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ON THE IMPORTANCE OF LOCAL SOURCES OF RADIATION FOR QUASAR ABSORPTION LINE SYSTEMS

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ABSTRACT

A generic assumption of ionization models of quasar absorption systems is that radiation from local sources is negligible compared with the cosmological background. We test this assumption and find that it is unlikely to hold for absorbers as rare as H I Lyman limit systems. Assuming that the absorption systems are gas clouds centered on sources of radiation, we derive analytic estimates for the cross section–weighted moments of the flux seen by the absorbers, of the impact parameter, and of the luminosity of the central source. In addition, we compute the corresponding medians numerically. For the one class of absorbers for which the flux has been measured, damped Lyα systems at $z \approx 3$, our prediction is in excellent agreement with the observations if we assume that the absorption arises in clouds centered on Lyman break galaxies. Finally, we show that consistency between observations of the UV background, the UV luminosity density from galaxies, and the number density of Lyman limit systems would require escape fractions of order 10%.

Subject headings: cosmology: theory — galaxies: formation — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The intergalactic medium (IGM) is thought to be photoionized by the UV radiation emitted by galaxies and quasars. Models of quasar absorption systems generally assume that the gas is exposed only to the mean background radiation that pervades the IGM. However, given that this background is produced by discrete sources, it cannot be strictly uniform.

The effect of fluctuations in the UV background (UVB) on the statistics of the forest of weak H I Lyα absorption lines, seen in the spectra of distant quasars, has been the subject of a large number of papers (e.g., Zuo 1992; Fardal & Shull 1993; Croft et al. 1999, 2002; Gnedin & Hamilton 2002; Linder et al. 2003; Meiksin & White 2003, 2004; Croft 2004; McDonald et al. 2005). These theoretical studies found that because most of the Lyα lines arise in the low-density IGM, far away from sources of ionizing radiation, global statistics of the forest are insensitive to fluctuations in the UVB. However, fluctuations in the H I ionization rate may become detectable in the Lyα forest at $z > 5$ (e.g., Meiksin & White 2003, 2004), and fluctuations in the He II ionization rate have already been detected at $z \gtrsim 2.5$ from comparisons of the H I and He II Lyα forests (e.g., Kriss et al. 2001; Smette et al. 2002; Shull et al. 2004).

In contrast to the Lyα forest, many metal and high column density Lyα absorbers are thought to arise in the extended halos of galaxies (Bahcall & Spitzer 1969), or at least in regions close to galaxies. It is therefore not obvious that neglecting the contributions of local sources of ionizing radiation, which is currently common practice, is justified for such absorption systems. Indeed, it has been argued on the basis of metal line column density ratios that there is evidence that some absorbers are exposed to a radiation field that is much softer than the general background, as would be expected if local stellar radiation were important (e.g., Giroux & Shull 1997; Boksenberg et al. 2003).

Here we show that if we assume that a certain class of absorbers resides in the extended halos[1] of a population of sources of UV radiation (such as galaxies), then one can estimate the typical flux from local sources to which the absorbers are exposed using only the luminosity density of the sources and the rate of incidence (i.e., number per unit redshift) of the absorbers . We do not need to know the relation between the cross section for absorption and the luminosity of the source.

We derive analytic formulae to estimate the moments of the local flux, as well as of the impact parameter and the luminosity of the central source, and apply them to galaxies and quasars. We find that UV radiation from local galaxies may well be important for absorbers rarer than Lyman limit (LL) systems (in agreement with the recent work of Miralda-Escudé 2005) and is likely far in excess of the background for absorbers as rare as damped Lyα (DLA) systems. We therefore conclude that the results from studies that employed ionization models of $N_{\rm H\,I} > 10^{17}$ cm^{-2} absorbers may need to be revised.

This paper is organized as follows. In § 2.1 we state and discuss the approximations and assumptions that we use to estimate the local flux. Section 2.2 contains the derivation of the mean flux, which we show to be close to the median for a wide range of models in § 4.2. Section 3 presents two complementary methods to compare the local flux to the background flux and contains some general conclusions. Using more restrictive assumptions, we derive expressions for the moments of the cross section–weighted flux, impact parameter, and luminosity in § 4.1. In §§ 5.1 and 5.2 we compute the contributions of galaxies and quasars to the local H I ionization rate and compare these with the background for various types of absorbers in § 5.3, where we also estimate the global escape fraction for H-ionizing photons. Finally, we summarize our main conclusions in § 6.

2. ESTIMATING THE FLUX

It is clearly beyond our means to compute the distribution of fluxes seen by a class of absorbers from first principles. Such a calculation would involve modeling radiative transfer in a characteristic volume of the universe, which would require specification of the full phase-space distribution of elements and sources, as well as of the spectra emitted by the sources. We would then

[1] By "halo" we mean a roughly spherical region centered on a source. It does not need to be virialized or even gravitationally bound.

still need to decide what we mean by the flux seen by an absorber as the absorbing gas clouds have a finite size. It is therefore necessary to make a number of simplifying assumptions. We present and discuss these assumptions in § 2.1 and estimate the mean flux in § 2.2. In § 4.2 we show that the median flux, which we can only compute by making additional assumptions, is generally close to the mean.

2.1. *Model Assumptions*

Consider a certain class of absorption systems with an observed rate of incidence $d\mathcal{N}/dz$. In practice, we define a class of absorbers by specifying an ion and a minimum column density $N_{\rm min}$. To enable us to compute the flux from local sources (e.g., galaxies) to which the absorbers are exposed, we make the following simplifying assumptions and approximations regarding absorbers with $N > N_{\rm min}$:

1. All absorbers reside in spherical halos that are each centered around a single source.
2. The flux seen by the absorber is dominated by its central source.
3. The probability that a sight line with impact parameter b relative to a source with luminosity L intersects an absorber residing in the halo around the source is $P_{\rm abs} = f_{\rm cov}$ for $b \leq R(L, N_{\rm min})$ and zero otherwise [i.e., the absorbing halo has a finite radius $R(L, N_{\rm min})$].
4. All of the gas contributing to the absorption resides at a distance $R(L, N_{\rm min})$ from the central source.
5. The central source is pointlike.
6. The product $f_{\rm cov} f_{{\rm esc},N}$, where $f_{{\rm esc},N}$ is the fraction of the emitted radiation that is able to propagate to the absorber, is independent of the luminosity of the source.

We now discuss each of these assumptions in turn.

The assumption that the absorbers are (or reside in) spherical halos centered on single sources will clearly break down for absorbers with gas densities around the cosmic mean, as these are typically distributed along sheets and filaments. However, it is probably a reasonable approximation for gas with densities $\gtrsim 10$ times the cosmic mean and/or for heavy elements whose distributions are likely concentrated toward galaxies.

The second assumption (radiation from sources in nearby halos is negligible) is conservative. We show in § 5.1 that it is likely to be a good approximation if the sources are galaxies and if the flux from the central source exceeds the background. However, if the sources are strongly clustered, then radiation from nearby halos could provide a nonnegligible contribution to the ionizing flux seen by the absorbers.

Assumption 3 ($P_{\rm abs} = 0$ for $b > R$) is probably reasonable provided that we define a class by its cumulative rate of incidence $d\mathcal{N}/dz(N > N_{\rm min})$. Since $d\mathcal{N}/dz(N > N_{\rm min})$ must decrease with increasing $N_{\rm min}$, the assumption implies that larger columns typically arise in sight lines with smaller impact parameters and hence that $f(N, z) \equiv d^2\mathcal{N}/dz\,dN$ is a decreasing function of N. Although it is possible to fabricate density distributions that would violate this assumption, it cannot be violated systematically because that would mean that the cosmic density of the ion in question, which is proportional to the integral $\int Nf(N, z)\,dN$, would diverge at large N. Moreover, the assumption that column density typically increases with decreasing impact parameter is supported by a large number of observational studies of the relation between absorption systems and galaxies (e.g., Lanzetta & Bowen 1990; Bergeron & Boisse 1991; Lanzetta et al. 1995; Chen et al. 1998, 2001a, 2001b; Bowen et al. 2002; Penton et al. 2002; Adelberger et al. 2003).

One might naively think that the assumption that column density increases with decreasing impact parameter would break down in the region within which the ionizing flux is dominated by the central source (i.e., the proximity zone). This would be a problem, as this is one of the regimes of interest here. However, the arguments given above indicate that this cannot generally be the case. Before discussing our remaining assumptions, we show that this is not a paradox.

Although the neutral hydrogen column density in a sight line passing close to a source can be small if the proximity zone is very large (as can be the case for bright quasars), the column density is unlikely to increase with the impact parameter for any given source. To see this, consider that in photoionization equilibrium the ionization balance is determined by the ratio of the ionizing flux to the gas density, which is independent of the radius if the flux is dominated by the central source and if the gas density profile is isothermal, which should be close to the situation of interest here. In general, for an optically thin gas in photoionization equilibrium that is irradiated by a central source we have $n_{\rm H\,I} \propto n_{\rm H}^2 \Gamma_{\rm H\,I}^{-1} \propto r^{-a}$ if $n_{\rm H} \propto r^{-(2+a)/2}$, where $\Gamma_{\rm H\,I} \propto r^{-2}$ is the photoionization rate for neutral hydrogen. Now consider a spherical cloud with density profile $n \propto r^{-a}$, where n is the number density of the species of interest. The column density in a sight line with impact parameter b is

$$N(b) \propto \int \frac{l}{(b^2 + l^2)^{a/2}} d\ln l. \tag{1}$$

For $a > 1$ the dominant contribution to the column density comes from $l \lesssim b$ and $N \sim n(b)b$. For example, for a singular isothermal sphere ($a = 2$) we have $N = \pi n(b) b \propto b^{-1}$, which is the scaling derived by Schaye (2001a, eqs. [3] and [4]) based on more general arguments. Hence, for reasonable density profiles the column density will increase with decreasing impact parameter.

There are two reasons why we would in general expect this trend to be even stronger for metals than for H I. First, since metals are produced in stars, it is natural to assume that their abundances relative to hydrogen are decreasing functions of R. Second, the ionization balance of many of the metals of interest will asymptote to a constant as more stellar radiation is added because (ordinary) stars essentially do not emit above 4 ryd and metals cannot be fully photoionized without these energetic photons.[2]

Assumption 4 is also conservative: assuming that all of the absorbing gas resides in a thin shell with radius R minimizes the flux from the central source. In fact, for a typical absorber it is probably a reasonable approximation to assume that all absorbing gas is at the maximum possible radius R. We already showed that for reasonable density profiles almost all of the absorption takes place in the densest part of the gas cloud that is intersected by the sight line, at radii slightly greater than b. The median impact parameter of random sight lines through a halo of radius R is $\langle b \rangle = R/\sqrt{2}$, slightly smaller than R. Hence, the column densities are typically dominated by gas at a distance $r \sim R$ from the source. We therefore expect that the assumption that all of the gas that contributes to the column density resides at a radius R will, for a typical absorber, result in an underestimate of the flux seen by the absorber by only a factor of a few.

[2] Note that this implies that for spectra with a sharp cutoff, such as those of galaxies, it is not true that the ionization balance depends only on the ratio of hydrogen-ionizing photons to the gas density (i.e., the ionization parameter).

Note that because of assumption 4, the flux seen by absorbers in some finite column density interval $N_{\rm min} \le N \le N_{\rm max}$ is identical to that seen by absorbers with $N > N_{\rm min}$.

Assumption 5 (pointlike sources) will be a good approximation for sight lines with $b \gg R_s$, where R_s is the radius of the source. For smaller impact parameters it will, however, lead to a large overestimate of the flux. Hence, our model should not be applied to absorbers with $R < R_s$.

Finally, assumption 6 ($f_{\rm cov} f_{{\rm esc},N}$ is independent of L) can be justified only by our ignorance. Given that we are still a long way off from being able to compute this factor from first principles, it would be hard to justify any particular dependence on L. Assuming that it is constant minimizes the number of free parameters.

The fraction of photons that is able to propagate to the absorber, $f_{{\rm esc},N}$, should not be confused with the conventional escape fraction $f_{\rm esc}$, which is the fraction of emitted photons that is able to escape the entire halo surrounding the source. They are different in general because the absorbers under consideration may in fact determine the global escape fraction $f_{\rm esc}$. Thus, we have $0 \le f_{\rm esc} \le f_{{\rm esc},N} \le 1$ in general with $f_{{\rm esc},N}$ asymptoting to $f_{\rm esc}$ for sufficiently small $N_{\rm min}$ and to unity for sufficiently large $N_{\rm min}$ (i.e., for column densities comparable to those surrounding the sources).

The covering factor $f_{\rm cov}$ $(0 < f_{\rm cov} \le 1)$ is unlikely to be much smaller than unity given that absorption-line systems typically contain multiple components and that sight lines that pass near to galaxies nearly always show absorption by metals and hydrogen (e.g., Bergeron & Boisse 1991; Lanzetta et al. 1995; Adelberger et al. 2003).

2.2. *The Mean Flux*

We are now in a position to estimate the flux from the central source to which a typical absorber is exposed. We compute the mean flux $\bar{F}$ by averaging the flux seen by an absorber over all source luminosities, weighted by the total cross section for absorption. Under the assumptions discussed above, a source of luminosity L provides a (proper) cross section for absorption of $f_{\rm cov}\pi R^2$ and the flux seen by the absorber is

$$F = \frac{L f_{{\rm esc},N}}{4\pi R^2}. \tag{2}$$

The average number of absorption systems per unit redshift and luminosity along a random sight line is

$$\frac{d^2\mathcal{N}}{dz\,dL}(z,\ L,\ N_{\rm min}) = \Phi(z,\ L) f_{\rm cov} \pi R^2(z,\ L,\ N_{\rm min}) \times \frac{c}{H(z)}(1+z)^2, \tag{3}$$

where Φ is the comoving luminosity function of the sources (i.e., the number of sources per unit comoving volume and per unit luminosity), c is the speed of light, and H is the Hubble parameter. The mean flux from the central source to which a class of absorbers with rate of incidence $d\mathcal{N}/dz(z,\ N > N_{\rm min})$ is exposed is thus

$$\bar{F}(z,\ N_{\rm min}) = \left(\int \frac{d^2\mathcal{N}}{dz\,dL}\,dL\right)^{-1} \int \frac{d^2\mathcal{N}}{dz\,dL} F\,dL \tag{4}$$

$$= \left[\frac{d\mathcal{N}}{dz}(z,\ N_{\rm min})\right]^{-1} \frac{c(1+z)^2}{4H(z)} f_{{\rm esc},N} \times f_{\rm cov} \int L\Phi(z,\ L)\,dL. \tag{5}$$

The important thing to note is that the result is independent of R. Thus, we do not need to specify the function $R(L)$ in order to compute the mean flux $\bar{F}$. Equation (5) is a key result of this paper; it provides a means to estimate the flux seen by a class of absorbers from its observed rate of incidence and the observed luminosity function of sources.

The mean flux is proportional to the luminosity density $\int L\Phi\,dL$. If the sources are galaxies, then this has the convenient consequence that $\bar{F}$ is approximately proportional to the comoving star formation density because most of the UV radiation is emitted by young stars.

If the luminosity function is a Schechter (1976) function,

$$\Phi(L)\,dL = \phi_* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*} \frac{dL}{L_*}, \tag{6}$$

then equation (5) becomes

$$\bar{F}(z,\ N_{\rm min}) = \left(\frac{d\mathcal{N}}{dz}\right)^{-1} \frac{c(1+z)^2}{4H} f_{{\rm esc},N} f_{\rm cov} k \phi_* L_* \Gamma(2+\alpha), \tag{7}$$

where $\Gamma(x)$ is the gamma function and $k = 1/(0.4 \ln 10)$ if ϕ_* is given per magnitude and $k = 1$ if ϕ_* is given per $\ln L$ (unless specified otherwise, we hereafter assume $k = 1$ and omit k from the equations). If, for some reason, the absorbers only reside in halos around objects with $L_{\rm min} < L < L_{\rm max}$, then the integral should of course be computed using these limits. For physically sensible luminosity functions (i.e., those that yield a finite luminosity density), $\int L\Phi\,dL \sim \Phi_* L_*$ and $\bar{F}$ will thus be insensitive to the limits as long as $L_{\rm min} \ll L_* \ll L_{\rm max}$.

3. COMPARING THE LOCAL FLUX TO THE BACKGROUND

To assess the importance of local sources, we need to compare the mean flux from the central source to the background radiation field. If the intensity of the background radiation is known, then we can directly compare it to our estimate of the mean flux (eq. [5]) and infer the critical rate of incidence below which local radiation dominates:

$$\left(\frac{d\mathcal{N}}{dz}\right)_{\rm crit} = \frac{d\mathcal{N}}{dz} \frac{\bar{F}}{F_{\rm bg}} \tag{8}$$

$$= \frac{1}{F_{\rm bg}} \frac{c(1+z)^2}{4H(z)} f_{{\rm esc},N} f_{\rm cov} \int L\Phi(z,\ L)\,dL, \tag{9}$$

where $F_{\rm bg}$ is the background flux. For sufficiently large $N_{\rm min}$ (i.e., small $d\mathcal{N}/dz$) $f_{{\rm esc},N} \to 1$ and the critical rate of incidence can be determined relatively accurately. But if $N_{\rm min}$ is much smaller than the column in front of the sources, then $f_{{\rm esc},N} \to f_{\rm esc}$ and the critical rate becomes proportional to the highly uncertain global escape fraction.

On the other hand, if we assume that the population of sources under consideration dominates the background, that the proper mean free path of the photons $\lambda_{\rm mfp}$ is known, and that $\lambda_{\rm mfp} \ll c/H(z)$ (such that cosmological redshift and evolution may be neglected), then the background flux is given by

$$F_{\rm bg} = (1+z)^3 \lambda_{\rm mfp}(z) f_{\rm esc} \int L\Phi(z,\ L)\,dL. \tag{10}$$

Substituting this into equation (9), we see that the critical rate of incidence becomes independent of both the source luminosity function and the intensity of the background:

$$\left(\frac{d\mathcal{N}}{dz}\right)_{\rm crit} = \frac{1}{\lambda_{\rm mfp}(z)}\frac{f_{{\rm esc},N}f_{\rm cov}}{f_{\rm esc}}\frac{c}{4H(z)(1+z)} \qquad (11)$$

$$= \frac{1}{4z_{\rm mfp}(z)}\frac{f_{{\rm esc},N}f_{\rm cov}}{f_{\rm esc}}, \qquad (12)$$

where $z_{\rm mfp}$ is the redshift interval corresponding to the mean free path.

For sufficiently large $N_{\rm min}$, $f_{{\rm esc},N} \rightarrow 1$ and the critical rate of incidence is inversely proportional to the highly uncertain global escape fraction $f_{\rm esc}$. But for sufficiently small $N_{\rm min}$, $f_{{\rm esc},N} \rightarrow f_{\rm esc}$ and the critical rate of incidence becomes independent of the escape fraction.

Hence, for column densities similar to those in front of typical sources, using equation (9) will probably give a more accurate estimate, whereas using equation (12) will likely yield the most accurate estimate for lower column densities. In general, we can measure the global escape fraction $f_{\rm esc}$ by comparing the two estimates, which comes down to comparing equation (10) with the measured intensity of the background. Of course, such a measurement is subject to the uncertainties in the luminosity density and in $\lambda_{\rm mfp}$. Moreover, if other sources contribute to the background, then the inferred escape fraction should be interpreted as an upper limit.

Equation (12) corresponds with equation (4) of Miralda-Escudé (2005) if we neglect evolution of the rate of incidence on timescales $\lesssim z_{\rm mfp}$, as we have done. However, Miralda-Escudé (2005) implicitly assumed $f_{\rm cov} = 1$ and $f_{{\rm esc},N} = f_{\rm esc}$. The last assumption may well break down for column densities similar to those in front of the sources, such as DLA systems.

The mean free path depends on the frequency of the photons. For energies between 1 and 4 ryd (i.e., between the ionization potentials of H I and He II), the mean free path depends mainly on the H I column density distribution of absorbers with column densities similar to those of LL systems ($N_{\rm H\,I} > 1.6 \times 10^{17}$ cm^{-2}). Unfortunately, this is exactly where the distribution is most uncertain because the H I absorption lines are on the flat part of the curve of growth, which makes it difficult to measure accurate column densities. Following Miralda-Escudé (2003), if we assume that the column density distribution is a power law $d\mathcal{N}/dN_{\rm H\,I} \propto N_{\rm H\,I}^{-\eta}$ with slope $\eta = 1.5$, as appears to be a reasonable fit at lower column densities (e.g., Kim et al. 2002), then it can be shown that $\lambda_{\rm mfp} = \lambda_{\rm LL}/\pi^{1/2}$, where $\lambda_{\rm LL}$ is the mean spacing between LL systems. This implies that $z_{\rm mfp}^{-1} = (d\mathcal{N}/dz)_{\rm LL}\pi^{1/2}$ and hence that the critical rate of incidence is proportional to that of LL systems:

$$\left(\frac{d\mathcal{N}}{dz}\right)_{\rm crit} \sim \frac{\sqrt{\pi}}{4}\left(\frac{d\mathcal{N}}{dz}\right)_{\rm LL}\frac{f_{{\rm esc},N}f_{\rm cov}}{f_{\rm esc}}, \qquad (13)$$

which is to be considered an order-of-magnitude estimate because it makes strong assumptions about the shape of the column density distribution. Note that this equation is less general than the previous ones because it applies only to photons with energy above (but near) 1 ryd.

If we assume that $f_{{\rm esc},N}f_{\rm cov} \sim f_{\rm esc}$, which is probably reasonable for $N_{\rm H\,I} \lesssim 10^{17}$ cm^{-2}, then we have $(d\mathcal{N}/dz)_{\rm crit} \sim (d\mathcal{N}/dz)_{\rm LL}$, in agreement with Miralda-Escudé (2005). Thus, we conclude that for hydrogen, local ionizing radiation is generally unimportant for $N_{\rm H\,I} \ll 10^{17}$ cm^{-2}. For LL systems local radiation is important, provided that the sources associated with these systems dominate the UVB (we expect this to be the case if the background is dominated by stars, as opposed to quasars). The rate of incidence of DLA systems is much smaller than that of LL systems (about a factor of 10 smaller at $z = 3$; Storrie-Lombardi et al. 1994; Storrie-Lombardi & Wolfe 2000), which implies that local sources dominate the H I ionization rate in DLA systems if the same population also dominates the UVB. Note that $\bar{F}$ may exceed $F_{\rm bg}$ by a very large factor if $f_{{\rm esc},N} \gg f_{\rm esc}$, as may well be the case for DLA systems.

4. A POWER-LAW MODEL FOR $R(L)$

Although we can compute the mean flux without specifying the function $R(L)$, the same is not true for a number of other interesting quantities, such as the variance of the flux and the cross section–weighted mean luminosity and impact parameter. It is, however, possible to obtain analytic solutions for these and other quantities if we make the following additional assumptions:

7. The luminosity function is a Schechter function.
8. The function R is a power law of L.

If

$$R = R_*\left(\frac{L}{L_*}\right)^{\beta} \qquad (14)$$

(assumption 8), then the normalization factor R_* is determined by the observed rate of incidence,

$$\frac{d\mathcal{N}}{dz} = R_*^2\pi f_{\rm cov}\phi_*\frac{c}{H}(1+z)^2\Gamma(1+\alpha+2\beta), \qquad (15)$$

which follows from integrating equation (3), and the flux (eq. [2]) is given by

$$F = F_*\left(\frac{L}{L_*}\right)^{1-2\beta}, \qquad (16)$$

where

$$F_* \equiv \frac{L_*f_{{\rm esc},N}}{4\pi R_*^2} \qquad (17)$$

$$= \left(\frac{d\mathcal{N}}{dz}\right)^{-1}\frac{c(1+z)^2}{4H}f_{{\rm esc},N}f_{\rm cov}\phi_*L_*\Gamma(1+\alpha+2\beta). \qquad (18)$$

Under these assumptions we can also solve numerically for the median luminosity and thus for the median flux and impact parameter. But before doing so in § 4.2, let us first consider what a reasonable value of β might be.

It is difficult to predict what the dependence of R on L should be, which is why it is so convenient that $\bar{F}$ is independent of this unknown function. In particular, it could well be different for different elements and for different $N_{\rm min}$. However, a reasonable guess might be that R scales with the virial radius, $R \propto r_{\rm vir} \propto M_{\rm vir}^{1/3}$, which yields $\beta = 1/[3(1-\gamma)]$ if $M/L \propto M^{\gamma}$. On the other hand, since $N \sim n(R)R$ (see § 2.1), which becomes $N \sim n(r_{\rm vir})r_{\rm vir}^2/R$ for a singular isothermal profile, it may be that $R \propto r_{\rm vir}^2$ [because $n(r_{\rm vir})$ is constant] and that $\beta = 2/[3(1-\gamma)]$ is thus a better guess.

Semianalytic models of galaxy formation (e.g., Benson et al. 2000) predict that mass-to-light ratios reach a minimum around L_*, but that the dependence of M/L on M is weak. For example, $\gamma \approx 0.1$, in which case we would expect $\beta \approx 0.37$–0.74, is a good fit to the predictions of Benson et al. (2000) (who modeled

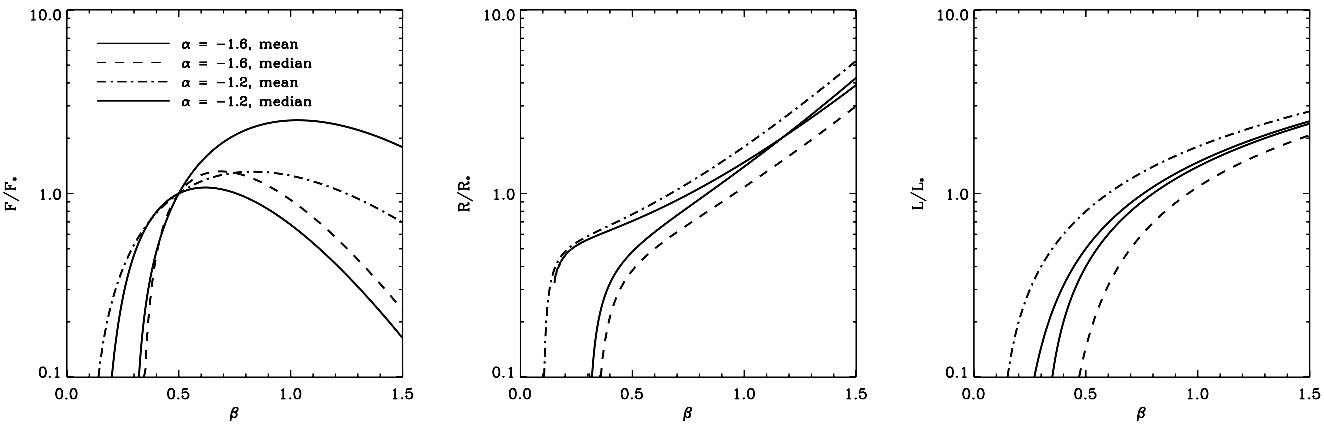

FIG. 1.—Flux from the central galaxy seen by the absorbers (*left*), the impact parameter relative to the central galaxy (*middle*), and the luminosity of the central galaxy (*right*) all plotted as a function of β, the exponent of the power law $R = R_*(L/L_*)^\beta$. In each panel both the (cross section weighted) mean and the median are shown for two different slopes of the faint end of the luminosity function: $\alpha = -1.6$ and -1.2. The quantities plotted are all dimensionless because the flux, impact parameter, and luminosity are plotted relative to the characteristic quantities F_*, R_*, and L_*. While the latter is the familiar characteristic luminosity appearing in the Schechter luminosity function (eq. [6]), the parameters F_* and R_* depend on β, the rate of incidence of the absorbers, the parameters of the luminosity function, and the factors $f_{\rm cov}$ and $f_{{\rm esc},N}$. Their values can be computed using eqs. (15) and (18). If the mean flux were plotted in physical units, rather than relative to F_*, then it would be independent of β. Note that the model predictions become unphysical at small β because $R_* \to 0$ as $\beta \to -(1+\alpha)/2$.

the B band at $z = 0$ for a ΛCDM model and a mass range $M \sim 10^{11}$–$10^{15}\ M_\odot$).

Assuming that $R(L)$ is indeed a power law, it is possible to measure β by imaging fields containing quasars. Chen et al. (2001a, 2001b) have done just this for the B band (the bluer bands are the most relevant here since we are interested in ionizing radiation) at $z < 1$. They found $\beta = 0.5 \pm 0.1$ for C IV and $\beta = 0.4 \pm 0.1$ for $N_{\rm H\,I} > 10^{14}$ cm^{-2}, in good agreement with our naive estimates.

Note that $\beta = 0.5$ is special as it gives a flux that is independent of luminosity: $F = F_*$. Hence, if β is indeed close to 0.5, as both observations and (handwavy) theoretical arguments seem to suggest, then this has the important implication that absorbers belonging to a given class [defined by their rate of incidence $d\mathcal{N}/dz(N > N_{\rm min})$] are nearly all exposed to approximately the same flux.

4.1. *Moments*

Armed with the fitting functions given by equations (6) and (14), it is easy to derive a number of characteristics of the absorbers. Substituting these functions into equation (5), we obtain the following expression for the mean flux:

$$\bar{F} = F_* \frac{\Gamma(2+\alpha)}{\Gamma(1+\alpha+2\beta)}. \tag{19}$$

The dependence of $\bar{F}$ on β is only apparent. To see this, note that $F_* \propto R_*^{-2} \propto \Gamma(1+\alpha+2\beta)$. As was shown in § 2.2, the mean flux is independent of $R(L)$ (and thus β) when expressed in physical units.

More generally, it is not difficult to show that the mth moment of the flux is given by

$$\langle F^m \rangle = F_*^m \frac{\Gamma[1+\alpha+m+2\beta(1-m)]}{\Gamma(1+\alpha+2\beta)}. \tag{20}$$

Note that $\langle F^m \rangle = F_*^m$ if $\beta = 0.5$. Similarly to the moments of the flux, we can derive the moments of the impact parameter

$$\langle R^m \rangle = R_*^m \frac{\Gamma[1+\alpha+\beta(2+m)]}{\Gamma(1+\alpha+2\beta)} \tag{21}$$

and the luminosity

$$\langle L^m \rangle = L_*^m \frac{\Gamma(1+\alpha+2\beta+m)}{\Gamma(1+\alpha+2\beta)}. \tag{22}$$

Recall that all of these moments are weighted by the cross section for absorption. Putting in numbers, for $\beta = 0.5$ and $\alpha = -1.6$ (-1.2) we obtain $\bar{L} = 0.9L_*$ ($1.3L_*$) and $\bar{R} \approx 0.5R_*$ ($0.8R_*$). Figure 1 shows $\bar{F}/F_*$ (*left*), $\bar{R}/R_*$ (*middle*), and $\bar{L}/L_*$ (*right*), all as a function of β and for two values of α as indicated in the figure.

4.2. *Medians*

Because F is a monotonic function of L (which is a consequence of our assumptions 4 [§ 2.1] and 8), the median flux $F_{\rm med} = F(L_{\rm med})$, and it can be seen from equation (3) that the median luminosity $L_{\rm med}$ can be obtained by solving the following equation:

$$\int_{L_{\rm min}}^{L_{\rm med}} \Phi R^2\, dL = \frac{1}{2} \int_{L_{\rm min}}^{L_{\rm max}} \Phi R^2\, dL. \tag{23}$$

It is easy to see from equation (16) that for $\beta = 0.5$ we have $F_{\rm med} = \bar{F} = F_*$ because in this case F is independent of L. The left panel of Figure 1 shows how the median flux and the mean flux compare for other values of β and for two values of the slope of the faint end of the luminosity function: $\alpha = -1.6$ and -1.2. The results shown in this figure are insensitive to $L_{\rm min}$ and $L_{\rm max}$ provided that $L_{\rm min} \ll L_* \ll L_{\rm max}$. The mean flux is typically greater than the median, but they differ by less than a factor of 2 for $0.35 < \beta < 0.85$ if $\alpha = -1.6$ ($0.22 < \beta < 1.05$ if $\alpha = -1.2$). Note that the power-law model for $R(L)$ becomes unphysical for low β because $R_* \to 0$ for $\beta \to -(1+\alpha)/2$.

The median impact parameters are shown in the middle panel of Figure 1, again for two values of α as indicated in the figure. As was the case for the flux, the medians are typically close to the means.

For the mean flux to be an order of magnitude greater than the median, we would require $\beta > 1.6$. Such a large value would be in conflict with the observations of Chen et al. (2001a, 2001b) and would probably imply an extremely low value of γ ($\gamma < -1.4$ for $\beta = 2/[3(1-\gamma)]$). Hence, although the median flux cannot be computed without specifying $R(L)$, it is within a factor of a few of the mean for plausible models. This gives us confidence that equation (5) gives a reasonable estimate of the typical flux seen by the absorbers. Thus, we expect that in general $F_{\rm med} \sim \bar{F} \sim F_*$.

5. APPLICATION TO OBSERVATIONS

The two types of sources that we consider are galaxies and quasars. We compute the characteristic flux at 1 ryd and the H I ionization rate for two relatively well measured luminosity functions: Lyman break galaxies (LBGs) at $z = 3$ (Steidel et al. 1999a) and quasars at $z = 2.3$ (Croom et al. 2004). Both of these luminosity functions were derived using samples selected in the rest-frame ultraviolet (UV). Hence, they do not include highly obscured sources, which may provide a substantial contribution to the total rates of star formation and accretion onto black holes in the universe. However, since such systems would likely also be absent from surveys of quasar absorbers, which typically target quasars that are exceptionally bright in the rest-frame UV, these luminosity functions are exactly what is needed for our purposes.

5.1. *Galaxies*

By combining their ground-based data with data from the Hubble Deep Field (HDF), Steidel et al. (1999a) find that, down to at least $0.1L_*$, the $z \approx 3$ luminosity function is well fitted by a Schechter function with parameters $\alpha = -1.60 \pm 0.13$, $\mathcal{R}_* = 24.48 \pm 0.15$ (AB magnitude), and $\phi_* = 4.45 \times 10^{-3}\ h^3$ Mpc^{-3} [for[3] $(\Omega_m,\ \Omega_\Lambda) = (0.3,\ 0.7)$ and $\langle z \rangle = 3.04$]. We note that because they relied on HDF data for $L < L_*$, which covers only a relatively small field, the faint-end slope may be subject to systematic errors due to cosmic variance.

$\mathcal{R}_*({\rm AB}) = 24.48 \pm 0.15$ at $z = 3.04$ yields $L_{\nu,*} = (5.72 \pm 0.79) \times 10^{28} f_{\nu,{\rm esc}}^{-1}\, h^{-2}$ ergs s^{-1} Hz^{-1} at rest-frame $\lambda = \lambda_{\rm eff}/(1+z) = 1715.35$ Å. Starburst99 (ver. 4.0; Leitherer et al. 1999) predicts $L_\nu(\lambda1715)/L_\nu(\lambda912) = 3.6$ for a continuous starburst (the result converges within 10 Myr) with a Salpeter initial mass function with upper and lower mass cutoffs of 100 and 1 $M_\odot$, respectively, and a metallicity $Z = 0.2\ Z_\odot$ [$L_\nu(\lambda1715)/L_\nu(\lambda912) = 4.1$ for $Z = Z_\odot$]. Using this value, we obtain $L_{\nu,*}(\lambda912) = (1.59 \pm 0.22) \times 10^{28} f_{{\rm esc},\lambda1715}^{-1}\ h^{-2}$ ergs s^{-1} Hz^{-1}. Equation (5) then gives

$$\bar{F}_\nu(\lambda912)_{{\rm LBG},z=3} = f_{\rm cov} \frac{f_{{\rm esc},N,\lambda912}}{f_{{\rm esc},\lambda1715}} \left(\frac{d\mathcal{N}}{dz}\right)^{-1} \times (4.43 \pm 0.90) \times 10^{-20}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}. \qquad (24)$$

Using the same Starburst99 model for the spectral shape, we find that this corresponds to an H I ionization rate of

$$\bar{\Gamma}_{{\rm H\,I},{\rm LBG},z=3} = (9.94 \pm 2.03) \times 10^{-12}\ {\rm s^{-1}} \times f_{\rm cov} \frac{\langle f_{{\rm esc},N} \rangle}{f_{{\rm esc},\lambda1715}} \left(\frac{d\mathcal{N}}{dz}\right)^{-1}, \qquad (25)$$

where $\langle f_{{\rm esc},N} \rangle$ is the average fraction of hydrogen-ionizing photons that escape to the absorber, weighted by the cross section for ionization. Neglecting evolution in the luminosity density, the values for $z = 2.3$ would be 0.90 times those for $z = 3$.

It is interesting to estimate the typical impact parameter of absorbers around LBGs. Assuming the power-law radius-luminosity relation (eq. [14]), equation (15) yields

$$R_{*,{\rm LBG},z=3} = \left(1.16 \times 10^2\ {\rm kpc}\right) \left(\frac{d\mathcal{N}}{dz}\right)^{1/2} [f_{\rm cov}\Gamma(2\beta - 0.4)]^{-1/2}, \qquad (26)$$

where we assumed $h = 0.7$. Using $\beta = 0.5$ gives $\bar{R} \approx (48\ {\rm kpc})(d\mathcal{N}/dz)^{1/2} f_{\rm cov}^{-1/2}$. To put this in context, DLA systems ($N_{\rm H\,I,min} = 2 \times 10^{20}$ cm^{-2}) have an observed rate of incidence $d\mathcal{N}/dz = 0.20$ at $z \approx 3$ (Storrie-Lombardi & Wolfe 2000). Hence, DLA systems are likely to have impact parameters of $\sim$10 kpc (see also Fynbo et al. 1999; Haehnelt et al. 2000). Comparing this with the half-light ratios of bright ($L \gtrsim L_*$) LBGs, which are typically about 2 kpc (0.″2–0.″3; Giavalisco et al. 1996), we see that the approximation of pointlike sources is likely to be reasonable. However, we do expect our model to overestimate the local flux for absorbers that are much rarer than DLA systems.

We can also use equation (26) to verify the validity of our assumption that the flux from nearby sources is negligible compared to that from the central source. Since galaxies with $L \sim L_*$ dominate the cosmic luminosity density, we would expect this assumption to be a good approximation if $(1+z)^3 R_*^3 \phi_* \ll 1$ if the galaxies were randomly distributed. From equation (26) we can see that this would imply $d\mathcal{N}/dz \ll 4 \times 10^2 f_{\rm cov}\Gamma(2\beta - 0.4)$. However, bright LBGs are observed to cluster: their inferred comoving correlation length is $r_0 = 5\ h^{-1}$ Mpc for a two-point correlation function of the form $\xi = (r/r_0)^{-1.8}$ (Steidel et al. 1999b). Hence, the expected number of galaxies within a distance R_* of an L_* galaxy is about $2.5[R_*(1+z)/r_0]^{-1.8}$ higher than for a random distribution, and we require $d\mathcal{N}/dz \ll 1 \times 10^2 f_{\rm cov}\Gamma(2\beta - 0.4)$ for the flux from nearby galaxies to be negligible. We see in § 5.3 that for $z \leq 4$ this condition is just satisfied if the flux (at around 1 ryd) from the central galaxy exceeds the background. However, given the approximate nature of this estimate, it is possible that we have underestimated the mean local flux by a factor of a few for classes of absorbers for which the flux from the central galaxy is not large compared with the background.

There is one class of absorbers for which the intensity of the local UV radiation has been measured: DLA systems with detectable absorption by C II*. Wolfe et al. (2004) have measured the UV flux at 1500 Å (rest frame) for the 23 absorbers in their sample of 45 $z \sim 2$–4 DLA systems for which they were able to obtain a positive detection of C II* absorption. By equating inferred cooling rates to grain photoelectric heating rates (given the measured dust-to-gas ratios), they find that their C II* absorbers are typically exposed to a flux that is within a factor of a few of $F_\nu \sim 4\pi 10^{-18.5} \approx 4 \times 10^{-18}$ ergs cm^{-2} s^{-1} Hz^{-1}. Our Starburst99 spectral template predicts $F_\nu(1500)/F_\nu(1715) = 1.12$, which yields $F_\nu(\lambda1500) = (2 \times 10^{-18}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}) f_{\rm cov} f_{{\rm esc},N,\lambda1500}/f_{{\rm esc},\lambda1715}$ for $d\mathcal{N}/dz = 0.1$ ($\approx 0.20 \times 23/45$, where 0.20 is the rate of incidence for $z \approx 3$ DLA systems measured by Storrie-Lombardi & Wolfe 2000). Thus, for the one class of absorbers for which the local UV flux has been measured, the prediction of our model is in excellent agreement with the observations. Measurements of the local flux based on H_2 lines confirm that the UV radiation field in DLA systems far exceeds the background (e.g., Hirashita & Ferrara 2005; Srianand et al. 2005).

The good agreement between our prediction for the flux to which DLA systems are exposed, which relied on the assumption that DLA systems arise in the halos of LBGs, and the measurement of Wolfe et al. (2004) suggests that DLA systems and

[3] Steidel et al. (1999a) quote $\phi_* = 1.6 \times 10^{-2}\ h^3$ Mpc^{-3} mag^{-1} for $(\Omega_m,\ \Omega_\Lambda) = (1.0,\ 0.0)$. We changed the units from per magnitude to per $\ln L$ by dividing by $0.4 \ln 10$, and we converted to $(\Omega_m,\ \Omega_\Lambda) = (0.3,\ 0.7)$ using the effective volumes listed in their Table 3.

LBGs may be drawn from the same population of galaxies, as has already been suggested on other grounds by Schaye (2001b) and Møller et al. (2002). If this is indeed the case, then we can read off the predictions of our model for the impact parameters and luminosities from Figure 1. For $\beta \approx 0.5$ and $z = 3$ we predict a median impact parameter med $(R) \approx 0.4R_* \approx 14$ kpc $\approx 1''.8$ (see eq. [26]) and a median luminosity med $(L) \approx 0.1L_*$.

5.2. *Quasars*

Using the double power-law fit to the luminosity function of quasars in the 2dF QSO redshift survey (Croom et al. 2004), we find $\int L\Phi(L)\,dL = 2.67 \times 10^{-6} L_*$ Mpc^{-3} and $M_{b_J,*} = -25.77$ for $(\Omega_m,\ \Omega_\Lambda,\ h) = (0.3,\ 0.7,\ 0.7)$ and $z = 2.3$. Assuming $b_J = B$, a power-law spectrum $F_\nu = F_\nu(\nu_{\rm LL})(\nu/\nu_{\rm LL})^{-\alpha_\nu}$, where $\nu_{\rm LL}$ is the frequency at the hydrogen Lyman limit, and a spectral index $\alpha_\nu = 1.8$ (Telfer et al. 2002), this gives $L_{\nu,*}(\lambda 912) = (5.23 \times 10^{30}$ ergs s^{-1} Hz$^{-1})f^{-1}_{{\rm esc},\lambda 1333}$ and thus a mean flux

$$\bar{F}_\nu(\lambda 912)_{{\rm QSO},z=2.3} = f_{\rm cov} \frac{f_{{\rm esc},N,\lambda 912}}{f_{{\rm esc},\lambda 1333}} \left(\frac{d\mathcal{N}}{dz}\right)^{-1} \times 5.05 \times 10^{-21}\ {\rm ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}. \quad (27)$$

For a power-law spectrum the H I ionization rate is $\Gamma_{\rm H\,I} = 9.51 \times 10^8 F_\nu(\nu_{\rm LL})/(3 + \alpha_\nu)$ s^{-1}. Hence, if there exists a population of absorbers that all reside in halos around QSOs, then such absorbers will on average be exposed to a local radiation field with an ionization rate

$$\bar{\Gamma}_{{\rm H\,I,QSO},z=2.3} = \left(1.00 \times 10^{-12}\ {\rm s^{-1}}\right) f_{\rm cov} \frac{\langle f_{{\rm esc},N}\rangle}{f_{{\rm esc},\lambda 1333}} \left(\frac{d\mathcal{N}}{dz}\right)^{-1}. \quad (28)$$

Since both $\bar{F}$ and the intensity of the UVB radiation are proportional to the luminosity density of the sources, the relative contributions of the central galaxies and quasars to $\bar{F}$ are identical to their relative contributions to the UVB.

However, although every quasar probably resides in a galaxy, only a few percent of galaxies host an active quasar (e.g., Steidel et al. 2002). Therefore, the mean flux from local quasars may not be very relevant to quasar absorption studies. Studies employing nonparametric statistics (such as the median and other percentiles) and studies using small samples of absorbers are unlikely to be significantly affected by local quasar radiation, unless the absorbing species requires the presence of a hard radiation source for its existence. It should, however, be noted that regardless of how small the fraction of time that a quasar is active, local radiation from quasars would be important if they are dormant for periods comparable to or smaller than the timescale for the establishment of ionization equilibrium. Although this timescale is typically very short for hydrogen ($\lesssim 10^5$ yr), it can be much longer for species with higher ionization potentials.

In the remainder of this paper we ignore radiation from local quasars.

5.3. *Comparison with the Background*

How does the flux from local sources compare to that from the extragalactic background? In § 3 we found that, relative to the background, the local flux is given by

$$\frac{\bar{F}}{F_{\rm bg}} = \left(\frac{d\mathcal{N}}{dz}\right)_{\rm crit} \left(\frac{d\mathcal{N}}{dz}\right)^{-1}, \quad (29)$$

where the critical rate of incidence can be computed using either equation (9) or equation (12). The former method requires a measurement of the luminosity density, the background flux, and the escape fraction to the absorber ($f_{{\rm esc},N}$), while the latter requires measurements of the mean free path and the ratio $f_{{\rm esc},N}/f_{\rm esc}$ and also requires one to assume that the sources associated with the absorbers dominate the background. As the absorber column density tends to the column in front of the sources, $f_{{\rm esc},N}$ asymptotes to unity, while for much lower absorber column densities it asymptotes to the global escape fraction $f_{\rm esc}$. Hence, provided that the mean free path is known and that the sources associated with the absorbers dominate the background, the second method is probably more reliable for all but the highest column densities. If the luminosity density, the background, and the mean free path are all known, then we can measure the global escape fraction $f_{\rm esc}$ by comparing the two methods.

We now apply both methods to hydrogen-ionizing photons. For other ions the calculation is entirely analogous to that for H I, except that a model of the spectral shape of the UVB is required because the rates of photoionization of heavier elements by the background have not been measured. For ions with ionization potentials $E_{\rm ion} < 4$ ryd we expect the critical rates of incidence to be similar to those of H I, but for ions with $E_{\rm ion} > 4$ ryd, such as O VI, the critical rates should be much smaller because stars (with the exception of Population III) emit very little radiation at these energies. Note, however, that even though local stellar radiation is unlikely to be important above 4 ryd, ionization models of O VI absorbers (as well as other ions with ionization potentials above 4 ryd) generally also use constraints from other species whose ionization balance is affected by the addition of radiation below 4 ryd.

First, we compute the critical rate of incidence using method 1 (i.e., eq. [9]). For the intensity of the UVB we use $\Gamma_{\rm H\,I}/(10^{-12}\ {\rm s^{-1}}) = (0.06, 0.67, 1.3, 0.9, 1.0)$ at $z = (0, 1, 2, 3, 4)$. These measurements were taken from[4] Davé & Tripp (2001) ($z = 0$), Scott et al. (2002) ($z = 1$), and Bolton et al. (2005) ($z = 2$–4). For redshift 3 we have already computed the mean ionization rate due to local sources (eq. [25]). We can scale this result to other redshifts if we assume that the luminosity density of ionizing radiation is proportional to the cosmological star formation density, for which we take $\dot{\rho}_*(z = 0) = 0.1\dot{\rho}_*(z = 1)$ and $\dot{\rho}_*(z > 1) = \dot{\rho}_*(z = 1)$ (e.g., Heavens et al. 2004 and references therein). We then find that

$$\left(\frac{d\mathcal{N}}{dz}\right)_{\rm crit} = (5,\ 9,\ 6,\ 11,\ 11) \frac{\langle f_{{\rm esc},N}\rangle f_{\rm cov}}{f_{{\rm esc},\lambda 1715,z=3}} \quad (30)$$

at $z = (0,\ 1,\ 2,\ 3,\ 4)$.

Second, we compute the critical rate of incidence using method 2, which reduces to equation (13) for H I, if we neglect the variation of the mean free path with frequency and if we assume that the H I column density distribution is of the form $d\mathcal{N}/dN \propto N_{\rm H\,I}^{-1.5}$ around the Lyman limit. Making this assumption and using $(d\mathcal{N}/dz)_{\rm LL} \approx (0.7,\ 1.0,\ 1.3,\ 2.0,\ 4.0)$ for $z = (0,\ 1,\ 2,\ 3,\ 4)$ (Péroux et al. 2005), we obtain

$$\left(\frac{d\mathcal{N}}{dz}\right)_{\rm crit} = (0.3,\ 0.4,\ 0.6,\ 0.9,\ 1.8) \frac{\langle f_{{\rm esc},N}\rangle f_{\rm cov}}{f_{\rm esc}} \quad (31)$$

[4] Where appropriate the measurements have been scaled to the currently favored cosmology ($\Omega_b h^2 = 0.0224$, $h = 0.71$; Spergel et al. 2003) using the relation $\Gamma \propto \Omega_b^2 h^3$ (e.g., Rauch et al. 1997).

at $z = (0, 1, 2, 3, 4)$. We stress that the ratio of f factors could be greater than unity for column densities similar to those shielding the sources.

Comparing equations (30) and (31), we find

$$\frac{f_{\rm esc}}{f_{{\rm esc},\lambda 1715,z=3}} = (0.06,\ 0.05,\ 0.09,\ 0.08,\ 0.16) \quad (32)$$

at $z = (0, 1, 2, 3, 4)$. These measurements of the global escape fractions result from the demand that the luminosity density due to LBGs gives rise to the measured UVB. Because the measurements of the luminosity density, the mean free path, and the intensity of the UVB are all uncertain by a factor of a few or more, these measurements should be taken as order-of-magnitude estimates only. Thus, we conclude that a global escape fraction $f_{\rm esc} \sim 10^{-1} f_{{\rm esc},\lambda 1715,z=3}$ is consistent with all the measurements. If quasars dominate the UVB, then the escape fraction should be smaller.

Steidel et al. (2001) measured $F_\nu(\lambda 1500)/F_\nu(\lambda 900) = 4.6 \pm 1.0$ from their composite LBG spectrum (after correction for intervening absorption), whereas our spectral template predicts an intrinsic value of $L_\nu(\lambda 1500)/L_\nu(\lambda 900) = 4.0$, implying that $f_{\rm esc} \sim f_{{\rm esc},\lambda 1500,z=3}$. Although this may be consistent with equation (32) within the errors (which are very poorly constrained), there is some tension between the two. However, since the galaxies studied by Steidel et al. (2001) were unusually blue, it is important to keep in mind that their measurements may not be representative for the population as a whole.

If $\langle f_{{\rm esc},N} \rangle f_{\rm cov} \sim f_{\rm esc}$, then local ionizing radiation becomes important for H I for LL systems. Absorbers with $N_{\rm H\,I} > 10^{19}$ cm^{-2} have rates of incidence much lower than LL systems (e.g., Péroux et al. 2005) and are thus dominated by local radiation. Since estimates of the local UV flux have generally not been available, the implication is that published results from ionization models of such systems may be significantly in error. Note that for $N_{\rm H\,I} > 10^{20}$ cm^{-2} the absorber columns are probably comparable to those in front of the sources, in which case $f_{{\rm esc},N}$ may be much greater than $f_{\rm esc}$, further boosting the local flux.

Comparison of the rates of incidence of metal line absorbers with the critical rates indicates that UV radiation from local galaxies may not be negligible for strong metal systems, such as those containing detectable absorption by ions in low ionization stages. For example, using the data from Boksenberg et al. (2003), who decomposed a large number of high-quality quasar absorption spectra into Voigt profiles, we find[5] $d\mathcal{N}/dz = 4.5$ for $\log N_{\rm min}$(C II) = 12 and $d\mathcal{N}/dz = 3.4$ for $\log N_{\rm min}$(Si IV) = 13, both at $z \approx 3$. These observed rates of incidence are likely to be overestimates of the true rates since many of the quasars in the sample of Boksenberg et al. (2003) were originally selected to contain DLA systems. Indeed, more than half of their C II systems with $\log N > 12$ and nearly half of their Si IV systems with $\log N > 13$ are associated with DLA systems. Other frequently studied metal line systems with low rates of incidence include Mg II systems ($d\mathcal{N}/dz \approx 1$ for systems with an equivalent width $W_\lambda > 0.3$ Å at $z \sim 1$; Steidel & Sargent 1992).

It is difficult to predict exactly how the physical properties inferred from ionization models would change if local radiation had been taken into account because the effects will depend on the ions involved, as well as on the rate of incidence of the absorbers. However, if the column density of H I is used as a constraint, then the addition of local radiation will generally tend to increase the inferred density and to decrease the inferred size of the absorber. The effects on the abundances of heavy elements are more difficult to predict and will likely be different for different elements.

6. CONCLUSIONS

We have constructed an analytic model to estimate the characteristic flux from local sources of radiation to which quasar absorption systems are exposed. Since many studies have shown that fluctuations in the UVB are unimportant for the low column density H I Lyα forest (at least at $z < 5$), we focused on the rarer systems with higher H I columns and/or detectable absorption by heavy elements.

The most important assumptions we made are that the absorption arises in a roughly spherical gas cloud centered on a source of ionizing radiation, that radiation from other nearby sources is negligible, and that the probability that a sight line intersects a total column density $N > N_{\rm min}$ is zero beyond some radius R (which may depend on the luminosity L and $N_{\rm min}$). The first assumption will break down for the low column density Lyα forest, which is thought to arise in a web of sheetlike and filamentary structures, but is likely to be reasonable for the rarer systems with higher H I columns and/or detectable absorption by heavy elements. The second assumption is conservative. We argued that it is likely to be a reasonable approximation for those absorbers for which we predict the flux from the central galaxy to exceed the background (around 1 ryd). The third assumption implies that higher columns arise in sight lines with smaller impact parameters, which we argued must typically be the case.

We showed that the mean flux from the central galaxy is proportional to the luminosity density of the sources and inversely proportional to the rate of incidence $d\mathcal{N}/dz(N > N_{\rm min})$ of the absorbers, but that it does *not* depend on the function $R(L,\ N_{\rm min})$. Assuming a power-law dependence $R \propto L^\beta$, we derived analytical expressions for the cross section–weighted moments of the flux, of the impact parameter, and of the luminosity. In addition, we computed the corresponding medians numerically. We found that for reasonable values of β, the distribution of fluxes is narrow and the mean (which is independent of β) is of the same order of magnitude as the median. For the special case of $\beta = 0.5$ all absorbers belonging to a class with a given rate of incidence are exposed to the same flux. Interestingly, both observations and naive theoretical arguments suggest that β is close to this value. This implies that there exists a characteristic flux to which absorbers with $N > N_{\rm min}$ are exposed, which can be estimated using equation (5).

We applied our model to two relatively well studied sources of ionizing radiation: LBGs at $z \approx 3$ and quasars at $z \approx 2$. We argued that galaxies are more relevant to quasar absorption systems because quasars are thought to be dormant for most of their lifetimes.

Our predictions are in excellent agreement with the observations for the one class of absorbers for which the flux has been measured: DLA systems at $z \approx 3$ with detectable absorption by C II*. Since our calculation assumed that the absorbers are centered on LBGs, this agreement suggests that DLA systems and LBGs may be drawn from the same underlying population of galaxies. We predicted (for $\beta \approx 0.5$) that DLA systems at $z \approx 3$ typically have impact parameters of order 10 kpc and that the median luminosity of their LBG counterparts is about $0.1L_*$.

[5] The columns quoted are integrated over the systems (i.e., the columns of the individual Voigt profile components were summed) and the rates of incidence are for systems at redshift $z = 2.5-3.5$. We only used data with observed wavelength redward of the quasar's Lyα emission line and with a redshift more than 4000 km s^{-1} blueward of the redshift of the quasar.

Predictions for classes of absorbers with other rates of incidence can easily be obtained from the expressions derived in §§ 2 and 4.

We used two different methods to compare the mean, local flux to the background. The first takes the luminosity density and the escape fraction to the absorber as inputs and requires knowledge of the background intensity. The second takes the mean free path for photons and the ratio of the escape fraction to the absorber and the global escape fraction as inputs and relies on the assumption that the sources associated with the absorbers dominate the background. We found that consistency between the two methods, which comes down to the requirement that the observed sources make up the observed background, requires a global escape fraction of order 10%.

For absorbers as rare or rarer than LL systems (which have $d\mathcal{N}/dz \approx 2$ at $z = 3$), local H-ionizing radiation becomes important. (Sub-)DLA systems are likely dominated by local radiation. Studies that have modeled the ionization balance of such systems assuming that they are exposed to the background only may therefore have produced spurious results.

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