Self-Absorption of Ionizing Radiation and Extended Narrow-Line Emission in High-Redshift QSOs

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ABSTRACT

We calculate the neutral hydrogen column density of self-absorption in QSOs predicted in a model where the QSOs are located in the same halos that contain the gas in damped Lyα absorption systems. The model is parameterized by the probability $P_0$ that any halo has an active QSO. We assume that the QSOs ionize the gas, but do not expel or heat it. The derived H I column densities produce negligible Lyman limit absorption, even in the lowest luminosity QSOs, with an optical depth of only $\sim 10\%$ for luminosity $L = 0.01L_*$, when $P_0 = 10^{-2}$. We also compute the He II Lyman limit self-absorption, which is slightly higher but still negligible. The self-absorption can be higher if the gas is highly clumped; only in this case the overall emissivity from QSOs could be significantly reduced due to absorption by the known damped Lyα systems, to affect the predicted intensity of the ionizing background or the epoch of He II reionization. The presence of the gas associated with damped absorption systems around QSOs could also be detected from the narrow Lyα emission line, which should have an angular extent of 0.1 to 1″ in typical high-redshift QSOs.

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

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1. INTRODUCTION

The origin of the ionizing background at high redshift has been a long-standing question (Bechtold et al. 1987; Miralda-Escudé & Ostriker 1990; Songaila, Cowie, & Lilly 1990; Madau 1991; Haardt & Madau 1996; Giroux & Shapiro 1996). The possible sources include QSO’s, star-forming galaxies, and the cooling radiation from hot gas in halos. One of the interests in measuring the intensity of the ionizing background is that, with the present understanding of the Ly\(\alpha\) forest as arising from the gravitational collapse of structure (see Rauch 1998 for a review), the observed mean flux decrement in the Ly\(\alpha\) forest provides a measurement of the parameter \(\Omega_b^2/\Gamma\), where \(\Omega_b\) is the baryon density in units of the critical density and \(\Gamma\) is the photoionization rate due to the background (e.g., Rauch et al. 1997, Weinberg et al. 1997, 1999; McDonald et al. 2000). Once \(\Gamma\) is known independently, the Ly\(\alpha\) forest provides a measurement of \(\Omega_b\) at low redshift which should agree with the values derived from Big Bang nucleosynthesis (O’Meara et al. 2001, Pettini & Bowen 2001) and from the Cosmic Microwave Background spectrum of temperature fluctuations (Netterfield et al. 2001, Pryke et al. 2001, Stompor et al. 2001), if our cosmological ideas are correct.

The proximity effect (see Scott et al. 2000 and references therein), consisting of the reduction of the number of Ly\(\alpha\) absorption lines in the vicinity of a QSO due to its own ionizing radiation, has been used to measure the intensity of the ionizing background, yielding a value \(\Gamma \simeq 2 \times 10^{-12}\). This method is subject to several possible systematic errors, including uncertainties in the QSO redshift, the effects of gravitational lensing of the QSO (which makes it seem more luminous), QSO variability over the photoionization timescale, or the clustering of gas around QSOs which may partially balance the ionization effect.

The simple counting of QSO’s as a function of flux in the sky can give us the emissivity of ionizing radiation, and by taking into account the absorption by the intergalactic medium, which is also directly determined in QSO spectra, we can calculate a lower limit to the background intensity under the assumption that sources other than QSO’s are not important (assuming that the escape fraction of ionizing photons from star-forming galaxies is negligible). This approach yields \(\Gamma \gtrsim 10^{-12}\), which implies a lower limit \(\Omega_b h^2 > 0.02\) (Rauch et al. 1997; McDonald et al. 2000, 2001).

In this paper, we examine if the ionizing radiation from QSOs could be significantly absorbed by hydrogen in the halo where the QSO is located, which normally produces the damped absorption systems, but is highly photoionized in the presence of the QSO. Although absorption by Lyman limit systems is taken into account when computing the intensity of the ionizing background, (Haardt & Madau 1996 and references therein), the absorbers have always been assumed to be uncorrelated with the QSOs, so any self-absorption arising in the halo of the QSO itself should be in addition to the one computed from the general
intergalactic gas. Of course, any such absorption should be directly observable in the QSO spectra; however, the self-absorption might be strong only in low-luminosity QSOs, where the gas is less highly photoionized, and surveys of Lyman limit systems have generally been done on the most luminous QSOs.

High redshift QSOs are also thought to be the sources that reionize He\textsc{ii} in the intergalactic medium, which could have occurred as late as \( z = 3 \) (see Heap et al. 2000 and references therein). It is also of interest to know if He\textsc{ii} ions in the QSO halos can produce significant self-absorption of the He\textsc{ii} -ionizing radiation from QSOs to delay the epoch at which the He\textsc{ii} reionization is completed.

Another interesting consequence of the photoionization of gas in the halo where the QSO resides is the extended narrow-line emission that should be produced by the recombinations, as recently discussed by Haiman & Rees (2001). We will examine the predicted flux in Ly\( \alpha \) emission.

2. MODEL

Our model for the self-absorption in QSO’s has two main parts. First, each QSO of luminosity \( L \) is assumed to be located in a Cold Dark Matter (CDM) halo of mass \( M \), with a unique relation \( M(L) \), and a probability \( P_0 \) that any halo will host a QSO. In other words, each halo can be either in an active state, in which case the QSO luminosity depends only on the halo mass, or in a quiescent state in which case there is no QSO (in reality we expect a dispersion in this \( M(L) \) relation; we will comment later on its effect on our results). Second, a spherical model of the gas density as a function of radius is adopted for each halo of mass \( M \), which reproduces the observations of damped Ly\( \alpha \) systems when the gas is all neutral. We then calculate the degree of ionization of the gas in photoionization equilibrium in the presence of the QSO flux, assuming that the density has not changed as a result of the photoionization heating or hydrodynamic winds from the QSO.

For the first part of the model, we can determine the relation \( M(L) \) once we know the distributions of both \( M \) and \( L \). We adopt the Press-Schecter formalism (Press & Schecter 1974; Bond et al. 1991) for the distribution of halo masses, with the CDM model with cosmological constant with parameters \( \Omega_\Lambda = 0.7, \Omega_m = 0.3, \Omega_b = 0.04, \) and \( h = 0.7 \). We use the parameter \( \delta_c = 1.69 \) (with top-hat filter) for the threshold overdensity required to form a halo, and the relations \( M = (4\pi/3) 18\pi^2 \rho_{\text{crit}} r_{\text{vir}}^3 \), and \( V_c^2 = GM/r_{\text{vir}} \) to relate halo mass, virial radius, and circular velocity.
For the QSO luminosity function (LF), we use the double power-law model of Pei (1995):

$$
\Phi(L_B; z) = \Phi^*/L_{B*}^\beta + (L/L_{B*})^\beta_k,
$$

where $L_B$ is the B-band luminosity. All our results will be presented at $z = 3$, when $L_{B*} = 1.2 \times 10^{13} L_{B\odot}$, and $\phi^* = 619.25 \text{Gpc}^{-3}$ (from Table 1 in Pei 1995, after correcting to our adopted cosmological model and Hubble constant). To convert to the luminosity per unit frequency at the Lyman limit, we convert to AB magnitude (see Oke 1974) using

$$
M_B = 5.4 - 2.5 \log(L_B/L_{B\odot}) = M_{AB}(4400\AA) + 0.12 \text{ (Schmidt, Schneider, & Gunn 1995)},
$$

and we use a spectral index $\alpha = 0.5$ from $\lambda = 4400 \text{Å}$ to $\lambda = 1216 \text{Å}$ (where $L_\nu \propto \nu^{-\alpha}$), and $\alpha = -1.77$ from $\lambda = 1216 \text{Å}$ to $\lambda = 912 \text{Å}$ (Zheng et al. 1997). This gives $L_{\nu*} = 1.18 \times 10^{31} \text{erg s}^{-1} \text{Hz}^{-1}$ at the Lyman limit.

Figure 1 shows the relation obtained between the B-band QSO luminosity and the halo mass, for four different values of $P_0$, by simply requiring that the total number of halos with mass greater than $M$ times $P_0$ is equal to the total number of QSOs with luminosity greater than $L$.

For the density profile of the gas in each halo, we use the same model as McDonald & Miralda-Escudé (1999): a spherically symmetric gas distribution with an exponential density profile,

$$
\rho(r) = \rho_0 \exp(-r/r_g).
$$

The two parameters of the mass distribution, the radius $r_g$ and the density normalization $\rho_0$, need to be chosen to match the observed column density distribution of the damped Lyα systems, when the density $\rho$ is assumed to be all neutral gas. We use the same parameters as McDonald & Miralda-Escudé (1999) at $z = 3$ (see their Fig.3): $c_g = r_g/r_{vir} = 0.04$, and $\rho_0$ determined by a fraction of the baryon mass in the halo in atomic gas form $f_{HI} = 0.1$, both assumed to be independent of halo mass. The resulting cumulative number of absorbers above a column density $N_{HI}$ per unit redshift is shown in Figure 2 as the thin line. The points in this figure are the observations from Storrie-Lombardi et al. (1996); to obtain these points, we divided the total number of absorbers shown in their Figure 4 by their total redshift pathlength, $\Delta z = 74.7$ (which we obtain by adding the redshift pathlength for their systems between $z = 2$ and $z = 3$, equal to 31.3, and for their systems at $z > 3$, which is 43.5, according to their Table 4).

The calculation of the self-absorption column density is then done simply by calculating the neutral fraction as a function of radius for each halo mass $M$ and corresponding QSO luminosity $L$, with the density profile in equation (2), computing the ionizing flux from the QSO at each radius, and assuming photoionization equilibrium with the recombination coefficient $\alpha_A = 4 \times 10^{-13} \text{cm}^3 \text{s}^{-1}$ (at an assumed gas temperature $T = 10^4 \text{K}$).
3. RESULTS

The predicted neutral hydrogen column density as a function of the QSO luminosity is shown in Figure 3. The Lyman limit optical depth, \( \tau_{LL} \), reaches unity at a column density \( N_{HI} = 1.6 \times 10^{17} \text{ cm}^{-2} \), indicated by the thin solid line. In general, \( \tau_{LL} \) is predicted to be quite small. Even for \( L = 0.01L_\star \), \( \tau_{LL} \simeq 0.1 \) for \( P_0 = 10^{-2} \). The predicted He \( \text{II} \) column density is shown in Figure 4. We have assumed a mean spectral index \( L_\nu \propto \nu^{-1.5} \) between the ionization edges of H\( \text{I} \) and He\( \text{II} \), which implies \( N_{\text{HeII}} = 13.4N_{\text{HI}} \) (we do not include self-shielding effects). Although the He\( \text{II} \) Lyman limit opacity is higher than for H\( \text{I} \), it still does not produce a very significant absorption. Integrating the quantity \( L e^{-\tau_{LL}} \) over the QSO luminosity function, we find that the overall reduction in the emissivity is a factor \((0.85, 0.94, 0.97, 0.99)\) for H\( \text{I} \), and \((0.71, 0.86, 0.93, 0.97)\) for He\( \text{II} \), for \( P_0 = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4} \), respectively. Notice that the reduction in the total ionization rate from the ionizing background is smaller than these factors because absorption is lower at frequencies above the Lyman limit.

It is easy to see that in our model, the H\( \text{I} \) column density is proportional to the halo mass divided by the QSO luminosity. At fixed \( r/r_g \), the gas density is constant, and the flux is proportional to \( L/r_g^2 \), so the neutral fraction goes as \( r_g^2/L \), and the column density goes as \( r_g^3/L \). Since \( r_g^3 \propto r_{\text{vir}}^3 \propto M \) (where \( r_{\text{vir}} \) is the virial radius of the halo), we have \( N_{\text{HI}} \propto M/L \). If the halo properties were independent of QSO luminosity, then of course \( N_{\text{HI}} \propto L^{-1} \). Our curves show a slower decrease of the column density with luminosity because of the increasing halo mass. The column density also decreases with \( P_0 \) at fixed \( L \) proportionally to the halo mass, which is shown in Figure 1.

Lyman limit absorption at the QSO redshift which decreases with luminosity. A possible difficulty is that, in photoionization equilibrium, an equal number of recombinations and photoionizations will take place, and about 38% of the recombinations are direct to the ground state and produce photons just above the Lyman limit frequency, smoothing the discontinuity due to the absorption. As we shall see below, the angular size of the damped systems from which these recombination photons would come is probably in the range \( 0.1-1'' \), and therefore difficult to resolve from the ground.

4. DISCUSSION

We have computed both the neutral hydrogen and helium column densities of self-absorption in QSOs in a model where the QSOs are located in the same halos that produce the damped Ly\( \alpha \) absorption systems. The model assumes that each QSO luminosity corresponds to a halo mass, and that the gas in damped Ly\( \alpha \) systems that is ordinarily present in a halo
in the absence of a QSO is only photoionized, but not expelled when the QSO is present.

The parameter that we vary in our model is the probability $P_0$ that a given halo has an active QSO. Large values of $P_0$ imply long-lived QSOs. For a radiative efficiency $\epsilon$, the Salpeter time for the growth of the black hole mass is $M c^2/(\epsilon L_{\text{Edd}}) \gtrsim 4 \times 10^8 \epsilon$ years. The typical time for the QSO luminosity function to evolve is $\sim 10^9$ years; if we require that the black hole mass function does not evolve on a shorter timescale, and that $\epsilon < 0.1$, then $P_0 < 0.04$. From Figure 3, this limits the self-absorption from the gas in damped Ly$\alpha$ systems to $\tau_{LL} < 0.02$ at $L_*$, and $\tau_{LL} < 0.2$ at $0.01L_*$.

An alternative to the assumption we made of a fixed relation between QSO luminosity and halo mass is that, even if QSOs are located in halos, there is little correlation between luminosity and halo mass. In this case, we can define a minimum halo mass $M_{\text{min}}$ that hosts QSOs above a certain luminosity $L_{\text{min}}$, with probability $P_0$; then, Figures 3 and 4 still give the HI and HeII column densities expected at $L_{\text{min}}$, but at higher luminosities the average column density would decrease as $N_{\text{HI}} \propto L^{-1}$, more rapidly than in Figures 3 and 4.

We note here a possible caveat of our model when $P_0 \gtrsim 10^{-2}$: the halos that account for most of the observed damped Ly$\alpha$ systems have velocity dispersions in the range 40 to 150 km s$^{-1}$, or, at $z = 3$, total masses of $10^{10}$ to $10^{12} M_\odot$ (e.g., Gardner et al. 1997). From Figure 1, this mass range corresponds to rather low QSO luminosities if $P_0 \sim 0.01$. This means that the absorption in QSOs of luminosities $\gtrsim 0.1 L_*$ is in this case due to halos with masses as large as $10^{13} M_\odot$, which could have different physical conditions than the more numerous lower-mass halos that are mostly responsible for damped Ly$\alpha$ absorbers.

The Lyman limit self-absorption shown in Figures 3 and 4 could be substantially increased if the absorbing gas is clumpy. We have assumed that the gas density in the halo is smoothly distributed, following the density profile in equation (2). However, the observations of multiple metal absorption lines associated with damped Ly$\alpha$ systems (e.g., Prochaska & Wolfe 1997) show that the gas is actually clumpy. The typical number of multiple absorbers that are observed tells us that the covering factor of these clumps is of order unity, but the clumping factor depends on the size of the clumps. The clumping factor may be not much larger than unity in a scenario like that proposed by Haehnelt, Steinmetz, & Rauch (1998), where the clumps are due to halo mergers and the complicated line structure arise in a continuous medium of halo gas from velocity caustics and moderate density variations. But the clumping factor could be high if the clumps were much smaller than the overall size of the damped Ly$\alpha$ systems. The absorbing column density increases proportionally to the clumping factor.

Another possible modification of the model we have used here is that the gas observed
in damped Ly$\alpha$ systems does not exist in every halo, but only in a certain fraction $f$ of halos. In order to preserve the rate of incidence of the observed absorption systems, we then need to increase the radius $r_g$ in equation (2) by a factor $f^{-1/2}$, and decrease the central density by $f^{1/2}$ to have the same column density distribution in the absence of ionization. With the same QSO luminosity, the HI column densities in the presence of the QSO are increased by a factor $f^{-1/2}$. Thus, making the damped Ly$\alpha$ absorbers bigger and less abundant would increase the amount of self-absorption, if QSOs are located in the halos that contain the damped Ly$\alpha$ systems. This could be the case, for example, if QSO activity usually takes place in recently merged halos with a lot of fresh gas.

4.1. Narrow-line emission

The absorption of the continuum ionizing radiation of a faint QSO by gas with velocity dispersions similar to those in damped Ly$\alpha$ systems implies that narrow Ly$\alpha$ emission lines should be observed, containing about a third of the energy that is absorbed in Lyman limit photons. This emission line could remain unresolved, since damped Ly$\alpha$ systems are small. For example, in a halo of mass $10^{12}$ $M_\odot$, $r_g = 3.15$ Kpc (see eq. [2]) at $z = 3$, corresponding to an angular size of 0.41″. This narrow emission line would be superposed with the common broad absorption lines in luminous QSOs.

The Ly$\alpha$ emission from halo gas around QSOs was recently considered by Haiman & Rees (2001). Their model assumes that all the baryons in a CDM halo are in an extended gas halo containing a hot and cold phase, with a large fraction of the baryons in the cold phase in most halos of interest (see their Fig. 1). In our model, with our choice of parameters $f_{HI} = 0.1$ and $r_g/r_{vir} = 0.04$, only 10% of the baryons are in the gaseous halo, but these are mostly concentrated within $\sim 10\%$ of $r_{vir}$. Since the gas density profile in the model of Haiman & Rees is roughly isothermal, their prediction for the abundance of damped Ly$\alpha$ systems in the absence of a central source should not be very different from that of our model, which we have shown agrees with the observations.

Generally, narrow Ly$\alpha$ emission may arise from gas over a wide range of radius and densities, not only associated with the damped absorption systems but with lower column density absorbers as well. The exponential gas density profile in equation (2) for our model is intended to approximate the effects of self-shielding when computing the number of damped systems in the absence of a central photoionizing source (when the photoionization is due to the external background), which should cause the neutral density to drop sharply outside the self-shielded region. But the total gas density is likely to drop more slowly. As an example, if $\rho_g \propto r^{-2}$, and the gas is mostly ionized, then the recombination rate per unit volume is
proportional to $r^{-4}$, and the Ly$\alpha$ surface brightness drops as $r^{-3}$. This "Ly$\alpha$ fuzz" should always be present in all halos as long as the gas is ionized, whether or not a central QSO is present. In the absence of a central QSO, the Ly$\alpha$ emission should have a core at the radius where the gas becomes self-shielded against the external background, or in other words, the radius at which Lyman limit absorption would be seen against a background source. When the QSO turns on, the gas within this core becomes ionized, and the steep power-law surface brightness profile can be extended inwards, making it much brighter. However, since Lyman limit systems are only $\sim 10$ times more abundant than damped Ly$\alpha$ systems, their typical extent in halos should be only $\sim 3$ times larger in radius than the damped systems, which as mentioned earlier would be hardly resolved from the ground. Therefore, the presence of a QSO can only increase the emitted Ly$\alpha$ in a central region of size $\sim 1''$, except in very massive and gas rich halos where the self-shielded region might be larger.

The Ly$\alpha$ surface brightness predicted by our model can be estimated from the H$\ I$ absorption column densities shown in Figure 3. Let us take, for example, the curves for $P_0 = 10^{-2}$ in Figures 1 and 3, and consider the case of a halo with $\sigma = 150 \text{ km s}^{-1}$, which implies a mass $10^{12} M_\odot$ at $z = 3$. Our model associates this halo with a QSO of $L_B \simeq 0.03L_* \simeq 10^{29.5} \text{ erg s}^{-1} \text{ Hz}^{-1}$, which has a Lyman limit absorption $\tau_{LL} \simeq 0.04$ from Figure 3. The frequency over which $\tau_{LL}$ decreases is $\Delta \nu \sim 10^{15} \text{ Hz}$, so the power absorbed in hydrogen photoionizations is about $10^{43} \text{ erg s}^{-1}$, and the power radiated in Ly$\alpha$ photons is $10^{42.5} \text{ erg s}^{-1}$, which at $z = 3$ produces a Ly$\alpha$ flux $\sim 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. If this flux is extended with a profile falling as $r^{-3}$, with a core of $\sim 0.5$ arc seconds (corresponding to the radius $r_g$ of the damped absorption system), the surface brightness would be $(10^{-17.5}, 10^{-19.5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ at angular separations of $(0.5, 3)''$, respectively. Just like the H$\ I$ absorption column density, this Ly$\alpha$ surface brightness can be increased by the clumping factor of the gas. In comparison, from Figure 2 of Haiman & Rees, they conclude that a similar halo (with $T_{vir} = 2 \times 10^6 \text{ K}$) would produce a Ly$\alpha$ surface brightness of $2 \times 10^{-16} \text{ Hz}$ at 3''. The large difference with our prediction of the Ly$\alpha$ surface brightness can be traced to the high clumping factor of the cold gas in the model of Haiman & Rees (see their eq. 1), and to their assumption that the Ly$\alpha$ flux comes mostly from a large region, close to the virial radius of the halo, whereas we assume it is much more concentrated to the center.

Recently, Steidel et al. (2000) have reported the discovery of two "Ly$\alpha$ blobs" of emission, with surface brightness $\sim 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, and angular scale of $\sim 10''$. While the surface brightness is similar to the expected value quoted above from a typical damped absorber once the gas is ionized, the angular scale is very large. These systems are therefore likely produced in exceptionally massive and gas rich halos.

To summarize, if extended gas is present in the halos where QSOs are located, with a
similar distribution as the average profiles derived from the observed damped Ly\(\alpha\) systems, then we should observe narrow-line Ly\(\alpha\) emission, extended over a region comparable to the size of damped Ly\(\alpha\) systems, which is typically less than 1\(^\prime\). As mentioned at the end of §3, there should also be extended emission of the Lyman continuum photons from direct recombinations to the ground state. We showed in Figures 3 and 4 that the absorption column densities expected are optically thin even for very low QSO luminosities; therefore, for fixed halo properties, the Ly\(\alpha\) fuzz should be easier to observe around fainter QSOs, which already produce sufficient flux to ionize all the halo gas, implying a Ly\(\alpha\) brightness independent of QSO luminosity (our Fig. 3 shows that \(N_{HI}\) decreases more slowly than \(L^{-1}\) with luminosity, which implies an increasing Ly\(\alpha\) surface brightness with luminosity, only because of the assumption in our model that brighter QSOs are located in more massive halos which contain more gas). If the absorption or the associated Ly\(\alpha\) emission are not observed at the predicted level, the conclusion should be that either QSOs are in halos that do not contain the average amount of gas that is inferred from the abundance of absorption systems, or the QSOs themselves have expelled this gas in winds.

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Fig. 1.— Relation between halo mass and QSO luminosity for different probabilities $P_0$. 
Fig. 2.— Cumulative number of absorbers per unit redshift as a function of H\textsubscript{I} column density. Squares are the observed values from Storrie-Lombardi et al. (1996); the thin solid line is the prediction of our model.
Fig. 3.— Neutral hydrogen column density as a function of QSO B-band luminosity for different probabilities $P_0$. The thin horizontal line indicates a Lyman limit optical depth of unity.
Fig. 4.— He\textsubscript{II} column density as a function of QSO B-band luminosity for different probabilities $P_0$. The thin horizontal line indicates a Lyman limit optical depth of unity.