac{v_c}{35.0\ {\rm km\ s^{-1}}}\right)^3 \sqrt{\frac{2H_0^2}{H^2(z)\Delta_{\rm vir}(z)}} \times \left[1 - \frac{2\Omega_\Lambda H_0^2}{3H^2(z)\Delta_{\rm vir}(z)}\right]^{-3} \ . \tag{12}$$

Thus, for a given z, we can relate M to v_c, provided we know $\Delta_{\rm vir}(z)$. This result can then be used for obtaining the mass density, either dark matter $[\Omega_{v_c}^{\rm halo}(z)]$ or baryonic $[\Omega_{v_c,b}^{\rm halo}(z)]$, contributed by halos having a circular velocity v_c.

Given the background cosmological model, our formalism can now be used for estimating the quantity $\Omega_{v_c,{\rm gas}}(z)$ for different values of v_c, which can then be compared with observations. Note that we have only one free parameter in our model, namely, v_c. It turns out that we can, in principle, predict the circular velocities of collapsed halos at different redshifts by comparing our model with DLA observations.

3. MODEL PARAMETERS AND RESULTS

We have considered two different cosmological models with these parameters:

1. Standard cold dark matter (SCDM): $\Omega_m = 1$, $\Omega_\Lambda = 0$, $h = 0.65$, and $\Omega_b h^2 = 0.02$.
2. Low-density cold dark matter (LCDM): $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.65$, and $\Omega_b h^2 = 0.02$.

The critical density for collapse δ_c is only weakly dependent on the Ω_Λ for flat cosmological models (Eke, Cole, & Frenk 1996); hence, we take it to be 1.69 for both models. The next cosmological input that is required is the form of the DM power spectrum. We take the following form for $P_{\rm DM}(k)$ (Efstathiou, Bond, & White 1992):

$$P_{\rm DM}(k) = \frac{Ak}{\left\{1 + [\alpha k + (\beta k)^{1.5} + (\gamma k)^2]^\nu\right\}} , \quad (13)$$

where $\nu = 1.13$, $\alpha = (6.4/\Gamma)\ h^{-1}$ Mpc, $\beta = (3.0/\Gamma)\ h^{-1}$ Mpc, $\gamma = (1.7/\Gamma)\ h^{-1}$ Mpc, and $\Gamma = \Omega_m h$. The normalization parameter A is fixed through the value of $\sigma_8 \equiv \sigma(R = 8\ h^{-1}\ \text{Mpc})$. We take the values of σ_8 to be given by Eke et al. 1996,

$$\sigma_8 = \begin{cases} (0.52 \pm 0.04)\Omega_m^{-0.46+0.10\Omega_m} & \text{if } \Omega_\Lambda = 0 , \\ (0.52 \pm 0.04)\Omega_m^{-0.52+0.13\Omega_m} & \text{if } \Omega_\Lambda = 1 - \Omega_m . \end{cases} \quad (14)$$

Given the above parameters, we can calculate the Press-Schechter mass function. However, since we prefer to work in terms of v_c rather than M, we need to know the quantity $\Delta_{\rm vir}(z)$ (see eq. [12]). For flat models with a cosmological constant, this is given by the fitting formula (Bryan & Norman 1998)

$$\Delta_{\rm vir}(z) = 18\pi^2 + 82x - 39x^2 ; \quad x \equiv \Omega_m(z) - 1 . \quad (15)$$

In Figure 1, we plot the quantity $\Omega^{\rm halo}_{v_c,b}(z)$ for the two different cosmological models and for three different values of v_c. It is clear that halos of lower circular velocities contain more mass at higher redshifts. There is quite a bit of uncertainty about the SFR. This is mainly due to our lack of knowledge of the extinction due to dust. The extinction has been modeled in various ways (see, for example, Steidel et al. 1999; Adelberger & Steidel 2000; Gispert, Lagache, & Puget 2000; Hopkins et al. 2001). In this work, we take the SFR data obtained from ultraviolet luminosity observations (Lilly et al. 1996; Connolly et al. 1997; Madau et al. 1996; Steidel et al. 1999) corrected for extinction by Steidel et al. (1999). The data can be fitted with a function of the form

$$\dot\rho_*(z) = \frac{ae^{bz}}{e^{cz} + d} , \quad (16)$$

with the parameters given by

$$a = 0.13 , \quad b = 2.2 , \quad c = 2.2 ,$$
$$d = 6.0 \quad M_\odot\ \text{yr}^{-1}\ \text{Mpc}^{-3} . \quad (17)$$

There are two effects that may modify the form and the absolute value of this SFR. The first modification is due to cosmology. The above data are for a flat $\Omega_m = 1$ universe, with $h = 0.5$. In order to use the same points for a different cosmology, one must note that the SFR is proportional to luminosity per volume, which in turn is inversely proportional to the distance for a given redshift. This means that while considering a flat universe with a cosmological constant ($\Omega_m + \Omega_\Lambda = 1$), we must multiply the above SFR by a correction factor

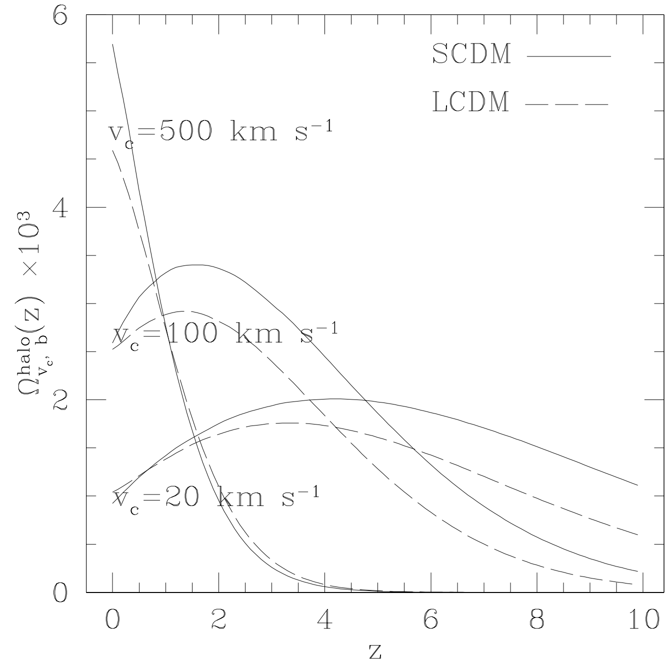

FIG. 1.—Fraction $\Omega^{\rm halo}_{v_c,b}(z)$ for two cosmological models and for three values of v_c as indicated in the figure.

$$C_{\rm cosm}(z) = \frac{h}{0.5}\frac{2[1 - (1 + z)^{-1/2}]}{\int_0^z dz' \left[(1 - \Omega_m) + \Omega_m(1 + z')^3\right]^{-1/2}} . \quad (18)$$

In Figure 2, we plot this correction factor for the two cosmological models of our interest. The correction for the SCDM model comes just because we are using $h = 0.65$ and is independent of z.

The second effect is due to the stellar initial mass function (IMF). The SFR is usually calculated from the observed luminosity using some particular IMF. The SFR data we are using are calculated using the standard Salpeter IMF with a slope $\Gamma = -1.35$ for a mass range 100–0.1 $M_\odot$ (Madau et al. 1996; Steidel et al. 1999). However, the real IMF probably becomes flatter below 1 $M_\odot$. Leitherer (1998) calculates that the extrapolation of the Salpeter IMF to 0.1 $M_\odot$ overestimates the SFR by a factor of 2.5. In this work, we take into account the flattening and eventual turning over of the IMF below 1 $M_\odot$ by simply reducing the SFR by a factor of 2.5.

Implementing both the corrections, we get the corrected SFR in the form

$$\dot\rho_*(z) = \frac{ae^{bz}}{e^{cz} + d}\frac{C_{\rm cosm}(z)}{2.5} , \quad (19)$$

with the parameters a, b, c, and d given in equation (17). Given $\dot\rho_*(z)$, we can calculate the quantity $\Omega_*(z)$ using equa-

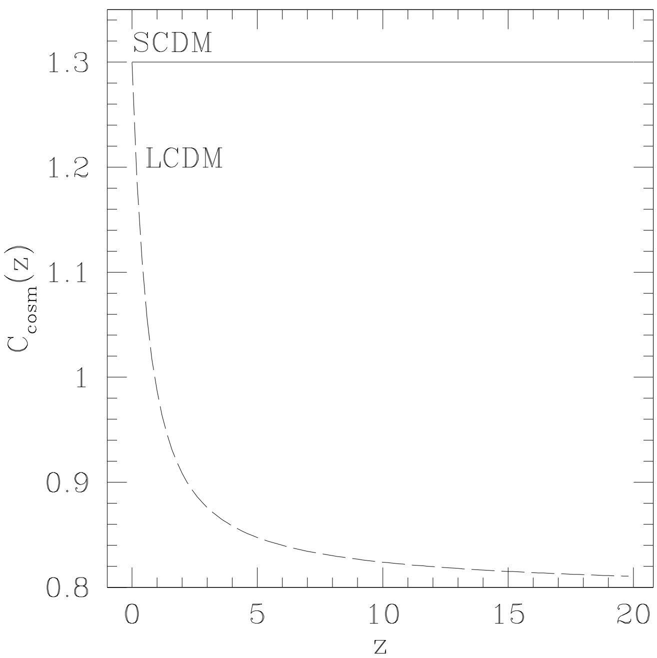

FIG. 2.—Correction factor for the observed SFR due to using a different cosmological model. The observed data points are for a flat $\Omega_m = 1,\ h = 0.5$ universe, while we are interested in cosmological models with different parameters (see text for the cosmological models considered in this paper). The correction factor is plotted as a function of z for the two cosmological models of our interest (SCDM and LCDM). The solid line denotes the correction for the SCDM model (arising because we use $h = 0.65$), while the dashed line is for the LCDM model.

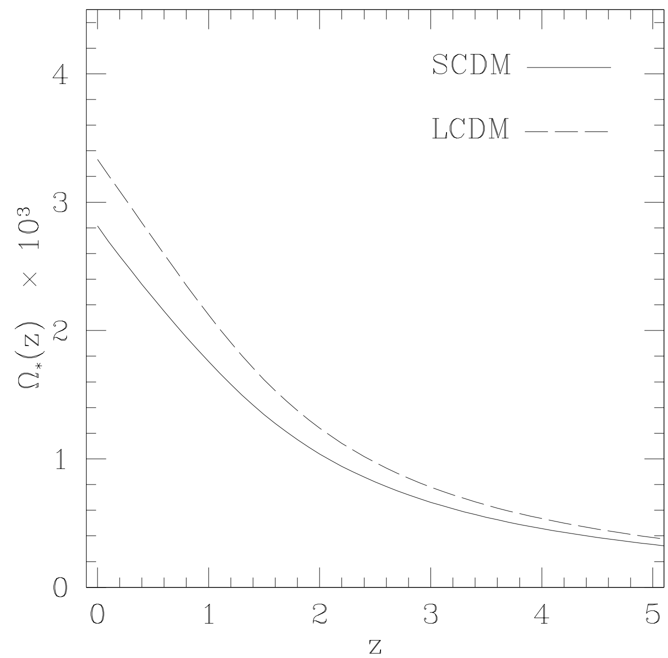

FIG. 3.—Density of matter contained in stars Ω_* as a function of z, plotted for two cosmological models.

tions (8) and (9). This quantity is plotted in Figure 3 for two cosmological models.

We now obtain the main result of our work, $\Omega_{v_c,\mathrm{gas}}(z)$, and compare it with DLA observations. We have already discussed how to compute the quantities $\Omega^{\mathrm{halo}}_{v_c,b}(z)$ (see eq. [5]) and Ω_* (see eqs. [8] and [9]). Given these two quantities, we can analytically compute $\Omega_{v_c,\mathrm{gas}}(z)$ using equation (6). The observed data used for comparing our model are obtained from Peroux et al. (2001). First, we consider a scenario in which the circular velocities of the collapsed halos do not have significant evolution, i.e., they are more or less constant over the redshift range. To be more precise, we consider a velocity range from $v_c = 200$ to 250 km s^{-1} for both the cosmological models and see how they compare with the observed points. Figure 4 shows the comparison within this velocity range.

As can be seen from Figure 4, the ballpark estimate of $\Omega_{v_c,\mathrm{gas}}(z)$ from our simple model is well within observational constraints. Furthermore, the general trend of evolution of $\Omega_{v_c,\mathrm{gas}}(z)$ is also reproduced.

In passing, we mention that we have plotted the mass density $\Omega_{v_c,\mathrm{gas}}(z)$ contributed by halos within a logarithmic velocity range. We could have plotted as well the quantity $\Omega_{\mathrm{gas}}(z)$, which is the mass density contributed by halos having a wide range of circular velocities (say, from $v_{c,\mathrm{min}} = 50$

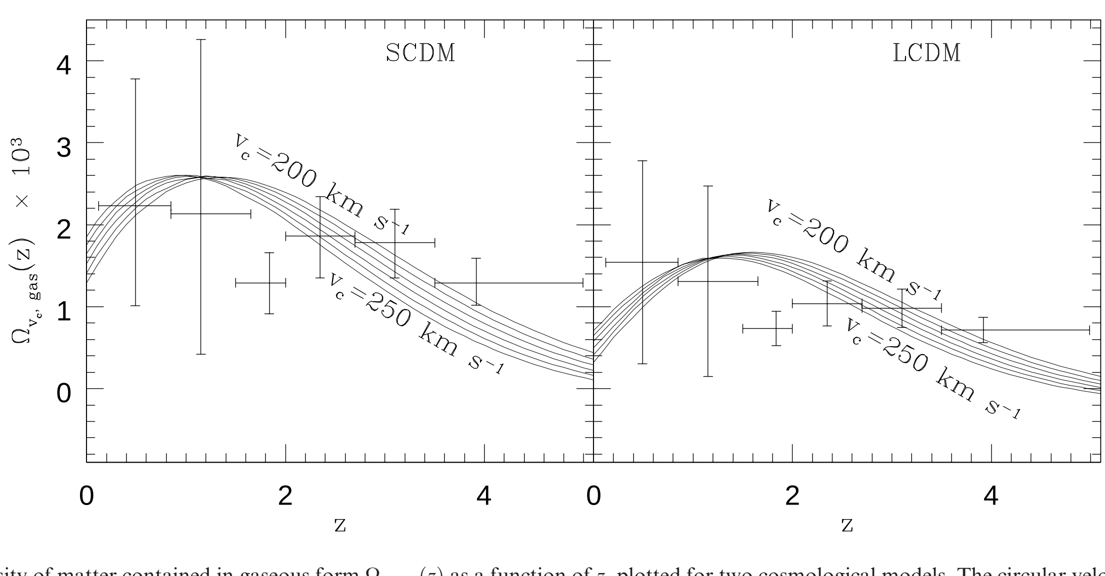

FIG. 4.—Density of matter contained in gaseous form $\Omega_{v_c,\mathrm{gas}}(z)$ as a function of z, plotted for two cosmological models. The circular velocity ranges from $v_c = 200$ to 250 km s^{-1} in both plots.

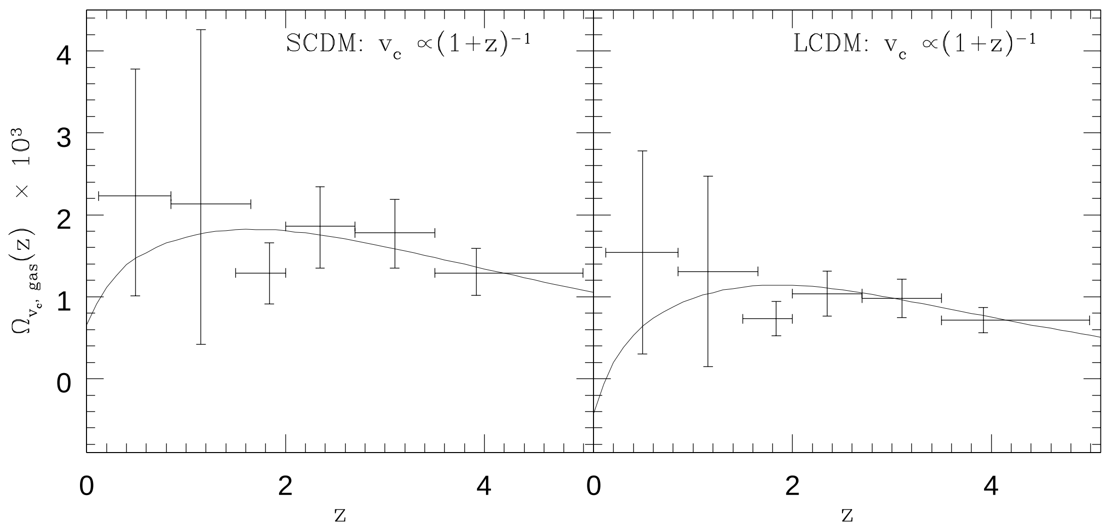

FIG. 5.—Density of matter contained in gaseous form $\Omega_{v_c,\mathrm{gas}}(z)$ as a function of z, plotted for two cosmological models. The circular velocity is assumed to be proportional to the scale factor. It is evident from the figure that this z dependence of v_c does not hold for $z < 1$.

to $v_{c,\max} = 250$ km s^{-1}; see Mo & Miralda-Escude 1994). Mathematically, this quantity can be obtained from $\Omega_{v_c,\mathrm{gas}}(z)$ through the relation

$$\Omega_{\mathrm{gas}}(z) = \int_{v_{c,\,\min}}^{v_{c,\,\max}} \Omega_{v_c,\,\mathrm{gas}}(z) \frac{d \ln M}{d \ln v_c} d \ln v_c \ . \quad (20)$$

However, when compared with observations, this quantity turns out to be much higher than the observed mass density contributed by DLAs. This means that either (1) most of the observed DLAs are hosted by DM halos with a small range of circular velocities, or (2) we are severely underestimating the SFR. At this stage, it is quite difficult to distinguish between the two possibilities.

Let us now return back to Figure 4. One notes that observational points in higher redshifts are better fitted by curves with lower velocities. For example, for the LCDM model, the point at $z = 2.35$ (*fourth from left*) has a better match with the curve having $v_c = 250$ km s^{-1} (a curve with a higher v_c will do still better), while the point at the highest redshift ($z = 3.92$) can be fitted with a curve of lower velocity ($v_c < 200$ km s^{-1}). This might motivate one to consider a second scenario in which the circular velocity falls as redshift increases.

It should be obvious that it is impossible to constrain the evolutionary pattern of v_c with such large error bars in the observational data. However, we illustrate how it can be done in principle. We consider a simple evolution of v_c parameterized as

$$\frac{v_c(z)}{250 \text{ km s}^{-1}} = \eta \left(\frac{1+z}{3} \right)^{-1} , \quad (21)$$

where η is a parameter of the order unity, to be fixed by comparing with observations. Figure 5 shows the comparison between our model and observations when v_c is given by the above relation. The values of η for the two cosmological models are

$$\eta \simeq \begin{cases} 1.167 & \text{for SCDM} , \\ 1.163 & \text{for LCDM} . \end{cases} \quad (22)$$

The simple evolution law of v_c matches with observations reasonably well, especially at $z > 2$. The match is not that good for $z < 1$, and one has to introduce more complicated redshift dependence to take care of this. We do not perform such exercise in this work, as it is difficult to constrain any parameter with such large observational errors.

We are thus able to show that our model, in spite of being extremely simple, is able to reproduce the broad observational trends for the quantity $\Omega_{v_c,\mathrm{gas}}(z)$ (the density of baryons contained within collapsed halos in gaseous form). The model can, in principle, be used to predict the circular velocities of the collapsed halos as a function of z.

It should be noted that the detailed model of Kauffmann (1996) gives somewhat lower circular velocities compared to ours. At this stage, it is difficult to compare our results directly with those of Kauffmann (1996). Since both have used the Press-Schechter formalism to calculate the mass in collapsed objects, the difference must lie in the estimation of SFR. We have used an observed estimate for the SFR. It is not obvious from the work of Kauffmann (1996) how the results for SFR match with observations.

As an extension of this work, we also calculate the distribution of circular velocities of the DM halos, using the Press-Schechter formalism (Haehnelt et al. 1998, 2000). However, we preferred to keep this paper simple and focused on one key idea only.

4. DISCUSSION

We have presented a simple analytical model for estimating the amount of matter left in gaseous form within the collapsed DM halos. The only ingredients for this model are (1) the Press-Schechter formalism for the collapse of DM halos and (2) the observational estimates of the SFR at different redshifts. Our model reproduces the mass contained in the baryonic gas that has cooled within the DM halos, as expected in observations. Furthermore, the broad trends seen in the observed data are reproduced in our model. We have used it to estimate the circular velocities of the collapsed halos at different redshifts, which might be compared with future observations.

The model has a couple of important uncertainties:

1. The observational estimate of the SFR is quite uncertain, mainly because of the extinction. There are different models for the extinction in the literature, and the resulting estimates differ quite a bit (Steidel et al. 1999; Hopkins et al. 2001). It is difficult to prove what is the best method to use at high redshift for estimating the extinction, since there are so few constraints. In our model, we have used the extinction-corrected data of Steidel et al. (1999), as their estimates are consistent with the submillimeter background (Adelberger & Steidel 2000).
Note that this uncertainty may have a large influence on the values of v_c calculated in this paper. For example, the SFR estimated by Hopkins et al. (2001) is about 5–6 times higher than what we have used at $z > 2.5$. Using such a SFR would have led us to use a higher value of baryonic matter density, so as to match the observations of $\Omega_{v_c,\mathrm{gas}}(z)$. The only obvious way to increase the total baryonic matter is to include the halos with lower velocities. Thus, there is a possibility that the halos with lower v_c than what is calculated in this paper might also contribute to $\Omega_{v_c,\mathrm{gas}}(z)$. Thus, the absolute values of v_c predicted in this work might have errors. However, the broad features (such as v_c decreasing with increasing z) are expected to still be valid.

2. In our model, we have neglected the feedback from supernovae and stellar winds, because there is no simple way to deal with them. This might have resulted in a slight underestimate of $\Omega_{v_c,\mathrm{gas}}(z)$. However, we do not expect this correction to modify the broad trends of the model.
We have found that our model matches the observations in the redshift range $2 < z < 5$, provided the circular velocities of the halos are within the range 100 km s^{-1} $\leq v_c \leq$ 250 km s^{-1}. Haehnelt et al. (1998, 2000) compare hydrodynamical simulations and observed data (Prochaska & Wolfe 1997) to conclude that the typical circular velocities of the halos at high redshifts are $\sim$100–200 km s^{-1}. This value is in agreement with our analysis. Also, kinematic studies of Ledoux et al. (1998) find that there is a trend for the velocity to decrease with redshift. The circular velocity cannot be predicted for lower redshifts ($z < 2$) because of the large errors on the observed $\Omega_{v_c,\mathrm{gas}}(z)$.

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