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EVOLUTION OF LYMAN-ALPHA CLOUDS AT LOW REDSHIFTS

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ABSTRACT

We examine the evolution of an intergalactic gas cloud confined by the gravity of cold dark matter in the minihalo model. Assuming that the evolution of the diffuse ultraviolet (UV) flux follows a power law function of the form $(1+z)^{\alpha_i}$ with a change in exponent at redshift z_c and a constant comoving number density of gas clouds, we can reproduce the evolution of the number of clouds per unit redshift at both high and low redshifts with $\alpha_L = 2$ for $z \leq z_c$ and $\alpha_H = -4$ (or -3) for $z > z_c$ with $z_c = 1.9$ (or 1.8). Such a small value of α_L implies much more UV flux at low redshifts than is expected from the luminosity function of observed quasars. Moreover, we find that the required intensity of this UV flux is consistent with observations of the Gunn-Peterson effect and of the continuum depression.

Subject headings: dark matter — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The Lyα forest is a type of quasar absorption system and this is one of the few probes available to explore the universe at high redshifts. Recently the *Hubble Space Telescope* (*HST*) has observed many quasars at low redshifts from space, finding many Lyα absorption lines in their spectra like those observed at high redshifts. Bahcall et al. (1993) reported results of quasar absorption lines as one of the key projects of *HST*. They found a remarkably large density of Lyα absorption lines.

The number of Lyα lines per unit redshift per unit equivalent width is written as (Lu, Wolfe, & Turnshek 1991; Bahcall et al. 1993)

$$\frac{d^2N}{dz\,dW}\,dz\,dW = \left(\frac{dN}{dz}\right)_0 (1+z)^\gamma \frac{1}{W^*} \exp\left(-\frac{W}{W^*}\right) dz\,dW\,, \tag{1}$$

where W is equivalent width in the rest frame. At high redshifts ($1.7 \lesssim z < 3.8$), the parameters of equation (1) are estimated to be $(dN/dz)_0 = 2.67$, $\gamma = 2.37 \pm 0.26$, and $W^* = 0.32$ Å (Lu et al.). While at low redshifts ($0 < z < 1.0$) they are estimated to be (Bahcall et al.) $(dN/dz)_0 = 15.14 \pm 1.97$ if $W^* = 0.32$ Å and $\gamma = 0.75$ are assumed or

$$\left(\frac{dN}{dz}\right)_0 = 15.56 \pm 4.79\,,$$
$$\gamma = 0.67 \pm 0.78\,, \tag{2}$$

if only $W^* = 0.32$ Å is assumed. The index γ at low redshift is very different from that at high-redshift. Using both high- and low-redshift data, Bahcall et al. excluded a single power law for the number density evolution of Lyα lines with a 93% significance level.

Ikeuchi & Turner (1991) explained this evolution of the number density using the pressure confined cloud model. In their model, the different γ at high- and low-redshifts results from different redshift evolution of the diffuse UV radiation. For adiabatically expanding clouds, $\gamma = 3 - 0.7j$, where j is the power law index describing the evolution of the diffuse UV flux as $J \propto (1+z)^j$ and $q_0 = 0.5$. Taking $j = 3.4$ at low redshifts (Boyle et al. 1991), they estimated $\gamma = 0.62$, and $\gamma = 3$ with $j = 0$ at high redshifts. Although this seems to reproduce the number density evolution of the Lyα forest successfully, we must make note of the rapid evolution of gas clouds themselves. The gas clouds expand and their neutral hydrogen column density decreases rapidly, which requires the existence of unreasonably massive clouds at low redshifts for observed ranges of H I column densities. Thus we cannot expect the Lyα absorption systems at low redshifts to belong to the same population as those responsible for the Lyα forest at high redshifts, given the pressure confinement model.

The minihalo model, proposed by Rees (1986) and Ikeuchi (1986), is another model designed to explain the Lyα forest. Intergalactic gas clouds are confined by the gravity of cold dark matter (CDM) in this model (Ikeuchi, Murakami, & Rees, 1988, 1989). In an earlier paper (Murakami & Ikeuchi 1993, hereafter Paper I) we examined the evolution of gas clouds confined by CDM and reproduced the number density evolution of the Lyα forest at high redshifts, assuming that the diffuse background UV flux changes as $(1+z)^\alpha$. We found $\alpha = -4$ suitably reproduces the number density evolution. In this case, increasing UV flux causes the slow expansion of the gas clouds and a decreasing neutral fraction of hydrogen. This results in a decreasing cross section for fixed H I column density, and hence, a decreasing probability of detection. At redshifts less than 2, we chose $\alpha = 4$ and found that the predicted number density was larger than that observed by *HST*.

In this *Letter*, we examine the evolution of gas clouds at low redshifts in order to reproduce the number density evolution observed by *HST*. In § 2, we describe our model and assumptions. In § 3, we present the results of the model and discuss the consequences of these results with regard to the evolution of the diffuse UV flux. Possibilities for future work are discussed in § 4.

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2. MODEL

As in Paper I, we consider a spherical bound system of gas and CDM. We calculate the hydrodynamic evolution of the gas cloud within a fixed CDM potential, solving equations (6)–(9) in Paper I. We take into account radiative cooling and heating due to photoionization and calculate the ionization state of hydrogen and helium with number density ratio $n_{\rm H}/n_{\rm He} = 9$, assuming ionization equilibrium (eq. [10] in Paper I).

We assume that a spherical system of gas and CDM is initially in hydrostatic equilibrium (eqs. [22]–[24] in Paper I) and that CDM has an isothermal density distribution with velocity dispersion $\sigma_d = c_s(T = 3 \times 10^4 \text{ K})$, i.e., $X = 3$ in Paper I. We fix this parameter in this paper for simplicity because we found that the number density evolution is not very sensitive to its variation. Initially the gas is in thermal equilibrium. We take the central density of CDM as $\rho_d(r = 0) = 10\rho_{\rm crit}(z = 10)$, i.e., $D = 10$ in Paper I. The intergalactic medium (IGM) outside the system is assumed to have density, $\rho_{\rm IGM}(z) = 0.01\rho_{{\rm crit},z=0}(1 + z)^3$. We here calculate the evolution of the IGM temperature initially assuming thermal equilibrium. The purpose of this is to estimate the optical depth for the Gunn-Peterson effect (Gunn & Peterson 1965; Steidel & Sargent 1987) and to calculate the contribution of the IGM to the continuum depression. Although this was not included in Paper I, we expect such an IGM evolution to have little effect on the evolution of gas clouds within minihalos.

Change in the diffuse UV flux irradiating a gas cloud induces evolution of the cloud. The diffuse UV radiation is believed to be the integrated radiation from distant quasars and galaxies. The observed number of quasars has a peak around $z = 2$ (Schmidt, Schneider, & Gunn 1991). Although we do not know the number nor emitting flux of galaxies at high redshifts, we may expect that the evolution of the diffuse UV flux changes around $z \sim 2$. We assume that the intensity of the UV flux at the Ly limit changes as a broken power law of $(1 + z)^{\alpha_i}$: α_L at $z \le z_c$ and α_H at $z \ge z_c$. We take $\alpha_H = -4$ or -3 at $z \ge z_c$ according to the results of Paper I. We examine several cases for α_L and z_c. To normalize the intensity, we take the intensity at Ly limit to be $J_{\rm LL} = 10^{-21}$ ergs s^{-1} cm^{-2} Hz^{-1} sr^{-1} at $z = 2$. The spectral index of the flux is assumed to be -1, as in Paper I.

We calculate each gas cloud evolution for several masses with different gas central densities. In this *Letter*, we take cloud gas masses ranging from $7 \times 10^5 M_\odot$ to $5 \times 10^7 M_\odot$ and CDM masses ranging from $9 \times 10^8 M_\odot$ to $4 \times 10^9 M_\odot$ for initially optically thin clouds. Assuming a cloud mass function of power-law form with index $\delta = 1.3$, we estimate the observable number density per unit redshift with equations (33) and (36) of Paper I. Here we determine the number density normalization to fit the observational result by Lu et al. (1991).

We also estimate the continuum depression assuming it comes from integrated absorption by intergalactic clouds and IGM. The continuum depression, D_A, is the average depression of a quasar continuum, $f_{\rm obs}$, between Lyα and Lyβ emission lines relative to the continuum, $f_{\rm cont}$, extrapolated from wavelengths longer than Lyα, (Schneider, Schmidt, & Gunn 1991 and references therein): $D_A = \langle 1 - f_{\rm obs}/f_{\rm cont}\rangle = 1 - e^{-\tau}$. The total optical depth, τ, is the sum of the optical depth due to the IGM and the effective optical depth due to intergalactic clouds:

$$\tau = \tau_{\rm IGM} + \tau_c \,. \tag{3}$$

For $\tau_{\rm IGM}$, we take the optical depth of the Gunn-Peterson test (Gunn & Peterson 1965; Steidel & Sargent 1987) as

$$\tau_{\rm IGM} = \tau_{\rm GP} = \frac{4.14 \times 10^{10} h^{-1} n_{\rm H\,I}(z)}{(1 + z)(1 + 2q_0 z)^{1/2}} \,, \tag{4}$$

where $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. For τ_c, we use equation (41) of Paper I. Using equations (42) and (43) from Paper I and the above equations, we estimate the expected continuum depression.

3. RESULTS

First, we compare our results for the number density evolution with the *HST* observations. Generally, larger α_L provides more Lyα lines per unit redshift because the smaller intensity of the diffuse UV flux at redshifts $z < z_c$ causes a larger H I column density for a given impact parameter. Conversely, z_c smaller than 2 causes a smaller number density for fixed α_L. Here we fix the normalization of the UV flux at $z = 2$. Further, clouds expand for $z > z_c$, which affects the number density evolution even at $z < z_c$ in the case of smaller α_L.

Comparing our results with observations (Fig. 1), we see that models with $\alpha_L = 2$ and $z_c = 1.9$ for $\alpha_H = -4$ or $z_c = 1.8$ for $\alpha_H = -3$ are the most successful in reproducing the observed number density. For the observed number at low redshifts, we use equation (2) because in the minihalo model we expect the same H I column density distribution of Lyα clouds at low- and high-redshifts and the same equivalent width distribution (Paper I). If $\alpha_L = 4$ or 3.4, expected from the luminosity function of quasars (Bechtold et al. 1987; Boyle et al. 1991), the expected number density of Lyα lines becomes larger than that observed and grows with decreasing redshift. This is in the

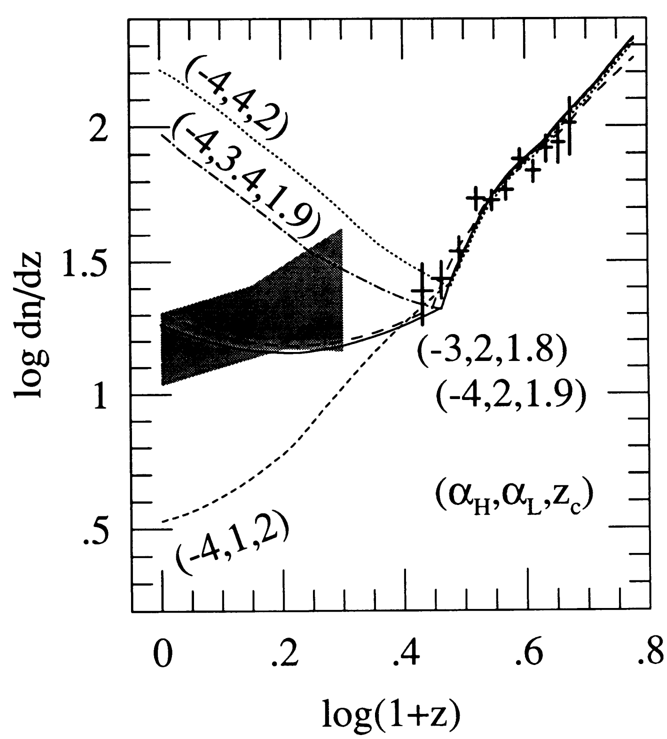

FIG. 1.—The number per unit redshift of Lyα clouds. *Crosses* denote observations by Lu et al. (1991), and the *hatched region* defines the expected number from the *HST* observations. *Curves* are calculated number densities for several sets of (α_H, α_L, z_c).

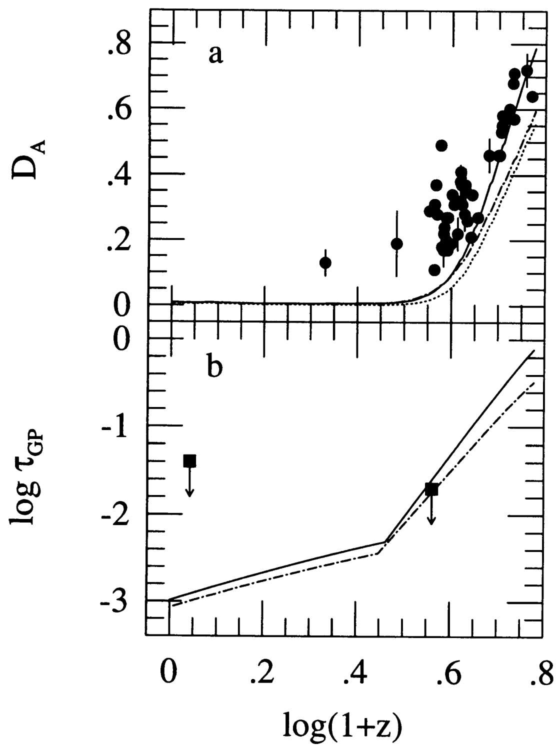

FIG. 2.—(*a*) The evolution of the continuum depression. Dots are observational results from Schneider et al. (1991). Solid line is a calculated model with $\alpha_H = -4$, $\alpha_L = 2$, and $z_c = 1.9$. Dotted line is a calculated model with the same parameters but the contribution of the diffuse neutral hydrogen is not included. Dash-dotted line is the case of $\alpha_H = -3$, $\alpha_L = 2$, and $z_c = 1.8$. (*b*) The evolution of the optical depth caused by the Gunn-Peterson effect. Squares are observed upper limits. *Solid line* and *dash-dotted line* are same as in Fig. 1.

opposite sense of the observations. However, if α_L is as small as 1, the small change in the UV flux has little effect on the evolution of clouds, and the clouds keep expanding even for redshifts, $z < z_c$. Thus, the intermediate case, $\alpha_L = 2$, seems most consistent with the number density observations. Charlton, Salpeter, & Hogan (1993) considered Lyα clouds as homogeneous slabs with external pressure and dark matter. The general tendency in the predicted evolution of the radiation field for their gravity-dominated clouds is consistent with our results; however, the cloud evolution at high redshifts has a large effect on the number density evolution at low redshifts for smaller α_L.

The calculated continuum depression evolves as in Figure 2*a*. Comparing the case $\tau = \tau_c$ (dotted line) and the case $\tau = \tau_c + \tau_{\rm IGM}$ (solid line), we find that the optical depth of diffuse intergalactic neutral hydrogen contributes to the continuum depression at only high redshifts. The case $\alpha_H = -3$ has smaller continuum depression than the case $\alpha_H = -4$; however, the observed continuum depression must be thought of as an upper limit since metal absorption lines between Lyα and Lyβ emission lines of QSOs also contribute. Given this uncertainty, our choice of model parameters do not conflict with the observations.

In Figure 2*b*, we show the calculated evolution of the optical depth due to the Gunn-Peterson effect and the observed upper limits: $\tau_{\rm GP} \le 0.04$ at $z = 0.1$ (Bahcall et al. 1991) and $\tau_{\rm GP} \le 0.02$ at $z = 2.64$ (Steidel & Sargent 1987). At low redshifts the expected optical depth is low enough, but at $z = 2.64$ it is almost same or somewhat larger than the observed limit. As seen in equation (4), the optical depth is proportional to the number density of neutral hydrogen. Using the expression of Black (1981), we obtain $n_{\rm H\,I} \sim \alpha({\rm H}) n_{\rm H}^2 / J_0 G_{\rm H}$ for highly ionized gas, where α(H) is the recombination rate of hydrogen, proportional to $T^{-3/4}$, and J_0 is the intensity of the diffuse UV flux. Thus $\tau_{\rm GP} \propto J_0^{-1}$. If we take the normalization of $J_{\rm LL}$ at $z = 2$ to be only 30% larger than one used in the calculations, the optical depth becomes smaller than the observed upper limit. We expect that the minihalo evolution is not affected significantly by such small increase of the diffuse UV flux and that the number density evolution will be about the same.

We can also roughly estimate the evolution of $\tau_{\rm IGM}$ with equation (4). Assuming $T_{\rm IGM} \propto (1+z)^t$ and taking $n_{\rm H} \simeq \Omega_{\rm IGM} \rho_{{\rm crit},0} (1+z)^3$, we obtain

$$\tau_{\rm IGM} \propto (1+z)^{-(3/4)t + 5 - \alpha_i - q_0}\,, \qquad (5)$$

where α_i is the exponent, α_L or α_H, of our model and $q_0 = 0.5$. In our calculation, $t \simeq 1$–2 and the calculated evolution fits well with above the equation.

From these calculations we can reproduce the number density evolution of the Lyα clouds at both high and low redshifts provided the diffuse UV flux is described by a broken power law with $\alpha_L = 2$ at $z \le 1.9$ and $\alpha_H = -4$ at $z > 1.9$ or with $\alpha_L = 2$ at $z \le 1.8$ and $\alpha_H = -3$ at $z > 1.8$. In the former case, we must take a little larger UV flux normalization, $J_{\rm LL} \ge 1.3 \times 10^{-21}$ ergs s^{-1} Hz^{-1} sr^{-1} at $z = 2$. These estimates are based on the assumption of constant comoving number density of minihalos.

4. DISCUSSION

In order to reproduce the number of Lyα lines per unit redshift at low redshifts, the preferred value of the exponent α_L is ~ 2. This means we predict a great more UV flux at $z = 0$ than in the case of $\alpha_L > 2$. At $z = 0$ the *Voyager* spacecraft tried to observe the background radiation from 912 to 1216 Å. The data provide $J_\nu < 6.08 \times 10^{-22} (\lambda/912$ Å) ergs s^{-1} cm^{-2} Hz^{-1} sr^{-1} (Holberg 1986; Henry 1991). The flux required by our model is well below this limit.

Boyle et al. (1991) estimated the evolution of the luminosity function of quasars for redshifts $z < 2.9$ and found strong luminosity evolution at $z < 2.0 \pm 0.1$ and constant comoving density. The evolution of the luminosity function is described by a power law, $L(z) \propto (1+z)^{3.5 \pm 0.05}$. We might suppose that the diffuse UV flux evolves with the same power-law function if the diffuse UV flux consists of the summed UV radiation from quasars. In this case, α_L would be 3.5 ± 0.05 and the expected number density of low-redshift Lyα clouds becomes larger than that observed, as seen in Figure 1. Furthermore, the amount of diffuse UV flux in this case is not enough to ionize the diffuse intergalactic neutral hydrogen in order to pass the Gunn-Peterson test. Some extra sources like young galaxies or obscured quasars are necessary.

Miralda-Escudé & Ostriker (1990) examined the evolution of diffuse UV flux considering contribution of obscured quasars and young galaxies. In their model 6, including the contribution of galaxies, they show α_L as small as ~ 2–2.5. Much more UV flux exists at low redshifts in this model and the exponent is quite similar to ours. Our results, consistent with Miralda-Escudé & Ostriker's, imply that the diffuse UV radiation comes not only from quasars but also galaxies.

By analyzing the proximity effect of the Lyα forest, Bajtlik, Duncan, & Ostriker (1988) estimated the diffuse UV flux as constant for $z = 1.9$–3.8. However, their method for analyzing the proximity effect may not be sensitive to redshift variance of the diffuse UV flux. In addition, we think that a clear correlation between the strength of quasar flux and the number deficiency of Lyα clouds near quasars has yet to be established. Failure to observe the number deficiency caused by quasars in front of an observed quasar (Crotts 1989; Dobrzycki & Bechtold 1991; Møller & Kjærgaard 1991) casts doubt on their model of the proximity effect and, hence, their estimation of the diffuse UV flux. We think that further work is required to determine the diffuse UV flux at high redshifts, and the proximity effect in the minihalos with $\alpha_H = -3$ or -4 should also be investigated.

We assume in our calculation that the comoving number density of clouds is constant. In the CDM scenario, minihalos result from density fluctuations and are destroyed by merging to create more massive systems. Such processes change the comoving number density of minihalos. Mo, Miralda-Escudé, & Rees (1993) estimated the number density evolution of minihalos with a simple model using the Press-Schechter formalism (Press & Schechter 1974). They found that the number density of Lyα lines decreases with slope similar to that of the observational data, $\gamma \sim 2.5$, owing to mergers into larger systems. Although their model is very simple, the result tells us that the merging processes significantly affects the number density evolution of the Lyα forest and that we must consider such processes in future work.

There remains the possibility that Lyα clouds at low redshifts do not belong to the same population as the Lyα forest at high redshifts. Maloney (1992) tried to model the number of Lyα lines observed toward 3C 273 (Bahcall et al. 1991; Morris et al. 1991) as due to disk galaxies. He concluded that either huge extended disk galaxies (500 kpc wide) or numerous dark galaxies are necessary to reproduce the number of the Lyα lines. Such galaxies seem too wide to be normal disk galaxies, while numerous dark galaxies might be thought of as dwarf galaxies or minihalos. The difference between dwarf galaxies and minihalos is the existence of stars which may change the distribution of neutral hydrogen. We cannot rule out the importance of such dwarf galaxies to the Lyα absorption lines.

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